PICOSECOND TIME MEASUREMENTS WITH A LINEAR ACCELERATOR AND RF SEPARATOR*

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Summary

A picosencond time measurement method is described based on the microwave properties of beams from electron linear accelerators or from possible remodulated external proton beams at proton synchrotrons. A conventional RF separator (RFS) is used operating at the same frequency as the microwave structure of beams and driven by the same master oscillator which modulates the beam. For example, the 2856 MHz microwave at SLAC corresponds to 350 psec between beam RF buckets; accelerated electrons with an RF phase bite of about 5 degrees are time structured and correspondingly have about 5 psec time spread in every 350 psec interval. Charged particles produced in interactions or decays originate with this time structure. An RFS is placed at the last stage of a double focussing spectrometer, providing a lever arm between it and the final (few mm) small spot size focus. Reference calibration charged particles are timed by setting the RFS relative phase to null deflections. Other observed particles arriving at different times than this standard are deflected a few tenths of a mm per psec of delay. A multi-wire proportional chamber (MWPC) having a 0.05 mm space resolution can provide time measurements with sub-picosecond resolution. The technique is used in an experiment to search for changes in the velocity of light with high energy photons at SLAC. The devised timing method is presented and the properties of a new, fine space resolution MWPC is demonstrated.

Introduction

One inherent value of microwave properties of beams from linear accelerators and remodulated external beams from synchrotrons is the availability of a fine time structure which makes possible timing measurements with picosecond resolution. The timing spread of these beams is determined by the microwave phase bite producing RF buckets of a few picosecond duration, separated in time by the period of the modulator frequency. However, the timing resolution made available by these beams is far beyond the capability of conventional particle detectors. For example, the timing spread in the best experimental photomultipliers is typically 600 psec under controlled laboratory conditions. Therefore, to take advantage of the available timing resolution, the applied particle detector system must also be based on a microwave technique. Such a method is devised for charge particles, based on the use of a conventional RF separator (RFS) which is installed in a focussing spectrometer, prior to the location of the final focal plane. A fixed deflection lever arm is provided by the distance between the RFS half-length position and the final focal plane where a small spot size is formed. In this application the RFS must operate at the same frequency as the microwave structure of the beam, by driving the separator with the same master oscillator which modulated the beam. Moreover, to be effective the technique must provide safeguards against short term instabilities due to pulsed beam steering and modulator amplitude variations and against long term instabilities caused by temperature changes, drifts and other beam geometrical effects.

Reference particles of fixed momentum produced in interactions or decays, originate with the same time structure as that of the incident beam. These particles are accepted by the spectrometer. The timing of these reference calibration charged particles is obtained by setting the RFS relative phase to null deflection. Hence, these particles receive no deflection and form a small spot at the last focus of the spectrometer with a certain shape and position which are measurable. Information on the shape and position of this spot is obtained by using a high space resolution x-y coordinate measuring detector, such as a two-dimensional multi-wire proportional chamber (MWPC) placed at the final focus. Other particles also accepted by the spectrometer, arriving at different times than this standard, are now deflected by the RFS. Depending on early or late arrivals, these particles form spots on one side or the other of the standard spot. The amount of deflection is proportional to the relative RF phase angle which is experienced by traversing particles. The particle arrival time determines the RF deflection phase angle which is translated to a deflection coordinate in space. The sensitivity in these measurements is determined by the microwave frequency, the RFS deflection amplitude, the deflection lever arm and the resolution of the space coordinate measuring detector.

In the following we demonstrate the application of this general technique by its usage in a particular experiment. The experiment[1] is a search for changes in the velocity of light with high energy photons, using the SLAC accelerator facility to provide a flight path of about 1 km for up to 15 GeV photons. We show that in statistical samples the method can yield a sensitivity of sub-picosecond timing measurement in the relative arrival times between reference particles and 15 GeV photons.

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Experimental Setup of Picosecond Timing Spectrometer

The accelerated electron beam of SLAC has a microwave structure of 2856 MHz. This corresponds to having 350 psec between beam RF buckets. Accelerated electrons with an RF phase bite of about 5 degrees are structured in time and accordingly have about 5 psec time spread in every 350 psec interval. With this microwave time structure each acceleration pulse is 1.6 μsec in duration which if need be, can be prepared to have a duration of down to 0.1 μsec. Accelerated electrons of 15 GeV are intercepted by a thin radiator placed in the vacuum beam pipe at the straight section of sector 22. This is a rotating target at 600 rpm which intercepts the beam 10 times/second.

As shown in Fig. 1, gamma-rays of energies $E_\gamma \leq$ 15 GeV are produced at the sector 22 radiator T_o and travel a distance of 1075 meters along with 15 GeV electrons. In this arrangement electrons of fixed energy are used as the time reference calibration particles. The timing spectrometer is based on a beam transport geometry which is designed to distinguish incident gamma-rays from incident electrons by imaging two distinct conversion targets; one emitting positrons from the pair-production process by incident gamma-rays and the other emitting positrons from the trident process by incident electrons. The spectrometer is actually a beam line with three focussing stages which is tuned to accept these positrons at a fixed momentum of say 14.5 GeV/c, with a momentum acceptance of $\Delta p/p \leq 1\%$. This is shown schematically in Fig. 1. The first stage of the spectrometer is mainly composed of existing electron beam switchyard equipment. The last two stages of the spectrometer is actually a retuned version of the first two stages of an existing RF separated secondary beam which is normally used with the 82 inch hydrogen bubble chamber (beam line 6). The target ordinarily used for beam line 6 is removed and instead an auxiliary bending magnet near that location is placed to turn the positrons by an angle equal to the secondary particle production angle for beam 6.

As shown schematically in Fig. 2 in a more detailed form, the positron source for the three stage spectrometer is a pair of conversion targets especially arranged and mounted in the field of the vertical bending magnet, B60. Thus, electrons and gamma-rays emanating from the primary target T_o at sector 22, some 1075 meters upstream, illuminate the conversion targets uniformly both in space and time throughout a beam spill. This uniformity of illumination is designed to make the timing spectrometer insensitive to geometrical drift effects of the accelerator and beam. The purpose of the beam line with the special conversion target arrangement is to form two small positron spots which are displaced vertically at the detector. The spectrometer optics are such that positrons in the lower spot are produced almost entirely by incident electrons at the conversion target T_1 and positrons in the upper spot are produced almost exclusively by incident gamma-rays at the conversion target T_2. The mechanism for making the distinction between the origin of the positrons in the two spots is illustrated in Fig. 2 and Fig. 3. T_1 and T_2 are thin sheets of material which together cover the entire area illuminated by electrons and gamma-rays, defined by the collimator PC60. T_1 lies in the upper half of the vertical plane and T_2 in the lower half.

Shown in Fig. 2 are the central rays of four "positron beams" emerging from B6C which are produced in four distinct combinations of incident particle and conversion target. These are the following cases: 1) Electrons of maximum energy E^- incident on T_1: positrons of energy $E^+ < E^-$ emerge in the direction of the spectrometer-beam axis and propagate through the transport system (E^+ is the energy accepted by the tuned secondary beam line). 2) Gamma-rays of maximum energy E^- incident on T_2: positrons of energy E^+ emerge in the direction of the spectrometer-beam axis and also propagate through the transport system as in case 1. 3) Electrons incident on T_2: here positrons emerge with a relative downward angle $\varphi_2 \sim \ell_2/E^-$ and are intercepted by a collimator in the remainder of the transport system. 4) Gamma-rays incident on T_1: in this case positrons emerge with a relative upward angle $\varphi_1 \sim \ell_1/E^-$ and as in case 3, are intercepted by a collimator. Thus, the image of each target corresponds uniquely to the identity of each incident particle.

The spectrometer geometrical acceptance is defined by the following collimators: a) an entrance aperture located near the first quadrupole set, Q60/61, b) two horizontal slits, displaced from the axis vertically and separated by 1 cm, placed at F1; c) an exit aperture located near the final quadrupole set, 6Q3/4. In the vertical plane, the quadrupole sets Q60/61 and 6Q1/2 form a positron image of T_1 and T_2 at F_1 in which positrons from electrons on T_1 (case 1) illuminate the upper slit and positrons from gamma-rays on T_2 (case 2) illuminate the lower slit. At this point, the axial displacement of T_1 and T_2 is not significant. Positrons of cases 3 and 4 are now intercepted by either the entrance collimator or the collimation at F_1. The last stage of the spectrometer-beam images F_1 on the detector both horizontally and vertically and recombines momentum to form two distinct "electron induced" and "gamma-ray induced" small spots. In the horizontal plane, the location of the conversion targets is treated as an aperture. That is, the quadrupole sets Q60/61 and 6Q1/2 couple the conversion targets and F_1 by parallel-to-point optics horizontally, whereas vertically, the coupling is by point-to-point optics. Finally, from F_1 to the detector the optics are the same both horizontally and vertically. Figure 3 illustrates to scale, the details of the vertical optics in the target-collimator arrangements, by means of a vertical phase space diagram projected at the conversion targets. The background of positrons from incident gamma-rays in the "electron induced" final spot is expected to be less than 10^{-2}; and correspondingly, the background of positrons from incident electron in the "gamma-ray induced" final spot is expected to be much less than this. From Fig. 3 it is evident that by steering in the vertical plane, using other magnets in the spectrometer which are not shown in Fig. 1, it is possible to image at the final focal plane only the conversion target T_1 or only T_2. Where normally the designed spectrometer-beam optics provide final dual spots uniquely due to e-γ, this vertical steering makes possible to obtain also dual spots strictly due to only e-e or only γ-γ incidence. This capability is necessary to make relative measurements possible of image separations between e-e and e-γ modes or between γ-γ and e-γ dual spots. Thus, reliance on absolute spatial measurements are avoided and geometrical systematic effects are removed in the actual timing measurement. The interchanging of the roles of T_1 and T_2, for example by placing T_1 at ℓ_2 and T_2 at ℓ_1 in Fig. 2, is accomplished equivalently by making a 180° flip in the relative microwave phase of the RFS. Thus, the conversion targets T_1 and T_2 are placed in stationary positions as shown in Fig. 2. These targets are designed to flip in or out of the B60 magnet aperture. They are made of $A\ell$, and insulated to provide a secondary emission signal for monitoring purposes.

Timing With High Resolution MWPC

A high spatial resolution MWPC is designed, fabricated and tested for application in the timing spectrometer. The sensitivity of the timing spectrometer is such that 1 degree of RF relative phase corresponds to 0.973 psec and 1 psec of relative delay is translated to 0.18 mm deflection for 15 GeV particles, at the final focal plane where the MWPC is located.

In the MWPC the high voltage anode planes have a wire spacing of 2 mm. The signal planes are orthogonal to these and have a wire spacing of 1 mm. Anode and signal planes are separated by 1.6 mm. Two multi-tapped delay lines are used to collect induced signals from each x,y signal plane. The resultant signal from each plane is due to proportional charge collection from several neighbouring wires, producing a gaussian-like pulse in which the center-of-charge of this distribution is an accurate coordinate of the passage of a charged particle. There is a fixed delay of 10 nsec between each signal wire of 1 mm separation. A gas mixture of 90% Ar and 10% CO_2 at 1 atmospheric pressure is used and the operating voltage of the chamber is at 1530 volts.

To simulate the characteristics of expected dual spots of the timing spectrometer, a linearity test is made with an Fe^{55} X-ray collimated by an aperture of 0.3 mm. The source is mounted on a precision microscope travelling platform. The centroid of coordinate distributions at fixed source positions is obtained and the result is displayed in Fig. 4. The picture inserted in this figure is the MWPC with an active area of 3.75×3.75 cm^2. The resulting standard deviation from a linearity response is 44 microns. Thus, it is demonstrated that the timing spectrometer is sensitive to sub-picosecond timing measurements in statistical samples, for relative delays at the level of 0.2 psec.

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References

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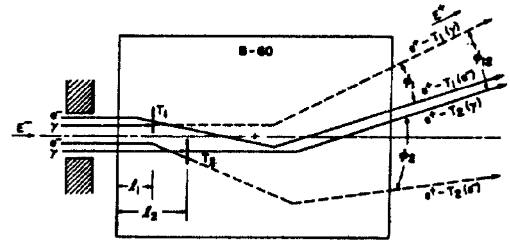
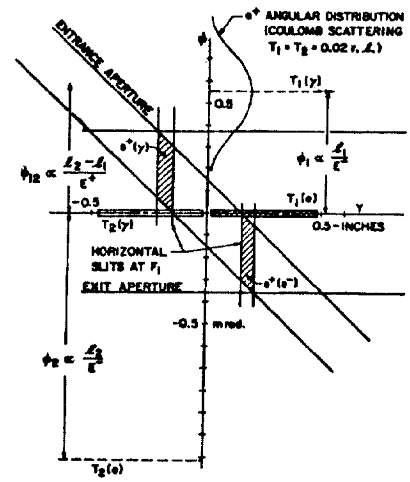
1. Z.G.T. Guiragossián, G. Rothbart, M. R. Yearian, R. Gearhart and J.J. Murray, SLAC proposal No. E-96 (July, 1972).



SCHEMATIC RAY DIAGRAM AT CONVERSION TARGETS IN B-60 MAGNET

Figure 2



BOUNDARIES IN VERTICAL PHASE SPACE AT CONVERSION TARGETS

Figure 3

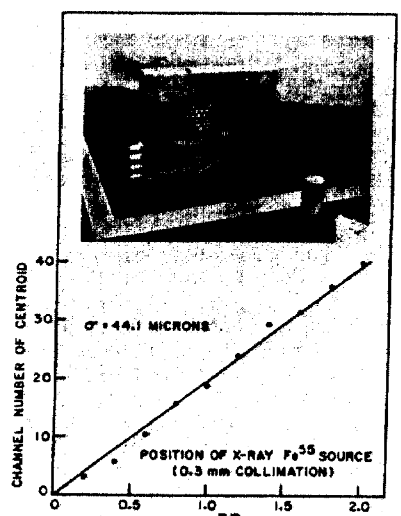
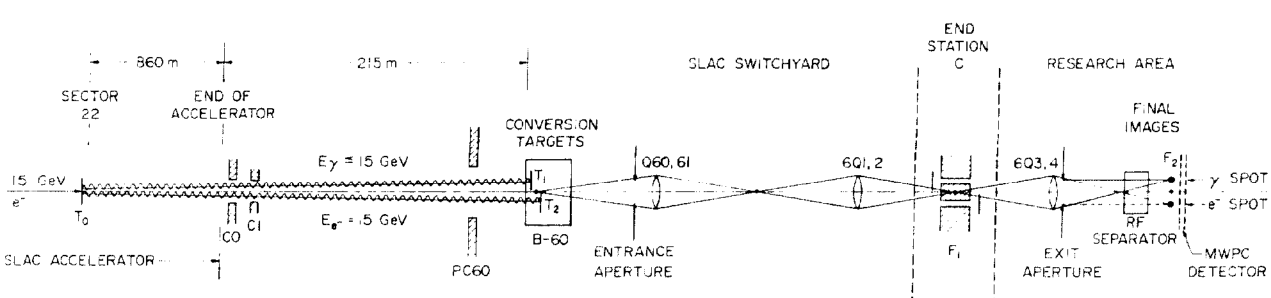


Fig. 4. High resolution multi-wire proportional chamber. Coordinate measurement response and positional sensitivity.



HEPL / SLAC VELOCITY OF LIGHT EXPERIMENT - OPTICAL SCHEMATIC - CONVERSION TARGETS TO DETECTOR

Figure 1