Time of Flight Technique

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Abstract

At first glance, the traditional Time of Flight (TOF) technique for identification of pions, kaons and protons seems to be ideally suited for the momentum range of particles produced at the Tau-Charm Factory. In the decays of τ leptons and charmed mesons most of the secondaries have momentum smaller then 1 GeV/c. The exception are the two- and three-body decays of ψ and ψ' where the region of interest extends to about 1.5 GeV/c. In the upper end of this momentum range the geometry of the detector will impose strict requirements on the necessary timing resolution.

1. Geometrical Considerations

A typical TOF counter in a e^+e^- storage ring experiment consists of a bar of plastic scintillator placed at the outer radius of the tracking chamber and parallel to the beam axis. Light generated by the passage of charged particles is transmitted through the light guides to the photomultipliers placed in the region of low magnetic field - usually outside the return yoke of the magnet[1].

In the axial magnetic field the minimum transverse momentum of particles reaching the counter is given in Table 1 as the function of the field strength and the radius of the tracking chamber.

Table 1

Minimum p_T of tracks reaching the outer radius of the tracking chamber in MeV/c.

	Radius,cm						
	40	60	80	100	120	140	160
Field,Tesla							
0.3	18	27	36	45	54	63	72
0.5	30	45	60	75	90	105	120
0.7	42	63	84	105	126	147	168
1.0	60	90	120	150	180	210	240
1.5	90	135	180	225	270	315	360

As can be seen,the requirement of Time of Flight particle identification at low momentum (e.g. for $p < 150$ MeV/c or $p_T < 100$ MeV/c) necessitates modest magnetic field.

The length of the counter depends on the radius of the tracking chamber and desired angular coverage.

$$length = 2 \cdot radius/tan\theta$$

For example, the requirement of angular coverage down to $cos\theta < 0.9$ at the radius of 100 cm implies counter length of 415 cm. Such length approaches the practical limit of the size of the counters constructed to date. The collection time of the light traversing full length of such counter is about 12 to 15 ns. This time convoluted together with the transit time of the signal through the standard photomultipliers (about 25 ns) is still comfortably smaller then the design machine bunch spacing of 52 ns.

2. Particle Identification Requirements

A particle with mass m and momentum p has velocity

$$\beta = \frac{p}{\sqrt{p^2 + m^2}}$$

For a path length L the time of flight is inversely proportional to its velocity β:

$$T = \frac{L}{c \cdot \beta}$$

Thus, two particles with the same momentum but different masses have different time of flight

$$T_1 - T_2 = \frac{L}{c}\left(\sqrt{1 + \frac{m_1^2}{p^2}} - \sqrt{1 + \frac{m_2^2}{p^2}}\right)$$

The momentum range over which particle separation is possible depends crucially on the timing resolution. In Fig.1 are shown the limits of the momentum range over which 3 sigma π-K separation is possible as function of the radius of the TOF system. The worst case i.e. shortest path length of the produced particles is assumed. As can be seen the timing resolution required for eg. 100 cm radius is of the order of 100 ps. However, the resolution of about 130 ps would be sufficient to cover full momentum range needed for the study of tau and charm mesons decays.

3. Contributions to the Timing Resolution

Contribution from the Scintillator

The probability distribution of photon emission after the passage of charged particle through the plastic scintillator depends on the chemical composition of the scintillator. In general the dominant process can be described by an exponential function[2]:

$$P(t) \simeq e^{-t/\tau}$$

where τ is a decay constant of the scintillator. The TOF resolution can be approximated by the uncertainty in the arrival time at the end of the counter of the first out of n photons[3]:

$$\sigma = \frac{\tau}{n}$$

Not all of the produced photons can be observed and there are several contributions to the photon collection inefficiency. These are dominated by the geometry and the attenuation length of the scintillator.

1. Geometry - only photons either emitted directly towards the photodetector or those that survive multiple internal reflections inside the counter arrive at the photodetector. Best collection efficiency is obtained for the photodetectors for which the active area of the phtocathode S is equal to the transverse cross section of the counter A. For all other cases the ratio of these two quantities S/A gives a good approximation of the photon collection efficiency. High segmentation of the TOF system allowes, therefore, not only to resolve particles travelling close by in space but also to minimize the light losses. The width of the optimal counter is thus equal to about 4.5 cm when using common $2''$ phototubes and the TOF system placed at the radius of 100 cm would consist of about 140 counters.

2. Attenuation - The process of the absorption of photons along their path in the scintillator is a major contributor to the attenuation of the signal. An additional component contributing to the effective attenuation length is the loss of photons due to the imperfections of the surface of the counter which change the path of the reflected photons and in particular allow them to escape by increasing their incident angle past the critical angle. A typical effective attenuation length of the TOF counters is of the order of 2 meters. The length of the counters is usually defined by the length of the tracking chamber and the attenuation effects limit the practical length to about 4 meters.

Contribution of the Photodetectors

Standard $2''$ photomultipliers used in TOF counters also contribute to the timing resolution through their transit time jitter i.e. the uncertainty in the time delay of the photomultiplication cascade inside the phototube. For an individual photon such uncertainty can be of the order or 200-300 psec. In practice the timing jitter depends on the number of photons detected and the details of the trigger. This contribution is reduced in practical counters to the range of 60 to 100 psec and is small in comparison to overall resolution in counters used so far. The phototube timing jitter will become significant for the counters aiming at the resolution of better then 100 ps. This may require either modifications of existing photomultipliers or application of multichannel plates which have the transit time jitter about one order of magnitude smaller then the photomultipliers.

Contribution from the Beam

The TOF measurement technique requires precise knowledge of the time origin of the event. In the storage ring experiment the longitudinal size of the colliding beams provides additional contribution to the timing resolution. For the machine design parameters presented by J. Jowett[4] σ_z of the beam is 6.2 mm. This will contribute 21 ps to the overal uncertainty of the TOF and can be neglected. However, the storage ring designs which require longer bunch length (e.g. σ_z= 25 mm for the G.Voss design[5]) may be incompatible with the TOF technology.

4. Depth Segmentation

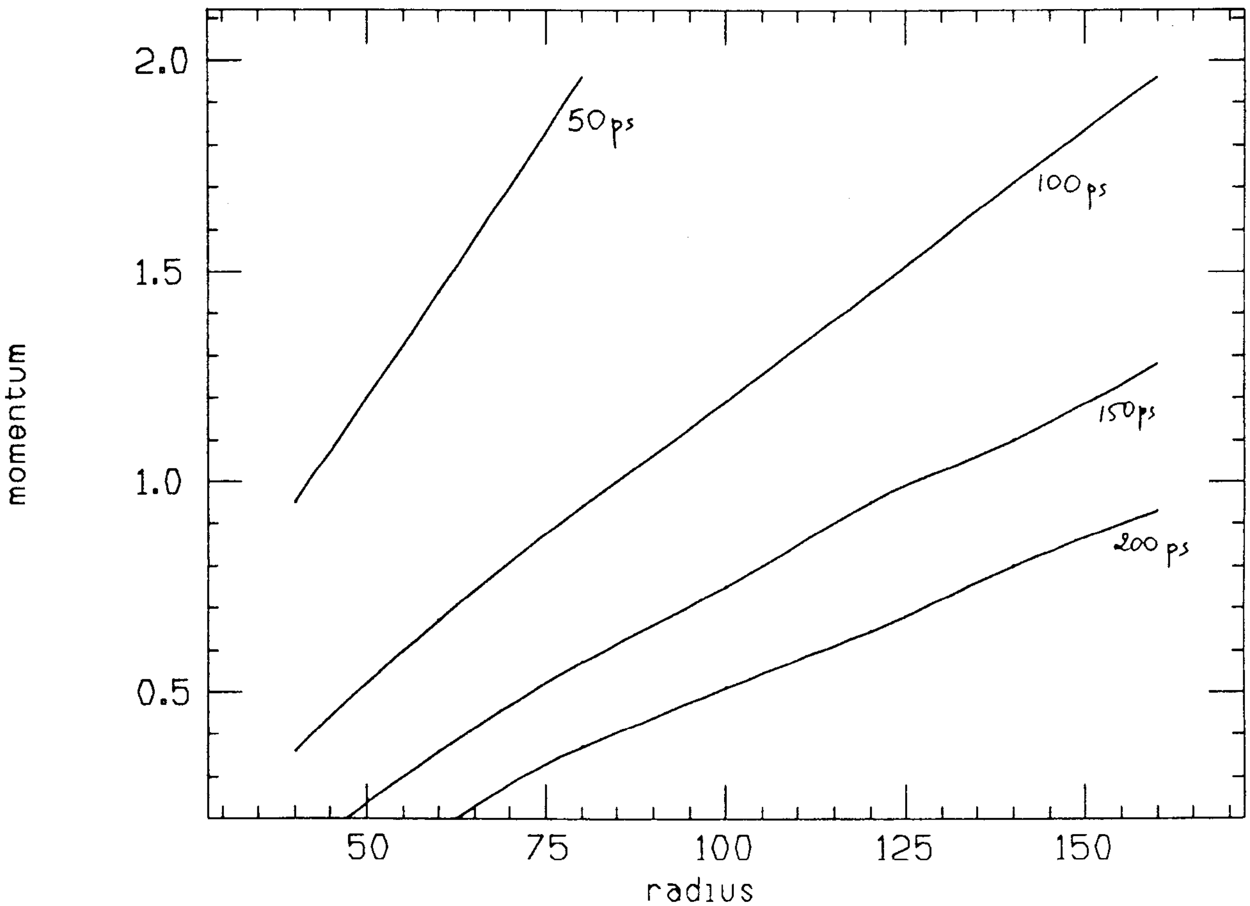
The additional limitation of the timing resolution comes from the time of passage of particle through the counter. For the typical 5 cm thick counter this time of passage for the particle traversing at 45° is 236 ps. This contributes 68 ps to the overall timing resolution (assuming box-like uniform distribution of emitted photons along the particle trajectory). Although further increase of thickness of the counters would increase the number of observed photons, the time of passage would also increase. Depth segmentation with independent readout has been proposed [3] as solution to this problem and preliminary results of the measurements with the depth-segmented system indicate that long counters (eg. 300 cm long) with timing resolution smaller then 100 ps are possible.

5. Conclusions

The Time of Flight technique is well suited to the requirements of the physics of the τ lepton and charmed mesons. For the reference design of the detector the particle identification needs at ψ and ψ' will require timing resolution of about 70 ps which is possible with depth segmented system.

References

1. W.B. Atwood, Lectures at the 1980 SLAC Summer Institute on Particle Physics: "The Weak Interactions". SLAC Report 239(1981) p.287.
2. J.B. Birks,"Theory and practice of scintillation counting", Pergamon Press (1964).
3. B. Milliken, R. Stroynowski, E. Wicklund "Timing measurements in particle physics experiments". CALT-68-1538. Proceedings of the Workshop on the Scintillating Fiber Detector Development, Fermilab 1988.
4. J. Jowett, Contribution to this workshop. Also CERN/LEP-TH/88-22.
5. G. Voss, Contribution to this workshop.



2.0
1.5
1.0
0.5
momentum
50
75
100
125
150
radius
50ps
100ps
150ps
200ps