RF Cherenkov Picosecond Timing Technique for High Energy Physics Applications

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Introduction

During usual time measurements in high energy and nuclear physics experiments:

1) Time information is transferred by secondary electrons - SE or photoelectrons - PE;

2) The SE and PE are accelerated, multiplied and converted into electrical signals, e.g. by using PMTs or other detectors;

3) Electrical signals are processed by common nanosecond electronics like discriminators and time to digital converters, and digitized.

- Parameters:

  a) Nanosecond signals;

  b) The limit of precision of time measurement of single SE or PE is about 100 ps (FWHM).

Streak Cameras

1) Time information is transferred by SEs or PEs;

2) The electrons are accelerated and deflected by means of ultra high frequency RF fields (the deflected electrons now carry time information);

3) The deflected electrons are multiplied and their position on the detector plane is fixed.
That position carries the time information.

Parameters:

a) The limit of precision of time measurement of single SE or PE is $\sigma \approx 1$ ps;

b) High and long-term stability - 200 fs/day - can be reached.

Commercial Streak Cameras provide slow or averaged information

This may be is the reason why they don't find wide application in high energy and nuclear physics experiments like regular PMTs.

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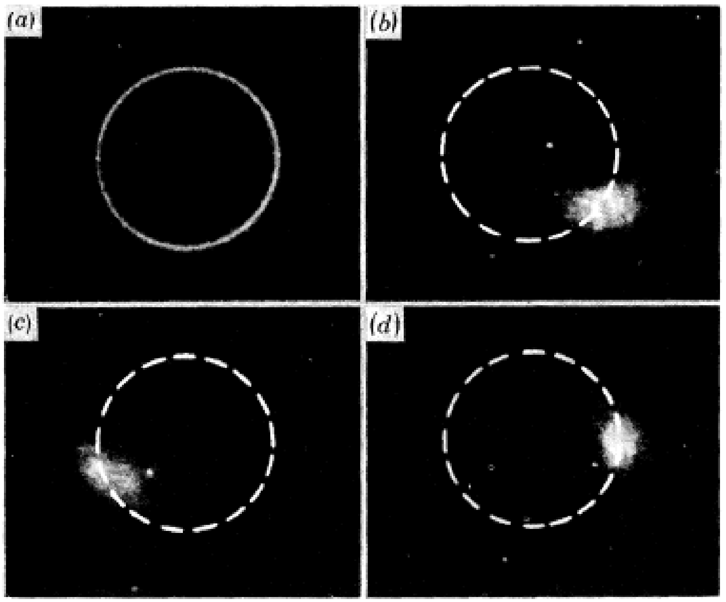
The Synchroscan picosecond streak camera system

By A. E. Huston and K. Helbrough
Hadland Photonics Ltd, Bovingdon, Herts. HP3 0EL, U.K.

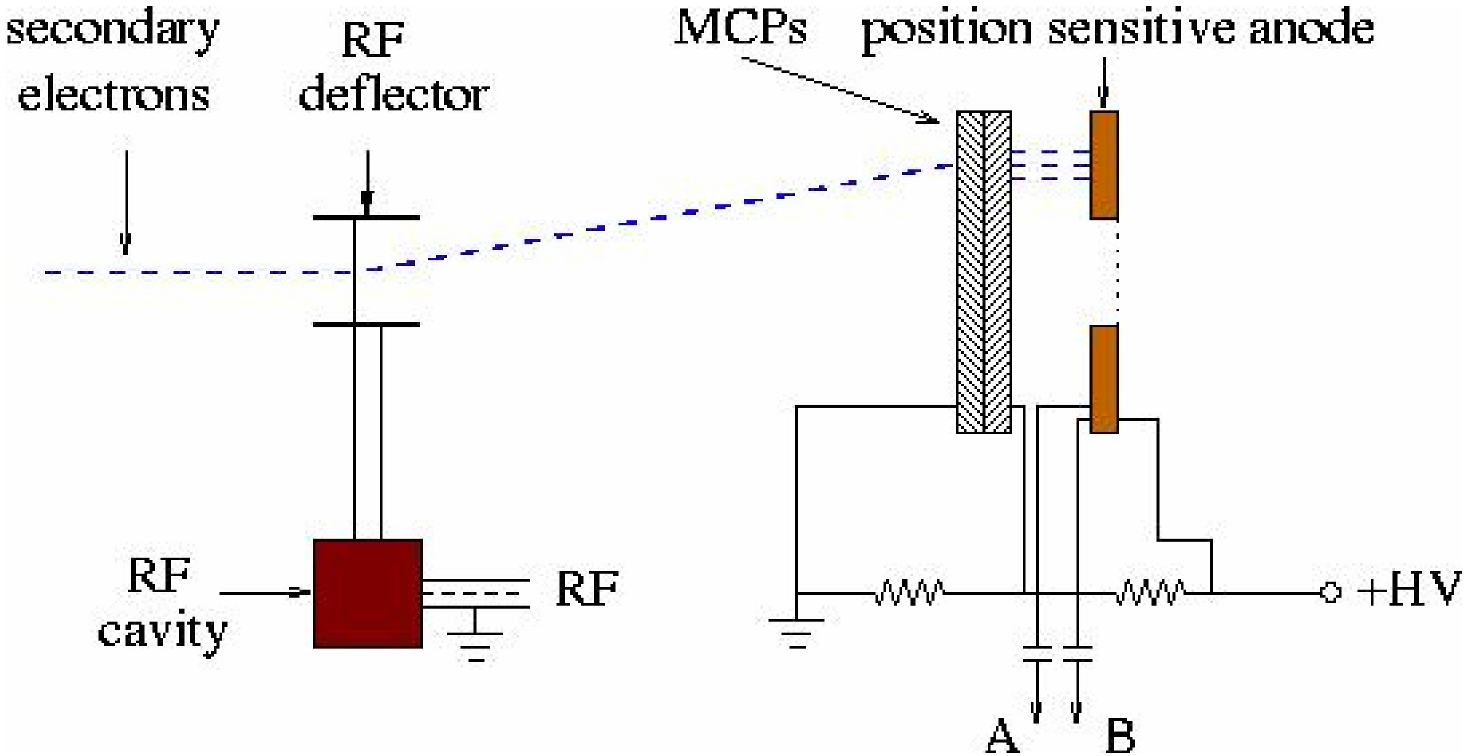


Average time is 10 s, each record is a result of summation of 2×10^9 events

Figure 4. Records taken with circular scan Synchroscan. (*a*) Test record showing circular deflexion at 201.25 MHz, with continuous illumination. (*b*–*d*) Recorded Čerenkov light showing variation of timing obtained by altering the experimental conditions.

New RF Time Measuring Technique

Operates like circular scan streak camera but provides nanosecond signals



Schematic layout of the new RF time measuring technique

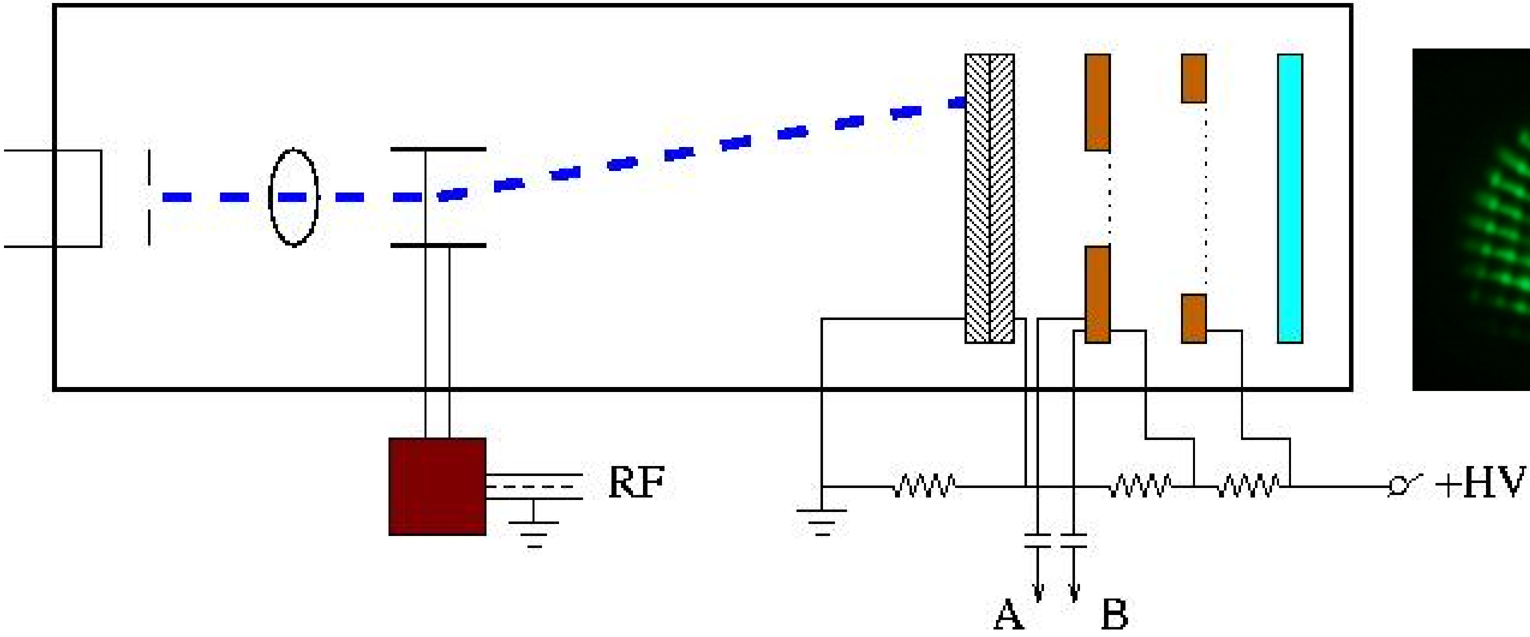
500 MHz RF Deflector

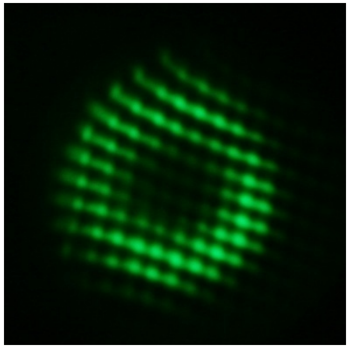
- No transit time effect due to special design of deflection electrodes.

- The deflection electrodes and λ/4 RF cavity form a resonance circuit with Q ≈ 130.

- 1 mm/V or 100 mradian/$W^{1/2}$ sensitivity for 2.5 keV electrons, which is about an order of magnitude higher than the existing RF deflectors can provide.

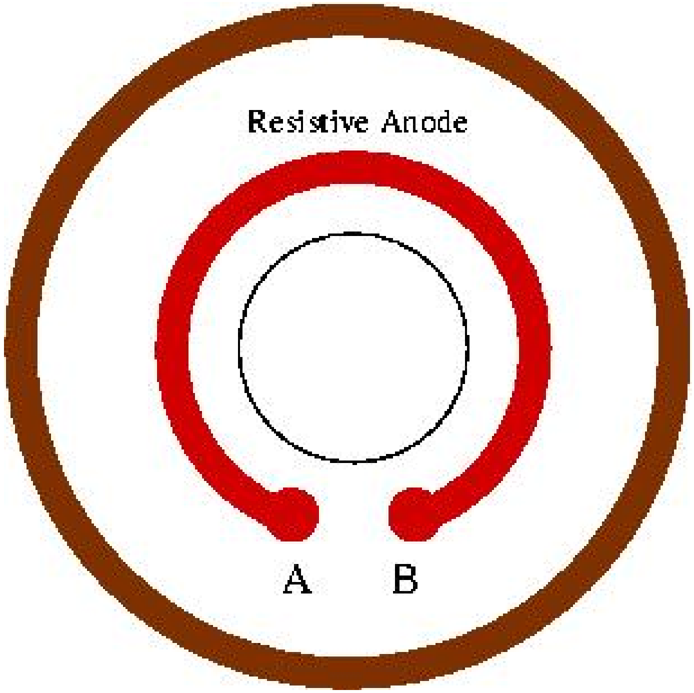
Electron Tube with RF Deflector and Position-Sensitive SE Detector

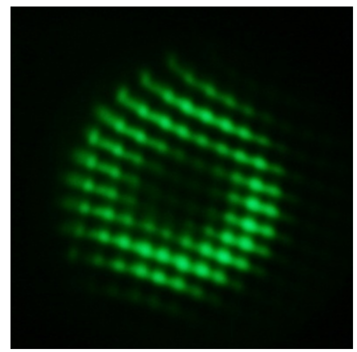




Schematic of the tube and photo of the circularly scanned and multiplied thermo-electrons on the phosphor screen.

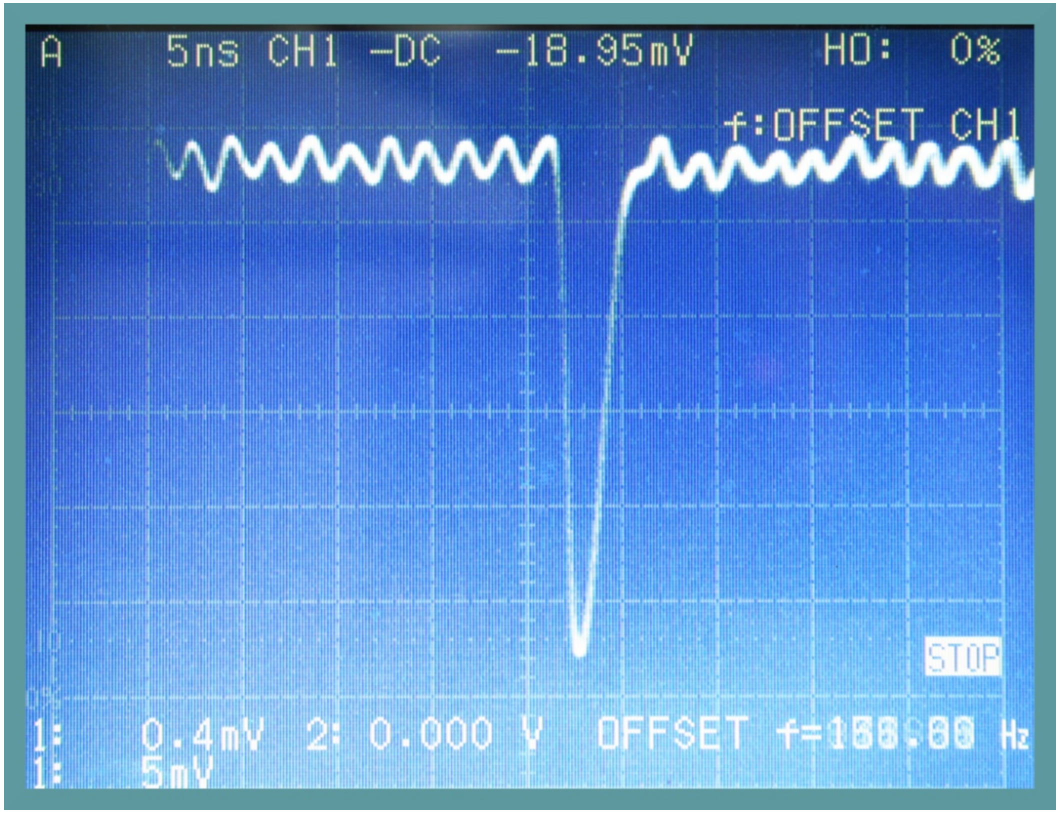
Resistive Anode





The image of electron circle is adjusted so that it appears on the resistive anode. Signals from A and B are used for determination of the multiplied electrons' position on the circle

SE Detector Signals



The signal A from the SE detector, RF source is on. The induced RF noise magnitude is negligible.

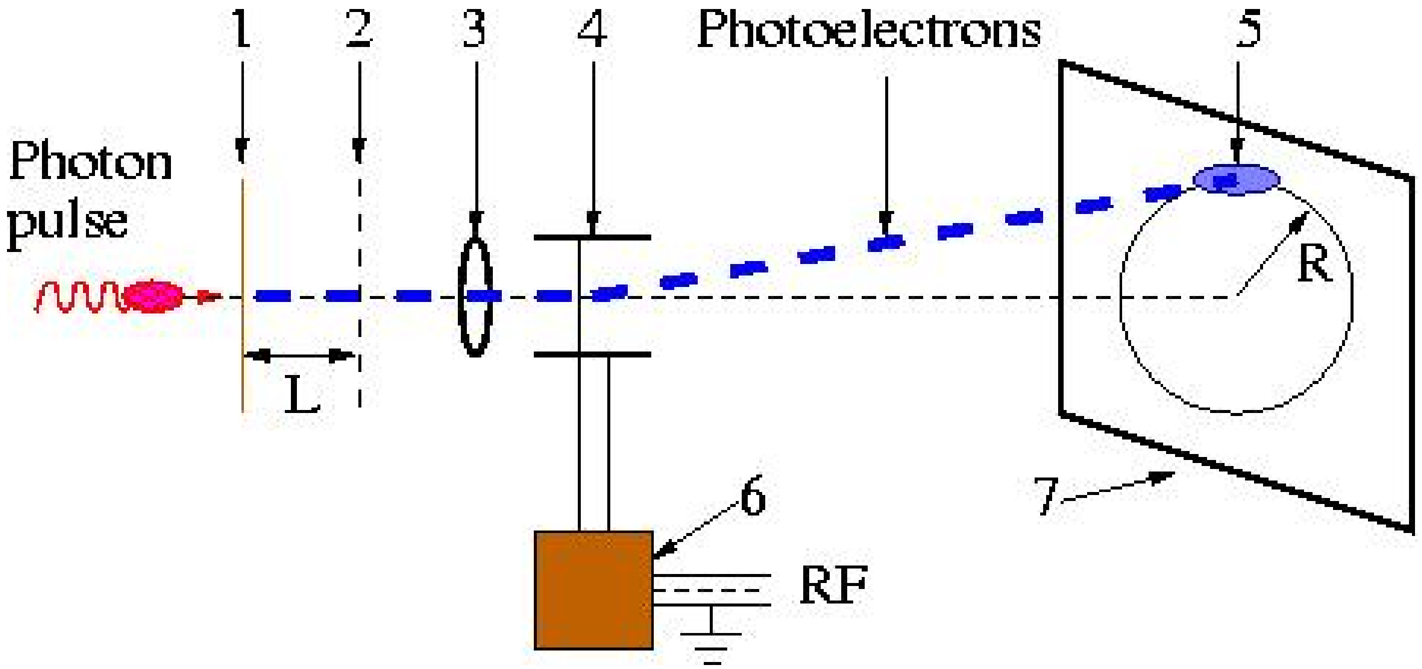
Uncertainty sources of time measurement with f = 500 MHz RF field

1.	Time dispersion of SE emission	$\leq$ 6 ps
2.	Time dispersion of PE emission	$\leq$ 2 ps
3.	Time dispersion of electron tube: chromatic aberration and transit time	$\leq$ 2 ps
4	So called "Technical Time Resolution" of the deflector: $\sigma = d/v$, where d is the size of the electron spot, $v=2\pi R/T$ is the scanning speed. For our case d = 1 mm, R = 2 cm, T = 2 ns	~20 ps
TOTAL		~21 ps
THEORETICAL LIMIT OF THE TECHNIQUE		**~1 ps**

New RF Time Measuring Technique: Summary

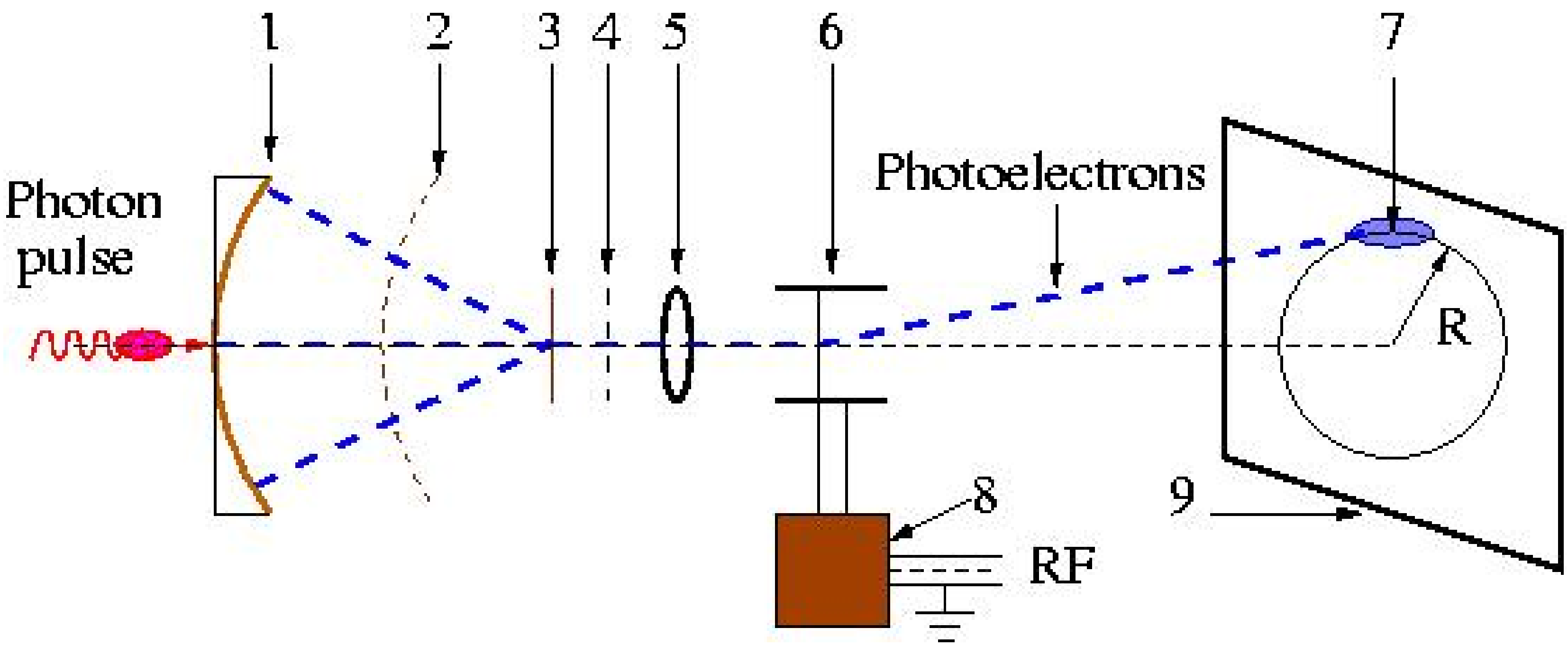
- High rate operation, like regular PMT's
- Synchronized operation with an RF source: synchroscan mode
- 20 picosecond time resolution.

RF Phototube with point-like Photocathode



The schematic layout of the RF phototube with point-like photocathode.
1 - photo cathode, 2 - electron-transparent electrode, 3 - electrostatic lens,
4 - RF deflection electrodes, 5 - image of PEs, 6 - $\lambda/4$ RF coaxial cavity,
7 - SE detector.

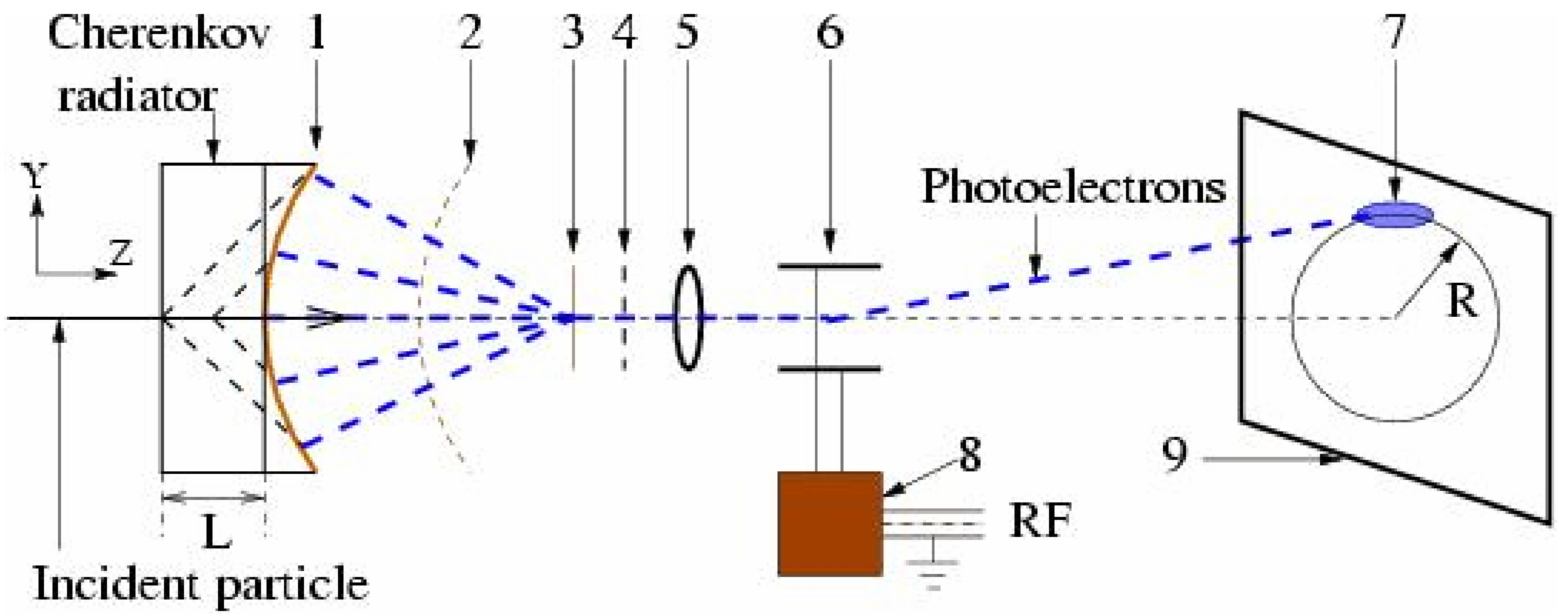
RF Phototube
with large-size Photocathode



1 - photo cathode (for 4 cm diameter photocathode the time dispersion of PE is ≤10 ps, FWHM), 2 - electron-transparent electrode, 3 - transmission dynode, 4 - accelerating electrode, 5 - electrostatic lens, 6 - RF deflection electrodes, 7 - image of PEs, 8 - $\lambda/4$ RF coaxial cavity, 9 - SE detector.

Cherenkov Time-of-Flight (TOF) and Time-of-Propagation (TOP) Detectors Based on RFPP

The time scale of Cherenkov radiation is ≤ 1ps, ideal for TOF

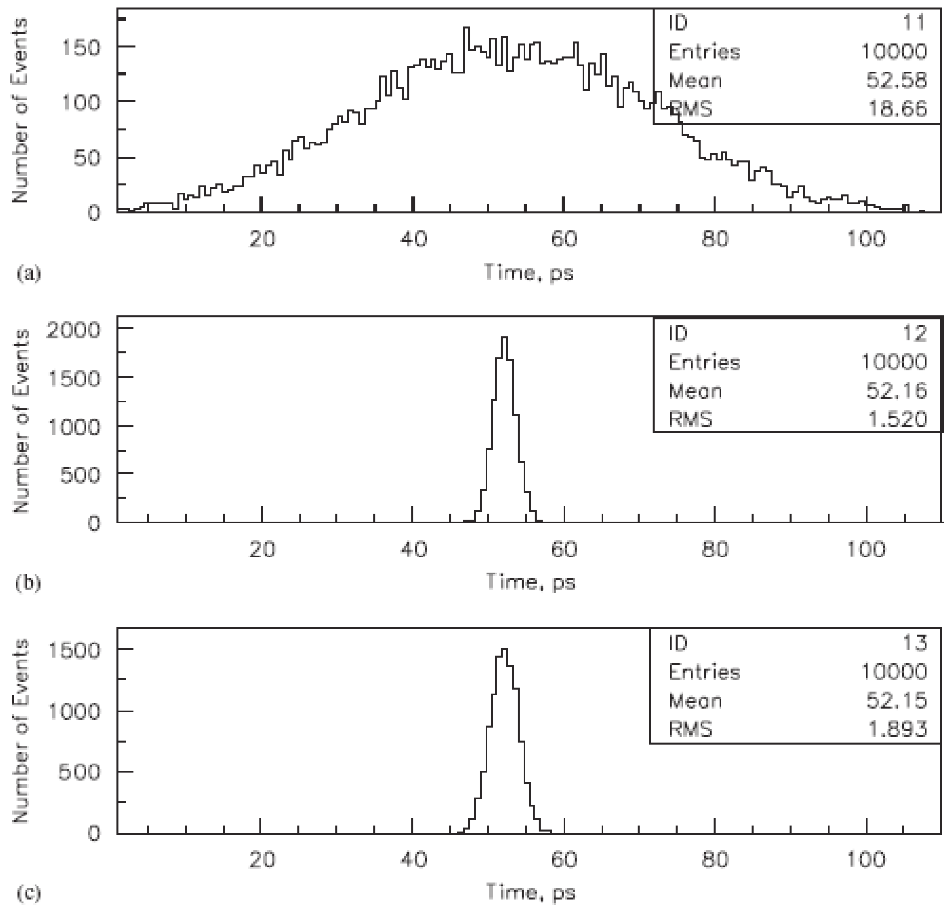


The schematic of Cherenkov TOF detector in a “head-on” geometry based on RFPP.

Monte Carlo Simulation of the Cherenkov TOF and TOP Detectors

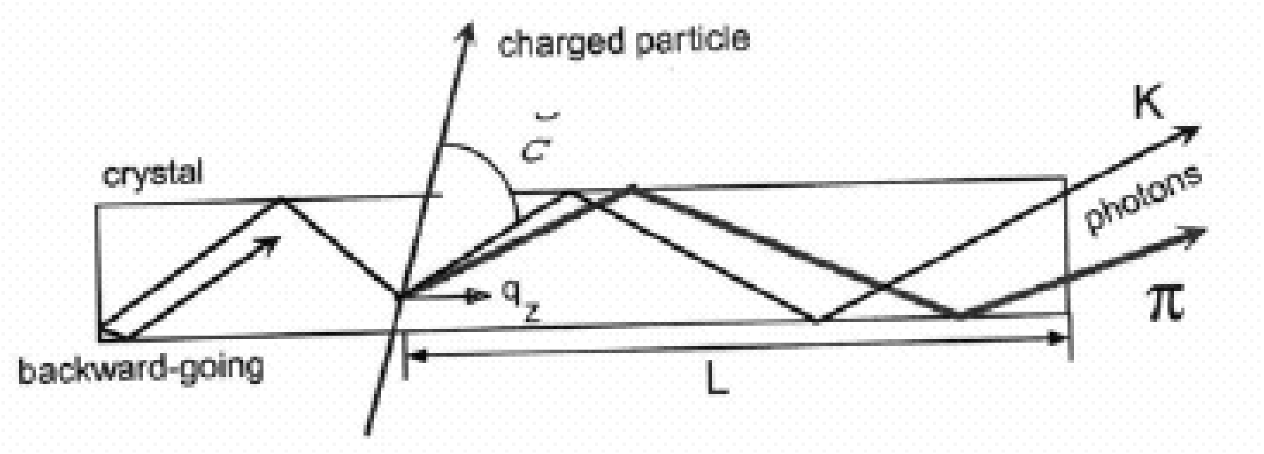
- Radiator of finite thickness
- The transit time spread of Cherenkov photons due to different trajectories
- The chromatic effect of Cherenkov photons ($n = 1.47 \pm 0.008$ in the case of quartz)
- The timing accuracy of RF phototube ($\sigma = 15$ ps)
- The number of detected photoelectrons - (for the quartz and bi-alkali photocathode Npe = 155 cm^{-1})

Time distribution of p = 5000 MeV/c pions in "head-on" Cherenkov TOF detector with L = 1 cm quartz radiator.



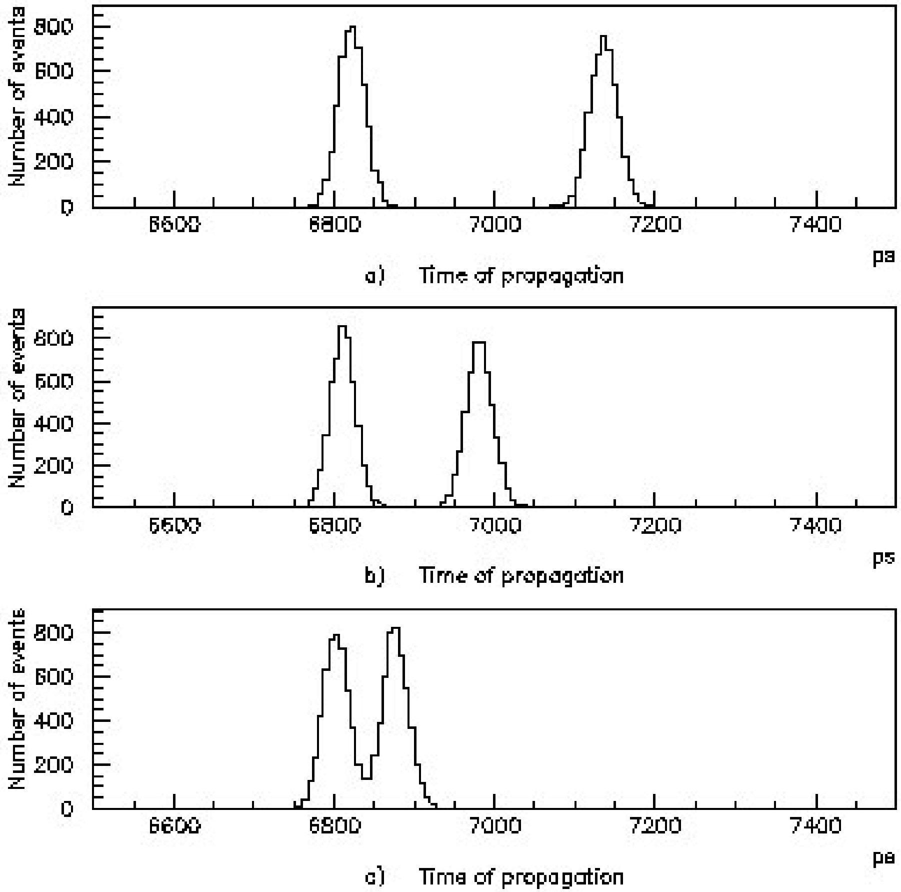
a) time distribution of single photoelectrons;
b) mean time distribution of 150 photoelectrons;
c) mean time distribution of 100 photoelectrons.

Cherenkov Time-of-Propagation (TOP) Detector Based on RFPP



$$\cos(\theta_c) = \frac{1}{\beta n(\lambda)} \qquad t_p = \frac{L_P n(\lambda)}{c} = \frac{L n(\lambda)}{c q_z}$$

The propagation time of the Cherenkov photons in the radiator is sensitive to β and can be obtained if the position, direction and momentum of particle are provided by other systems.

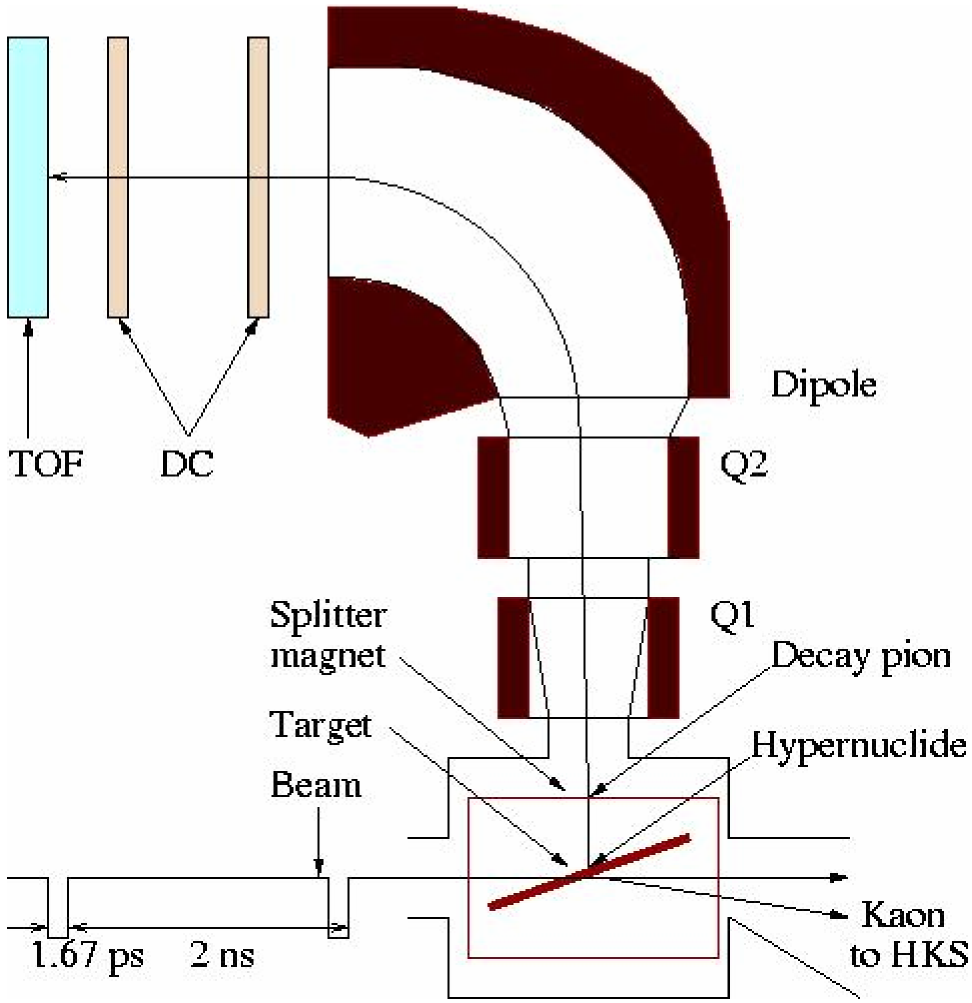


Average time of propagation distributions for forward going photons with $|\Phi_c| \leq 15°$ and L = 100 cm, for π (left histograms) and K (right histograms), θ=90° and p =1.5 (a), 2.0 (b), 3.0 (c) GeV/c momentum. Total number of events is 10000 with 50% π and 50% K tracks.

RF Timing technique and RF driven accelerators or photon sources opens new possibilities for nuclear, fundamental and applied physics

- Cherenkov TOF detectors based on RF phototubes opens unprecedented possibilities for hypernuclear studies at CEBAF, JLab, USA
- RF phototubes can be used for precise measurements, e. g. for precise testing theory of relativity
- It is ideal tool for diffuse optic tomography applications

Decay Pion Spectroscopy of Hypernuclei at JLab



Schematic of the decay pion spectrometer- HπS

Decay Pion Spectroscopy of Hypernuclei at JLab

- Binding energy resolution σ~100 keV
- Time resolution 20 ps
- Expected rate for the HπS with Cherenkov TOF based on RFPP is $\sim 3 \times 10^5$/day
- For comparison, the total emulsion data on π^--mesonic decays of hypernuclei amount to some 3.6×10^4 events from which of about 4000 events are identified

Conclusions

- Principles of a new RF time measuring technique have been developed
- Prototype setup has been built and demonstrated to work
- The RF time measuring technique can have many applications in physics and other fields.