RF Time Measuring Technique With Picosecond Resolution and Its Possible Applications at JLab

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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.
  The signals' arrival time is thus measured.

- **Parameters:**

  a) High operation rate, up to 100 MHz;

  b) Nanosecond signals;

  c) The limit of precision of time measurement of single SE or PE is $\sigma \approx 100$ ps.

Streak Cameras

- 1) Time information is transferred by SEs or PEs;

  2) The electrons are accelerated and deflected (the deflected electrons now carry time information);

  3) The deflected electrons are multiplied and their position in space 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.

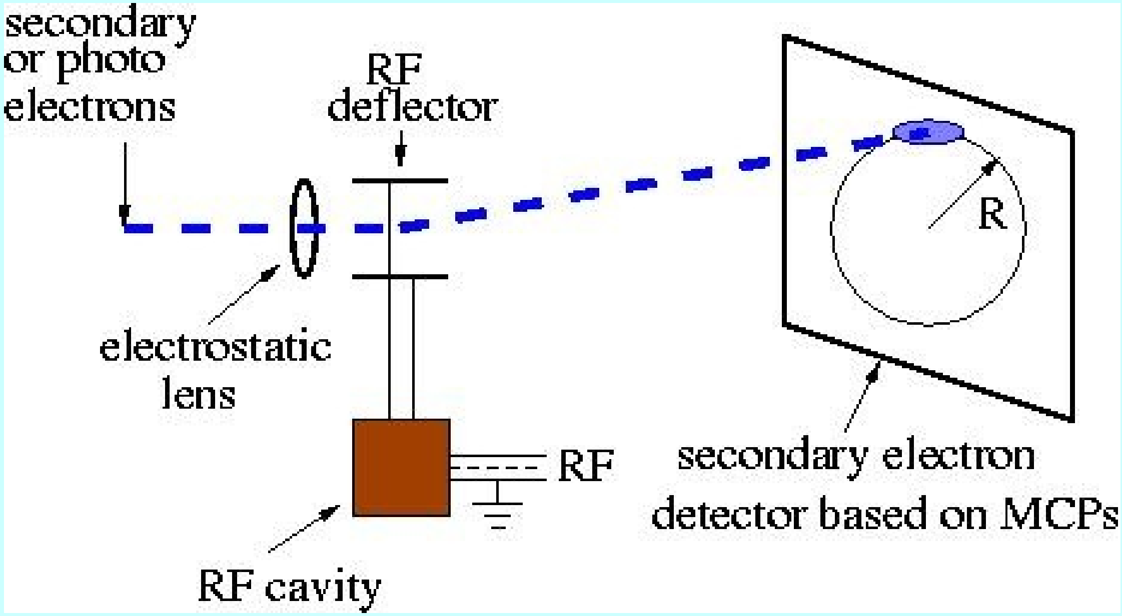
  b) Synchronized operation with RF source is possible (Sinchroscan mode);

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

Commercial Streak Cameras provide slow or averaged information

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

RF Time measuring technique : the basic principle



The basic principle of the RF time measuring technique or streak camera principle is conversion of the information in the time domain into spatial domain by means of ultra high frequency RF fields.

The techniques involve usage of a lens; RF deflection system; SE detection system.

New RF Time Measuring Technique

Operational principles are the same as Streak Cameras but provide fast signals like PMTs

This have been reached by using

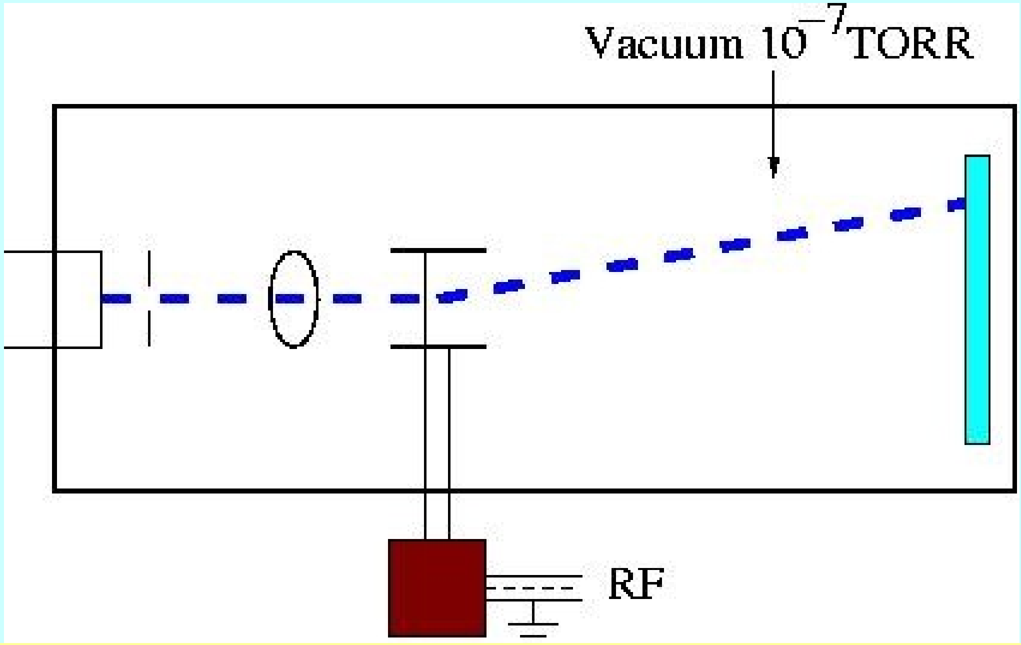
dedicated RF deflection system

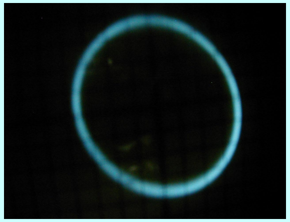
And

position sensitive SE detector based on MCPs

Experimental Setup

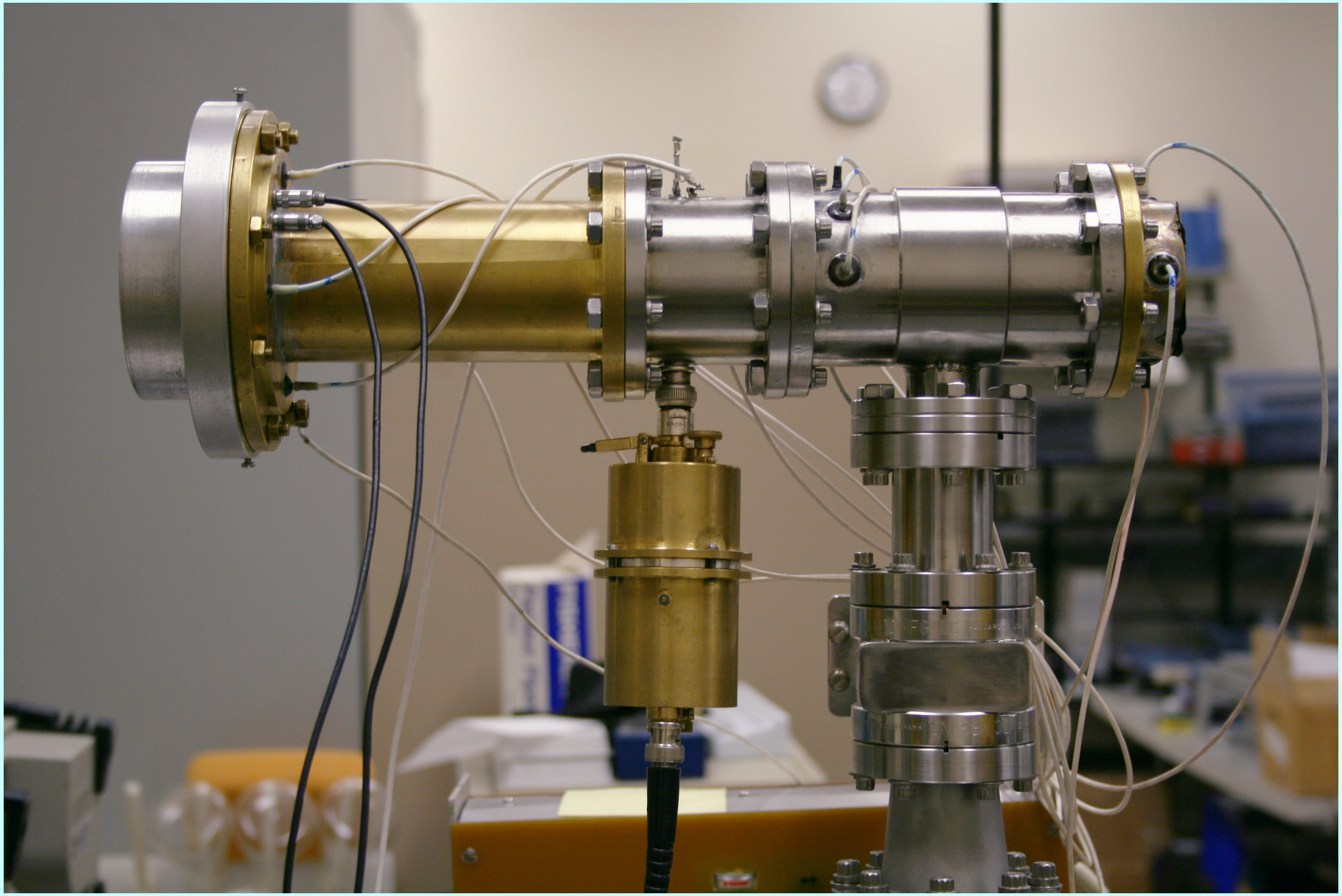
- For experimental investigations, an oscilloscope's electron tube has been used.
- This allowed us to visualize the operation and tuning of the electron tube.





Schematic of the experimental setup and photograph of the circularly scanned 2.5 keV thermo-electrons on the phosphor screen.

Experimental setup in EEL



Our 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 $Q \approx 130$.**
- **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.**

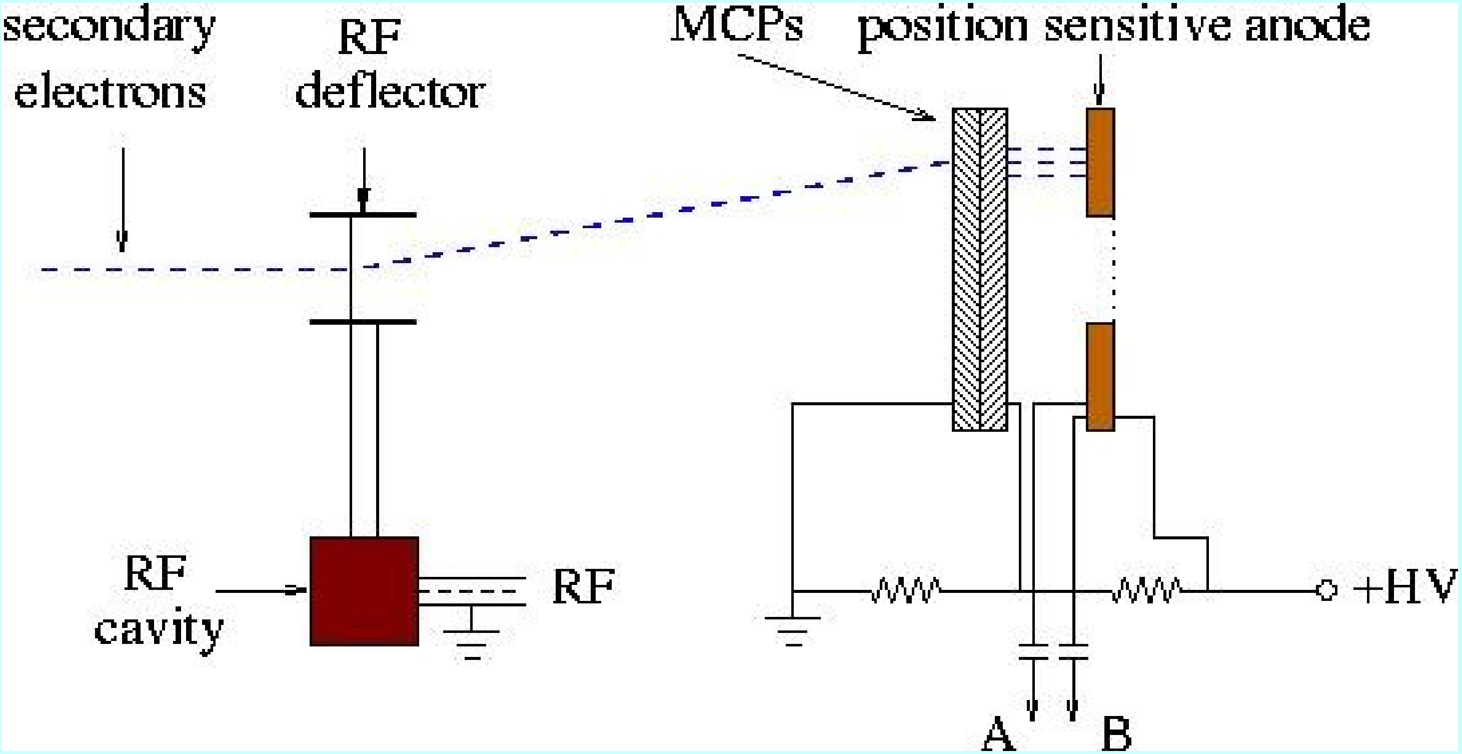
- **About 1 W RF power at 500 MHz is enough in our case to scan 2.5 keV electron beam circularly and reach 2 cm radius or ~20 ps resolution.**

For comparison

- **17 W RF power at 500 MHz was used to reach 2 cm radius in previous efforts:**

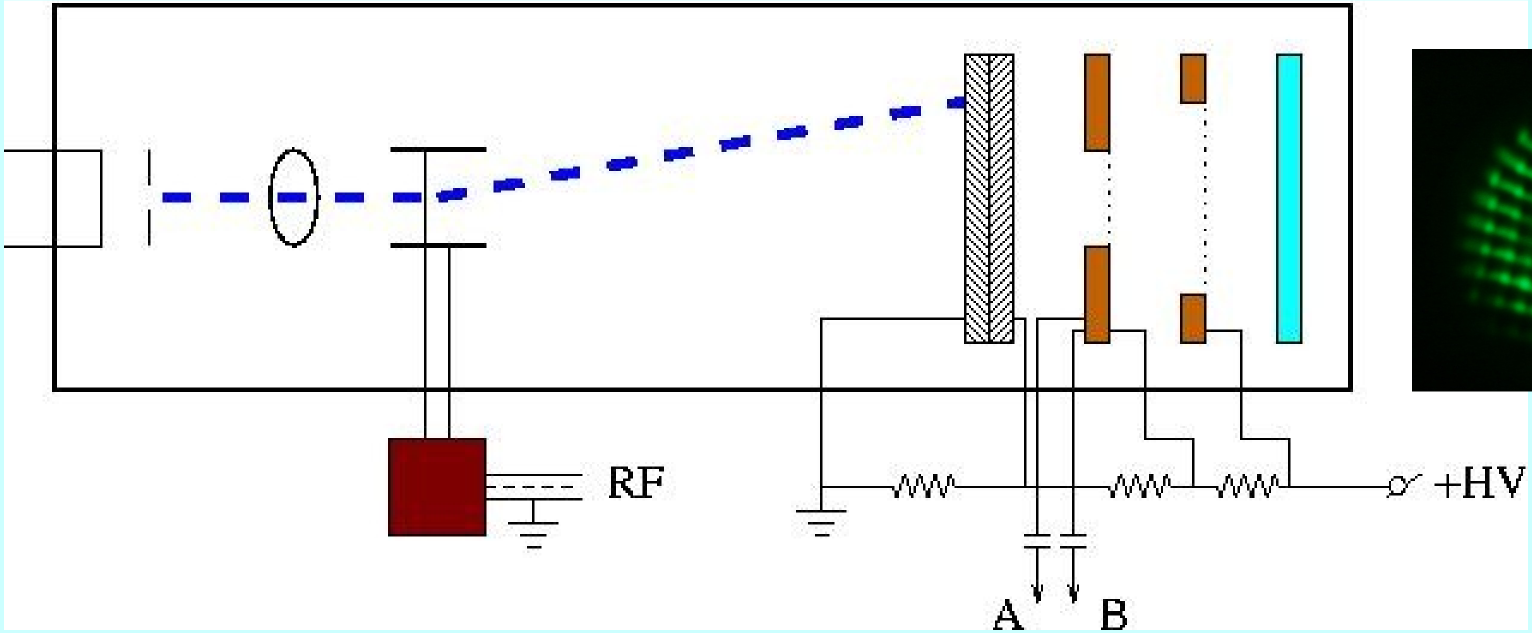
G. I. Bryukhnevitch, S. A. Kaidalov, V. V. Orlov, A. M. Prokhorov et all., PV006S Streak Tube For 500 MHz Circular-Scan Operation, Electron Tubes and Image Intensifiers, Proc. SPIE 1655 (1992) 143.

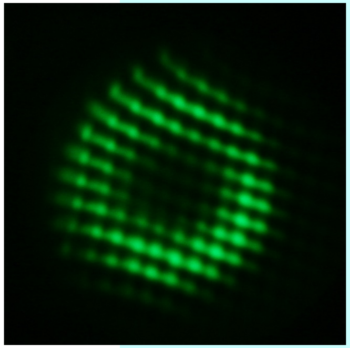
Position Sensitive Secondary Electron Detector



Schematic layout of the position sensitive detector based on two "chevron" type MCP system with position sensitive resistive anode

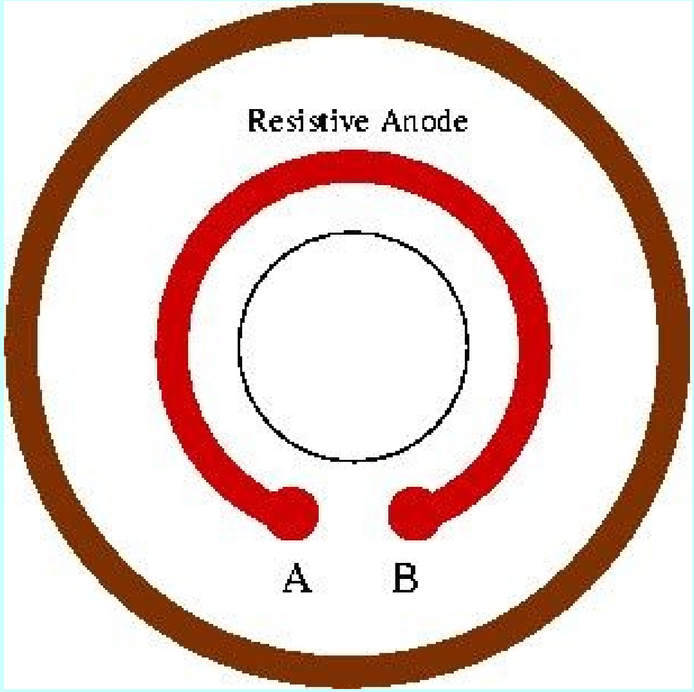
Electron tube with position-sensitive SE detector

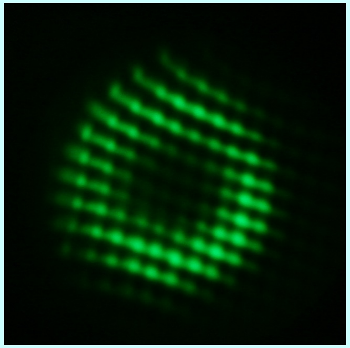




Schematic of the tube and photograph of the circularly scanned and multiplied thermo-electrons on the phosphor screen.

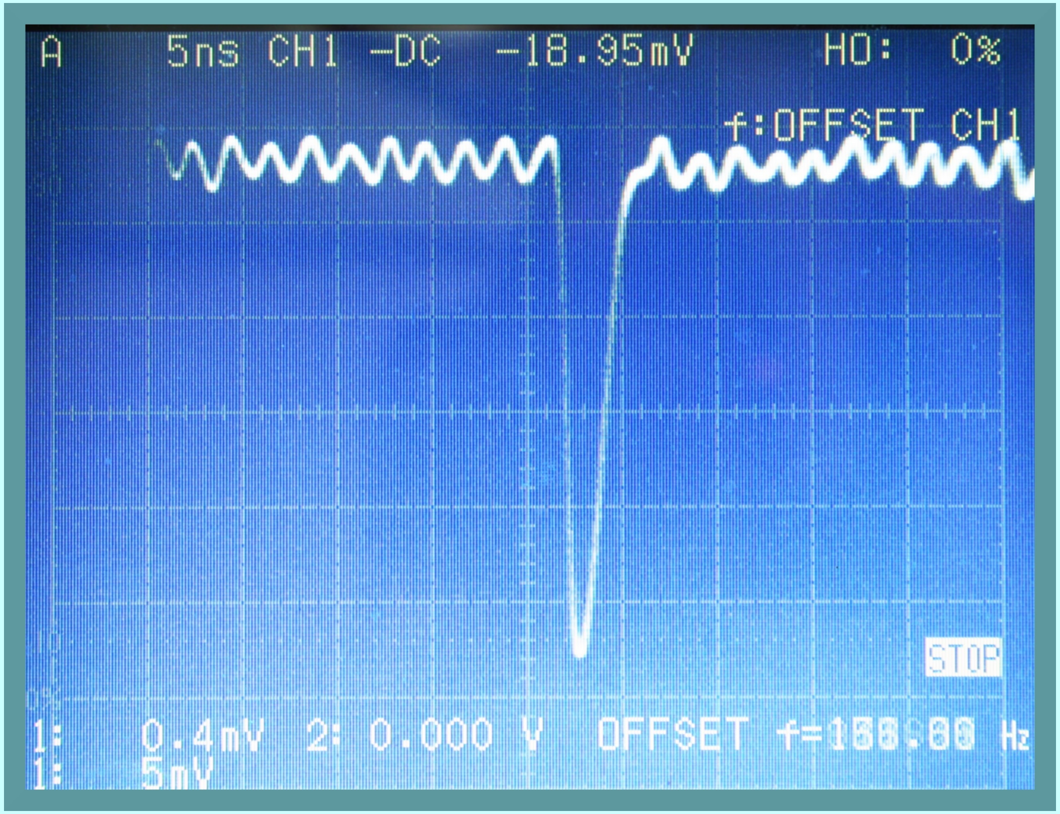
Resistive Anode





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* ≤ 6 ps

2. Time dispersion of PE emission ≤ 2 ps

3. *Time dispersion of electron tube (chromatic aberration and transit time)* ≤ 2 ps

5. 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

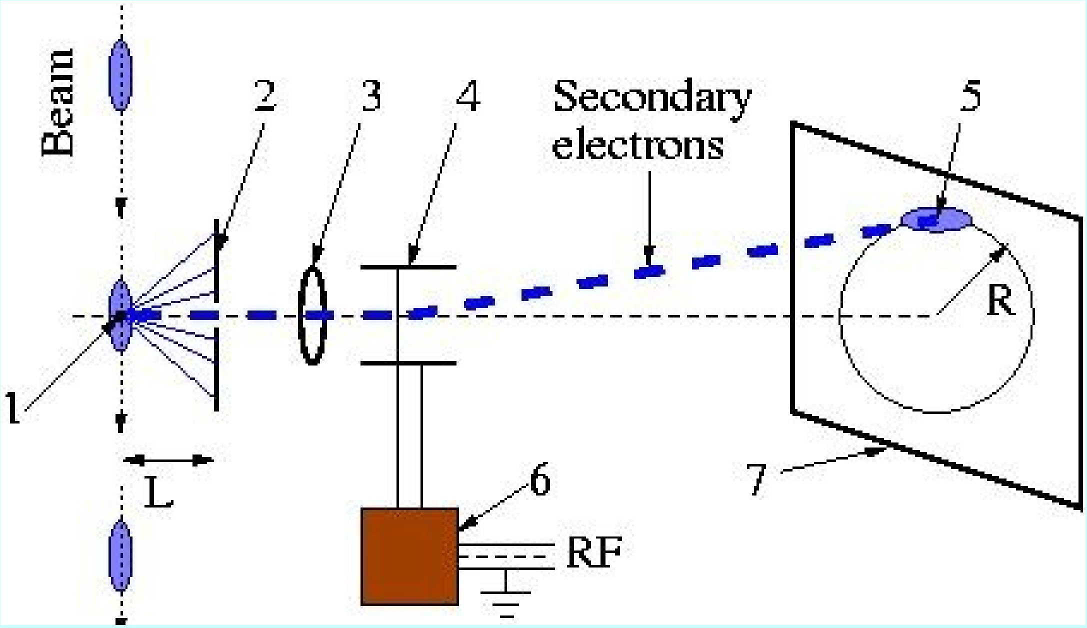
TOTAL ~21 ps

THEORETICAL LIMIT OF THE TECHNIQUE ~1 ps

New RF time measuring system summary

- High rate operation, like regular PMT's.
- Synchronized operation with an RF source is possible.
- 20 picosecond time resolution.
- In other words, the proposed technique combines advantages of circular scan streak cameras and PMTs.
- The time resolution can be improved easily by operating at 1500 MHz.

Possible applications at JLAB
Bunch time structure detector



Principal scheme

1 - thin wire target

2 - electron transparent accelerating electrode

3 - electrostatic lens

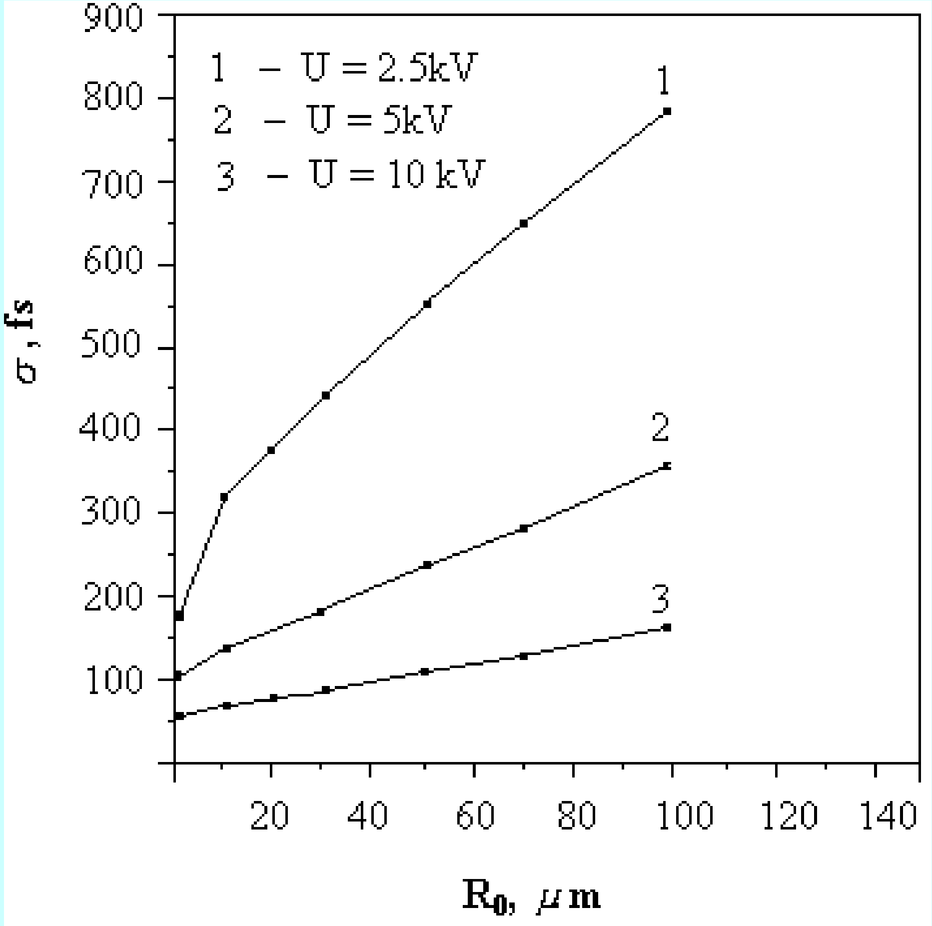
4 - RF deflection electrodes

5 - secondary electrons (SEs)

6 - λ/4 coaxial RF cavity

7 - SE position sensitive detector

The thin wire target (emitter)

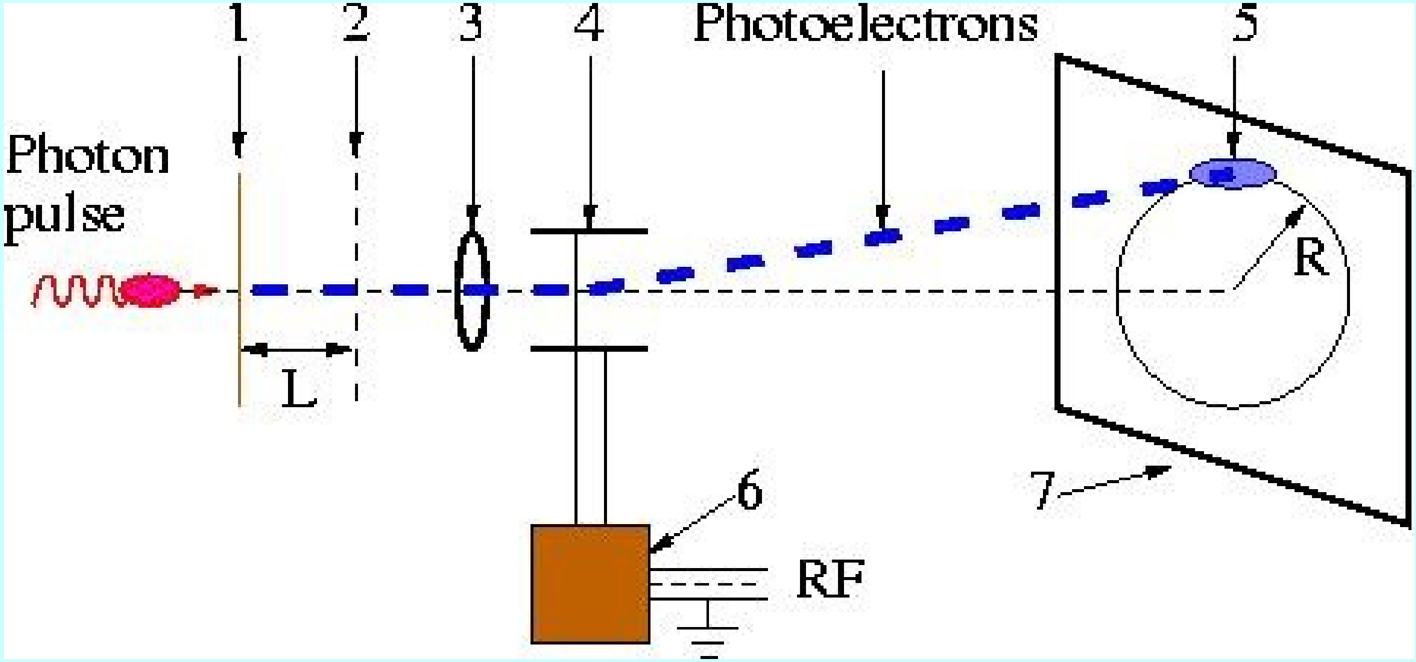


Time dispersion of electron's arrival time at accelerating electrode, vs. wire radius. Monte Carlo simulation.
The time dispersion due to chromatic abberation is minimal for wire targets.

Summary of bunch time structure detector

- High rate, fast, nonintegrated information
- Synchroscan operation is possible simply by using RF signal from master oscillator of the accelerator (main frequency, higher harmonics or sub harmonics)

Radio Frequency Picosecond Phototube - RFPP with point-like photocathode. (We have applied for funding, as a new project)



The schematic layout of the RF phototube with point-like photocathode.

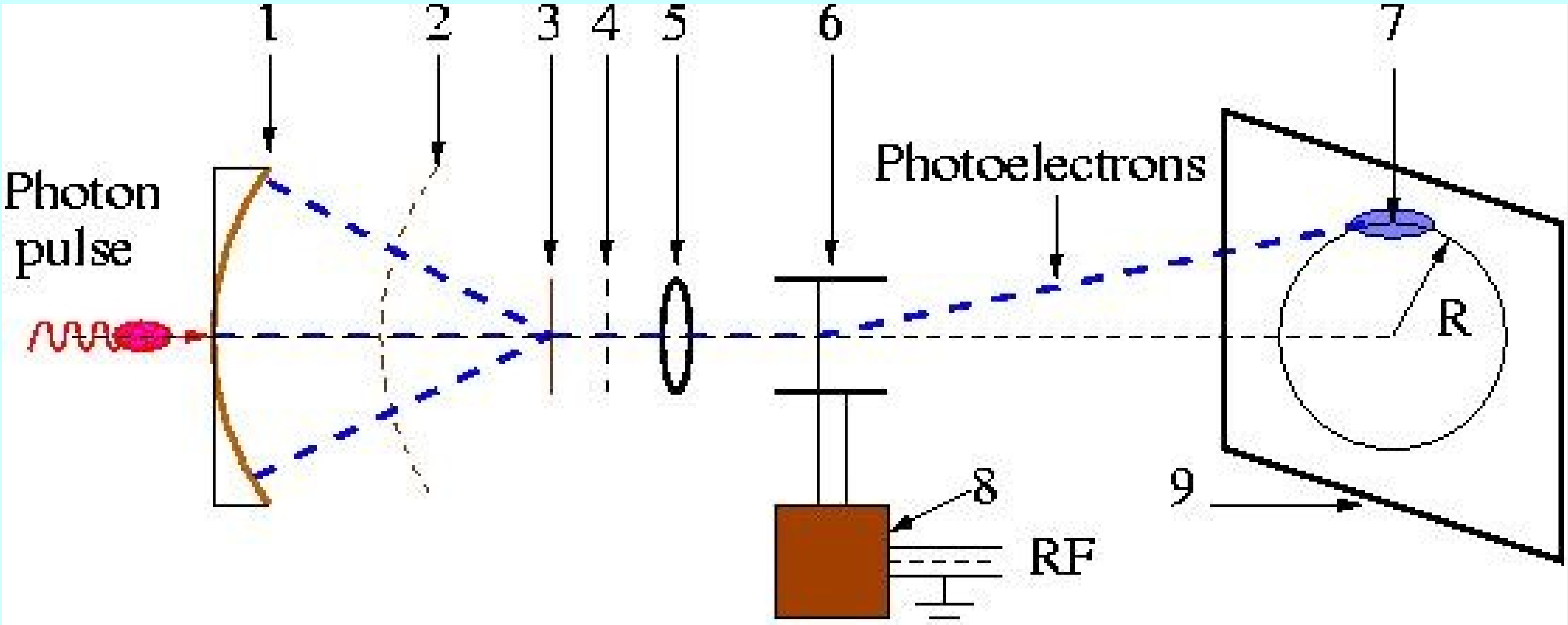
1 - photo cathode, 2 - electron-transparent electrode, 3 - electrostatic lens,

4 - RF deflection electrodes, 5 - image of PEs, 6 - $\lambda/4$ RF coaxial cavity, 7 - SE detector.

Bunch time structure detector based on RFPP with point like photocathode

- By using optical transmitting system, the Cherenkov light can be transmitted several ten meters from the beam, to RF phototube.

RFPP with large-size photocathode
(We have applied for funding, as a new project)



The schematic layout of the RF phototube with large-size photocathode.

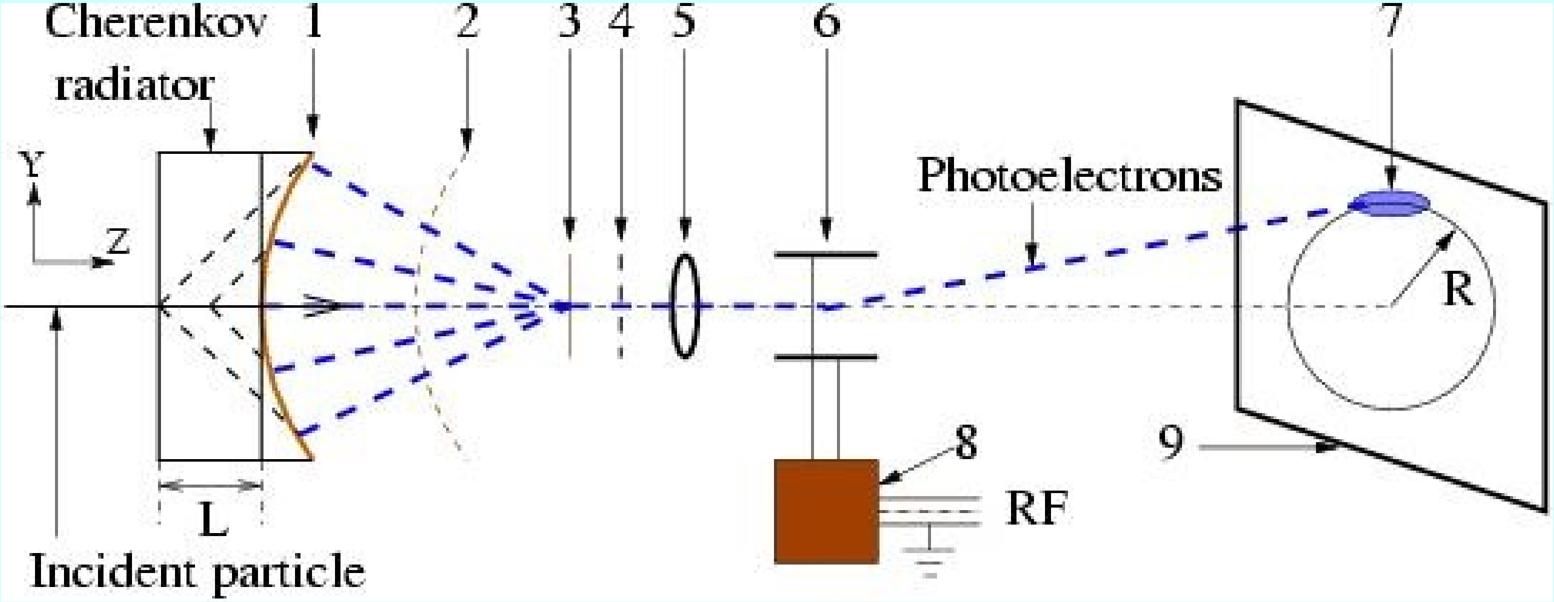
1 - photo cathode (for 4 cm diameter photocathode the time dispersion of PE is ≤10 ps, FWHM), 2 - electron-transparent electrode, 3 - transmission dynode,

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

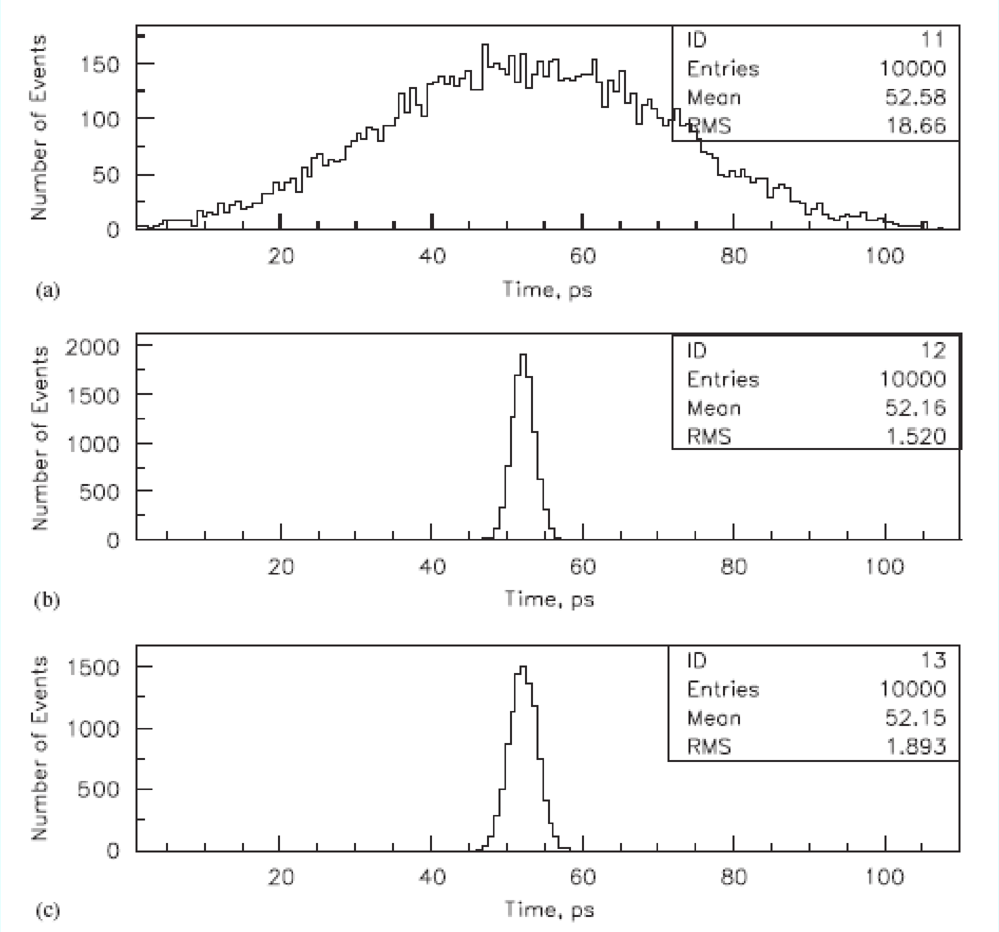


The schematic of Cherenkov TOF detector in a "head-on" geometry based on RFPP.

Monte Carlo Simulation of the Cherenkov TOF and TOP Detectors

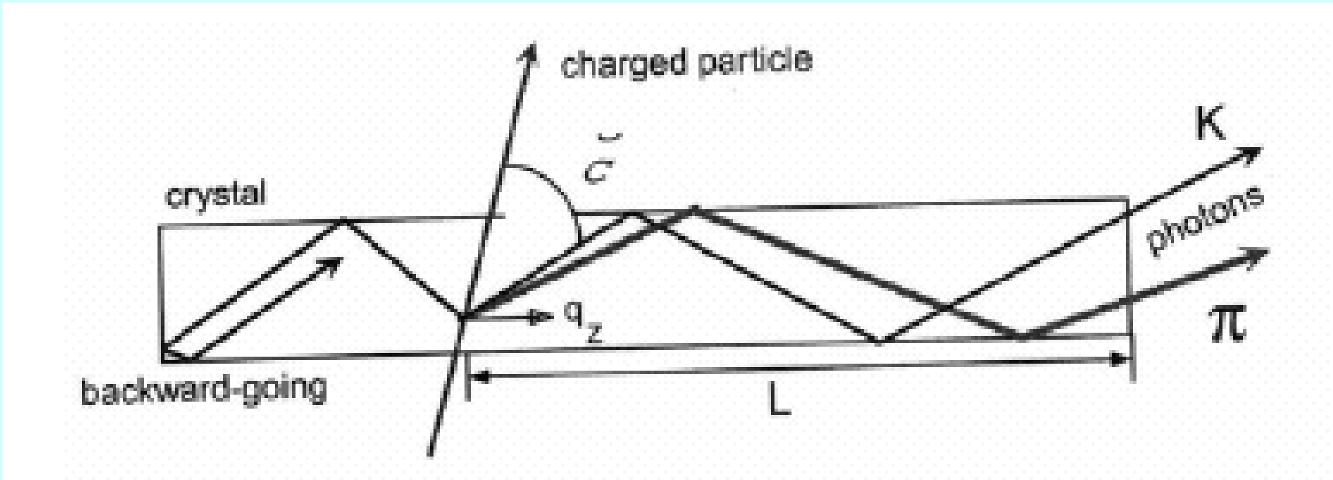
- Radiator of finite thickness
- The transit time spread of Cherenkov photons due to different trajectories
- The chromatic effect of Cherenkov photons ($n = 1.47 \pm 0.008$ in the case of quartz)
- The timing accuracy of RF phototube (σ = 15 ps)
- The number of detected photoelectrons - (for the quartz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

Time distribution of p = 5000 MeV/c pions in “head-on” CherenkovTOF 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

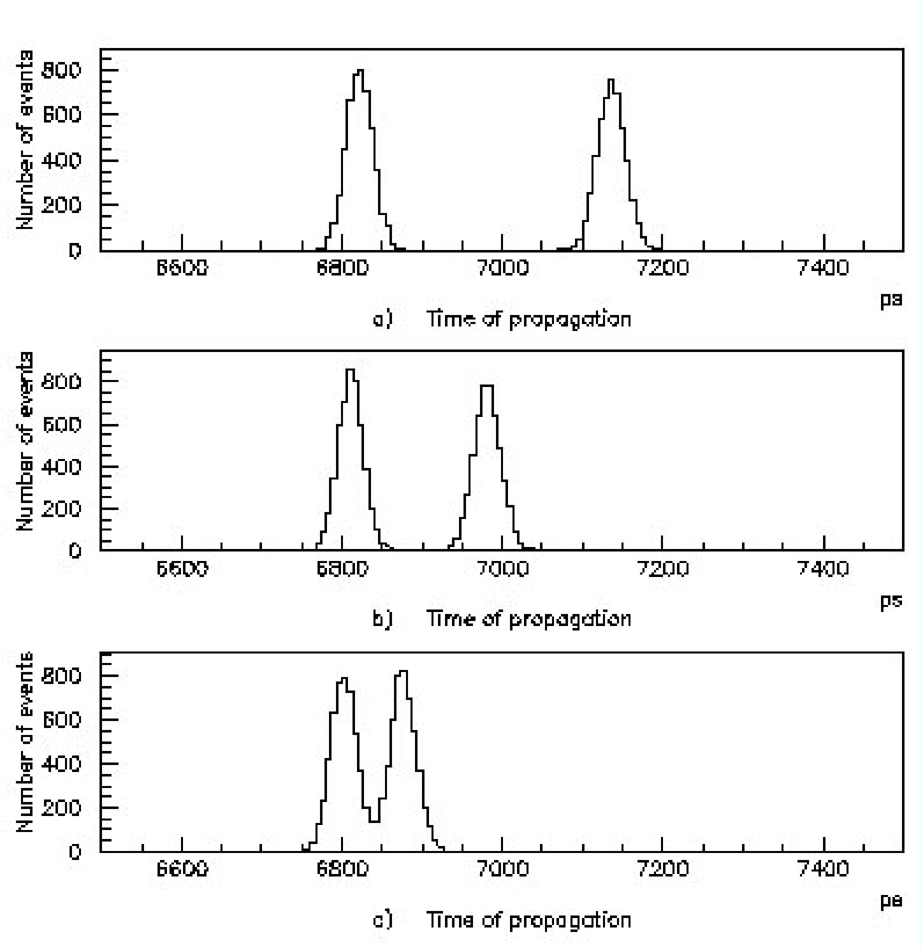
Cherenkov Time-of-Propagation (TOP) Detector Based on RFPP



$$\cos(\theta_c) = \frac{1}{\beta n(\lambda)}$$

$$t_p = \frac{L_P n(\lambda)}{c} = \frac{L n(\lambda)}{c q_z}$$

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.

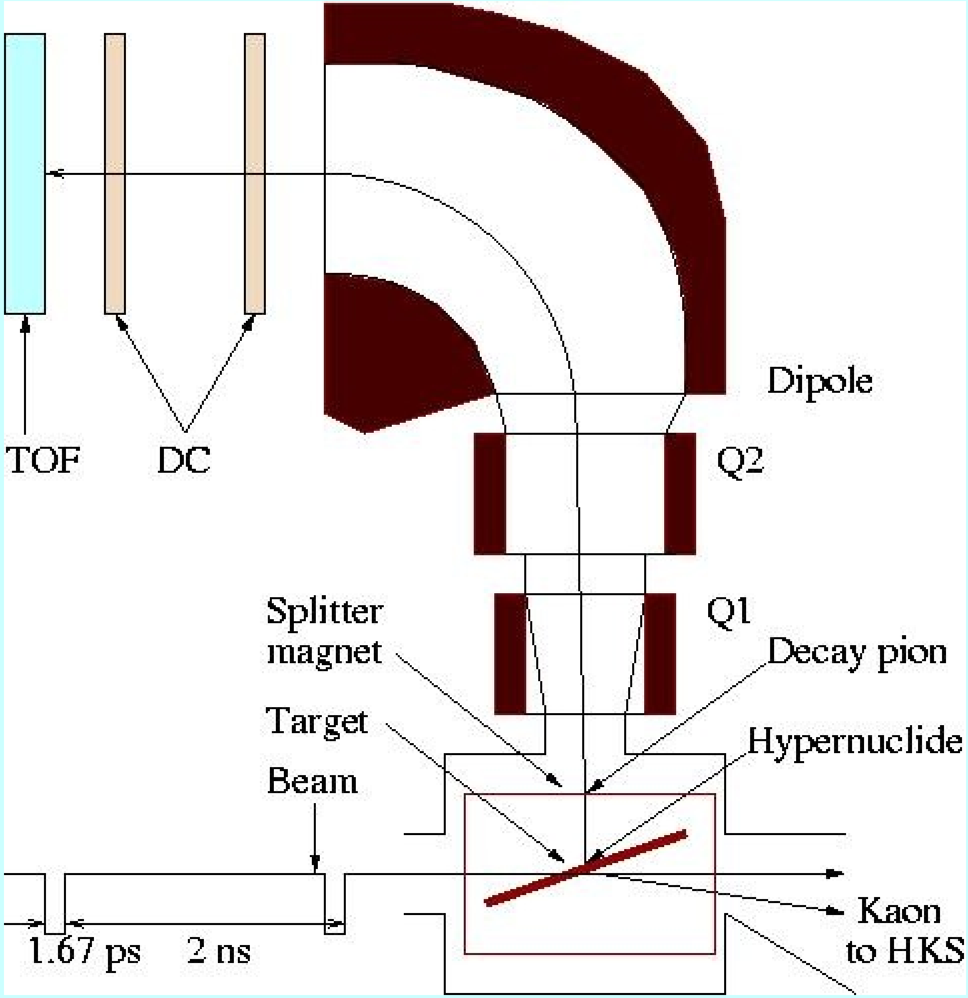


Average time of propagation distributions for forward going photons with $|\Phi_c| \leq 15°$ and L = 100 cm, for π (left histograms) and K (right histograms), θ=90° and p =1.5 (a), 2.0 (b), 3.0 (c) GeV/c momentum. Total number of events is 10000 with 50% π and 50% K tracks.

Study of hypernuclei by pionic decay at JLab (LOI-07-001)

Proposed program includes

- Precision measurements of binding energies of hypernuclei
- Studies of exotic, extremely rich halo hypernuclei such as $^{8}H_{\Lambda} \rightarrow {}^{8}He+\pi^{-}$
- Measurements of electromagnetic rates (and moments) using a "tagged-weak π-method."



Schematic view of the decay pion spectrometer (HπS).
Decay pion momenta are in the range 90-135 MeV/c

- **Binding energy resolution 100 keV.**
- **Time resolution 20 ps.**
- **Angular acceptance 30 mSr.**
- **Expected rate (at 30 microamperes beam current, 100 mg/cm^2 carbon target) for the** HπS **with Cherenkov TOF based on RFPP is ~3×10^5/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.**

Exotic application: perform direct measurement of one-way light speed anisotropy at JLab

In some theories light speed anisotropy in space is expected

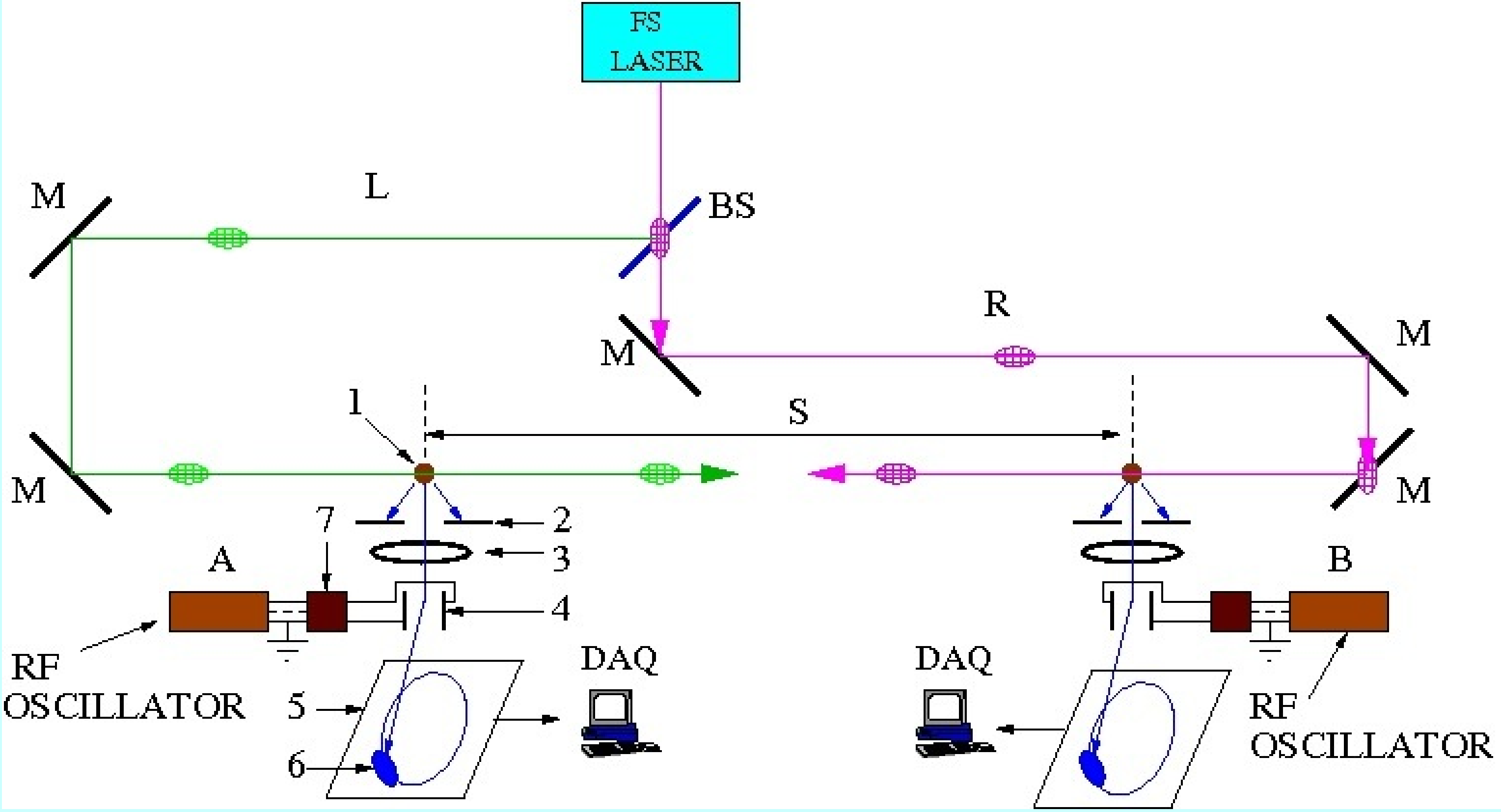
$$c(\theta)=c_0\times[1+c_1\cos(\theta)+c_2\cos^2(\theta)]$$

θ is the angle between the light propagation path and the direction of motion of the Earth with respect to a universal reference frame.

Current experimental limit on one way light speed anisotropy measured directly is

$$c_1<3.5\times10^{-7}$$ Krisher et al, Phys. Rev. D42,731,1990

- Using the RF time measuring technique and ps photon beam of JLab's FEL, this limit can be improved by 2-3 orders of magnitude.



The schematic diagram of the experimental setup.

BS - beam splitter; M - mirror;

A and B - two independent RF oscillators;

FS Laser - source of short light pulses;

DAQ - electronics and data acquisition system.

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.

Participants

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