

GAS TIME-OF-FLIGHT CHERENKOV DETECTOR WITH RADIOFREQUENCY PHOTOTUBE FOR FP420*

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In this paper, the gas Cherenkov detector with radiofrequency phototube is considered as a fast-timing detector for FP420 project. The detector serves for precise Time-of-Flight measurements of forward going protons, capable of accurate vertex reconstruction and background rejection at high luminosities. The proposed technique is a high resolution (~ 5 ps FWHM for a single proton), high rate ($\sim$ MHz) and highly stable (less than 1 ps) timing technique capable to detect up to several tens events in a short (~ 1 ns) time interval.

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1. Introduction

Recently a new R&D project FP420 has been proposed [1] for the study of the key aspects of the development and installation of a silicon tracker and fast-timing detectors in the LHC tunnel at 420 m from the interaction points of the ATLAS and CMS experiments. The Time-of-Flight (TOF) detector separation is about 850 m. These detectors would measure precisely very forward protons in conjunction with the corresponding central detectors as a mean to study Standard Model (SM) physics, and to search for and characterise new physics signals. The FP420 detectors must be capable of operating at the LHC design luminosity $L \approx 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. At these luminosities the overlap (or pile-up) background becomes a significant concern. High precision TOF detectors at 420 m can be used to obtain a large reduction of this background. The experiment needs only to measure the relative arrival time $t_L - t_R$ of the two protons, with an error less than

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10 ps rms. In addition to detector performance, a precise measurement of the arrival time difference between forward protons in the TOF detectors also requires a reference timing signal at each detector with a $t_L - t_R$ jitter smaller than 5 ps rms. The design goal is to achieve a timing resolution of 10 ps in the detectors with negligible jitter in the reference timing system. This corresponds to the interaction vertex measurement accuracy of 2.1 mm from the tagged protons.

Two types of Cherenkov TOF counters were considered for FP420: GAS Time-of-Flight (GASTOF) and QUARtZ Timing Cherenkov (QUARTIC). The GASTOF has a C_4F_{10} gas radiator of 20–30 cm length. The expected mean number of photoelectrons for a 30 cm thick radiator is about 10, while the distribution of arrival time of photons at the photomultiplier tube (PMT) face is about 4 ps, FWHM. Consequently the time resolution of GASTOF is dominated by transit time jitter in the PMT and the subsequent electronics.

In this work it is proposed to use the RadioFrequency (RF) phototube [2] to detect Cherenkov photons in GASTOF. The expected time resolution of RF phototube for single photoelectrons is about or less than 15 ps, FWHM.

2. Radiofrequency phototube

The RF phototube [2] combines the advantages of a vacuum PMT and a circular scan streak camera. This kind of phototube is capable of detecting optical signals and providing nanosecond signals, like fast PMT, for future event by event processing of each photoelectron with resolution better than 20 ps.

The operational principles of such a device for large-size photocathode are shown in Fig. 1.

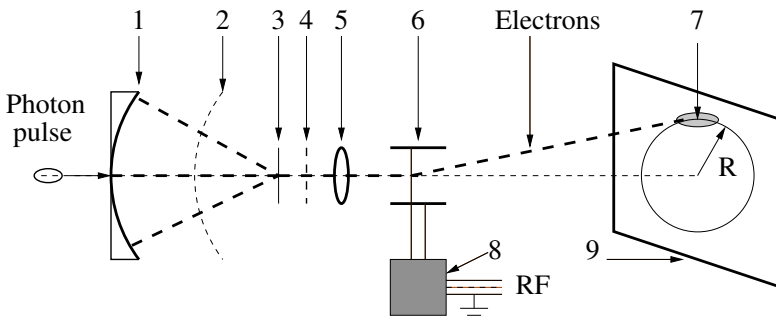


Fig. 1. The schematic layout of the RF phototube with large size photocathode. 1 — the photo cathode, 2 — the electron transparent electrode, 3 — the transmission dynode, 4 — the accelerating electrode, 5 — the electrostatic lens, 6 — the RF deflection electrodes, 7 — the image of SEs, 8 — the RF coaxial cavity, 9 — the SE detector.

To minimise the transit time jitter we propose to use “spherical-capacitor” type immersion lens and transmission dynode. Such an immersion lens implies a configuration consisting of two concentric spheres of which the outer one is a photocathode (1) and the inner one is an electron transparent electrode (2). This configuration has a number of advantages *e.g.* the possibility of having high accelerating field near the photocathode, between photocathode (1) and electrode (2), to form a perfect crossover outside of this electric field and a complete lack of transit time dispersions in the crossover for electrons with equal initial energies. The transmission dynode (3) is placed in the crossover. In a tube with similar structure and with 40 mm diameter photocathode but without transmission dynode, less than 10 ps (FWHM) temporal resolution has been achieved [3]. The primary photon pulse hits the photocathode (1) and produces photoelectrons (PEs). The produced photoelectrons are accelerated in the “spherical-capacitor” region and focused on the crossover where they pass through transmission dynode (3) producing secondary electrons (SEs) on both sides of the dynode. Low energy SEs produced on the rear side of the transmission dynode are accelerated with the help of the electron transparent electrode (4) and enter into the electrostatic lens. The time structure of these SEs is identical to time structure of PEs within error of a few ps. The electrostatic lens (5) then focuses the electrons onto the screen at the far end of the tube, where SE detector (9) is placed. Along the way the electrons pass through the circular sweep RF deflection system, consisting of electrodes (6) and the $\lambda/4$ coaxial RF cavity (8), which operates about 500 MHz. They are deflected and form a circle on the screen of the detector where the time structure of the input photon signal is transferred into spatial SE image (7) on a circle, calibrated in time by the sweep itself, and detected. The detection of the RF analysed SEs is accomplished with a position sensitive detector based on multichannel plates. In this way the RF phototube transposes the linear time axis into a circle one. The corresponding phases of the applied RF field are then fixed, detected and stored. Meanwhile, in such a detection system the timing error sources are minimised because SEs are timed before the necessary further signal amplification and processing. Practically, the RF deflection system operates as a high frequency oscilloscope and performs the time measurements of SEs before the electron multiplication process starts in the detector. The electron multiplication process in this case is used to determine the position of SEs on the scanning circle.

Basically two factors determine the time resolution of such a device:

1. technical time resolution of the “spherical-capacitor” type immersion lens — $\Delta\tau_{il}$ which is determined by the dispersion of the electron transit time between the photocathode and the transmission dynode and in a carefully designed system $\Delta\tau_{il} \leq 10$ ps, FWHM [3],

2. technical time resolution of the RF deflector, $\Delta\tau_d = d/\nu$, where d is the size of the electron beam spot or the position resolution of the secondary electron detector (if the electron beam spot is smaller) while $\nu = 2\pi R/T$ is the scanning velocity. Here T is the period of the RF field and R is the radius of the circular sweep on the position-sensitive detector. The position resolution of the SE detector based on multi-channel plates is about 0.1 mm, rms. The electron beam spot for the commercial tubes is about or less than 0.5 mm, FWHM. Therefore, for a properly designed tube with $T = 2 \times 10^{-9}$ s ($\nu_{\text{RF}}^0 = 500$ MHz), $R = 2$ cm, one has $\nu \geq 0.5 \times 10^{10}$ cm/s and $\Delta\tau_d \leq 10$ ps, FWHM.

The total time resolution for a single PE of such an RF timing technique, $\Delta\tau_{\text{RF}}$, is determined mainly by these two factors, $\Delta\tau_{\text{RF}} = (\Delta\tau_{\text{il}}^2 + \Delta\tau_d^2)^{1/2}$, and is less than 15 ps, FWHM. The time resolution can be improved, if necessary, by improving characteristics of the tube or by using higher RF frequencies, since it is possible to operate the developed RF deflector and scan circularly keV electrons in the frequency range 500–1500 MHz.

The detection of the SEs is accomplished with position sensitive detector based on a dual, chevron type micro-channel plates, MCPs. Position determination can be performed in two basic architectures:

1. direct readout: array of small ($\sim 1\text{mm}^2$) pixels, with one readout channel per pixel,
2. interpolating readout: position sensor is designed in such a way that the measurement of several signals (amplitudes or times) on neighbouring electrodes defines the event position. The position resolution limit for both cases (amplitude or times) is $\Delta x/x \sim 10^{-3}$.

The typical signal from a single SE induced on the position sensitive anode consists of two parts:

- the signal generated in MCP by circularly scanned 2.5 keV SE,
- the signal induced by the RF deflector's noise which is about an order of magnitude smaller than the amplitude of amplified in MCP signals of a single PE.

Thus, the signals from such a device can be processed by using common nanosecond-time electronics (amplifiers, discriminators, logic units, analog-to-digital converters and *etc.*), and time resolution better than 15 ps, FWHM, can be achieved for a single PE.

3. GASTOF Cherenkov detector with RF phototube at FP420

To be able to explore the full advantages of the Cherenkov GASTOF at FP420 we propose to use the RF phototube with dedicated position sensitive anode which combines the individual and extrapolating readout schemes, simultaneously. The position sensitive anode consists of n pixels, where each pixel itself is a position sensitive sensor *e.g.* is a piece of resistive anode. Each pixel operates like an independent PMT in a fixed time interval $\Delta T = T/n$, where T is the period of the RF field. The total number of pixels, n , will be determined taking into account the requirement of the experiment to detect all the events per bunch crossing with negligible pile-up. The signals from left and right sides of each pixel are used to determine:

1. the number of fired pixel,
2. the position of SEs on the fired pixel.

By this way it is assumed to detect all the events per bunch crossing with negligible pile-up and maximum capable time resolution (~ 15 ps, FWHM) for single PEs. Each forward proton produces $N_{\text{pe}} = 10$ PEs. Consequently, it can be timed within an error of $15/N_{\text{pe}}^{1/2} \approx 5$ ps, FWHM. In addition, the signals from pixels can be used to perform a regular timing within error of about 100 ps, rms.

The RF phototube, just as the streak cameras, can be operated in synchroscan mode which opens unprecedented opportunities for precise time measurements with periodic photon sources or at accelerators [4]. Figure 2 shows a schematic of synchroscan operation of a GASTOF Cherenkov detector with RF phototube at FP420. The RF signal $V_{\text{RF}}(t)$ for driving the RF phototube is taken from the master oscillator of LHC. This signal can be written in the form

$$V_{\text{RF}}(t) = V_{\text{RF}}^0 \sin(2\pi\nu_{\text{ph}}^0 t + \phi_{\text{RF}}(t) + \phi_{\text{RF}}^0),$$

where we have assumed that the amplitude V_{RF}^0 is constant. The quantity $\nu_{\text{RF}}^0 = 400$ MHz is the constant nominal frequency and t is the ideal proper time of master oscillator. The phase $\phi_{\text{RF}}(t)$ contains the deviations, random and systematic, relative to the ideal periodic variations, ν_{RF}^0 . The quantity ϕ_{RF}^0 represents the nominal phase which is constant for a given setup.

We assume that the LHC proton beams as well as forward protons at FP420 have the same time structure, with the same random and systematic deviations, $\phi_{\text{RF}}(t)$. The photoelectrons from Cherenkov radiation, produced by forward protons in GASTOF, pass through the RF deflector at the time moment t^i and fix the total phase of the RF master oscillator

$$\Phi_{\text{RF}}^i = 2\pi\nu_{\text{RF}}^0 t^i + \phi_{\text{T}}(t^i) + \phi_{\text{RF}}^0$$

somewhere on the scanning circle, determined by ϕ_{RF}^0 . Here the phase $\phi_{\text{T}}(t^i)$ contains both the random and systematic deviations relative to the ideal periodic variations due to the RF phototube. The time moment t^{i+1} for the next forward proton will be transposed to the phase

$$\Phi_{\text{RF}}^{i+1} = 2\pi\nu_{\text{RF}}^0 t^{i+1} + \phi_{\text{T}}(t^{i+1}) + \phi_{\text{RF}}^0.$$

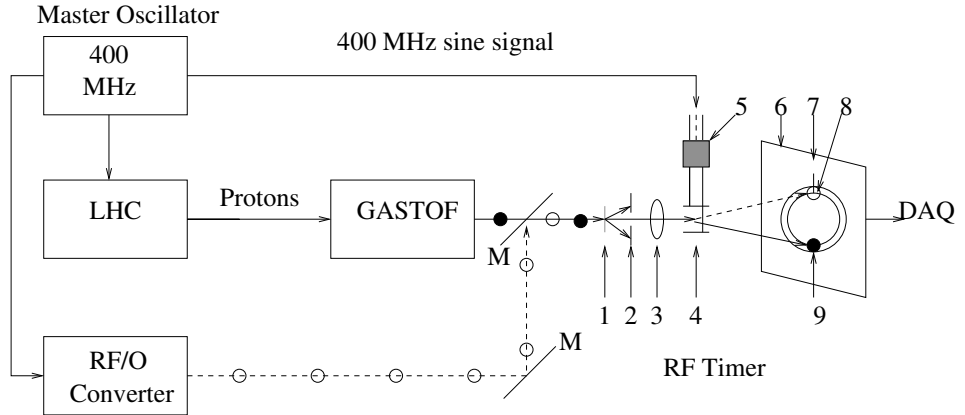


Fig. 2. Schematic of the GASTOF with RF phototube at FP420. 1 — the photo cathode, 2 — the accelerating electrode, 3 — the electrostatic lens, 4 — the RF deflection electrodes, 5 — $\lambda/4$ RF coaxial cavity, 6 — the SE detector, 7 — an arbitrary reference, 8 — the image of PEs from reference photon beam, 9 — the image of PEs from Cherenkov radiation, M — is the mirror.

For the ideal phototube, without any random and systematic drifts ($\phi_{\text{T}}(t) = 0$), the interaction region of protons in LHC is transferred precisely (the timing resolution for protons is about 5 ps, FWHM) into some region on the scanning circle and stay stable because the produced PEs match in phase the proton bunches. In this case the RF sine-like signal from the master oscillator plays the role of time reference. By using events detected in the left and right GASTOFs the relative arrival time $t_{\text{L}} - t_{\text{R}}$ of the two protons can be reconstructed with an error less than 10 ps, FWHM. The instability of streak cameras has been investigated in [5] and it has been demonstrated that the time drift has a stochastic nature and having a linear time dependence is about or less than 10 fs in 1 s. It is expected that the instability of RF phototube will be at the same level as that of the streak cameras. Therefore, the systematic error of the relative time measurements performed by streak camera or RF phototube in short (< 1 s) term is less than 10 fs. This fact can be used for an absolute time calibration of GASTOF with RF phototubes by using the early arriving PEs or the mean

time of events obtained in a short (< 100 s) time intervals for which the time drifts of left and right phototubes are less than a picosecond, by this way decreasing the time drifts in tubes.

The time drift of photon tubes can be almost eliminated by using a dedicated photon pulse train phase locked with proton bunches. For this purposes the RF sine-like signal from the LHC master oscillator is converted into optical pulse train by using radiofrequency to optical (RFO) converter based on recently developed optical frequency comb (OFC) technique [6]. The generated photon pulses with picosecond time durations are directed to the RF phototube along with GASTOF photons from FP420, as schematically shown in Fig. 2. The resulting photoelectrons are detected with total phase

$$\Phi_{\text{RF}}^{\text{REF}} = 2\pi\nu_{\text{RF}}^0 t^{\text{REF}} + \phi_{\text{RFO}}(t^{\text{REF}}) + \phi_{\text{T}}(t^{\text{REF}}) + \phi_{\text{RF}}^0$$

relative to an arbitrary fixed reference (7) on the position sensitive detector and can be used as a reference point. Here the phase

$$\phi(t) = \phi_{\text{RFO}}(t^{\text{REF}}) + \phi_{\text{T}}(t^{\text{REF}})$$

contains both the random and systematic deviations relative to the ideal periodic variations, due to the RFO converter and phototube, respectively. The time instability of such a reference photon pulse train is about or less than $10^{-14}/\tau$ [6].

The GASTOF Cherenkov photon pulses of the FP420 are also directed to the photocathode and detected with total phase relative to an arbitrary reference (7)

$$\Phi_{\text{RF}}^{\text{EXP}} = 2\pi\nu_{\text{RF}}^0 t^{\text{EXP}} + \phi_{\text{T}}(t^{\text{EXP}}) + \phi_{\text{RF}}^0.$$

If the position (9) of PEs from the GASTOF is determined relative to the position (8) of PEs from the reference beam, the long term drifts related to the phototube can be excluded. Indeed, the total phase differences of the reference photon beam and photons from the experiment are

$$\Delta\Phi_{\text{RF}} = \Phi_{\text{RF}}^{\text{EXP}} - \Phi_{\text{RF}}^{\text{REF}} = 2\pi\nu_{\text{RF}}^0 (t^{\text{EXP}} - t^{\text{REF}}) + \Delta\phi_{\text{RFO}} + \Delta\phi_{\text{T}},$$

where $\Delta\phi_{\text{RFO}} = -\phi_{\text{RFO}}(t^{\text{REF}})$, $\Delta\phi_{\text{T}} = \phi_{\text{T}}(t^{\text{EXP}}) - \phi_{\text{T}}(t^{\text{REF}})$, and ν_{RF}^0 is the nominal frequency of the LHC master oscillator. In this way the time interval $t^{\text{EXP}} - t^{\text{REF}}$ between photons from the experiment and reference beam is expressed through the value of ν_{RF}^0 , with the random and systematic deviations relative to the ideal period equal to $\Delta x_{\text{RFO}} + \Delta x_{\text{T}}$, where $\Delta x_{\text{RFO}} = \Delta\phi_{\text{RFO}}/2\pi\nu_{\text{RF}}^0$ and $\Delta x_{\text{T}} = \Delta\phi_{\text{T}}/2\pi\nu_{\text{RF}}^0$. For short time intervals, $t^{\text{EXP}} - t^{\text{REF}} \leq 1$ s, the figures $\Delta\phi_{\text{RFO}}$ and $\Delta\phi_{\text{T}}$ are less than 10 fs. In this way a 200 fs stability for hours has been achieved for streak cameras [5]. The 200 fs is determined by statistics which is achievable with streak cameras.

The RF phototube allows performing the measurements with megahertz frequency. Therefore the long term instabilities of the proposed timing system due to systematic drifts of the RFO converter and RF phototube can be decreased to be less than 10 fs even for very rare events.

4. Conclusions

The RF phototube and timing technique seems to be ideal for applications in fast timing GASTOF detector at FP420. It is high resolution (~ 5 ps FWHM for single proton), high rate ($\sim$ MHz) and highly stable (less than 1 ps) timing technique capable to detect up to several tens of events in a short (~ 1 ns) time interval. Meanwhile, the FP420 R&D project seems to be an ideal arena for demonstrating capabilities of this novel timing technique which has a great potential of revolutionising and dramatically improving the time measurement concept in different fields of science and technology.

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