PICOSECOND PHOTON DETECTORS FOR THE LHC*

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The principles of a time resolved single photon counting system, based on the hybrid GHz radio frequency photomultiplier tube, RF PMT, are presented. The time resolution and minimal time bin of the technique is about one picosecond. The average rate of the technique can reach GHz. The detection and readout systems are based on commercial microchannel plates, electron bombardment avalanche photodiodes and regular nanosecond electronics. Timing characteristics of the RF PMT were obtained by means of Monte Carlo simulations. For electron optics simulations, SIMION 8 software has been used. The operation of the dedicated GHz radio frequency deflector and a hybrid RF PMT was investigated by means of a thermionic electron source. Possible application at the LHC Atlas Forward Proton experiment is discussed.

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1. Introduction

Very accurate, stable and high rate measurements of time intervals between two or more Cherenkov radiation flashes induced by forward protons are needed in the LHC ATLAS Forward Proton, AFP experiment [1]. The detector of Cherenkov radiation must be capable to detect single photons produced by forward protons with negligible pile-up and time resolution better than 10 ps. For every bunch crossing of the LHC collider, *i.e.* at every 25 ns interval, protons are expected at forward left and right directions. These protons will be localized in time by the ~ 200 ps bunch crossing time

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interval. About 10 detected photoelectrons, PEs, are expected from each proton. Therefore, an ultra high time resolution photon detector capable of operating at a prompt rate of about 100 GHz and an average rate of 1 GHz is needed.

In this paper, we consider the principles of a time-tagged time-resolved, single-photon counting system, based on the hybrid GHz radio frequency photomultiplier tube, RF PMT [2, 3], for application at the LHC AFP experiment. Timing characteristics of the RF PMT have been investigated by means of Monte Carlo simulations. These predict that a time resolution better than 10 ps can be achieved. The operation of the GHz radio frequency deflector employed by the hybrid RF PMT was investigated by substituting a thermionic electron source for the photocathode. The detection and readout systems of the RF phototube are based on the commercial microchannel plates, MCPs, electron bombardment avalanche photodiodes, EB APDs [3] and regular nanosecond electronics. These investigations demonstrated that a hybrid RF PMT based Cherenkov detectors can, in principle, meet the requirements of the LHC AFP experiment.

2. Radio frequency photomultiplier tube

A schematic diagram of a RF PMT with a small size cathode is given in Fig. 1. Incident photons strike the photocathode, producing photoelectrons, PEs, which are accelerated to 2.5 keV between the photocathode and an electron-transparent electrode. They are then focused in an electrostatic lens and pass through the dedicated, circular-sweep RF deflection system. PE's passing through RF deflector are deflected and form a circle on the screen of the PE detector, where the time structure of the input photon signal is transformed into the spatial structure of electron image on a circle.

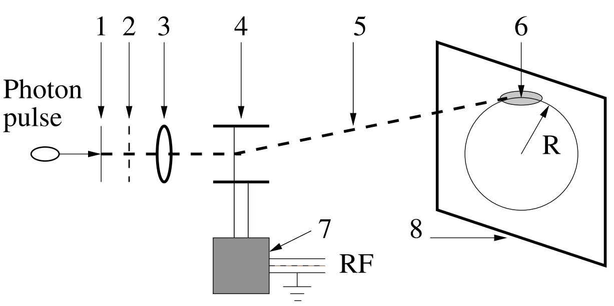

Fig. 1. Schematic diagram of a small area photocathode RF PMT: 1 — photocathode, 2 — electron transparent anode, 3 — electrostatic lens, 4 — electrodes of the RF deflector, 5 — RF deflected PE, 6 — spot of PE on the PE detector, 7 — $\lambda/4$ coaxial RF cavity, 8 — PE detector.

The detection of the RF analysed PEs is accomplished with a position sensitive (PS), PE detector. The time resolution for a single PE of this RF timing technique, $\Delta\tau_{\rm RF}$, is determined by the transit time spread, $\Delta\tau_{\rm t}$ of PEs in the electron tube and the time resolution of the RF deflector, $\Delta\tau_{\rm d}$: $\Delta\tau_{\rm RF} = \sqrt{\Delta\tau_{\rm t}^2 + \Delta\tau_{\rm d}^2}$. The transit time spreads (TTS) were simulated by means of the SIMION 8 software. For an optimized tube geometry calculated TTS as a function of applied accelerating voltage are shown in Fig. 2. In the simulations PE energies were assumed distributed uniformly in the range of 0–1 eV, while their initial directions are taken to be isotropic.

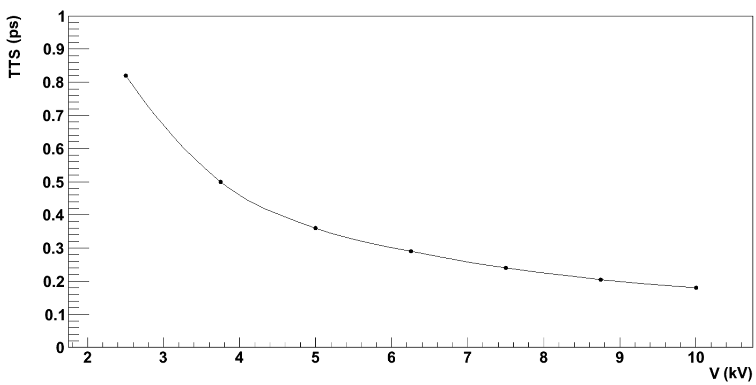

Fig. 2. Simulated TTS *vs.* applied accelerating voltage.

By definition, the RF deflector time resolution $\Delta\tau_{\rm d} = D/\nu$, where D is the size of the PE beam spot on the detector screen or the position resolution of the detector (if the PE beam spot is smaller), while ν is the scanning speed: $\nu = 2\pi R/T$. Here, R is the radius of the circle and T is the period of the RF field. For the properly designed 1 GHz RF PMT tube and PE detector with position resolution less than 0.1 mm, $\Delta\tau_{\rm d} \approx 1$ ps.

A schematic diagram of the RF PMT with a large size photocathode is given in Fig. 3.

The primary photon pulse strikes the photocathode and produces PE. These electrons are accelerated in the "spherical-capacitor" region and focused on the crossover where they pass through a transmission dynode producing secondary electrons (SE) on both sides of the dynode. Low energy SE produced on the rear side of the transmission dynode are accelerated by the electron transparent electrode and enter into the electrostatic lens. SE passing through the RF deflector are deflected onto a circle on the screen of the PE detector and detected, similar to the case of the small-size cathode.

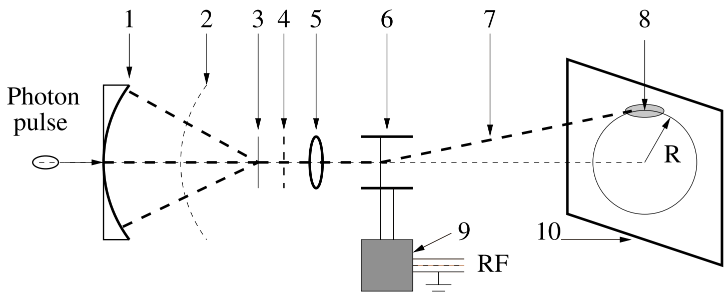

Fig. 3. The schematic layout of the RF phototube with large size photocathode. 1 — photocathode, 2 — electron transparent electrode, 3 — transmission dynode, 4 — accelerating electrode, 5 — electrostatic lens, 6 — RF deflection electrodes, 7 — RF deflected SE, 8 — spot of SE on the PE detector, 9 — $\lambda/4$ RF coaxial cavity, 10 — PE detector.

The TTS of PE at the crossover, simulated by means of the SIMION 8 software, as a function of applied accelerating voltage between the cathode and the accelerating electrode are shown in Fig. 4. For an optimized large size photocathode RF PMT, the TTS can be as low as ~ 5 ps.

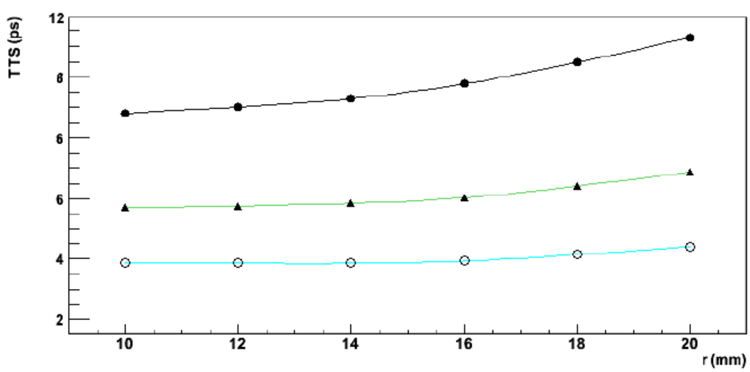

Fig. 4. Simulated TTS of PE at the crossover *vs.* cathode radius for 3 applied accelerating voltages between cathode and accelerating electrode in a "spherical-capacitor" region. Filled circle 2.5 kV, triangle 5.0 kV, open circle 10 kV.

3. RF deflector and readout anode architecture

The RF deflector consists of $\lambda/4$ coaxial RF cavity, operating at 500–1000 MHz frequencies, and deflection electrodes [2]. These electrodes form a wire cavity with a quality factor $Q \gtrsim 100$. The resonant frequency can be fixed at the desired value by using a $\lambda/4$ coaxial cavity or an additional variable capacitor. The sensitivity of the RF deflector at resonance frequencies is about 0.1 rad/$W^{1/2}$. A $\sim$ 20 V (peak to peak) RF sine wave is sufficient to produce a scanning circle with a few cm scanning radius on the PE detector plane.

We have tested the operational principles of a PE detector consisting of dual MCP chevron assemble and, alternatively, a hybrid PE detector consisting of a single MCP plate followed by a 20 micrometer scintillator foil readout by APD (Hamamatsu S1 0362). The nanosecond signal, generated by circularly scanned 2.5 keV electrons incident on the dual MCP chevron assemble and detected directly by a position sensitive resistive anode consists of two parts: signals generated by 2.5 keV electrons and RF induced noise. The single electron induced signals are an order of magnitude larger than the RF induced noise and they can be processed by regular fast electronics (see [3], Fig. 3).

The nanosecond signals, generated by circularly scanned 2.5 keV electrons incident on the hybrid PE detector and detected by the APD, are displayed in Fig. 5. As in the former case, the single electron induced signals can be processed by regular nanosecond electronics.

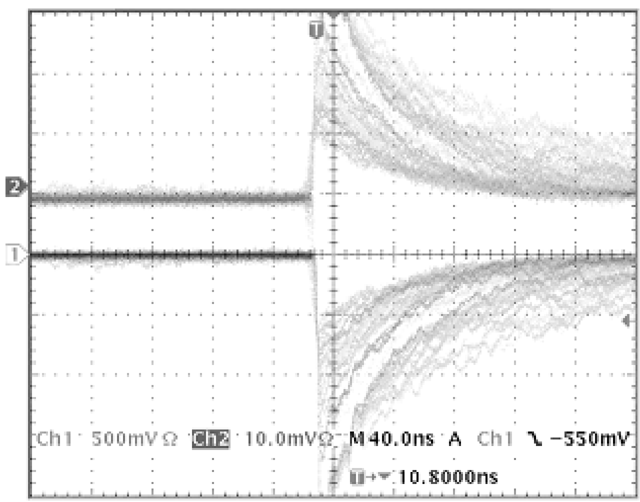

Fig. 5. Nanosecond signals directly from APD (top) and after preamplifier (bottom).

There are basically the two readout methods to locate the position on the scanned circle: interpolation readout and pixel-by-pixel readout. Interpolation readout needs only two readout channels by applying charge-division or delay-line time difference techniques. However, it can only bear a moderate counting rate. For example, with the dual MCP chevron assemble the anticipated rate is about 1 MHz. The pixel-by-pixel readout anode permits needed high counting rates.

4. Pixel-by-pixel readout anode

In this case, the PE detector of the RF PMT consists of an array of small size ($D \times D$ mm^2) pixels, with one readout channel per pixel. For a scanning circle with radius $R_0 = 20$ mm and $D = 0.1$ mm, we have about 1000 independent channels (see Fig. 6). In such a system, each pixel operates as a $\Delta T \cong 1$ ps time gated independent photon counting channel. Meanwhile, all channels are phase locked and by recording numbers of RF cycles (macro-time) and fired channel (micro-time), a time tagged and time resolved single photon counting system may be achieved. In such a photon detector, 1 ps (10 ps) time resolution may be achieved for small (extended) size photocathodes. The bandwidth of such a photon counting system is about THz (*i.e.* two photons with 1 ps lag can be separated). This system should thus be able to digitize the optical waveforms with duration less than T ($T = 10^{-9}$ s for $\nu^0_{\rm RF} = 1$ GHz) with a precision of 1 ps. The prompt rate can reach THz in that all 1000 pixels can be fired simultaneously in one ns time interval.

The average rate of a single photon counting system will be determined mainly by the PE detector, while a high average rate can be achieved by using a hybrid PE detector.

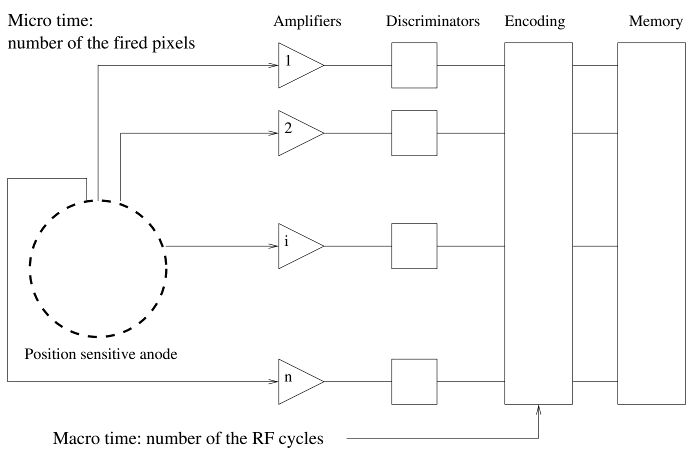

Fig. 6. Schematic of a timing system based on the pixelated anode RF PMT.

5. Hybrid photoelectron detector

We consider two types of hybrid PE detectors for the LHC, AFP project [1]. The first type of hybrid PE detector consists of a single MCP and an array of sub-mm^2 EB APDs, designed for few keV electron detection; one readout channel per APD. For the LHC AFP project, we will need ~ 200 channels, each channel covering about 1 ps time interval. In a single MCP plane the multiplication factor is ~ 1000, while in an APD it is about 200 due to the energy of the electrons and about 100 due to avalanche process. So the total multiplication factor of such a hybrid detector will be about 2×10^7. The rate that a single MCP based detector can achieve is 5×10^{10} cm^{-2}s^{-1} [4] and the rate of single channel APD is ~ 5 MHz. Therefore, the rate of a 200 channel hybrid PE detector based RF PMT can be as high as 1 GHz.

The design of the second type hybrid PE detector is similar to the first one. In this case, instead of an array of EB APDs, an array of APDs operating in a Geiger mode (*e.g.* an array of windowless G-APDs or G-APDs covered by thin scintillation foil) will be used. Both designs meet the requirements of the AFP project.

The RF PMT will be operated synchronously with the LHC bunches [5], *i.e.* the master oscillator of LHC will be used as a reference clock. Such an operation is similar to the synchroscan operation of streak cameras and the anticipated phase stability (time drift of RF PMTs) is 1–2 ps over periods of hours [6]. Meanwhile, it will be continuously calibrated by using a reference reaction, interaction point of which will be determined by the ATLAS central detectors. In principal, better than 1 ps synchronization between left- and right-hand side of forward proton Cherenkov detectors could be achieved.

R&D, in collaboration with manufacturing companies, is needed to develop prototypes of these hybrid RF PMTs. These would then require testing in real experimental conditions.

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