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Single Photon THz Timer

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Abstract. A time-tagged, time-resolved single photon THz counting system, based on the recently developed, GHz, radio-frequency photomultiplier tube (RF PMT) is considered. The proposed technique is capable for detecting single photons with 1 ps resolution over virtually unlimited time spans. Over a period of around 100 ns the technique would be capable of THz rates, while longer term average rates of up to GHz could be achieved. The detection and readout systems of the RF PMT are based on commercial multichannel plates (MCP), electron bombardment avalanche photodiodes (EB APD) and regular nanosecond electronics.

Keywords: radio frequency photomultiplier tube, single photon counting, picosecond time resolution, THz rates

1 Introduction

The detection of visible light underpins a wide range of scientific, engineering and applied techniques. At present, the detection of optical signals, down to the single-photon level, is carried out with devices such as Avalanche Photodiodes (APD), vacuum Photomultiplier Tubes (PMT), Hybrid Photon Detectors (HPD) and Streak Cameras (SC).

APD, PMT, HPD and SC enable one to obtain precise time information about the detected photons, which is necessary in many diverse fields such as particle detection in high energy and nuclear physics, astrophysical imaging and medical imaging. The time resolution limit of current APD, PMT or HPD for single photoelectron detection is about 100ps FWHM. These devices provide fast, instantaneous readout in the form of nanosecond electronic signals, which is crucial in multimodal analysis. The time resolution of SC is of the order of 1 ps or better. However, SCs so far have not found wide application in fields such as elementary particle physics, nuclear physics and bio-medical imaging. This is related mainly to the inability of available SC devices to provide fast, instantaneous readout. The basic principle of SCs or any radio frequency (RF) timing technique is the conversion of the information in the time domain to a spatial domain by means of a RF deflector. We have developed a new method for circular scanning of keV electrons in the 500-1000 MHz frequency range [1]. The sensitivity of this new and compact RF deflector is about an order of magnitude higher than that of previous deflectors. Potentially it has a number of applications in fixed-frequency cathode-ray-tube based instruments. Combination of our RF deflector with a position sensitive electron multiplier provides the basis of a new device, the RF PMT [2, 3]. Such a photomultiplier tube combines the advantages of a regular PMT or APD and a SC. It would be capable of detecting optical photons and providing fast (~ns) output signals, similar to a fast PMT. The principles of deflection and position sensitive electron detection have been verified using a demountable prototype tube and a sealed vacuum tubes with functional photocathode is under construction. For such a device the expected time resolution for single photons would be ~1 ps, counting rates of ~1 MHz could be sustained and the RF PMT would fit in well with the regular Time Correlated Single Photon Counting (TCSPC) technique

[4]. In principle, with a dedicated spiral scanning (Sec. 2.3) system and electron detector, the rate could be increased up to the THz level.

2 RF PMT

A schematic diagram of a RF PMT with a small size cathode is given in Fig. 1.

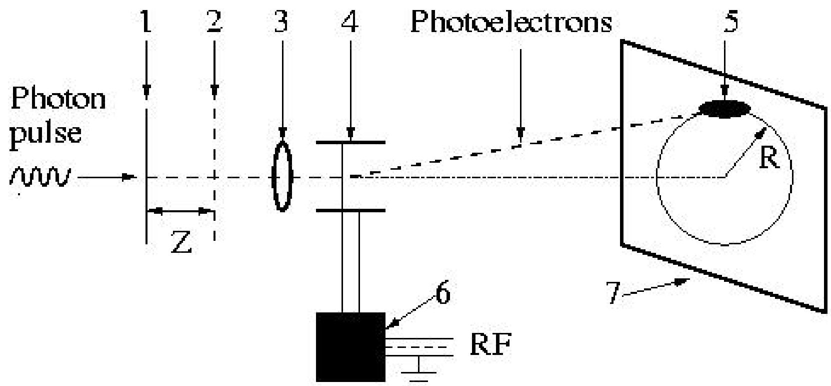


Figure1. Schematic diagram of a small-area cathode RF PMT: 1-photocathode, 2- electron transparent anode, 3-electrostatic lense, 4- electrodes of the RF deflector, 5-spot of photoelectrons on the photoelectron detector, 6-RF source, 7-photoelectron detector.

Incident photons strike the photocathode, producing photoelectrons (PE’s), 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 circular-sweep, RF deflection system [1]. 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 a spatial electron image on a circle.

The detection of the RF analyzed PE’s is accomplished with a position sensitive PE detector. The time resolution for a single PE, for a properly designed 1 GHz RF deflector coupled to a PE detector with position resolution less than 0.1 mm, is about 1ps.

A schematic diagram of a large-area photocathode RF PMT is given in Fig. 2.

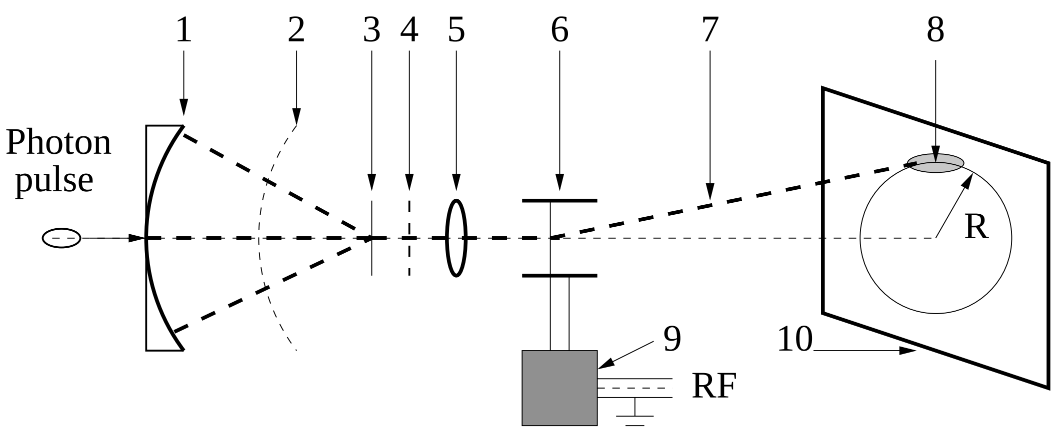


Figure 2. The schematic layout of a RF PMT with a large size photocathode. 1- spherical photocathode, 2- electron transparent electrode, 3- transmission dynode, 4- accelerating electrode, 5-electrostatic lens, 6- RF deflection electrodes, 7-RF deflected SE, 8- spot of SE on the electron detector, 9- RF source, 10- PE detector.

The primary photon pulse strikes the photocathode and produces PE's. These electrons are accelerated in the "spherical-capacitor" region and focused on the crossover where they pass through a transmission dynode, producing secondary electrons (SEs) on both sides of the dynode. Low energy SEs produced on the rear side of the transmission dynode are accelerated by the electron transparent electrode and enter into the electrostatic lens. SEs passing through the RF deflector are deflected to a circle on the screen of the PEs detector and detected, similar to the case of the small-size cathode. For an optimized photocathode of a few cm in diameter, transit time spread of PE's at the crossover can be as low as 5 ps.

2.1 RF Deflector

The RF deflector has a helical shape and performs circular sweeps of keV electrons by means of RF fields in a frequency range 500-1000 MHz [1]. By converting the time dependence of incident electrons to a hit position on a circle, this device can potentially achieve sub picosecond timing. The system can be adjusted to the velocity of the electrons to exclude the reduction of deflection sensitivity due to finite transit time effects. The deflection electrodes form a resonant circuit, with quality factor Q higher than 100, and at resonance, the sensitivity of the deflection system is around 1 mm per V of applied RF input. A ~20 V (peak-to-peak) RF sine wave is sufficient to produce a scanning circle with a few cm in radius on the PE detector plane.

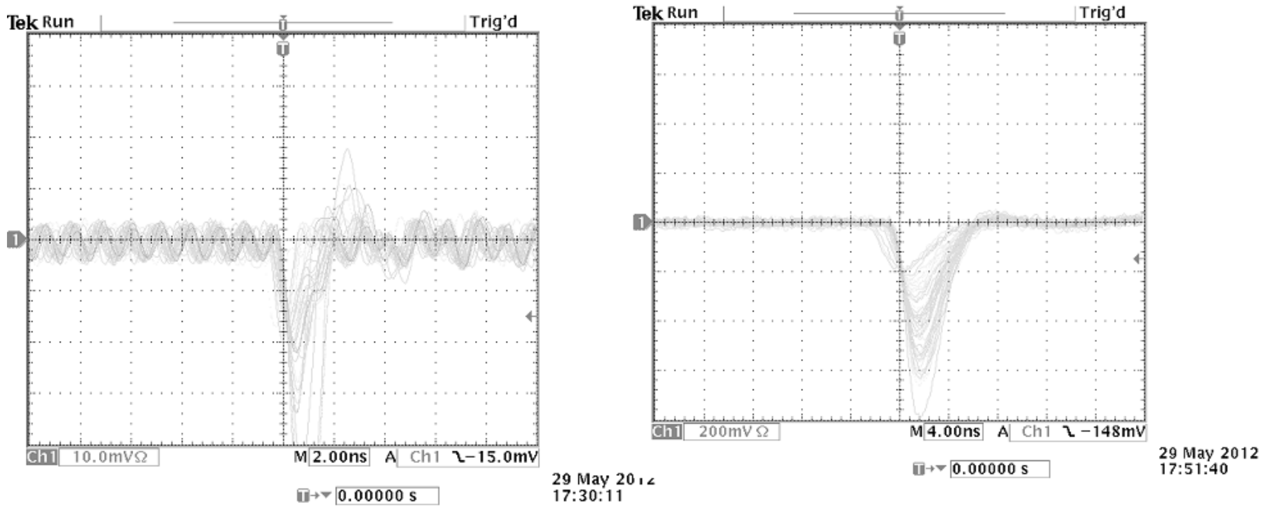
2.2 Electron Detector and Readout Schemes

We are considering three types of PE detectors: a MCP based PE detector; an EB APD based hybrid PE detector and an EB APD based PE detector.

A dual MCP chevron type configuration is used to obtain gains up to ~10^6. The position sensitive anode is situated directly behind the second MCP and the dead time of the second MCP limits the rate of the PE detector to a few MHz. The position sensitive anode could be a simple resistive device or a pixelated device with a pixel size less than 1mm.

The hybrid PE detector consists of a single MCP plane and an array of sub-mm^2 EB APDs designed for ~1 keV electron detection, with one readout channel per APD. In a single MCP plane, we would have a multiplication factor of ~1000, a factor of about 200 in an APD due to the energy of the electrons and a factor of around 100 due to the avalanche process. Therefore, the total multiplication factor of such a hybrid detector would be about 2×10^7. The rate that a detector based on a single MCP plane can achieve is around 5×10^{10} $cm^{-2}s^{-1}$ (see [5] and references therein), and the maximum rate of a single channel APD is ~5 MHz. Therefore, the rate of a RF PMT, based on a hybrid PE detector, could be as high as 5 GHz.

The EB APD based PE detector consists of an array of APDs designed for 2.5 keV electron detection operating in a Geiger mode (G-APD). The rate of a single channel G-APD is ~5 MHz. By using a properly developed spiral scanning system (sec. 2.3) to spread the hits on an array of Mega pixel G-APDs, it will be possible to create a single photon continuous THz timing system with about 1 ps resolution.



a) b)

Figure 3. Nanosecond signals directly from readout anode (a) and after preamplifier (b).

We have tested the operational principles of a PE detector consisting of either a dual MCP chevron assembly or alternatively a hybrid PE detector. The latter consisted of a single MCP plate followed by a 20 micrometer scintillator foil read out by an APD (Hamamatsu S1 0362). The nanosecond signal, generated by circularly scanned 2.5 keV electrons incident on the dual MCP chevron assembly and detected directly by a position sensitive resistive anode is shown in Fig. 3a. The signal after a preamplifier stage analyzed by a 500 MHz scope is displayed in Fig. 3b.

The signal from the anode (Fig. 3a) 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.

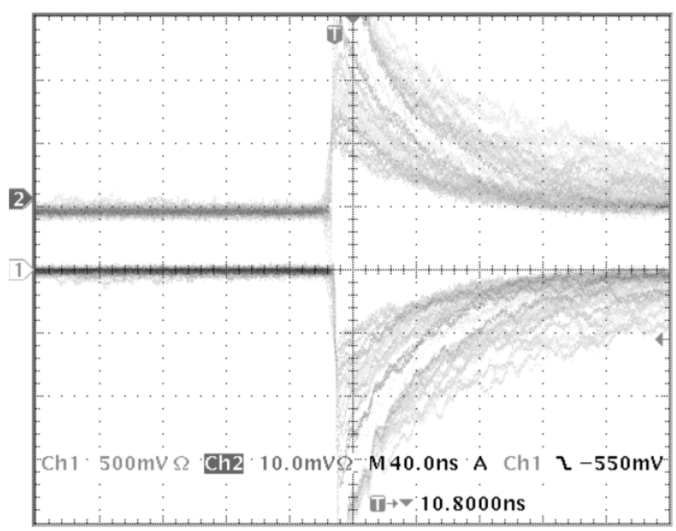


Figure 4. Nanosecond signals directly from APD (top) and after preamplifier (bottom).

The signals, generated by circularly scanned 2.5 keV electrons incident on the hybrid PE detector and detected by the APD are displayed in Fig. 4. Although they have a fast rise time, the relatively slow decay time could limit achievable rates.

Basically there are the two readout methods to locate the position on the detector plane: interpolation readout or pixel-by-pixel readout. Interpolation readout needs only a few readout channels and dedicated electronics. However, it can only bear a moderate counting rate. For example with the dual MCP chevron assembly, the anticipated rate is about 1 MHz. The pixel-by-pixel readout anode permits much higher counting rates.

2.3 Spiral Scanning System for keV Electrons

Having achieved circular scanning with an RF deflector, the next step is to create an RF deflector with spiral scanning. The idea is based on the effect of amplitude beating by adding two harmonic signals with close frequencies ω_1, ω_2. Two operating RF deflectors, RFD1 or RFD2 individually, by using sinusoidal voltages with frequencies ω_1 and ω_2 the trajectories of scanned electrons will follow circumferences with radii R_1 and R_2. Operating the RFD1 and RFD2 deflectors simultaneously results in spiral scanning with frequency $\omega_{beat} = |\omega_1 - \omega_2|$, and maximum and minimum radii $R_1 + R_2$, $|R_1 - R_2|$. A map of the transverse coordinates R_x and R_y for the case of $\omega_2 = \omega_1 + 0.1\omega_1$ and $R_2 = 2R_1$ is presented in Fig. 5. In this case, the trajectories of the scanned electrons form a spiral with a factor 10 extended periods. Fig. 5a shows the 5 periods down towards the centre, Fig. 5b the five periods upwards from the centre and Fig. 5c one full spiral period. In practice, it should be possible to maintain a very high time resolution for all periods. The down and up spiral periods can be separated by using suitable dedicated electronics.

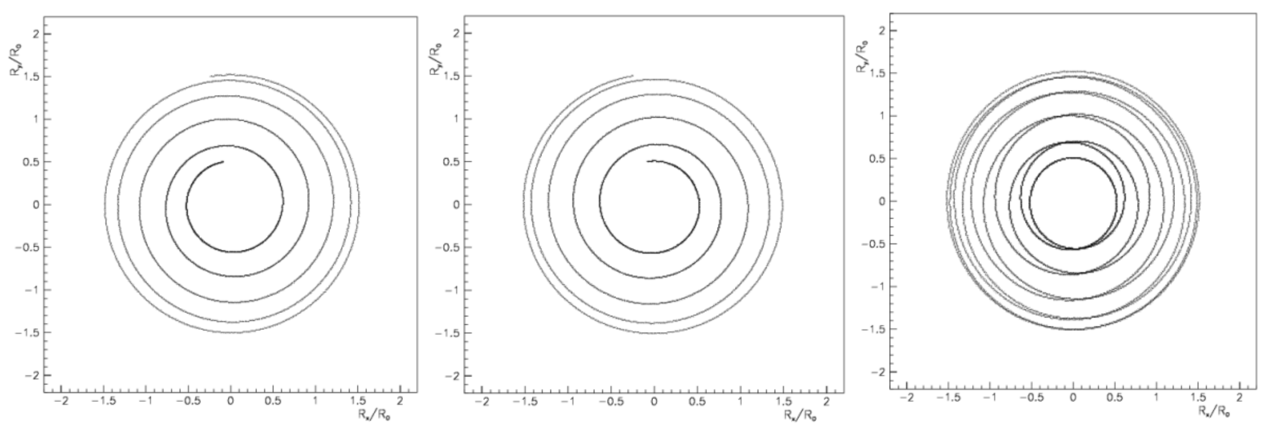
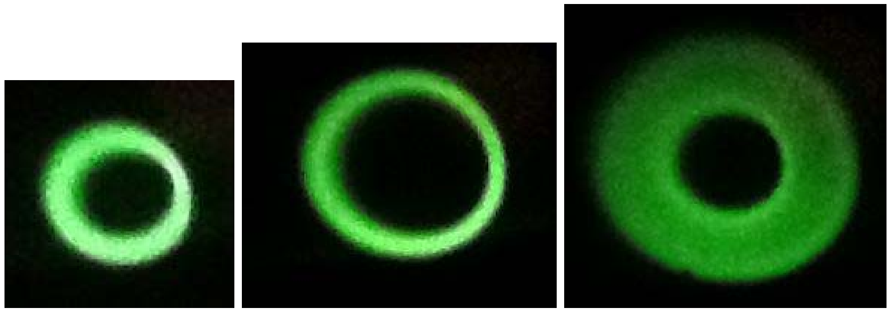


Figure 5. Map of the transverse coordinates R_x and R_y for the case of $\omega_2 = \omega_1 + 0.1\omega_1$ and $R_2 = 2R_1$.

Preliminary experimental studies to achieve spiral scanning by using two RF deflectors were carried out using an experimental setup with a thermionic electron source, electrostatic lens and phosphorus screen. The parameters of the deflectors RFD1 and RFD2 were tuned to operate at frequencies $\omega_1 = 500$ MHz and $\omega_2 = 550$ MHz and produce circles with radii R_1 and $R_2 = 2R_1$ when operating individually (Fig. 6a,b). The image of the deflected 2.5 keV continuous electron beam at the phosphorus screen, when both deflectors are operating simultaneously, has approximately a uniform distribution between radii $R_1 + R_2$ and $|R_1 - R_2|$. This is due to summing of the huge number periods of the formed spiral (Fig. 6c).



a) b) c)

Figure 6. Images of the deflected 2.5 keV continuous electron beam at the phosphorus screen.

3 The RF PMT and optical frequency comb

Recently, a revolutionary kind of light source, called an Optical Frequency Comb (OFC) has been developed (see [6] and references therein). The OFC, usually based on mode-locked lasers, may be used to transform coherently from optical to microwave frequencies. In the frequency domain, it provides the ultimate in stability for microwave frequencies. In the time domain, it provides the ultimate in stability against clock-walk. The derived microwave frequencies may be used to drive the RF PMT synchronously with the OFC, employing a *fs* photon pulse train as an excitation photon beam and as a reference to correct internal time drifts in the RF PMT. Therefore, a combination of the OFC and RF PMT would result in a new high resolution (1 ps for single photons), high rate ($\geq$ 1 MHz) and highly stable (10 *fs*/hr) time measuring technique for single photons [7].

4 THz timing processor

High counting rates can be achieved by using pixelated readout, which could be a pixelated semiconductor wafer or an array of small size detectors. In the case of circular scanning on the detector plane a circle with constant radius R_0 and width d is produced. By using an array of small size pixels, with one readout channel per pixel for R_0=20 mm and d=0.1 mm one has about 1000 independent channels (see Fig. 7).

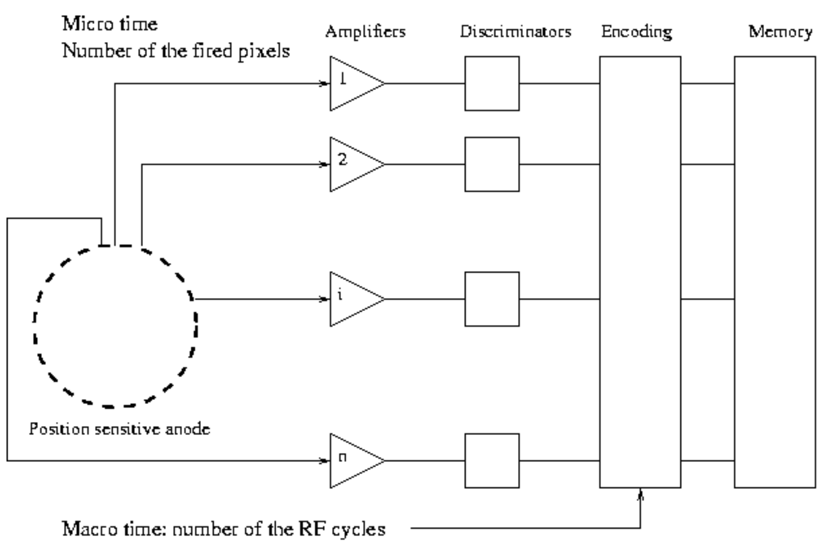


Figure 7. Schematic view of a THz bandwidth timing system based on the pixilated anode RF PMT.

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, i.e. macro-time, and fired channel (micro-time), one achieves a time tagged and time resolved single photon counting system with ~1 ps resolution. The bandwidth of such a photon counting system would be about THz (i.e. two photons with 1 ps lag could be separated). This system would be able to digitize an optical waveform with duration less than T ($T = 10^{-9}$ s for $\nu_{RF}^{0} = 1$ GHz) with a precision of 1ps. The prompt rate could reach THz, i.e. all 1000 pixels could be fired simultaneously in a one ns time interval, while the longer term averaged rate would be at the GHz level, depending on the speed of data readout. By using a properly designed spiral scanning system, the number of pixels could in principle be increased by orders of magnitude, and consequently the rate could be increased up to the THz level.

5 Conclusions

The principles of a time-tagged time-resolved, single-photon THz counting system, based on the RF PMT are laid out. The time resolution, minimal time bin and long-term time stability of the technique is about a 1 ps. The prompt rate of the technique with a dedicated spiral scanning system could reach THz over a short interval of about 100 ns, while the longer term averaged rate would be at the GHz level, depending on the speed of data readout. In principle, THz rate continuous operation would be achievable by suitable configuration of the spiral scanning deflection system and readout electronics. The detection and readout systems would be based on commercial MCP, EB APD or even their combination along with regular nanosecond electronics. Prototype sealed vacuum and demountable tubes with functional photocathodes are under consideration.

The single photon THz counting system would revolutionize the time correlated single photon counting technique and could find applications in many fields of science and technology including fundamental physics, high-energy physics, time-domain astrophysics and biomedical imaging. R&D, in collaboration with manufacturing companies, is needed to develop prototypes of this new timing technique.

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