A Picosecond Resolution Optical Sensor for TCSPC Applications at CANDLE

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Ultrafast Beams and Applications
02-05 July 2019, CANDLE, Armenia
Time-Correlated Single Photon Counting (TCSPC)

- Single photons detection
- Measurement of their arrival times in respect to a reference signal
- Accumulation of photon events statistics by means of repetitive light source
- Building up the distribution of the photons over the time after the excitation pulse
- The photon distribution represents the waveform of the optical signal
The Radio Frequency Photomultiplier Tube (RF PMT)

<table>
<thead>
<tr>
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<th>Time Resolution</th>
<th>Counting Rate</th>
<th>Readout</th>
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</thead>
<tbody>
<tr>
<td>PMT, APD, HPD</td>
<td>25 ps</td>
<td>Few MHz</td>
<td>Fast</td>
</tr>
<tr>
<td>Streak Camera</td>
<td>1 ps</td>
<td>Few 10 KHz</td>
<td>Slow</td>
</tr>
<tr>
<td>RF PMT</td>
<td>1 ps</td>
<td>Few MHz</td>
<td>Fast</td>
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</tbody>
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- **Sensitive photo-detector, capable of registering single photons**: optical photons produce electrons on a photo cathode, which are accelerated to keV energies, multiplied and detected.

- **Conversion of information in the time domain into a spatial domain**: Scanning photo-electrons by means of helical RF deflectors.

- **Fast signal output** as with regular PMTs

- **Picosecond level timing resolution** as with streak cameras

**RF PMT combines advantages of PMT, APD, HPD and Streak cameras**
Streak Principle: convert time dependence of an optical signal to a spatial dependence of the accelerated photo-electron

Time resolution $\sigma < 1$ ps
Time stability stability - 200 fs/h
Time drift is $\sim 10$ fs/s;
Image processing rate is $\sim$ few 10 kHz

see e.g. W. Uhring et al., Rev. Sci. Instr. V.74, 2003
RF Circular Scanning Deflector for keV Electrons

Helical electrodes: optimised to the velocity of the transiting electrons
Loss of deflection sensitivity due to finite transit time effects is avoided.
Electrodes form a resonant circuit, with $Q > 100$.
On resonance, sensitivity of the deflection system
$\sim 1$ mm/V or $0.1$ rad/W$^{1/2}$
$\sim 1$ W (into 50$\Omega$) RF power sufficient to scan 2.5 keV electrons circularly 2 cm radius.
Order of magnitude reduction in required RF power

L. Gevorgian et al., Nucl. Instr. and Meth. A785, 175, 2015
RF Spiral Scanning for keV Electrons

Amplitude beating

2 RF deflectors RFD₁ RFD₂ operating at \( \omega_1, \omega_2 \) individually give circular trajectories radii \( r_1, r_2 \)

RFD₁₂ simultaneously: spiral scanning \( \omega_{beat} = \omega_1 - \omega_2 \) max radius \( r_1 + r_2 \) min radius \( r_1 - r_2 \)

Operational spiral-scan RFPMT requires pixel anode

\[ w_2 = 1.1w_1, \quad r_2 = 2r_1 \]

Spiral with factor 10 extended period

Preliminary experimental results
Time resolution of RF PMT

- **Physical time resolution of the photocathode:** For the typical thickness of semitransparent bialkali photocathode $\Delta l \approx 20nm$ and $\Delta \epsilon = 1eV \Delta \tau_p \leq 10^{-12}s$

- **Physical and technical time resolution of the electron tube:** in a carefully designed system, for small-sized photocathode, these can be minimized to be in sub picosecond range

- **Technical time resolution of the RF deflector** $\Delta \tau_d = d/v$; $d$ - convolution of the size of the electron beam spot and the position resolution of the electron detector, $v = 2\pi R/T$; with $d = 0.01cm$, $R = 2cm$ and $T = 10^{-9}s$ $\Delta \tau_d = 1ps$
• CANDLE mode locked lasers provide 50 MHz, 0.5-9 ps wide photon pulses
• CANDLE master oscillator can be used to drive the RF PMT synchronously with the laser photon beam
• Laser pulse will serve as an excitation photon beam and as a time reference
RF PMT and Stimulated Emission Depletion Microscopy

Excitation pulsed laser beam marks a region in fluorescent sample

Spontaneous emission region is confined by a second STED beam

STED microscopy overcomes the diffraction limit

Spatial resolution is of the molecular scale

The emission point of the fluorescent photon, parameterized in terms of a Point Spread Function (PSF), is correlated to the emission time of that photon.

Time-gated detection using pulsed excitation and continuous STED beams substantially improves the spatial resolution

Measuring the times of fluorescent decay photons down to the ps level would have the potential for ultra high spatial resolution
RF PMT and Diffuse Optical Tomography

- Laser pulses are directed at the tissue under study
- Photon times are measured after they leave the tissue
- Using RF PMT for time measurements instead of regular PMTs will vastly reduce the instrumental distortion and improve quality of imaging
First prototype of vacuum sealed RF PMT is built by Photek Ltd. (UK) and currently is being tested in YerPhI
Outlook

- Operational principles of RF timer for kev electrons are verified experimentally
- Spiral scanning developed and demonstrated experimentally
- 1st Prototype vacuum sealed RFPMT with circular scan and simple resistive anode constructed by Photek Ltd. (UK). Test studies are underway in Yerevan
- 2nd Prototype vacuum sealed RFPMT with circular scan to be manufactured later 2019 early 2020
- Development of the demountable RFPMT with spiral scan is on-going
- Pixel-anode and readout electronics are under development