Ultra-fast photomultiplier tubes based on radio frequency technique for Cherenkov photon detection

The photo-electrons produced in a photocathode pass through a RF deflector and then create signals in a device such as MCP. This is shown to achieve excellent time resolutions at the level of 10 ps. They can be operated at a rate up to 100 MHz for the detection of single photons and electrons.

- Regular photon sensors and timing technique
- RF timing technique
- Advanced RF timing technique
- Time Resolved Photo-Electron Spectrometer
- R&D to reach few 1 ps resolution
- R&D with Timepix3 Cam
- Production of the prototype vacuum sealed RFPMTs with Photek Ltd.
- Cherenkov radiation detection

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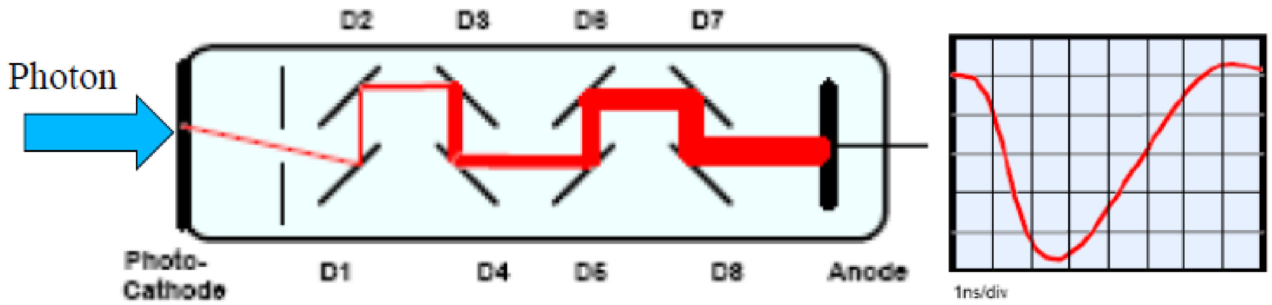
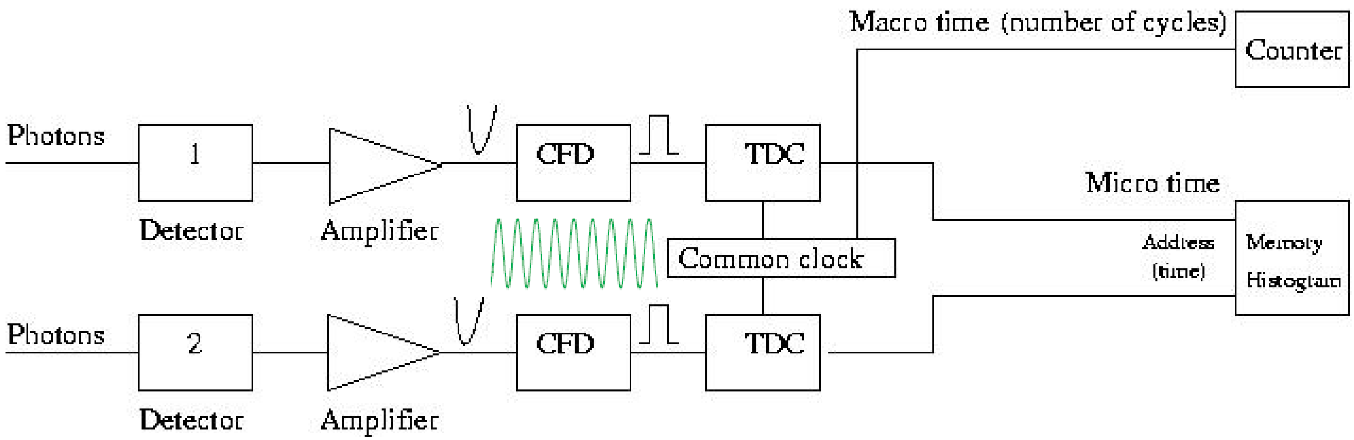
Regular Photon Sensors and Timing Technique



Gain ~ 10^6 -10^7
Fast ~ns output pulse



The timing jitter of the regular timing electronics is ~ 1 ps.

Rate ~ 1 MHz

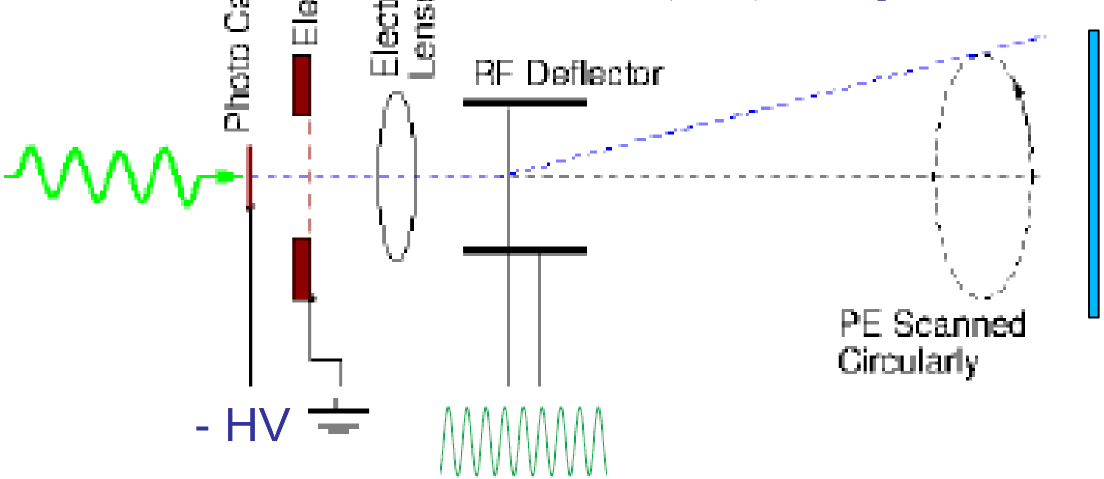
Vacuum PMT; SiPM; APD; HPD: typical time jitter ~ few tens ps

Single photon detection with less than 10 ps resolution is possible by means:
SNSPDs- Superconducting Nanowire Single-Photon Detectors

Radio Frequency, RF Time Measuring Technique of Single Electrons and Photons or Streak Principle

Time ➡ (X,Y)

Passing through RF deflector, electrons are deflected and fix the phase of the RF field (clock) on the position sensitive detector as a point.



Position Sensitive Detector, e.g. CCD

Slow readout: few kHz

Schematic of the RF timing technique

Timing jitter of the commercial Streak Cameras ~ 0.2 ps

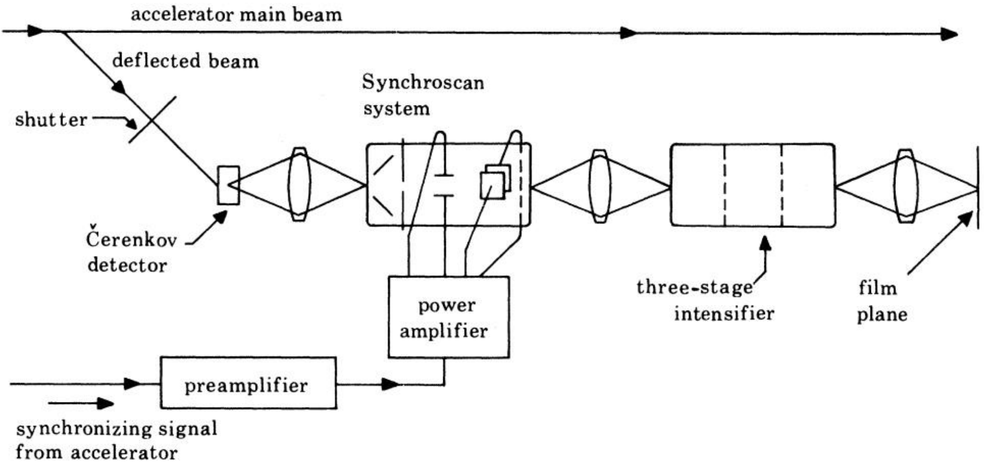
Theoretical prediction of the timing jitter is less than 0.1 ps

Cherenkov radiation detection by circular scan streak camera opereting in a Synchroscan mode

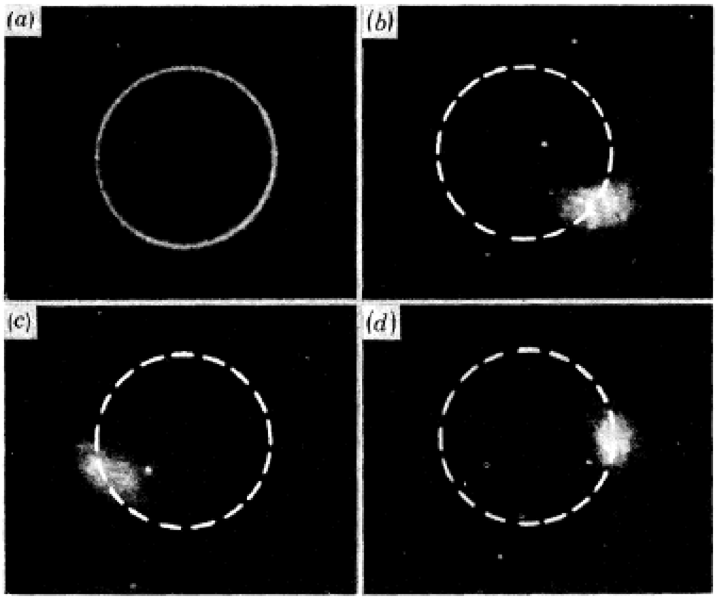
Phil. Trans. R. Soc. Lond. A **298**, 287–293 (1980)
Printed in Great Britain

The Synchroscan picosecond streak camera system

By A. E. Huston and K. Helbrough
Hadland Photonics Ltd, Bovingdon, Herts. HP3 0EL, U.K.



Scheme of circular scan Synchroscan camera for recording Cherenkov radiation

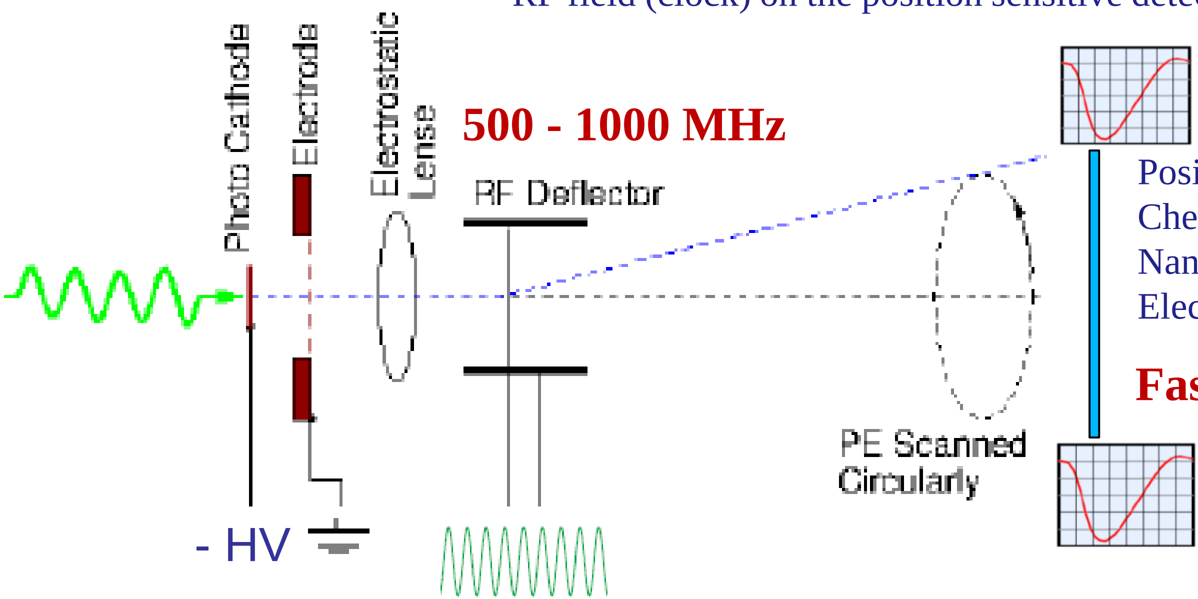


Record taken with circular scan Synchroscan. (a) Test record showing circular deflection at 201.25 MHz, with continuous illumination. (b-d) Record Cherenkov light showing variation of timing obtained by altering the experimental conditions. Each record is a result of summation of 2×10^9 events

Advanced RF Time Measuring Technique of Single Electrons and Photons

Time ➡ (X,Y)

Passing through RF deflector, electrons are deflected and fix the phase of the RF field (clock) on the position sensitive detector as a point.



Position Sensitive electron Detector
Chevron MCP, Delay Line Anode,
Nanosecond Signals, Regular
Electronics

Fast readout→ few MHz

Schematic of the advanced RF timing technique

Time Resolution Budget

Physical Time Resolution

1. Physical time scale of the photoelectron emission $< 10^{-14}$ sec
2. Time delay and spread in the photocathode $\approx 10^{-13}$ sec
3. Chromatic aberration due to photoelectron initial energy spread $\Delta\varepsilon$ is $2.34 \times 10^{-8} (\Delta\varepsilon)^{1/2}/E$, E is the accelerating field near the photocathode in V/cm, for $\Delta\varepsilon$ = 1eV and E = 25 kV/cm the time spread is 10^{-12} sec

Technical Time Resolution of the tube

1. Time spread, FWHM, of the carefully designed tube with 100μm diameter photocathode is 10^{-13} sec, and with few cm diameter photocathode is 10^{-11} sec

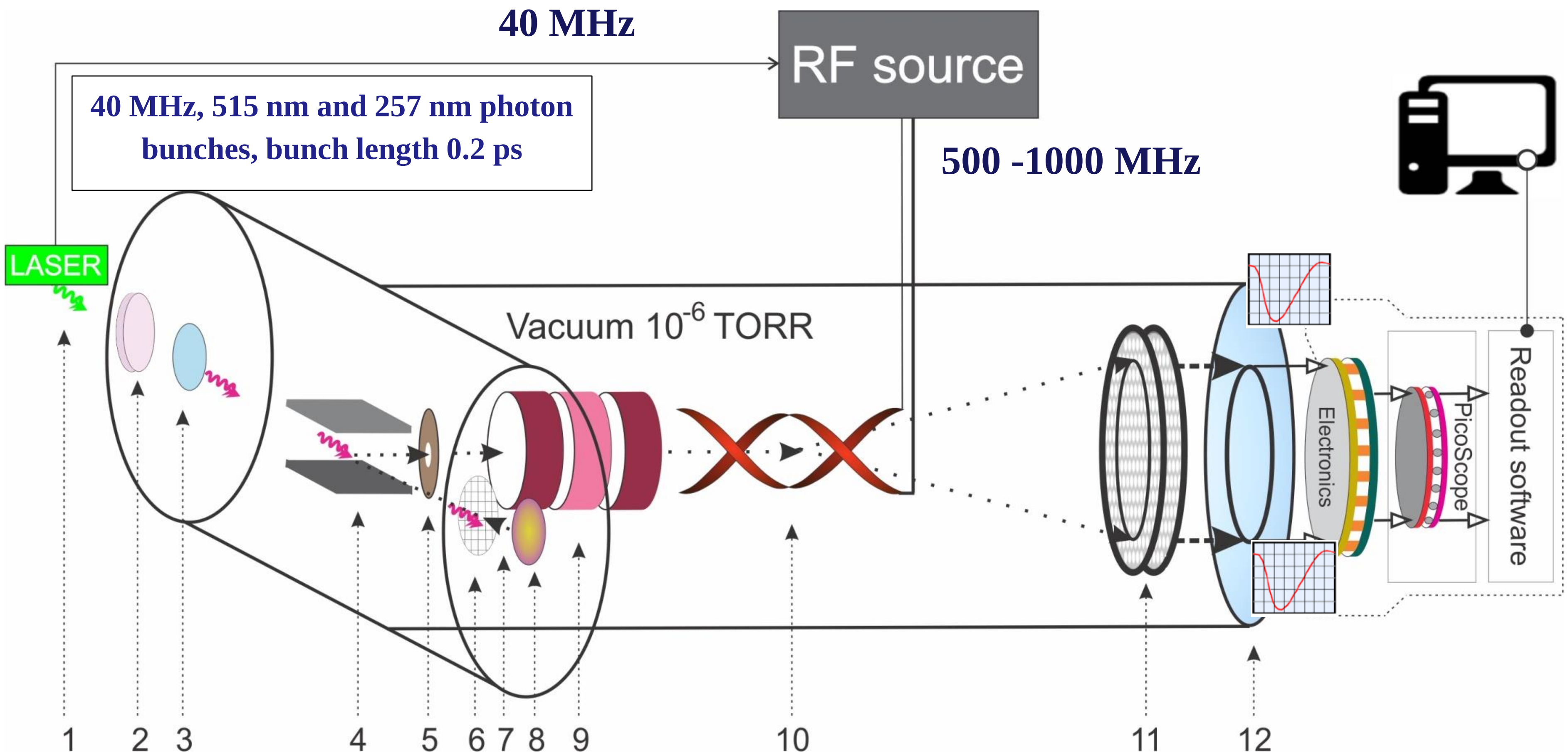
Technical Time Resolution of the RF Deflector

1. Time resolution of the RF deflector is d/v, where d is determined by the size of the electron beam and photoelectron detector position resolution, $v = 2\pi R/T$ is the scanning speed, R is the radius of the scanning circle, T is the period of the RF frequency. For R = 1.25 cm, d = 100μm and, $T = 10^{-9}$ sec (GHz RF frequency) $v = 7.85 \times 10^{9}$ cm/sec and time resolution is $\sim 10^{-12}$ sec

R. Carlini et al., Proposal for a photon detector with picosecond resolution, Advanced Radiation Sources and Applications, Ed. Helmut Widemann, NATO Science Series, Vol. 199, p. 305. Springer (2006).

Test Setup: Time Resolved Photo-Electron Spectrometer at AANL

Demountable RFPMT

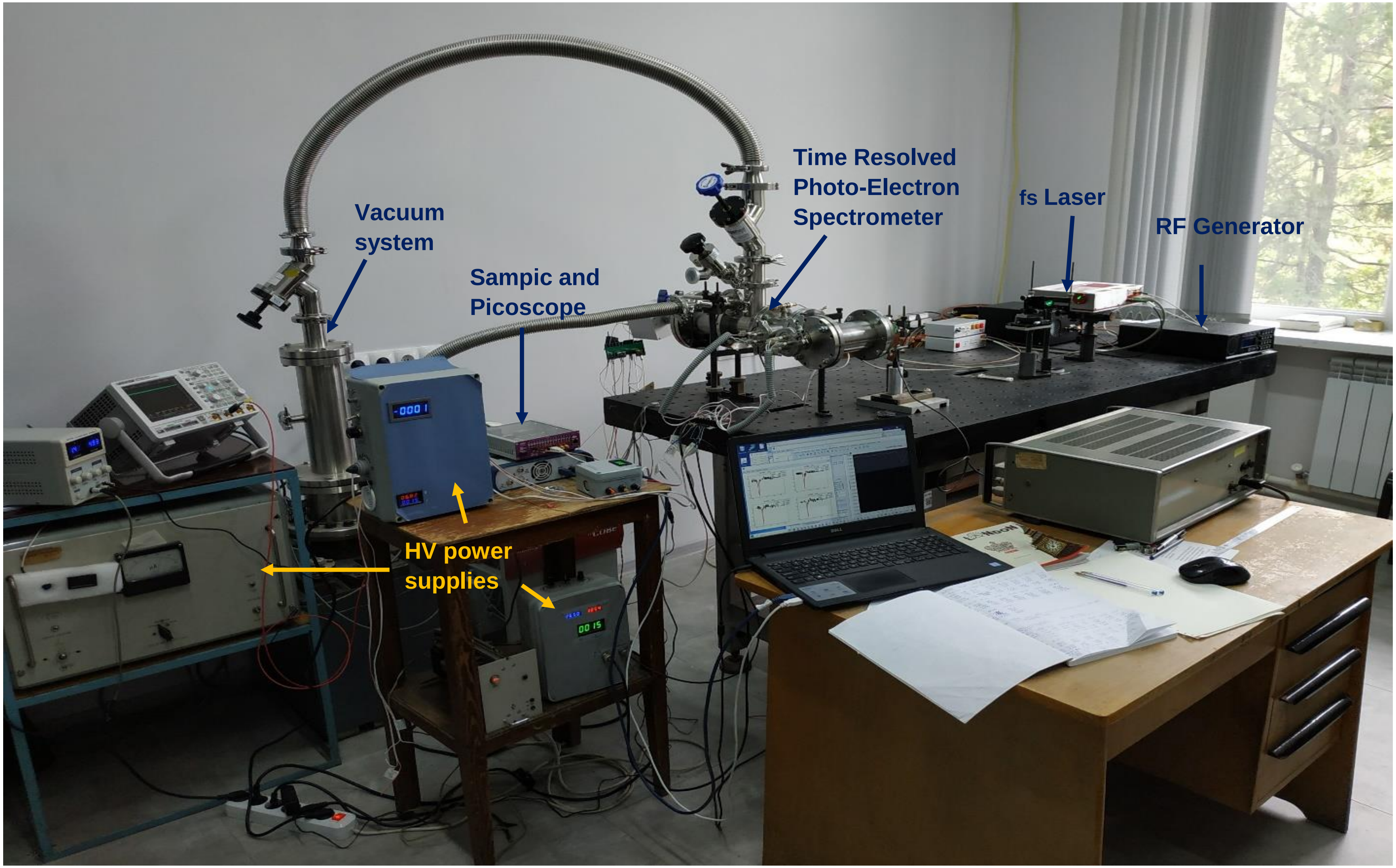


Schematic of the technique

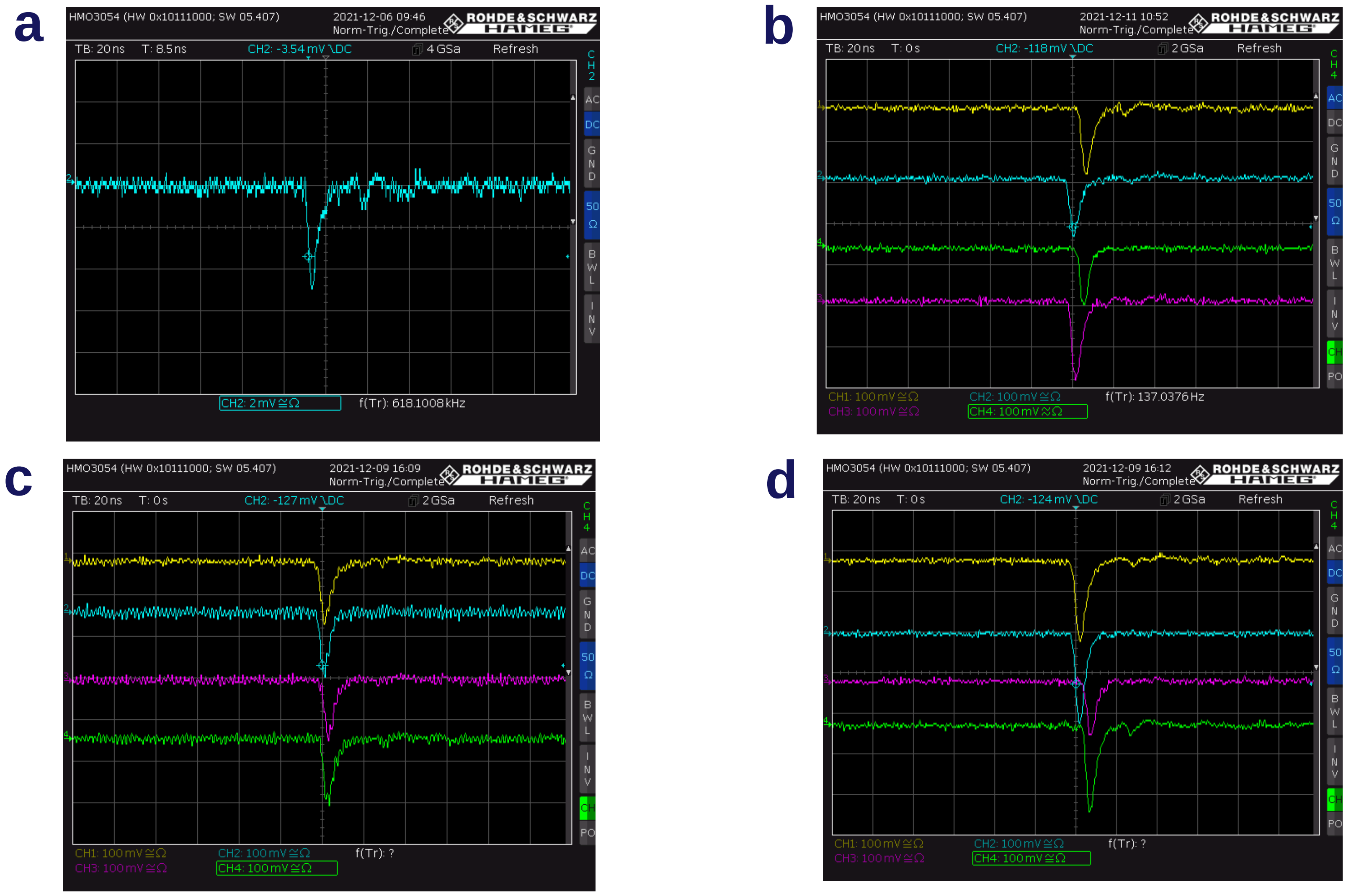
1-laser photon pulse; 2-nonlinear crystal; 3-quartz window; 4-magnet; 5-collimator; 6-accelerating electrode; 7-photoelectron; 8-photocathode; 9-electrostatic lens; 10-RF deflector; 11-MCP detector; 12- delay line anode

Test Setup at AANL: Time Resolved Photo-Electron Spectrometer

General View

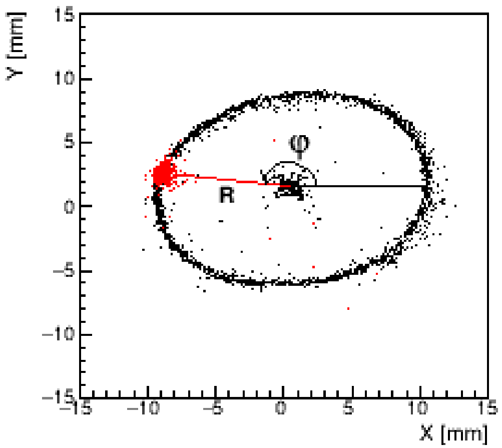


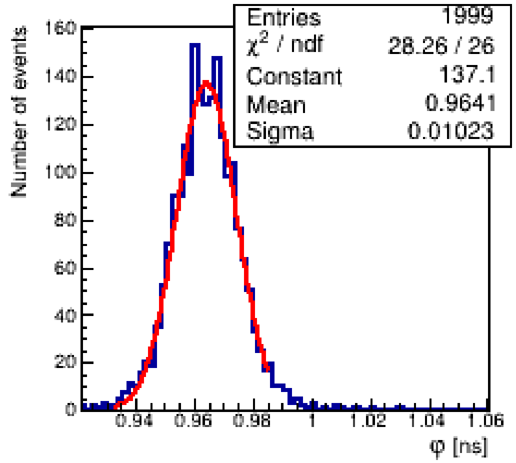
The typical signals from the delay line position sensitive anode

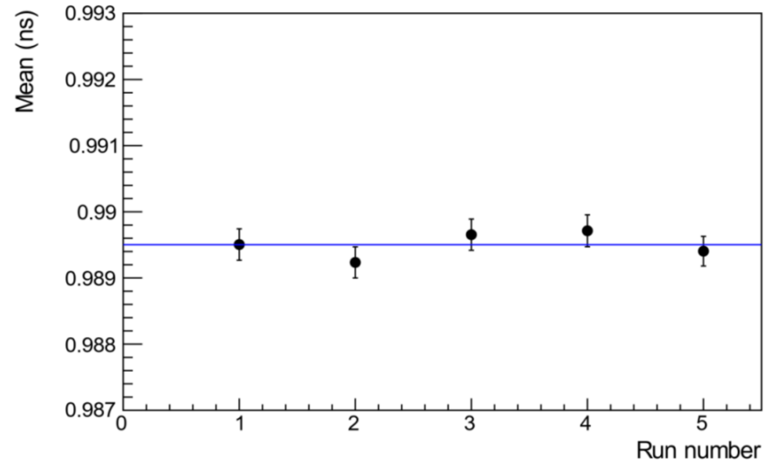


(a) raw signal from the anode; (b) amplified signals, RF off;
(c) typical signals with 500 MHz RF on; (d) typical signals with 1000 MHz RF on.

Test studies with femtosecond laser







Left: 2D image of anode hit positions. The point in the center of the circle is an image of electrons with RF turned OFF. The circle is an image of the scanned electrons when the 500 MHz RF is ON but not synchronized with the laser. The red spot on the circle corresponds to phase distributions of RF-synchronized photoelectrons for a fixed phase;

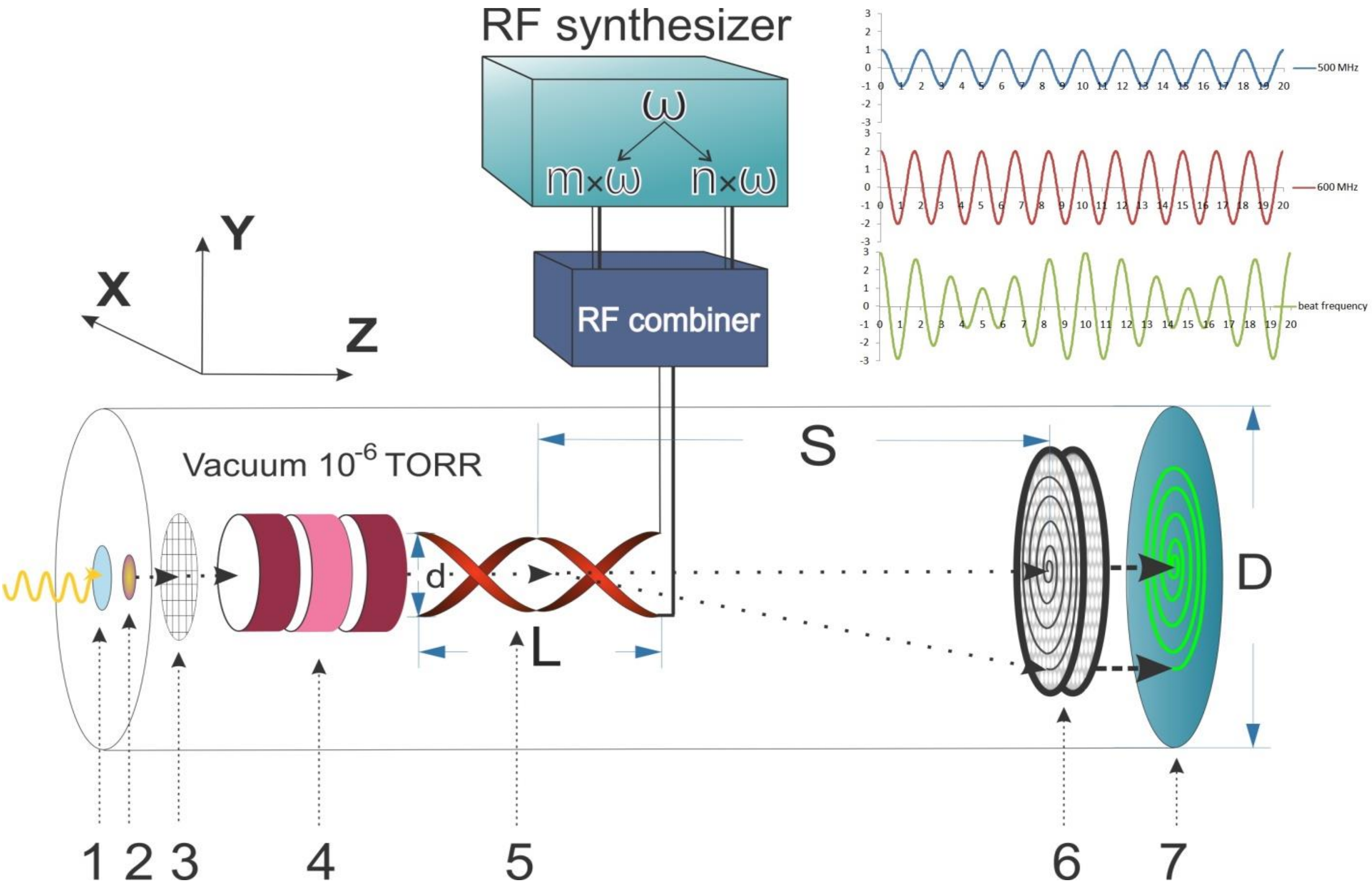
Middle: Distribution of phase (φ) of the electrons in the case of RF synchronized laser;

Right: The mean values of sequentially measured time distributions in a one-hour period.

HIGH RESOLUTION (≤ 10 ps), HIGH RATE (~MHz), HIGHLY STABLE (≤ 0.5 ps, FWHM) timing technique for single electrons and photons.

A. Margaryan et al., Nucl. Instr. & Meth. A566, 321 (2006)
Amur Margaryan et al., Nucl. Instr. & Meth. A1038, 166926 (2022)
Simon Zhamkochyan et al., JINST 19 C02014 (2024)

The Radio Frequency PhotoMultiplier Tube-RFPMT

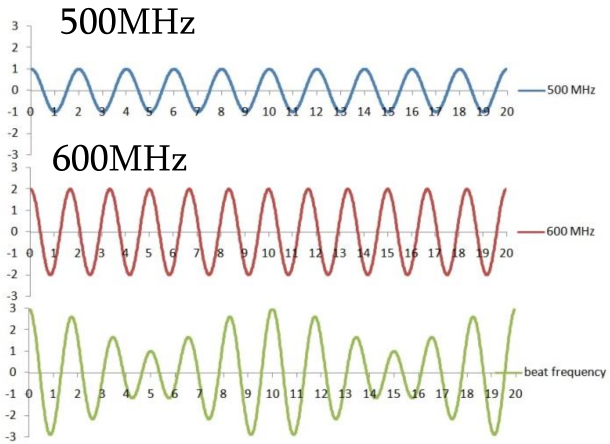


Schematic of the technique

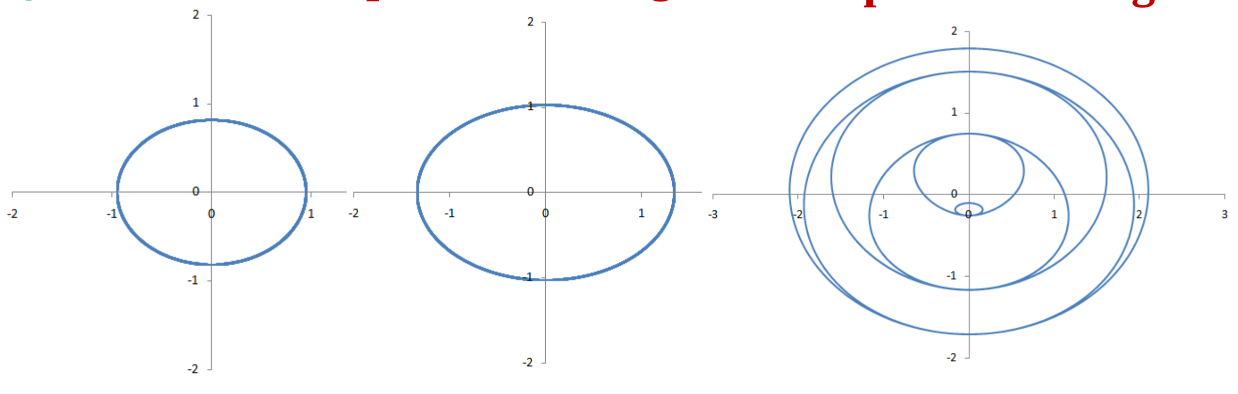
1-quartz window; 2-photocathode; 3-accelerating electrode; 4-electrostatic lens; 5-RF deflector; 6-MCP detector; 7-position sensitive anode

Spiral Scanning RF Timer with DL anode

Theory | **Circular/elliptical scanning** | **Spiral scanning**

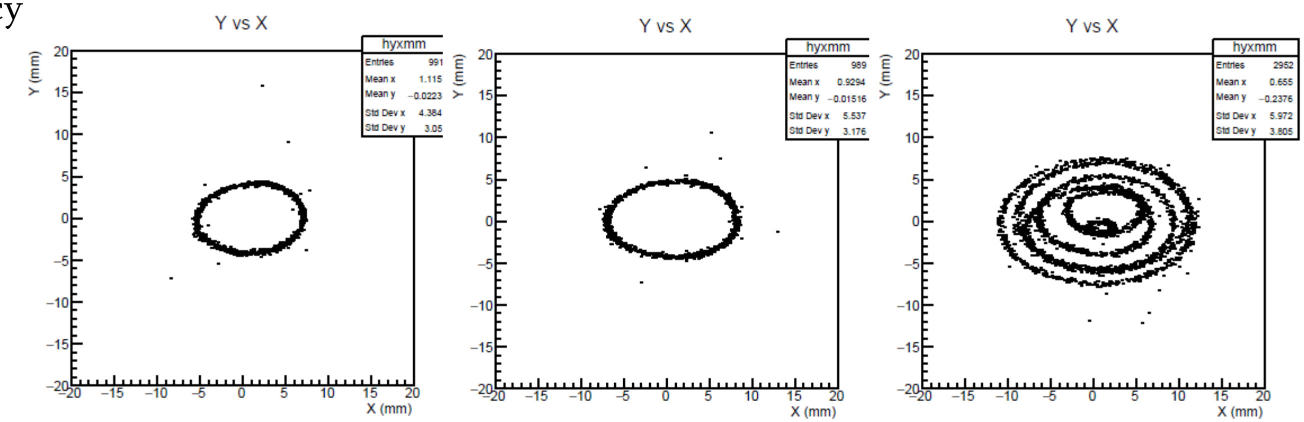


500&600 MHz = Beat Frequency



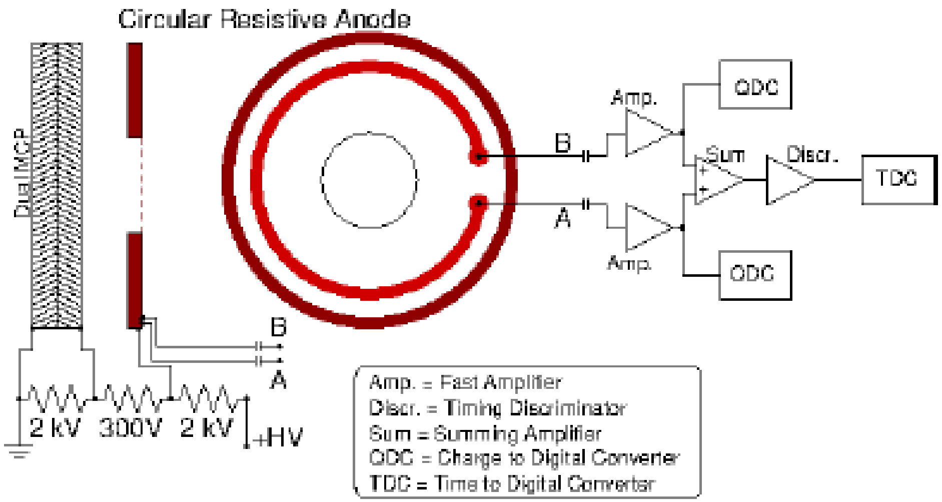
f_1 = 500 MHz f_2 = 600 MHz 500 & 600 MHz

Experiment

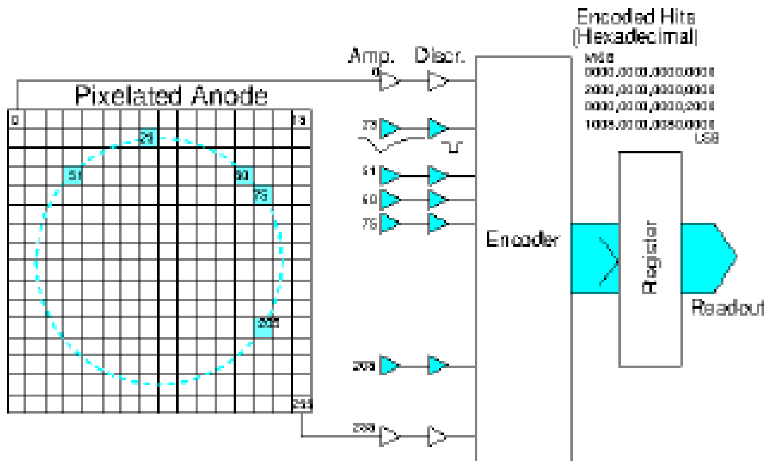


Spiral scanning RF Timer is a Doorway into the High Resolution, High Rate and Highly Stable Continues Timing Technology

The Readout System of the RF Timer



- **RFPMT Mk-1**: post-deflector dual-MCP followed by circular resistive anode
- Q_1 - Q_2 → pos. on circle → micro-time
- Macro-time Sum → Discr. → TDC
- **RFPMT Mk-2**: pixelated anode single photon detection and readout capability for each pixel pad
- Pattern of fired pixels → micro time → time distribution of incident photons Range = 1 RF cycle
- Macro time from RF cycle counter

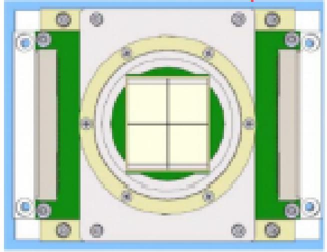


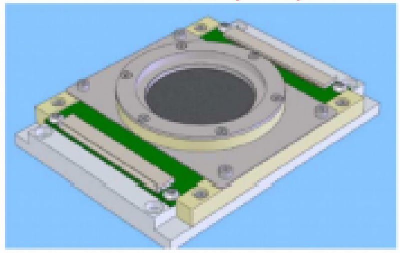
Simplified readout scheme for a 16 x 16 pixel anode
Real pixel detectors (e.g. Timepix) 256 x 256, with more extensive data recording capability

Spiral scan would extend micro time range
And make fuller use of pixel detector

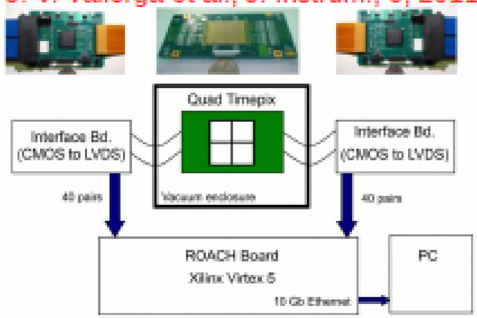
Medipix/Timepix Pixel ASICs

A.S. Tremsin et al., IEEE Trans. Nucl. Sci. 60, 578, 2013





J. V. Vallerga et al., J. Instrum., 6, 2011.



- Fast parallel (LVDS) readout
- FPGA based data processor can be programmed to suit application
- GPU could be used for more complex image reconstruction algorithms

- 4 x Timepix used with MCP electron multiplier 28 x 28 mm
  200 MHz/cm^2

Each Timepix

- 256 256 array 55 µm pixels, 14.1x14.1 mm
- Each pixel contains preamp and 14 bit counter, rate of 100 Khz/pix.
- Noise ~75*e* rms...allows low MCP gain operation
- Three acquisition modes are available
  Number of counts above the threshold (typically set at 3000 e)
  Time-over-threshold ~ Pulse Amplitude
  Time-of-arrival (ToA) w.r.t. trigger
- Timepix3 ToA resolution ~1.5 ns
  Sparcified data readout
  T. Poikela et al., Jinst. 9, C05013, 2014

Test studies with Timepix3 Cam are underway

The Radio Frequency Photomultiplier Tube

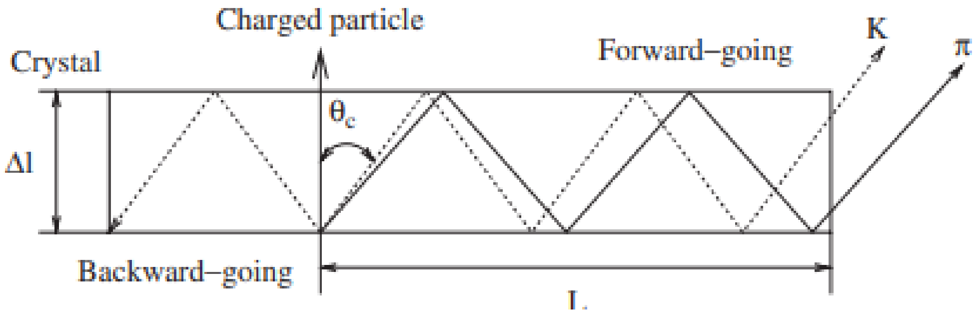
- Sensitive, low-noise photo detector...will register single photons. As with standard PMT optical photons produce electrons on a photo cathode which are accelerated, multiplied and produce a signal at the anode
- Convert the time dependence of an optical signal to a spatial dependence
- Scan photo electrons through a set of RF deflectors. This idea is also applied in streak cameras
- RFPMT differs from a streak camera since it has a fast signal output similar to that from a standard PMT...more sophisticated output also envisaged
- Tests of a new design of helical RF deflector performed successfully
- Test studies demonstrated 10 ps resolution and 0.2 ps/hours stability
- Activities to achieve few ps timing resolution are underway
- Test studies with Timepix3 Cam are underway
- Small size photocathode Circular-Scan RFPMT under construction by Photek Ltd. (UK)

Applications

- Fundamental Studies: Comparison of Clocks
- Astrophysics: Brown -Twiss experiments
- High Energy and Nuclear Physics: Cherenkov TOF and TOP; High Energy Physics; Nuclear and Hypernuclear studies
- Biomedical Studies: Fluorescence Lifetime Imaging and Foster Resonance Energy Transfer (FLIM, FRET)
- Optical Microscope: Stimulated Emission Depletion (STED)
- Medical Imaging: TOF- Diffuse Optical Tomography; 10 ps TOF - PET Challenge
- Material Science: Time Resolution Photoemission Spectroscopy, Positronium Annihilation Lifetime Spectroscopy (PALS)
- 3D Imaging: Laser Imaging Detection & Ranging (LIDAR)

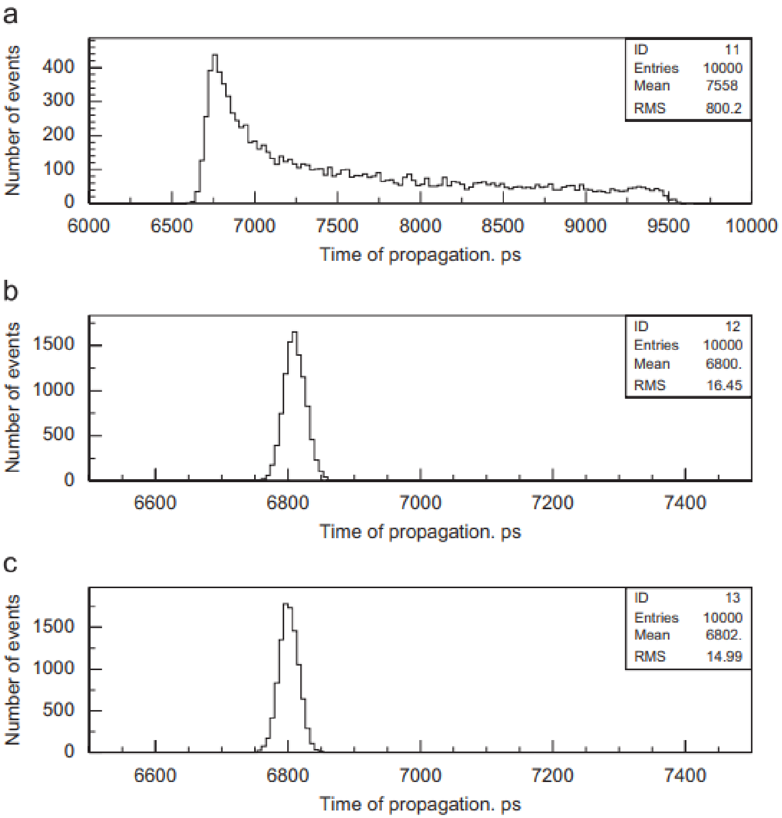
For all of these applications the most important figure of merit is the single photon timing resolution and stability

Cherenkov Time-of-Propagation (TOP) Detector



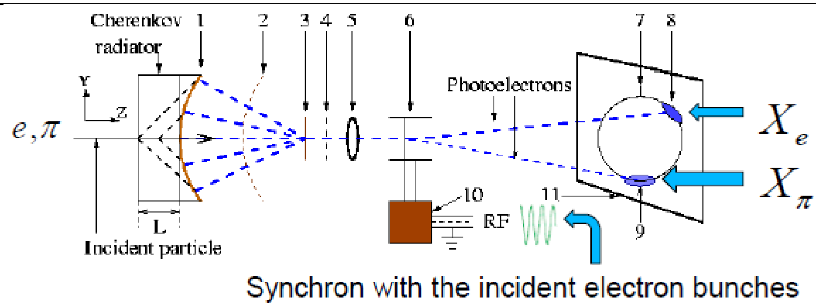
$$\cos(\theta_c) = \frac{1}{\beta n(\lambda)} \qquad t_p = \frac{L_P n(\lambda)}{c} = \frac{L n(\lambda)}{c q_z},$$

The time of propagation, TOP, of the Cherenkov photons in the radiator is sensitive to β, and β can be determined from measured TOP if the position, direction and momentum of particle are provided by other systems

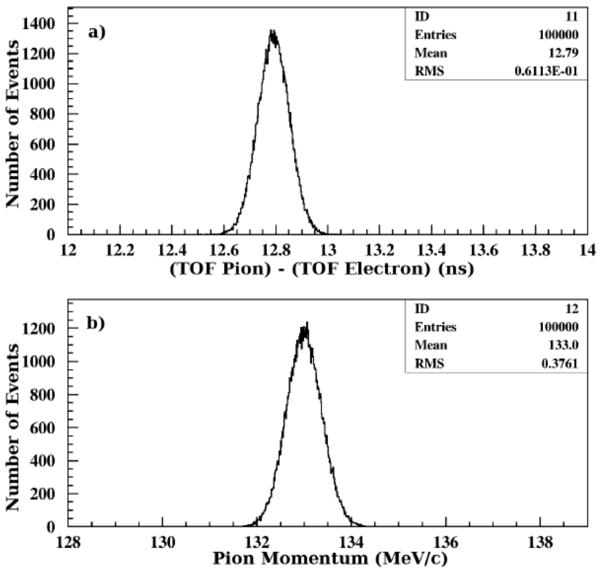


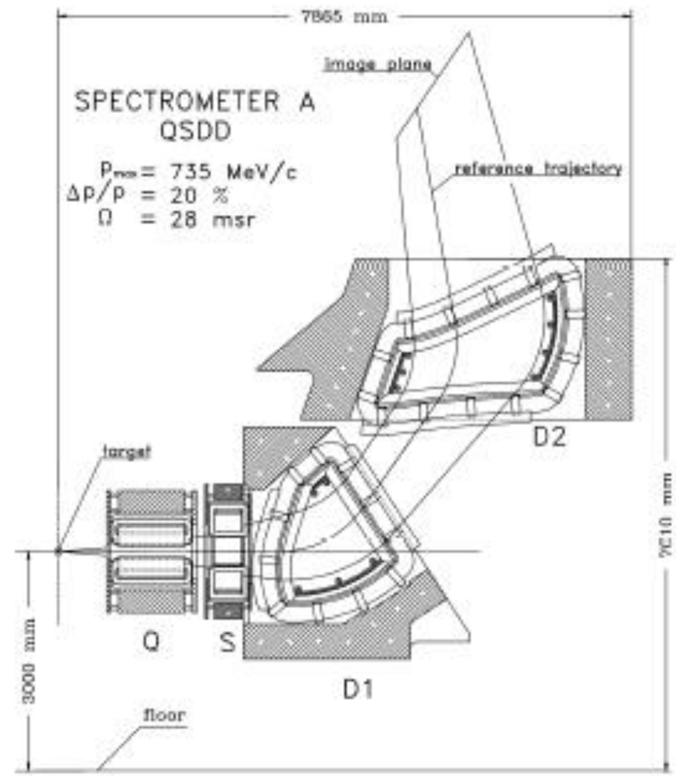
Time of propagation distribution of single and FW going photons for tracks of 2 GeV/c pions, $\theta_c = 90°$, with $|\Phi_c| \leq 45°$ (a), and mean time distribution of all detected photons for the cases with $|\Phi_c| \leq 15°$ (b) or with propagation times ≤ 6950 ps (c).

Calibration of the magnetic spectrometers with an accuracy 1:10^4 by TOF measurement of pair of particles



The Cherenkov Detector with the RFPMT





The SpekA at the Mainz Microtron MAMI

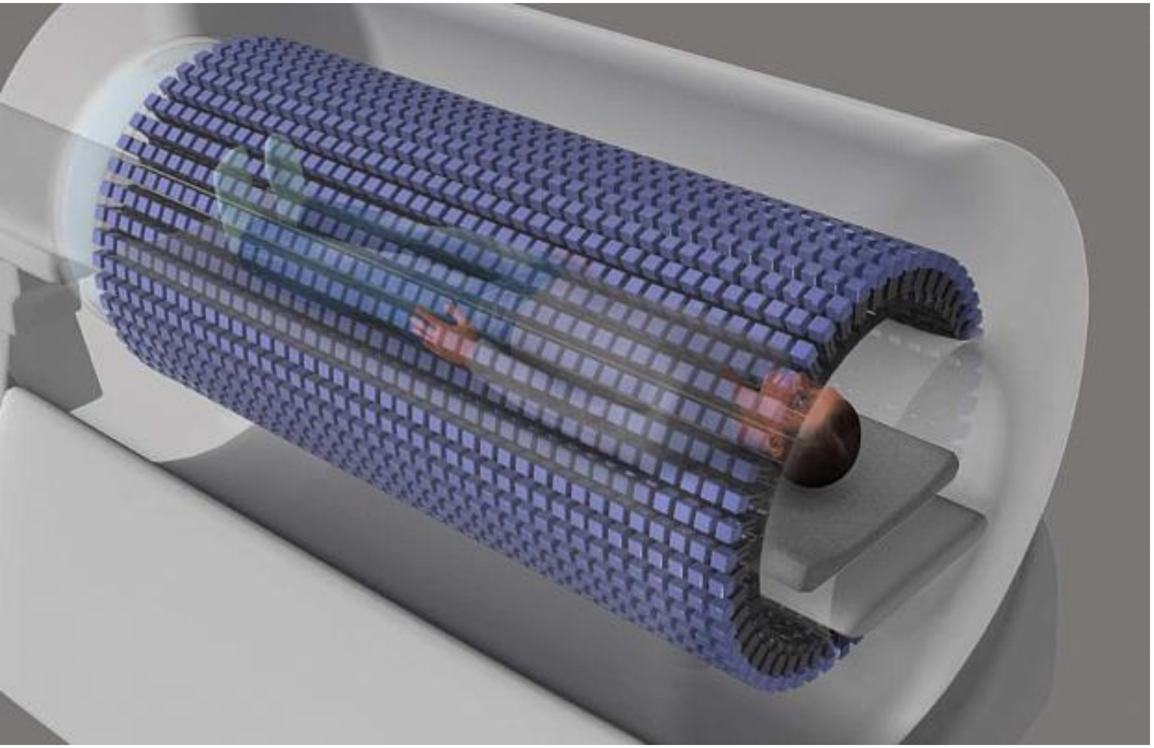
The distributions of the $t_\pi - t_e$ (a) and p (b). The mean values are:12791.4 ps and 133.00 MeV/c

A. Margaryan, J. Annand, P. Achenbach et al., High Precision Momentum Calibration of the Magnetic Spectrometers at MAMI for Hypernuclear Binding Energy Determination, Nucl. Instrum. Meth. A 846 (2017) 98.

A. Margaryan et al., Delayed Pion Spectroscopy of Hypernuclei, J. Phys. Conf. Ser. 496 (2014) 012006.

Few 10 ps Whole Body TOF-PET

Dream Medical Imaging Technique



https://the10ps-challenge.org

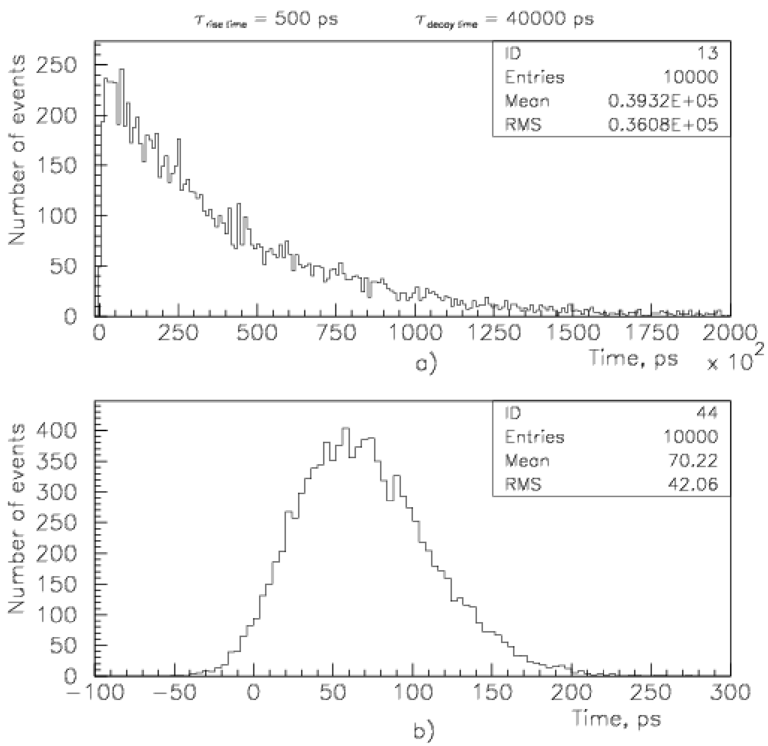
1. Reduction of the radiation doses to negligibly low levels;
2. Reduction of the synthesized quantity of radiopharmaceutical needed for each examination, and thus of the relatively high cost currently associated with in-vivo molecular imaging procedures;
3. And more…

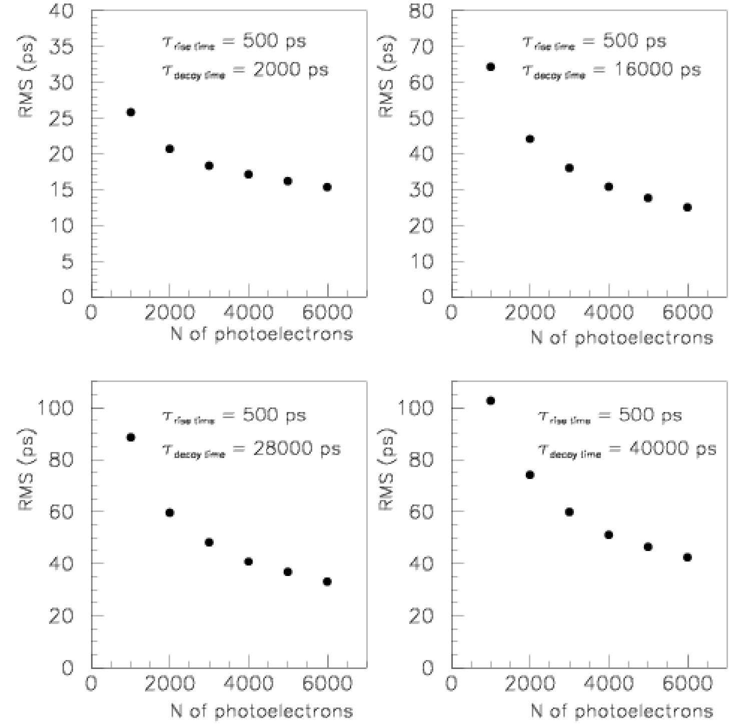
RFPMT is ideally suited for the next generation TOF-PET applications

- Few 10 ps resolution and highly stable timing
- Possibility of synchronously operation of huge number detectors

Ani Aprahamian, Amur Margaryan, Vanik Kakoyan, et al. Advanced Radio Frequency Timing AppaRATus (ARARAT) Technique and Applications, arXiv2211.16091

TOF-PET with RFPMT





(a) The timing distribution simulated with be-exponential timing model, photon detector timing resolution is included, rise time 500 ps, decay time 40000, detector resolution 20 ps.

(b) The distribution of the first photoelectron, PE times from total number of 6000 PEs in each event

The scintillator detector timing resolution, calculated with a firs photoelectron as a function of photon detector timing resolution.

A. Margaryan, V. Kakoyan, S. Knyazyan, Acta Physica Polonica B, Proceeding Supplement, Vol. 4, N. 1, 107 (2011)

Advanced Radio Frequency Timing AppaRATus

Ani Aprahamian[a,h,1,8], Vanik Kakoyan[a,1,2], Simon Zhamkochyan[a,1,2], Sergey Abrahamyan[a,4,5], Hayk Elbakyan[a,2,3], Hasmik Rostomyan[a,2,5,8,10], Anna Safaryan[a,2,5,10], John Annand[b,2,3,5], Kenneth Livingston[b,2,3,5], Rachel Montgomery[b,2,3,5], Patrick Achenbach[c,1,2,5,8], Josef Pochodzalla[d,5,8], Dimiter L. Balabanski[e,5,8], Satoshi N. Nakamura[f,2,5,8], Viatcheslav Sharyy[g,2,5,9], Dominique Yvon[g,2,5,9], Khachatur Manukyan[h,2]

a) A.I. Alikhanyan National Science Laboratory, b) School of Physics & Astronomy, University of Glasgow, c) Thomas Jefferson National Accelerator Facility, d) Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, e) Extreme Light Infrastructure- Nuclear Physics (ELI-NP), f) Department of Physics, Graduate School of Science, the University of Tokyo, g) Département de Physique des Particules Centre de Saclay, h) Department of Physics and Astronomy, University of Notre Dame

Activities: 1 management, 2 R&D, 3 hardware, 4 software, 5 test studies, 6 fundamental studies, 7 quantum technologies, 8 nuclear physics, 9 imaging, 10 material science

Current Status

1. 10 ps resolution advanced RF Timer of single electrons and photons is developed
2. RF Timer based Photo-Electron Spectrometer is developed
3. R&D is started to achieve ~1 ps resolution
4. Activities are started to produce vacuum sealed Radio Frequency Photo-Multiplier Tubes with Photek Ltd.

Our foreign collaborators are mainly interested in applications of the advanced RF timing technique

Thank you for your attention