A Picosecond Resolution Optical Sensor for TCSPC Applications at CANDLE

Simon Zhamkochyan for RF PMT collaboration

Yerevan Physics Institute

(Alikhanyan National Science Laboratory)

Yerevan, Armenia

Ultrafast Beams and Applications

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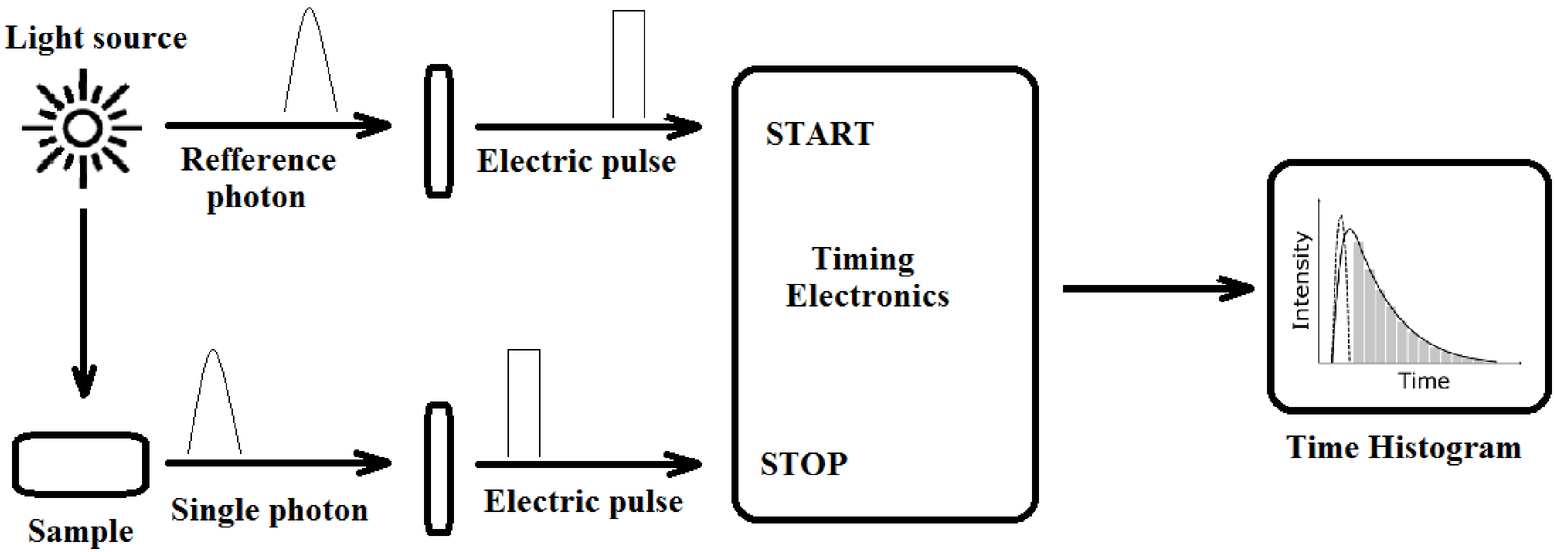
Time-Correlated Single Photon Counting (TCSPC)

- 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)

	Time Resolution	Counting Rate	Readout
PMT, APD, HPD	25 ps	Few MHz	Fast
Streak Camera	1 ps	Few 10 KHz	Slow
RF PMT	1 ps	Few MHz	Fast

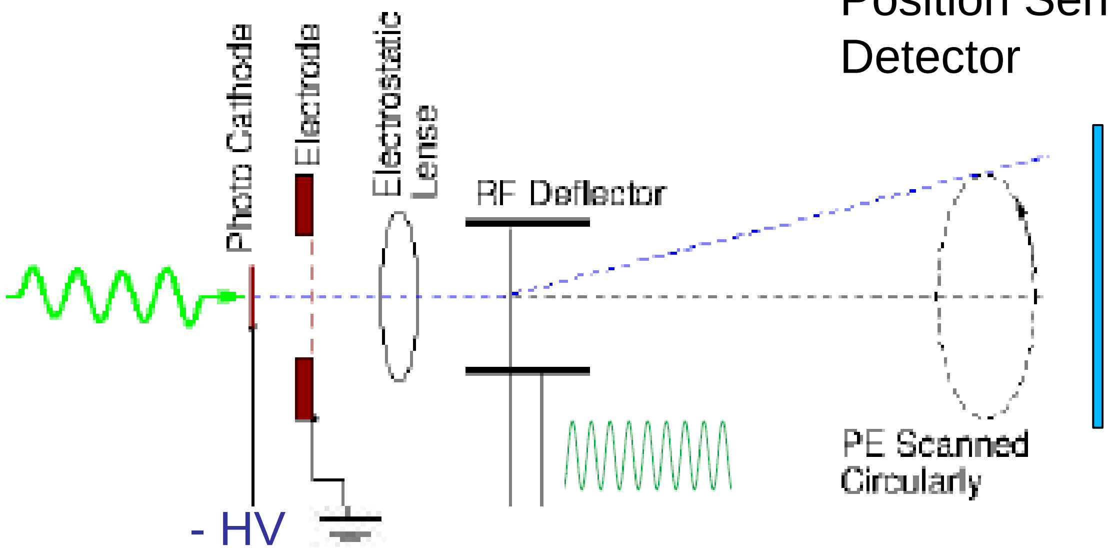
- **Sensitive photo-detector, capable of registering single photons:** optical photons produce electrons on a photo cathode, which are accelerated to keV energies, multiplied and detected.
- **Conversion of information in the time domain into a spatial domain:** Scanning photo-electrons by means of helical 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

Radio Frequency Time Measuring Technique

Streak Principle: convert time dependence of an optical signal to a spatial dependence of the accelerated photo-electron

Position Sensitive Detector



(X,Y) = Time

Image Readout
e.g. by using CCD

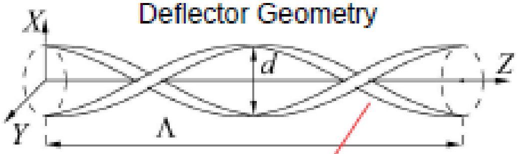
Schematic of the Streak Principle

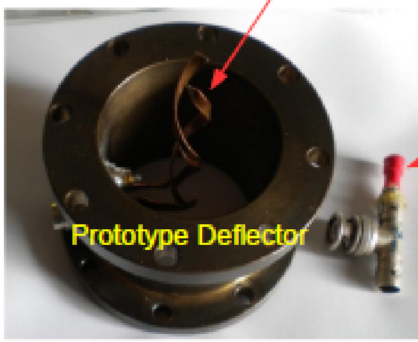
Time resolution σ < 1 ps
Time stability stability - 200 fs/h
Time drift is ~10fs/s;
Image processing rate is ~few 10 kHz

see e.g. W. Uhring et al., Rev. Sci. Instr. V.74, 2003

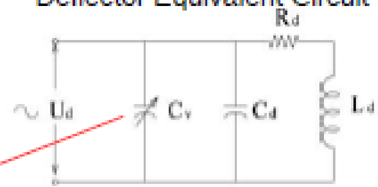
RF Circular Scanning Deflector for keV Electrons

Deflector Geometry

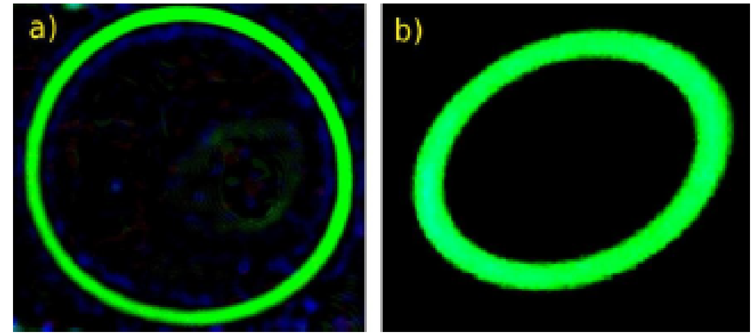




Deflector Equivalent Circuit

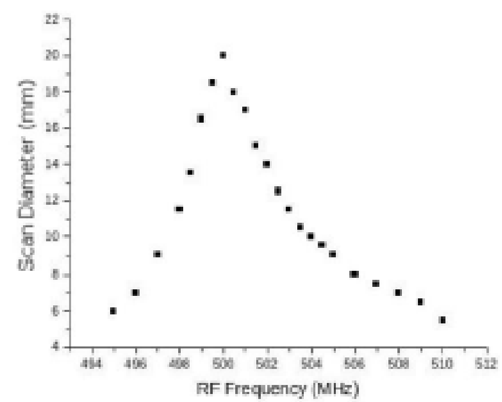


C_v tunes resonant behaviour to desired RF frequency



Deflected 2.5 keV electron beam @ phosphor screen.
Deflector: Λ=3 cm, d=1 cm, U_d=20 V,
U_a 2.5 kV, D=12 cm.
Applied RF frequencies (a) 1000 MHz; (b) 750 MHz.

- 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 ~1 mm/V or 0.1 rad/$W^{1/2}$
- ~1 W (into 50Ω) RF power sufficient to scan 2.5 keV electrons circularly 2 cm radius.
- Order of magnitude reduction in required RF power



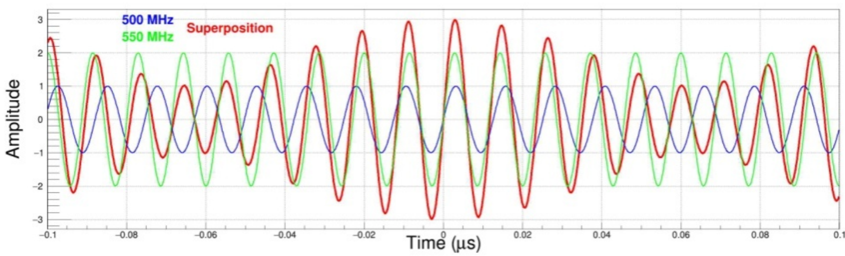
Diameter scanning circle vs RF frequency
500 MHz deflector. Λ = 6 cm, d = 1 cm,
U_d = 10 V, U_a = 2.5 kV, D = 12 cm.

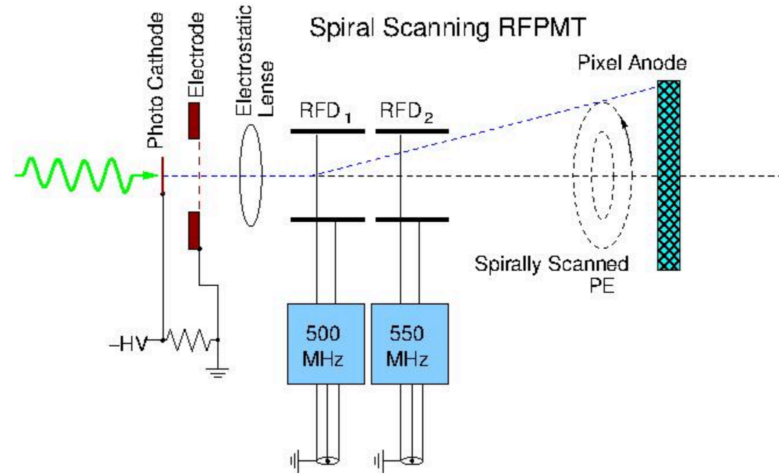
L. Gevorgian et al., Nucl. Instr. and Meth. A785, 175, 2015

RF Spiral Scanning for keV Electrons

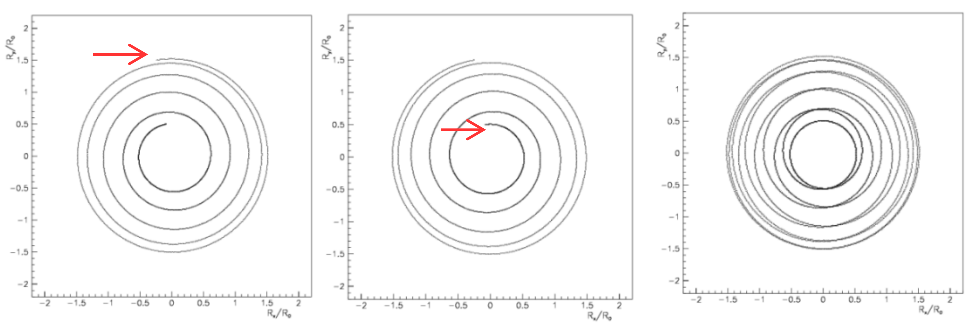
- Amplitude beating
- 2 RF deflectors RFD_1 RFD_2 operating at ω_1, ω_2 individually give circular trajectories radii r_1, r_2
- $RFD_{1,2}$ simultaneously: spiral scanning $\omega_{beat} = \omega_1 - \omega_2$ max radius $r_1 + r_2$ min radius $r_1 - r_2$
- Operational spiral-scan RFPMT requires pixel anode

$$w_2 = 1.1w_1, \quad r_2 = 2r_1$$

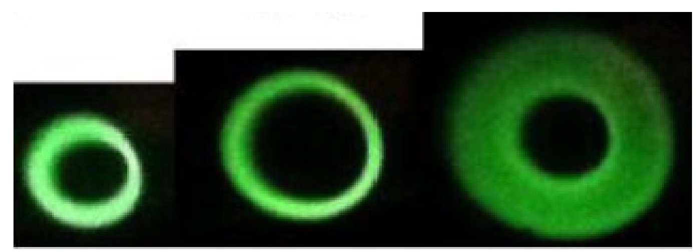




Spiral with factor 10 extended period



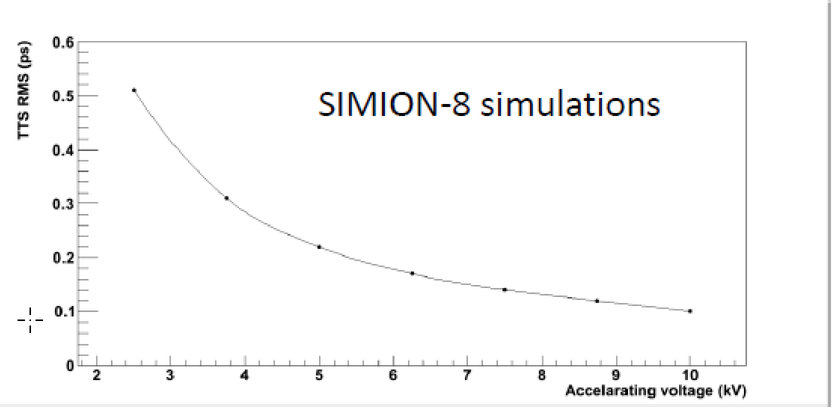
Preliminary experimental results



Time resolution of RF PMT

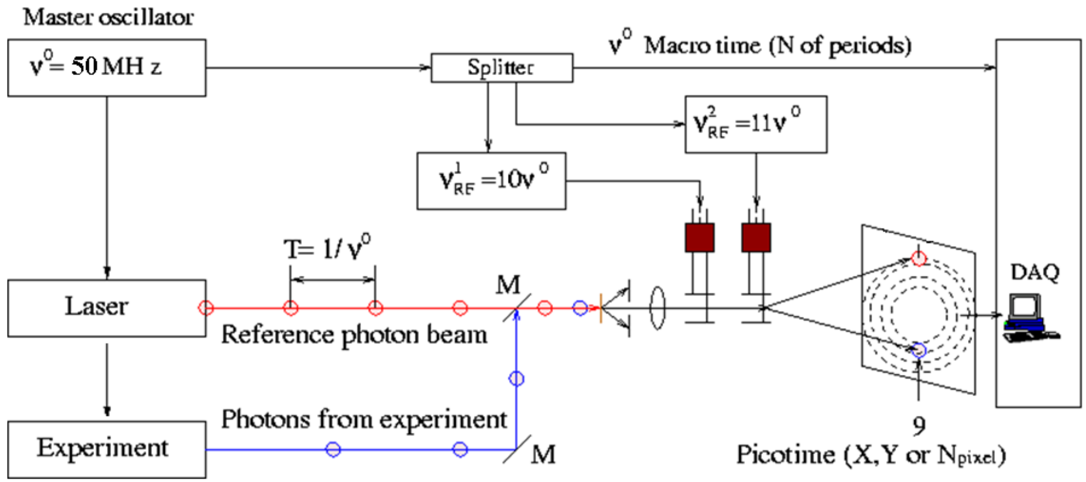
- **Physical time resolution of the photocathode:** For the typical thickness of semitransparent bialkali photocathode $\Delta l \cong 20nm$ and $\Delta\varepsilon = 1eV$ $\Delta\tau_p \leq 10^{-12}s$

- **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 $d = 0.01cm$, $R = 2$cm and $T = 10^{-9}$ s $\Delta\tau_d = 1ps$

TCSPC technique with spiral scan RFPMT at CANDLE



- 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

- Time is determined by numbers of the spiral scan cycle (macro time) and pixel (micro time)
- Time resolution is about 1 ps
- Bandwidth is about THz
- The time drift with reference photon beam is less than 10 fs/day
- Throughput rate: from few MHz to GHz (THz is a final goal)

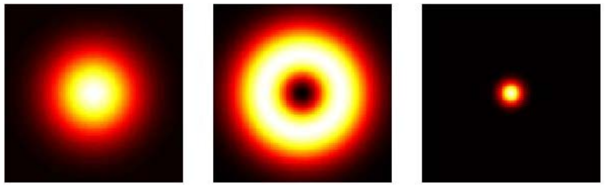
RF PMT and Stimulated Emission Depletion Microscopy

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

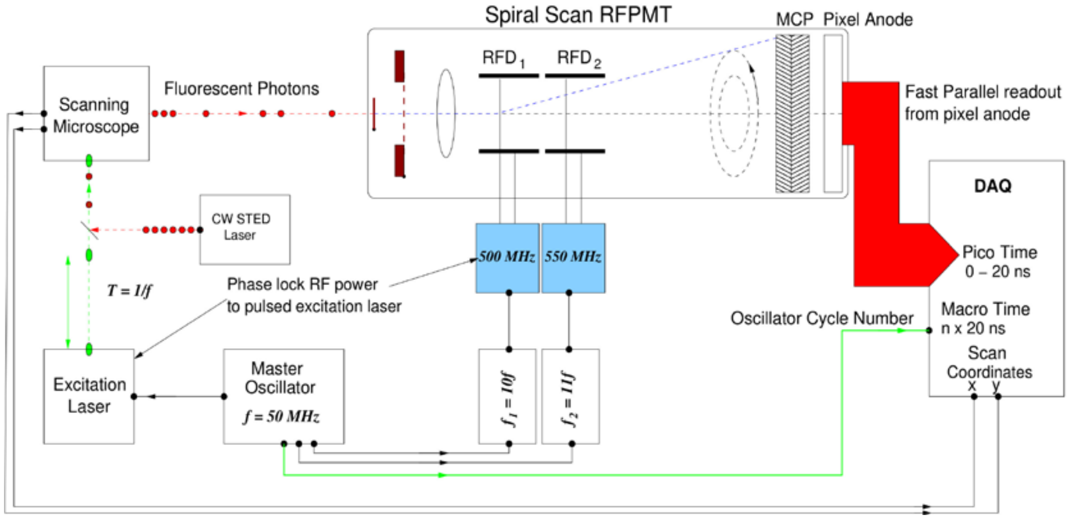
Spatial resolution is of the molecular scale



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.

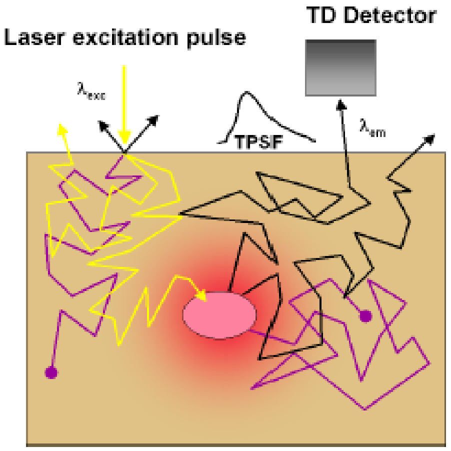
Time-gated detection using pulsed excitation and continuous STED beams substantially improves the spatial resolution

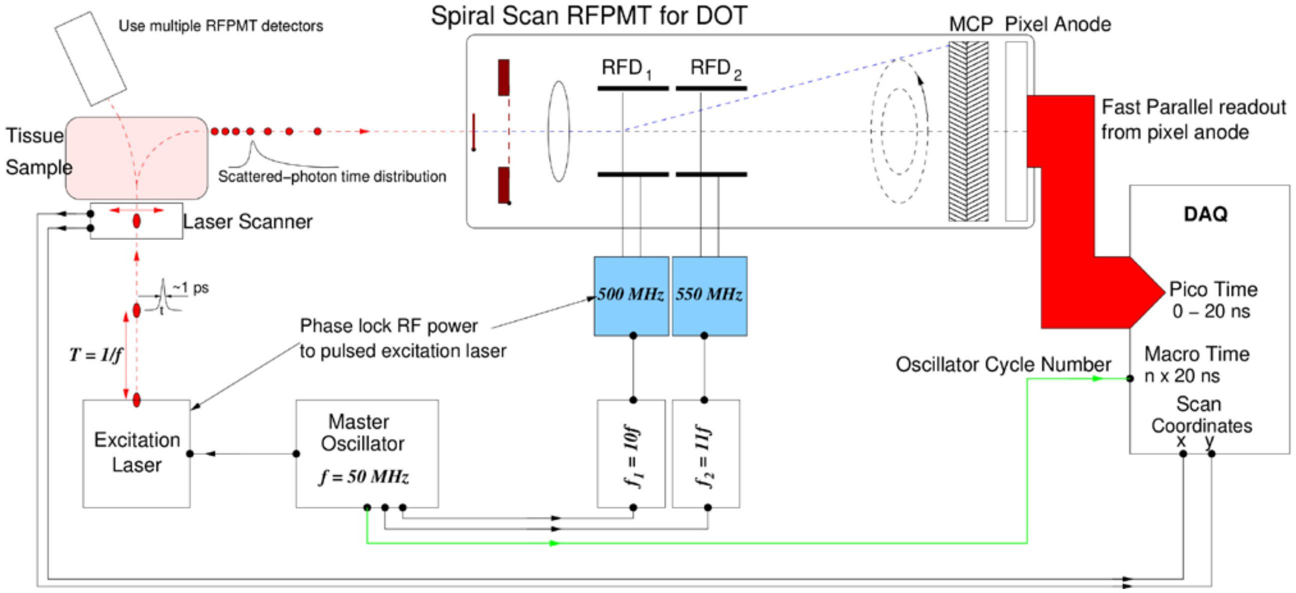
Measuring the times of fluorescent decay photons down to the ps level would have the potential for ultra high spatial resolution



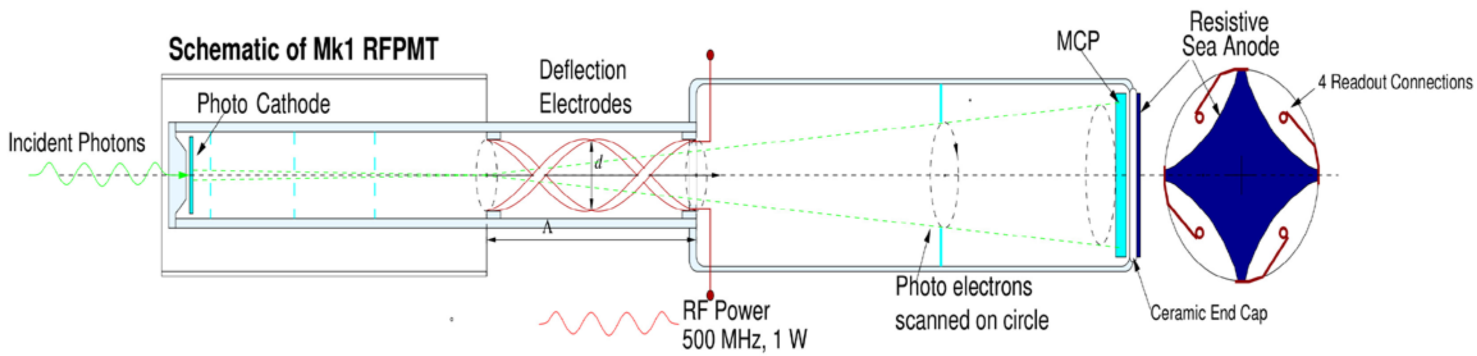
RF PMT and Diffuse Optical Tomography

- 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**