Measurement of the passage of time
is an ancient preoccupation

10000 yr BP

5000 yr BP

1300 yr BP

Spiral scanning of keV electrons: applications in picosecond photon sensors

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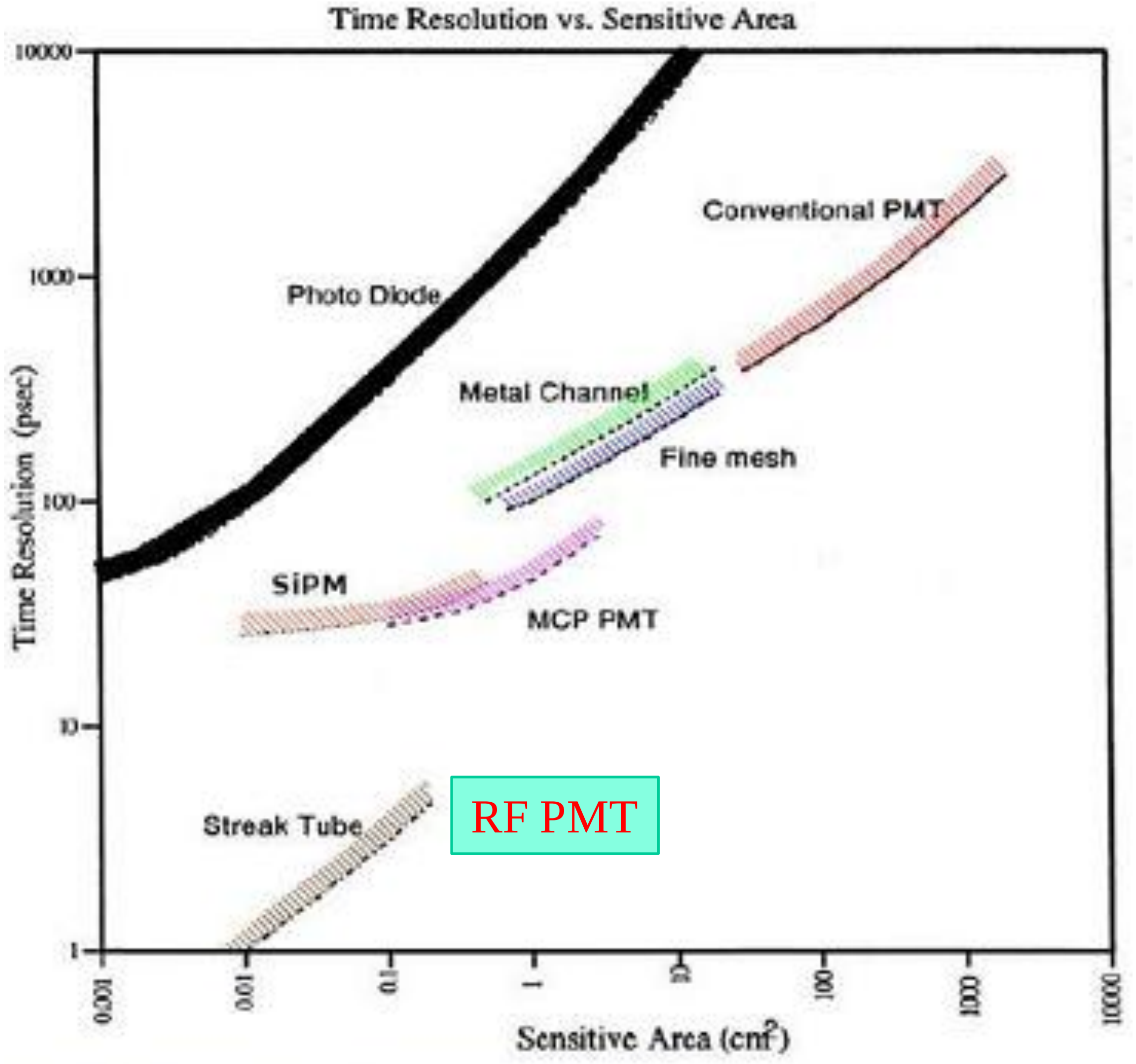
Picosecond Timing Workshop, Prague 8-9-10 June

Outline

- **Single Photon Timing Status**
- **Radio Frequency Timing: principles of operation**
- **Helical Shape RF Deflector: circular scanning**
- **Pixelated anode: a new photon timing technique**
- **Spiral Scanning: application of 2 RF deflectors**
- **Applications in photon sensors**

Single photon detection with high time resolution is needed for physics and medical applications



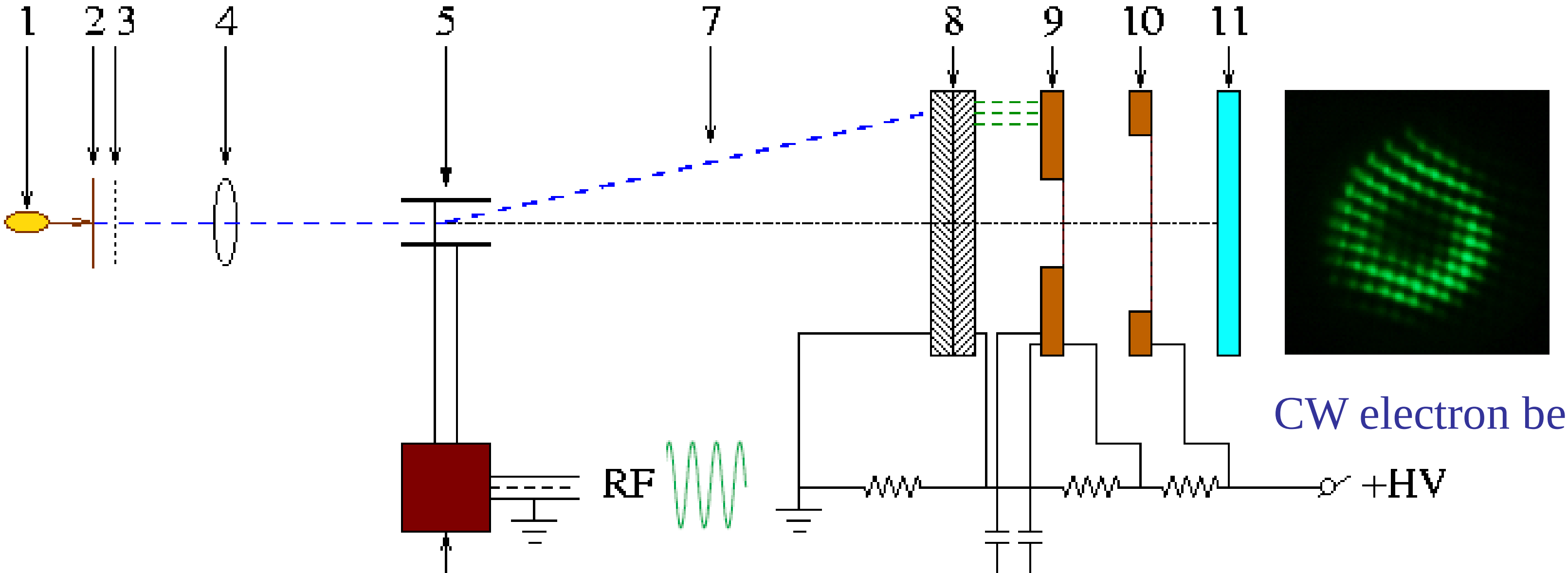
modified from K.Arisaka NIMA 422 (2000)

Current Situation

Streak tube & Radio Frequency, RF PMT can detect single photons with time resolution better than 10 ps

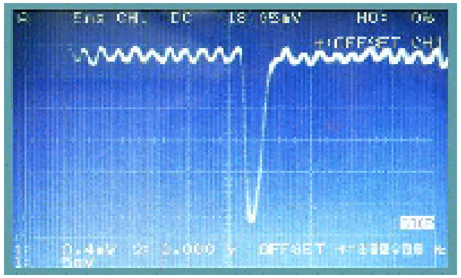
Radio Frequency Timing Technique

Principal scheme of the Streak Camera and RF PMT



CW electron beam

500-1000 MHz
Sinusoidal Voltages Pick-to-Pick 20V



Single photoelectron induced signal

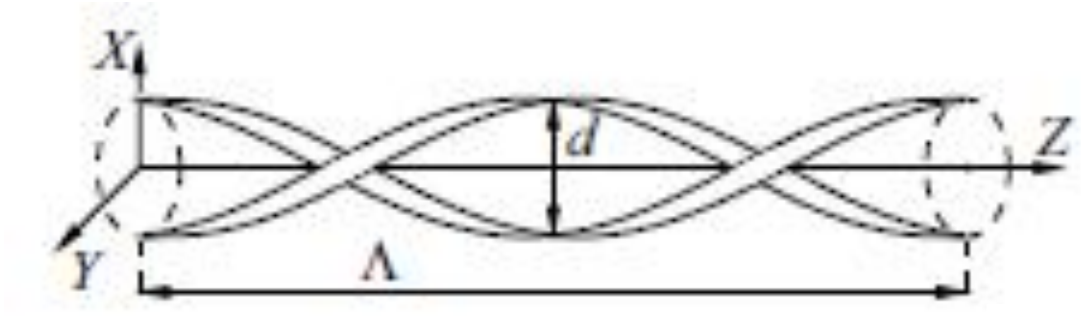
Streak Camera: Image Readout

RF PMT: Nanosecond Signal Readout

Transit Time Spread ~1 ps; Bandwidth ~ THz

RF PMT: A. Margaryan et al., Nucl. Instr. and Meth. A566, 321,2006

Helical Shape RF Deflector



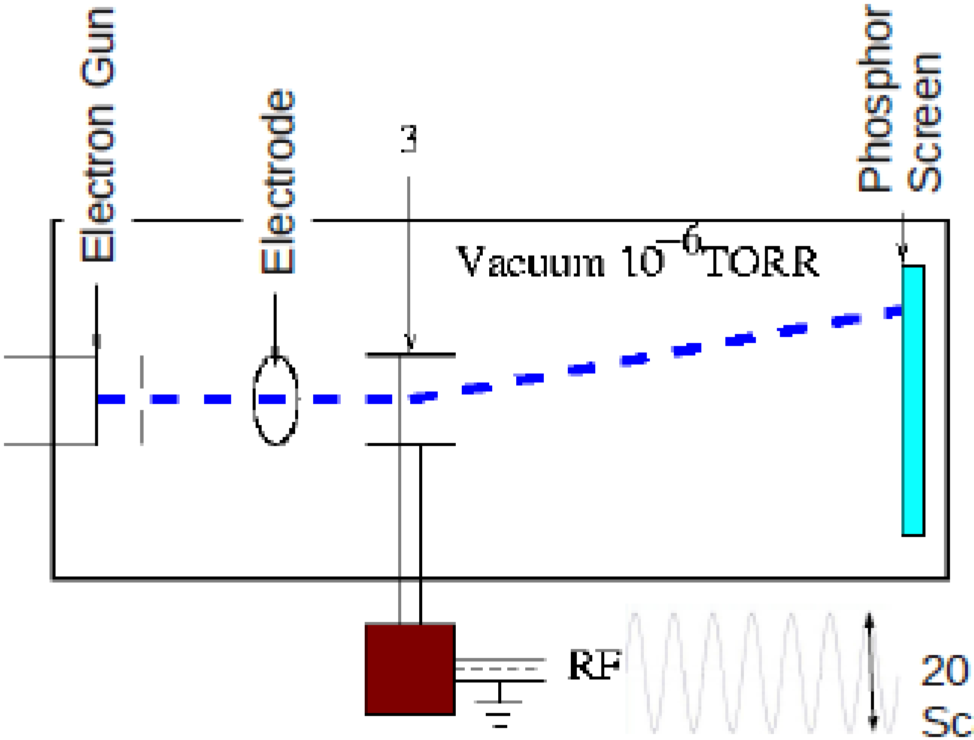
Shamaev Resonance
T = Λ/v

v - is the electron velocity
T - is the RF Voltage period
Λ – is the perod of deflector

No reduction of the deflector sensitivity due to transit time
Shamaev -1951

Top: schematic of the Shamaev helical shape RF deflector;
Bottom: side view. L. Gevorgian et al., Nucl. Instr. Meth. A 785 (2015)

RF Scanning System
Evacuated Test Tube with Thermionic Cathode



20 V, 0.5 → 1 GHz
Scan radius 1 mm/V (0.1 rad/$W^{1/2}$)

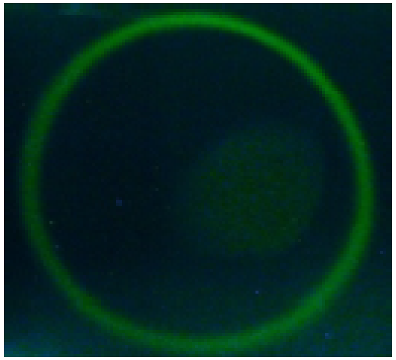
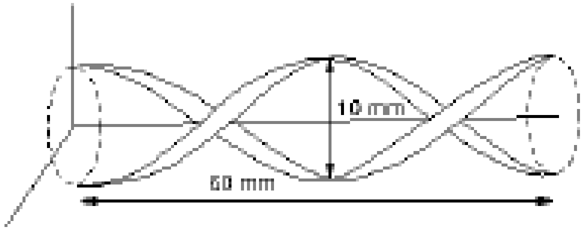


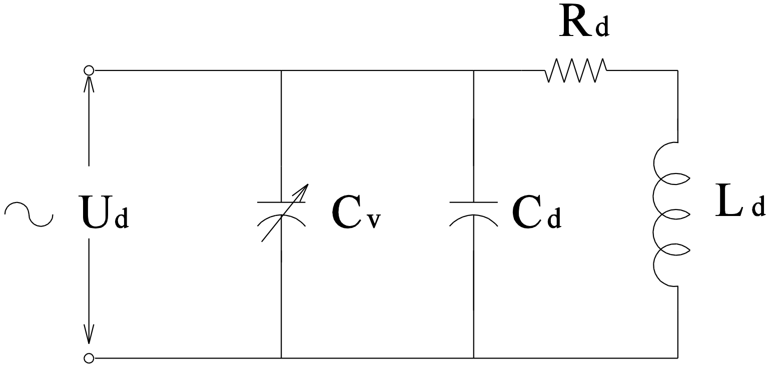
Image of CW electron beam
circle with radius ~20 mm



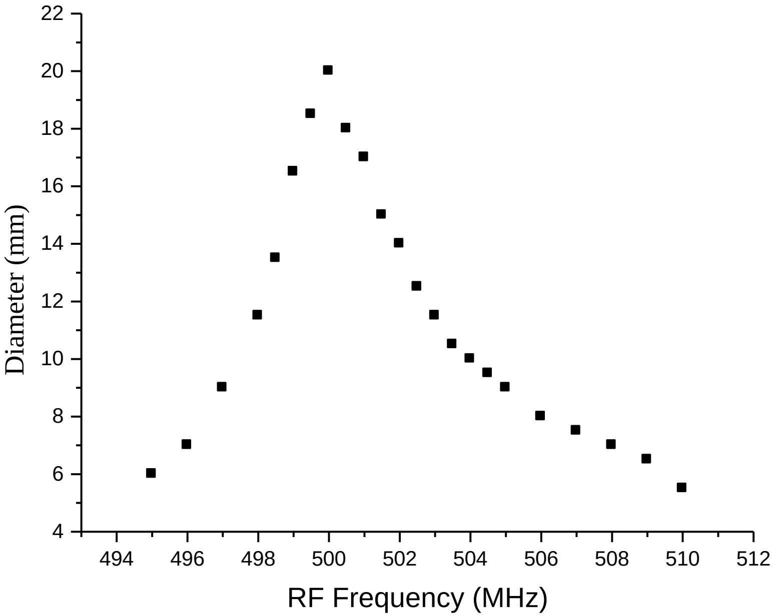
Actual structure of RF deflectors
for 500 MHz operation

Helical Shape RF Deflector: Resonance Circuit

RF deflector in a tube form a resonance circuit



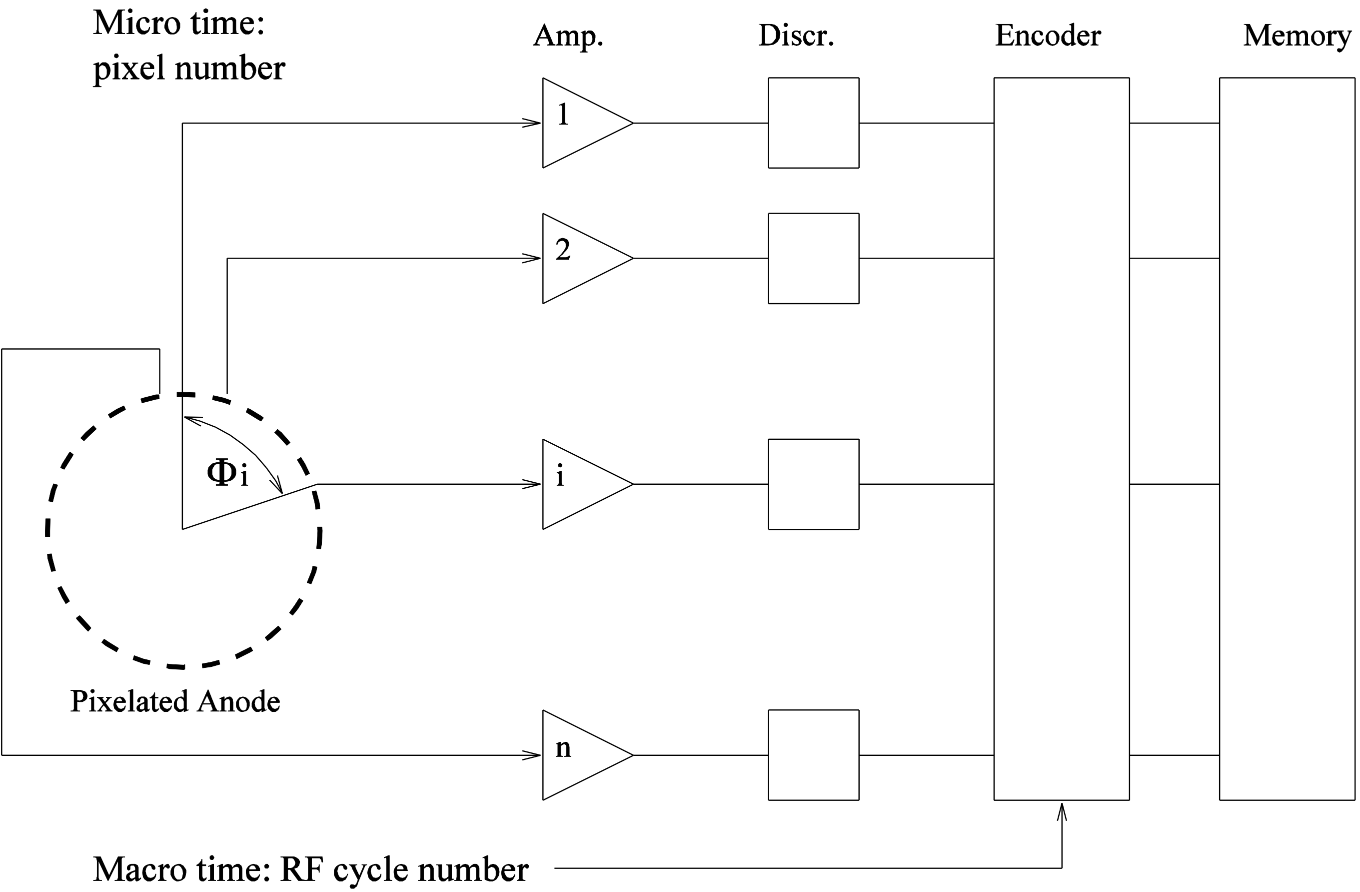
Schematic of the resonance circuit.



Diameter of the scanning circle as a function of RF frequency for 2.5 keV electrons.

New Timing System with Circular Scan

Pixelated anode



- Pixel number directly related to the hit time or RF phase Φ
- Pixels are phase locked and can be operated parallel
- Records short flash with high precision
- Or record the time dependence of an extended signal
- Gets more complicated if signal covers more than 1 RF cycle
- Extend micro time range by spiral scan

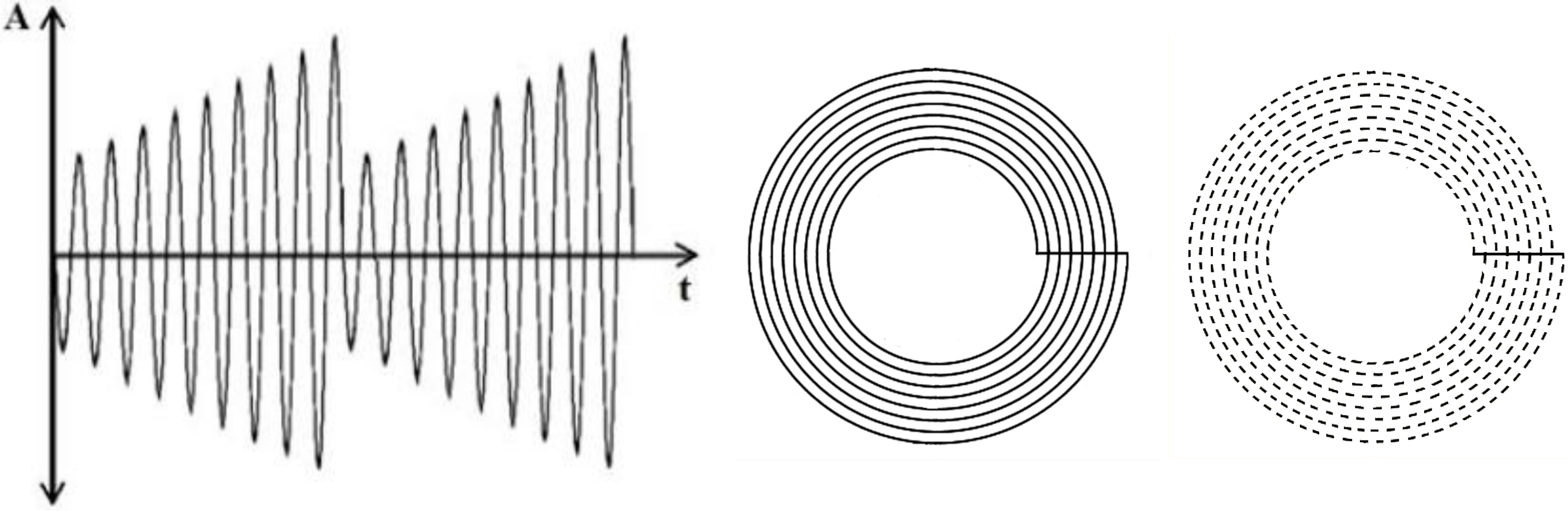
Time = N/ν + Φ/2πν   No TDC necessary

Time resolution = ΔΦ/ 2πν

ν is a RF frequency: ν = 1 GHz, 20mm radius

→8 ps/mm→80 fs/10 μm   fs time scale achievable

Spiral Scanning: RF Amplitude Modulation



Saw-tooth amplitude modulated
1Ghz sinusoidal RF Voltage

Image of photo-electrons
on the detector plane

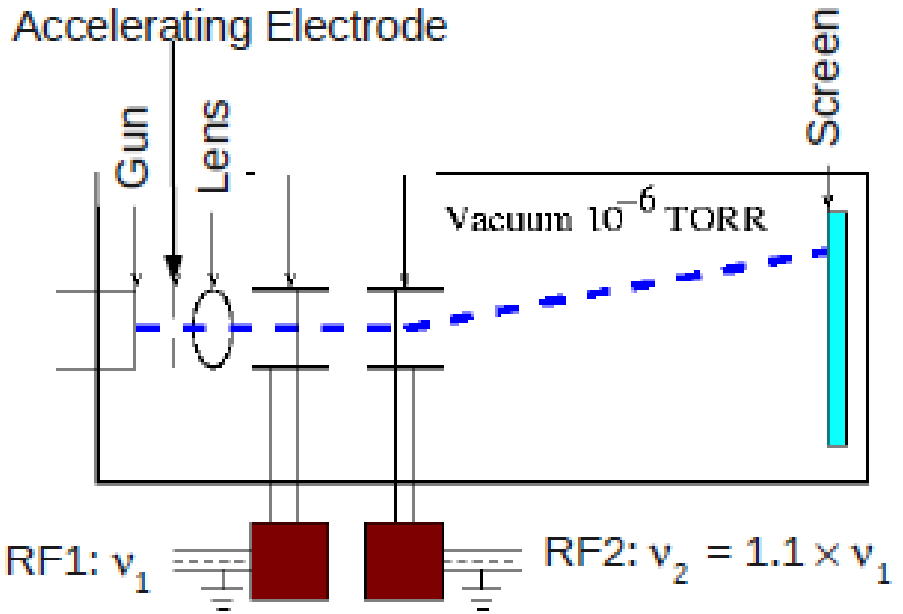
Position sensitive
multi-pixel anode

Schematic of the Spiral Scanning System

Fast RF amplitude modulation with RF cavity or resonance circuit is problematic

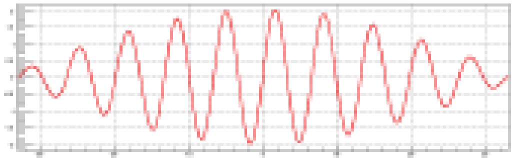
Y. D. Chernousov et al. NIM-A451, 2000, 541

Spiral Scanning with 2 RF Deflectors



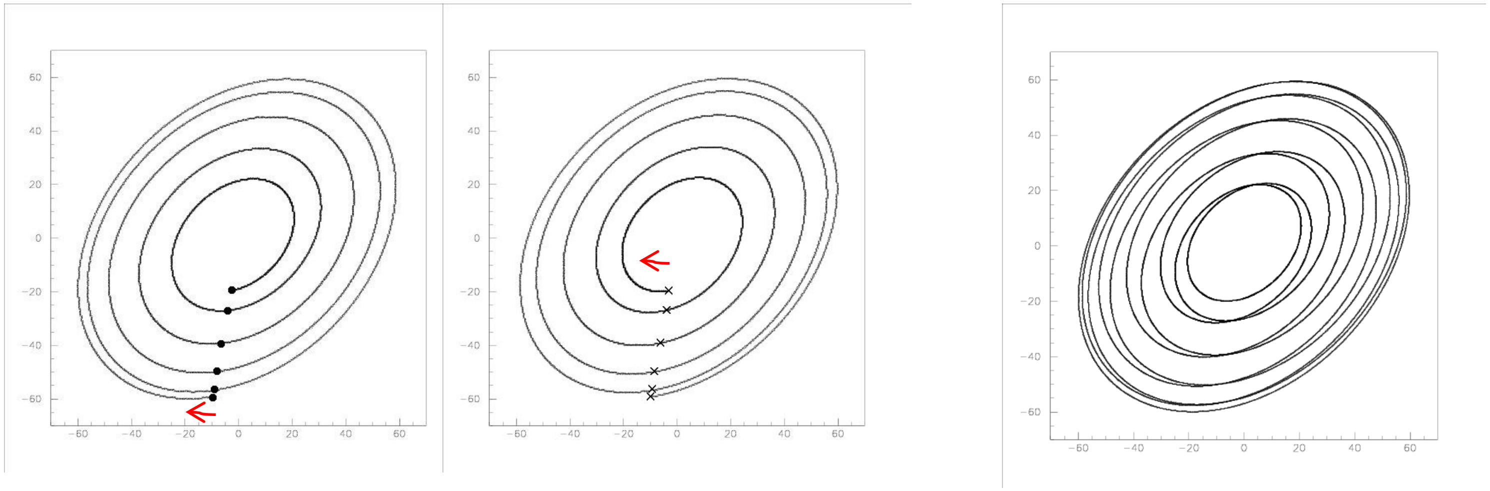
Spiral scan: Theory with 2 Helical Deflectors

- Apply 2 RF fields, of slightly different frequency
- "Beat" in superposed response modulates radius of scanned circle



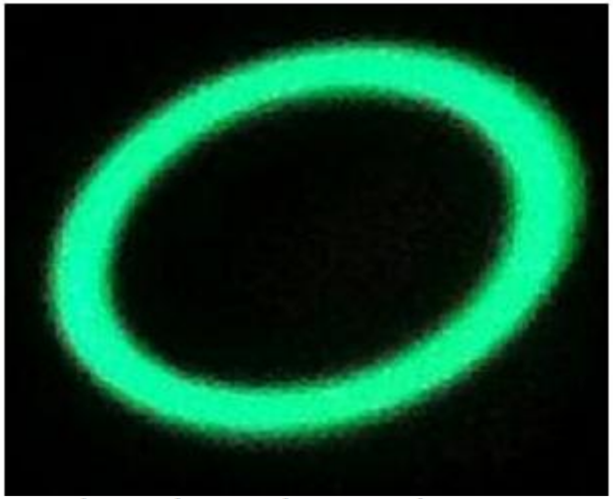
- Period of Spiral

  $\tau = 1/(\nu_2 - \nu_1) = 10\,\tau_1$ → few 100 ns
- Pixelated anode necessary

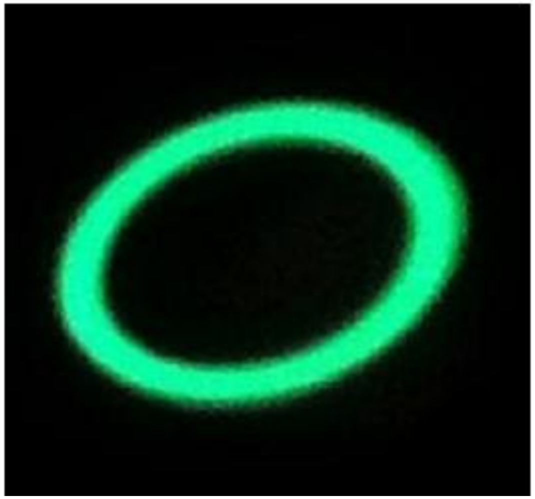


Spiral Scanning: Experiment with Phosphor Screen

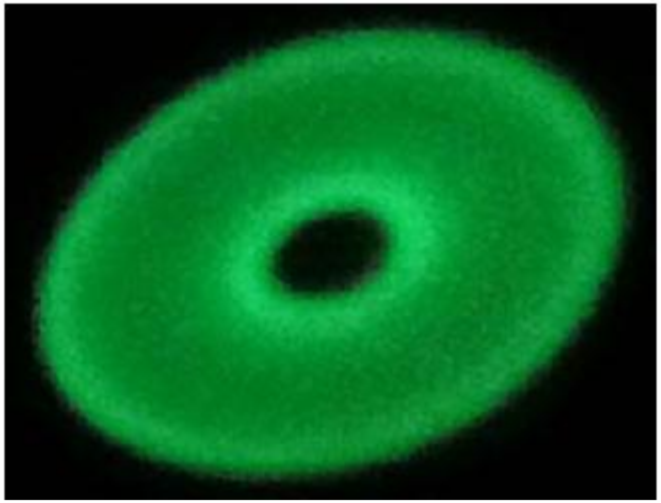
750 MHz Only

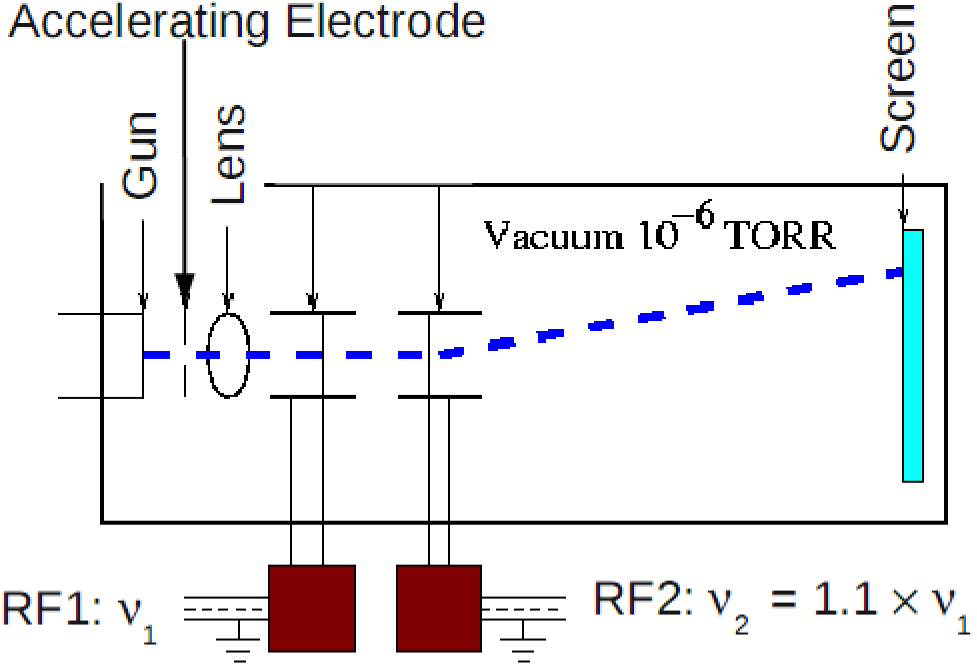


825 MHz Only



750 & 825 MHz Combined

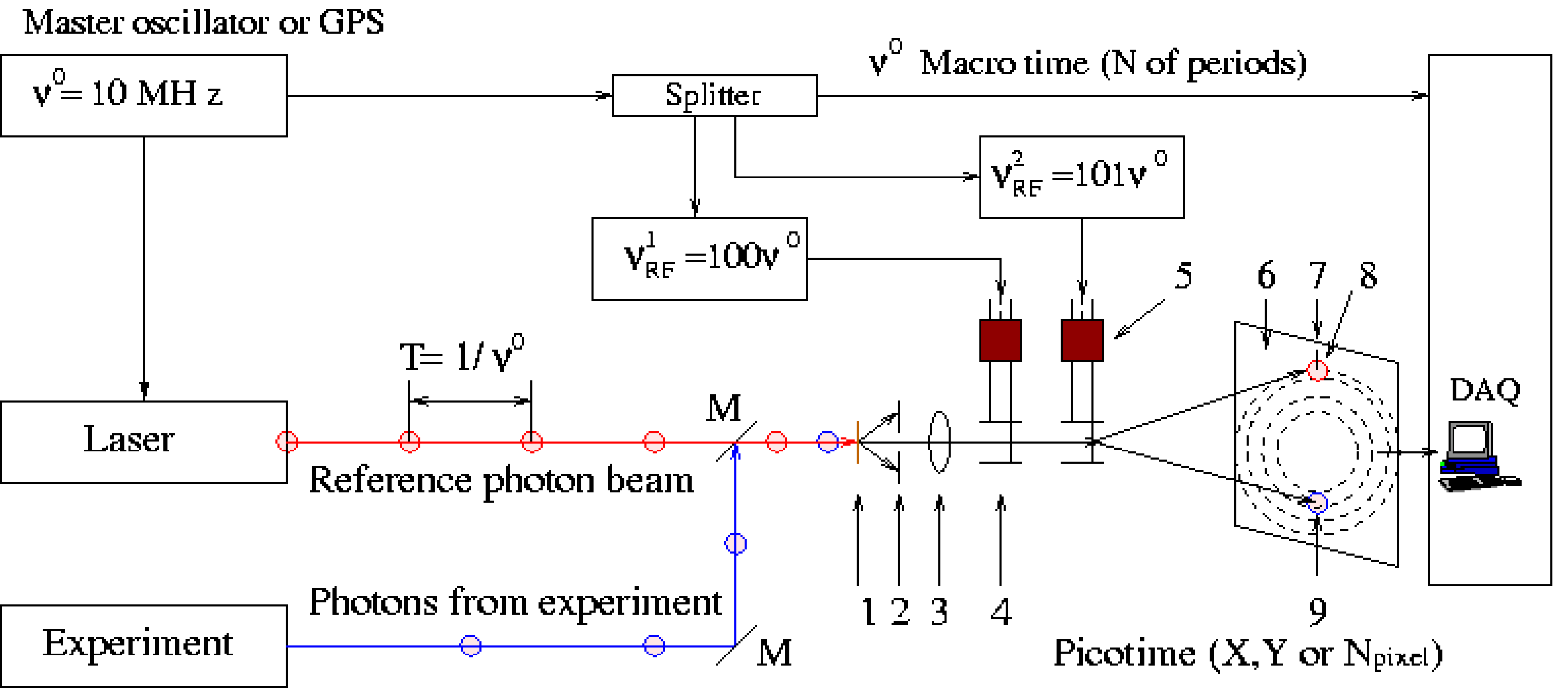




Period of the spiral can range from few 10 ns to few 100 ns

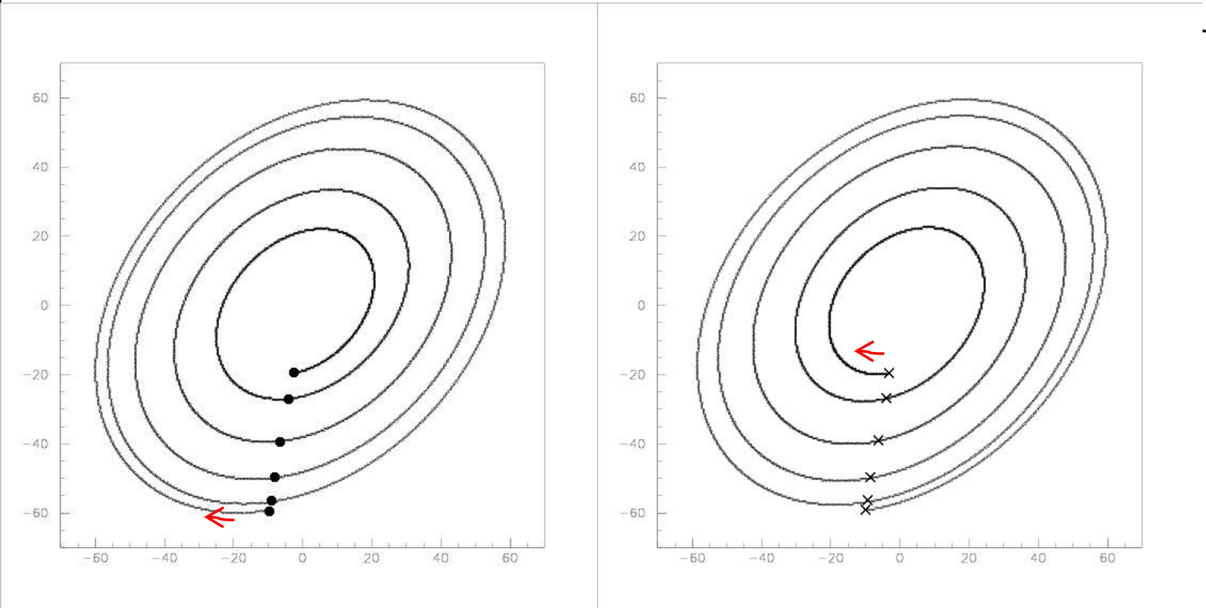
Overlapping can be avoided by properly designed RF system or gated detector

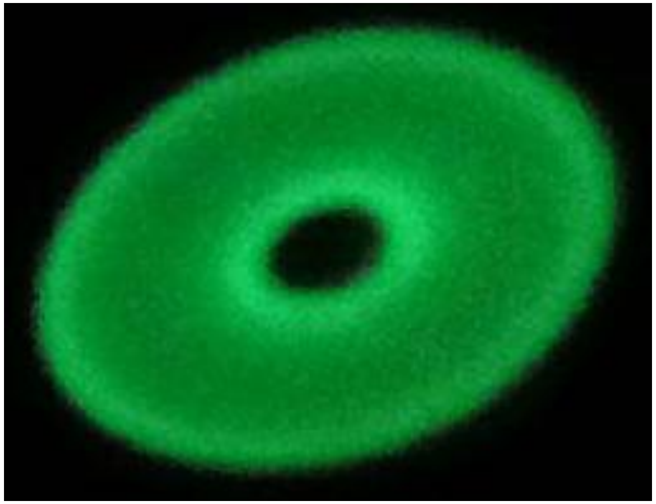
New Timing system with spiral scan RF PMT or Streak Camera



a) Time is determined by numbers of the spiral scan cycle (macro time) and pixel (micro time)
b) Minimum time interval: is about or less than 1 ps
c) Bandwidth is about THz
d) The time drift with reference photon beam is about few10 fs/day
e) Throughput rate: from few MHz up to GHz

Spiral Scanning RF PMT





Half periods can be seperated by properely designed RF sinusoidal Voltage or Gated Detector

PE beam can achive 10 µm size

Minimum time interval few 100 fs

Readout Technique

MCP single plane with 256×256 pixellated anode CMOS ASICs (application specific integrated circuits) such as TIMEPIX readout

MCP Gain: < 50000

Dinamic range: 1-200 milion count per second

High position resolution: σ =10 µm

John Valerga et al. *Sensors 2013, 13, 4640-4658*

Spiral Scanning RF PMT & Hybrid PE Detector

Hybrid PE Detector

MCP single plane and G-APD (windowless or thin scintillator foil covered).

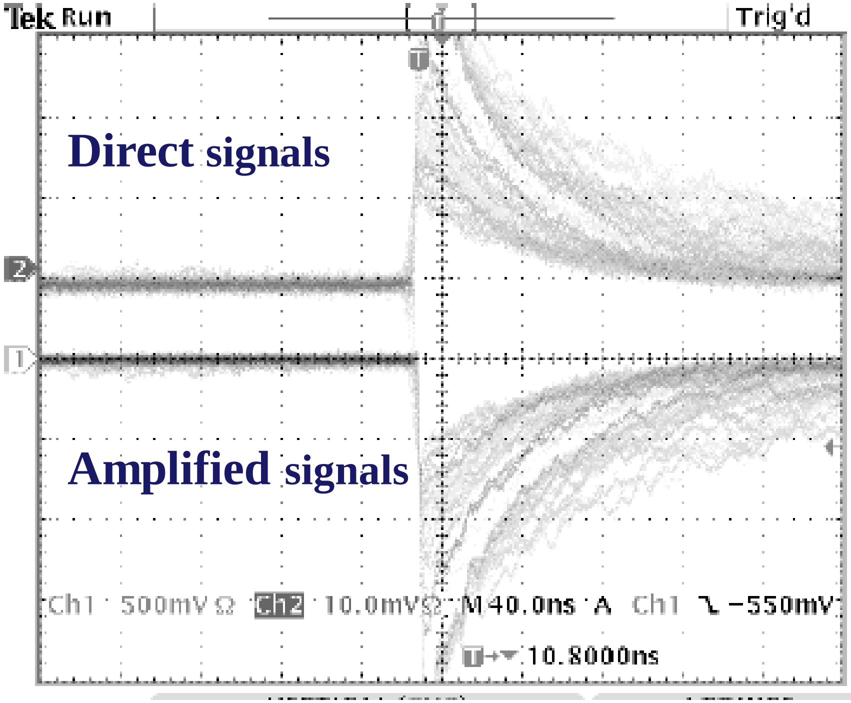
MCP Gain: 10-100

Dinamic range: 1- few Giga count per second

Experiment atYerevan

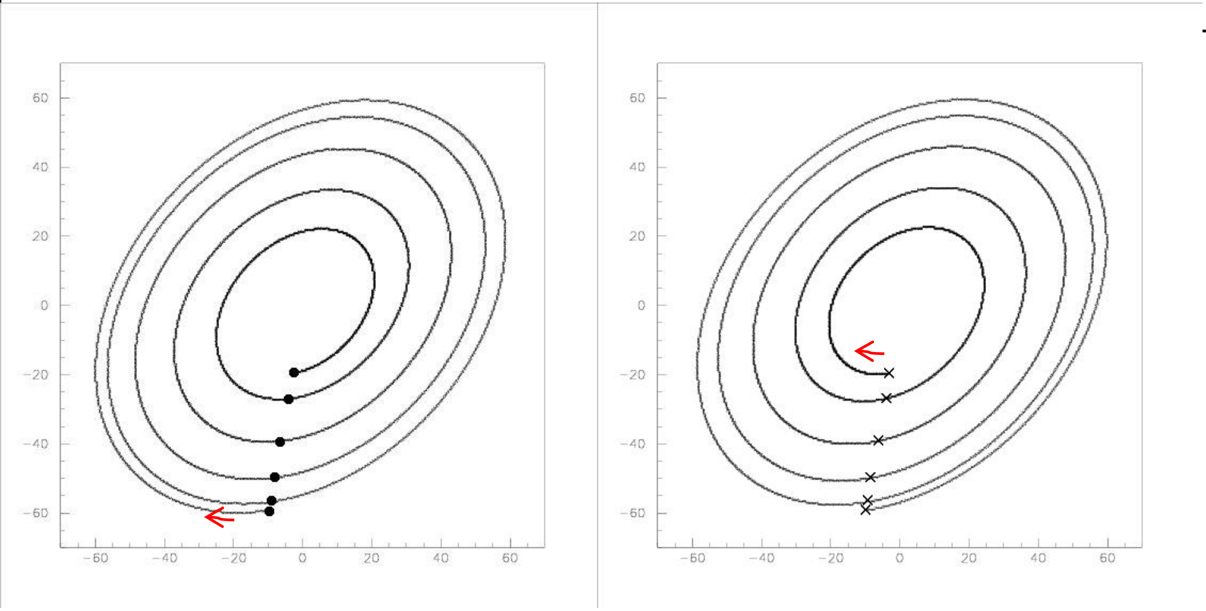
Single plane MCP + MPPC (Hamamatsu S10362) covered by 20 µm plastic scintillator foil; MCP Gain : 10-100

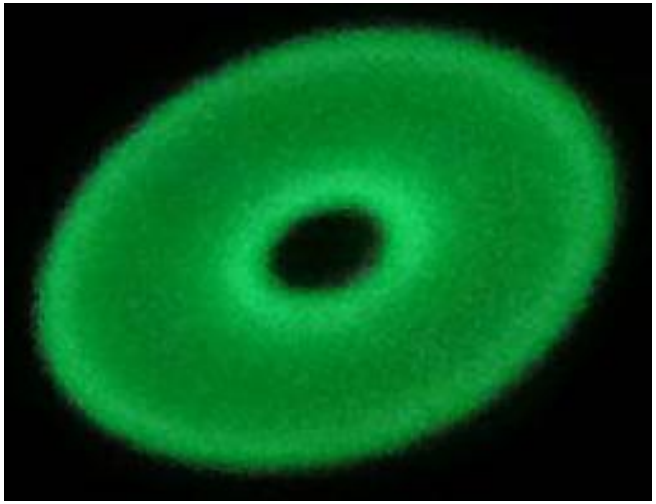
Forward to few GHz Photon Detector



C. Joram et al., considered luminescent anode made from a LYSO scintillator, NIM A(2010)

Spiral Scanning Streak Camera





Half periods can be seperated by properely designed RF sinusoidal Voltage

PE beam can achieve few 10 ❍m size

Minimum time interval: few 100 fs

Readout Technique

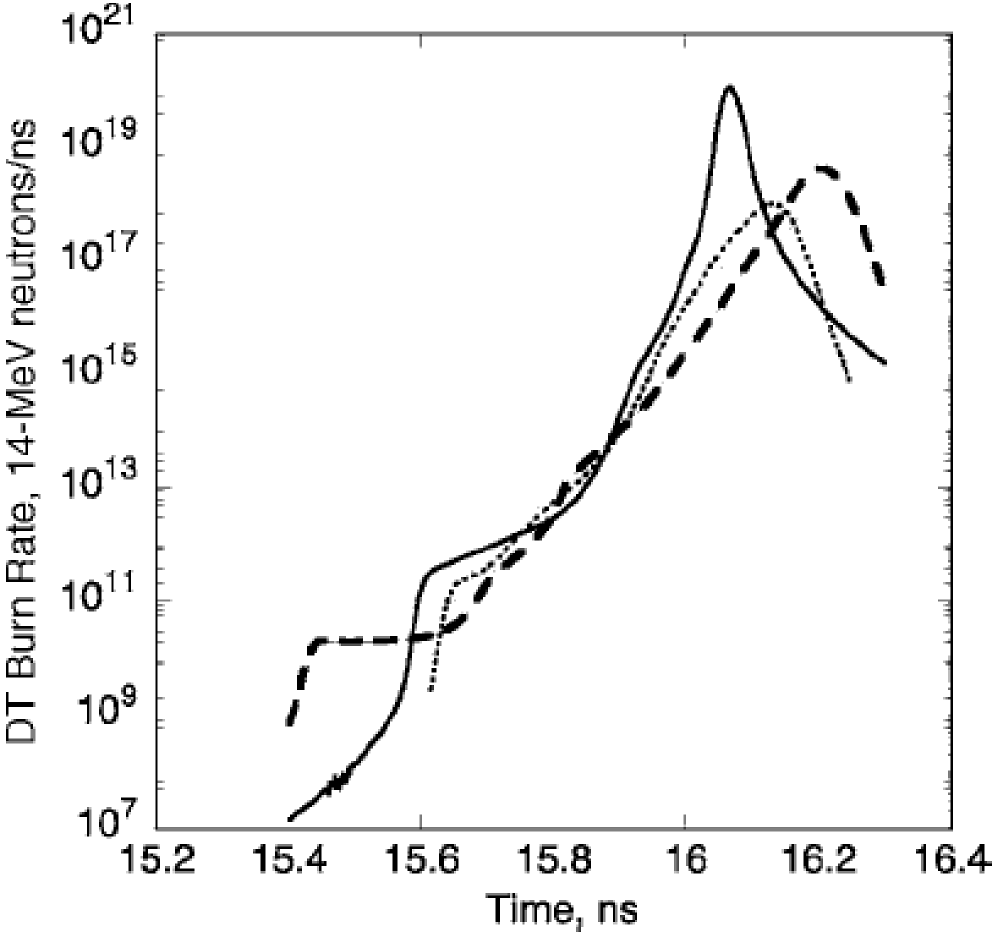
ISIS: ultra-high-speed image sensors with in-situ CCD signal storage

4,500 frames per second (fps) for 256×256 pixels	1991
One milion frames per second (Mfps) for 256×256 pixels	2001
16 Mfps for 256×256 pixels	2011
16.7 Mfps for 300×300 pixels or 5.2 Tpixel per second	2013

1 Gfps→ theoretical limit

Takeharu G. Etoh et al. *Sensors 2013, 13, 4640-4658*

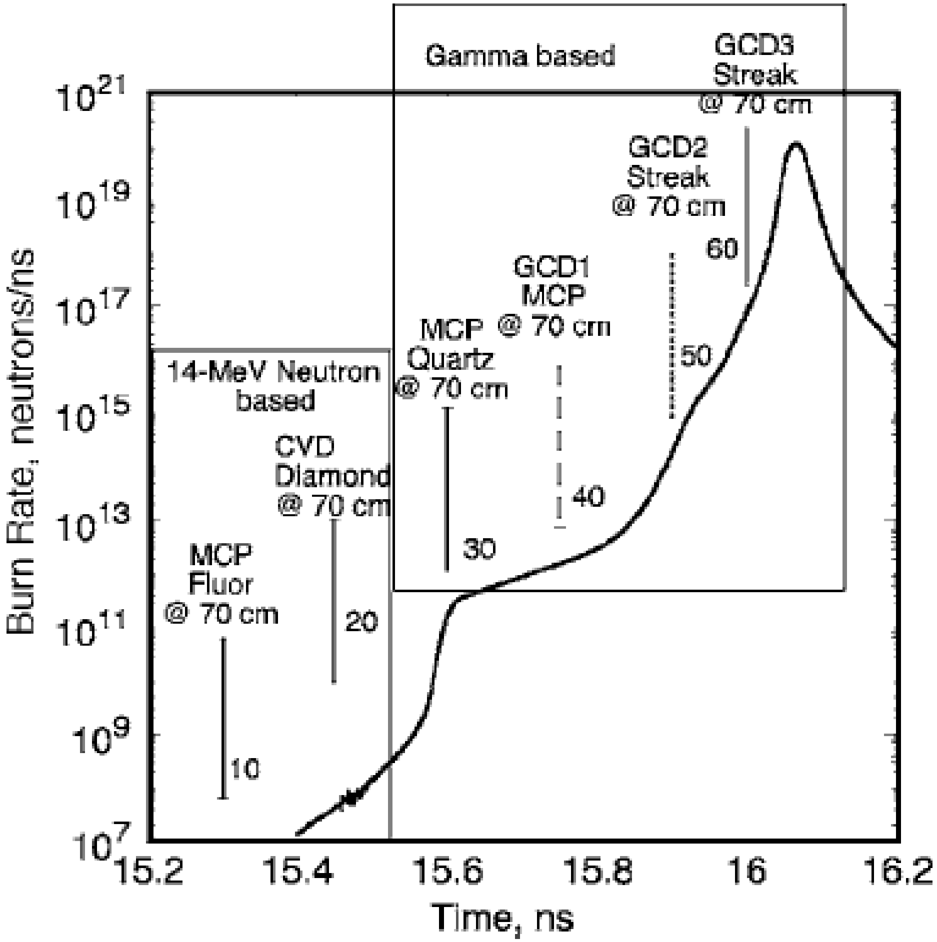
Temporal measurement of thermonuclear burn in laser-driven inertial confinement fusion



Burn rate versus time for an ignition (solid line) and two non ignition implosion cases.

J. M. Mack et al., Rev. Sci. Instr. 77, 10E728 (2006)

Application to Reaction History

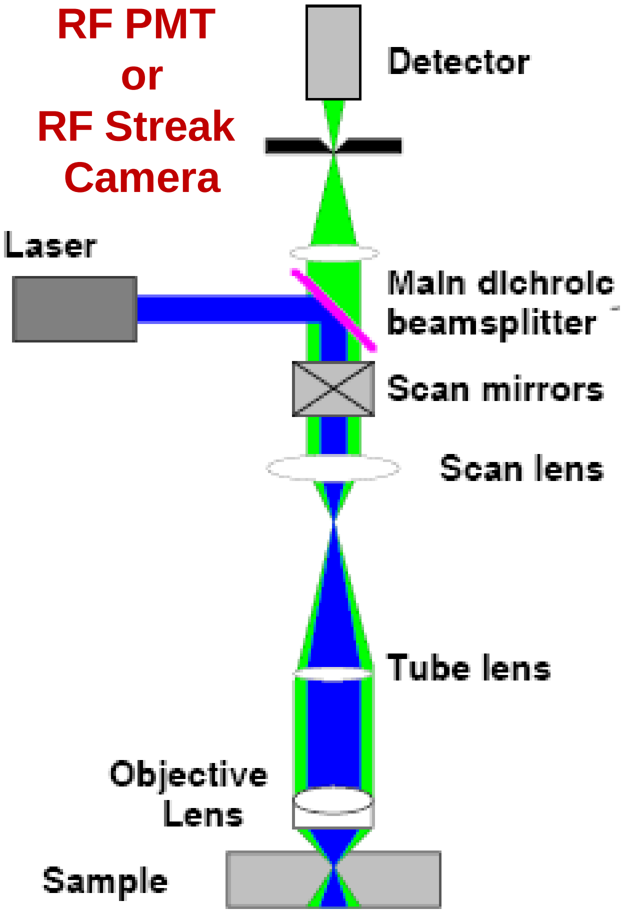


d+t→α(3.5 MeV) + n(14.1 MeV)

d+t→γ(16.7 MeV)/n(14.1 MeV)~5×10-5

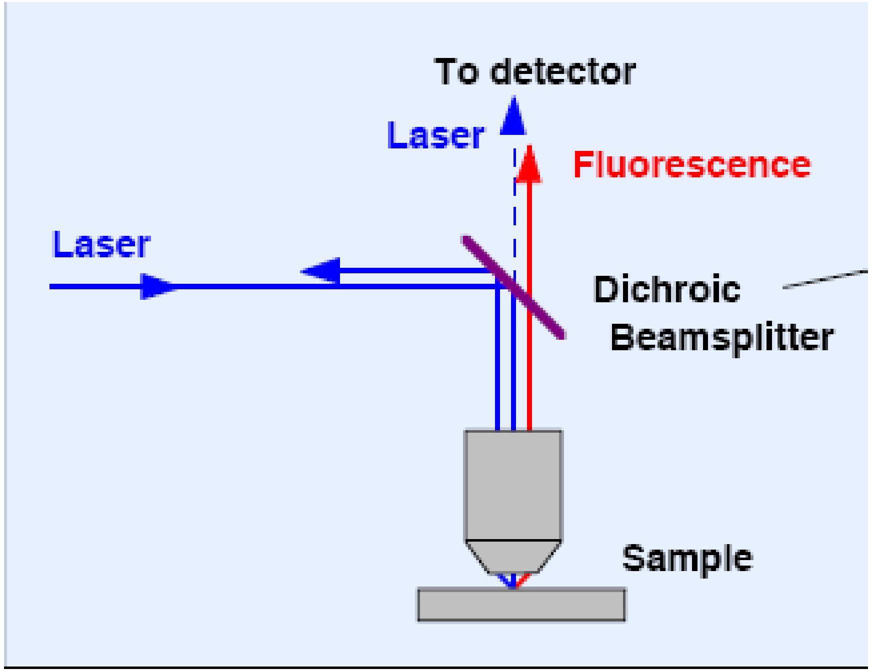
One possibility for full-coverage reaction-history measurement with overlap regions.
J. M. Mack et al., Rev. Sci. Instr. 77, 10E728 (2006)

Fluorescence Lifetime Imaging→PS Nanoscope

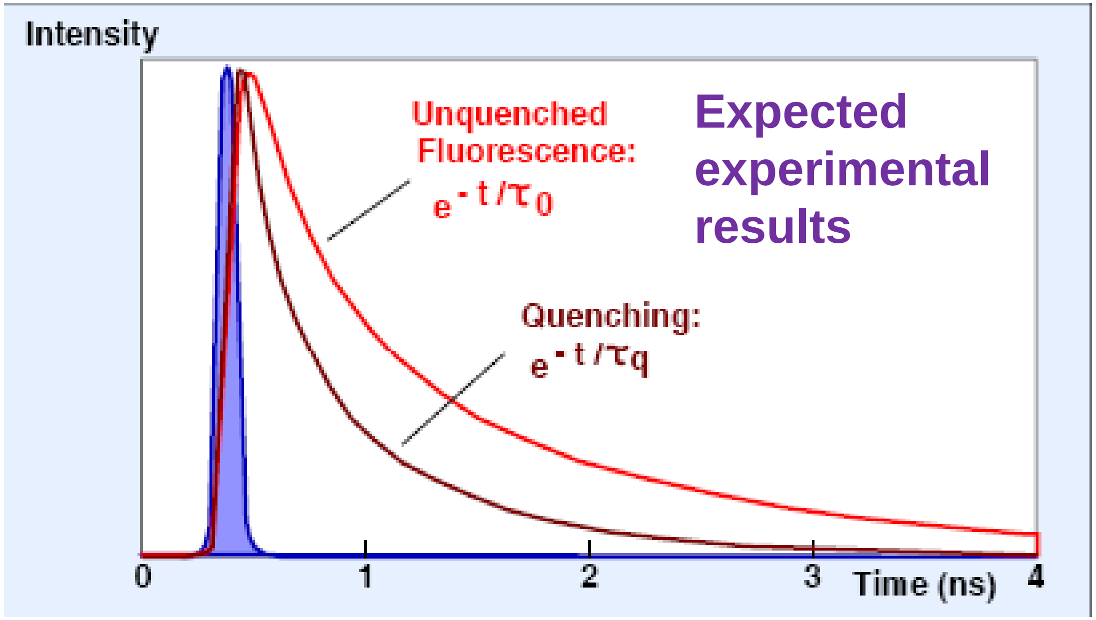


RF PMT or RF Streak Camera

Schematic of the experimental setup

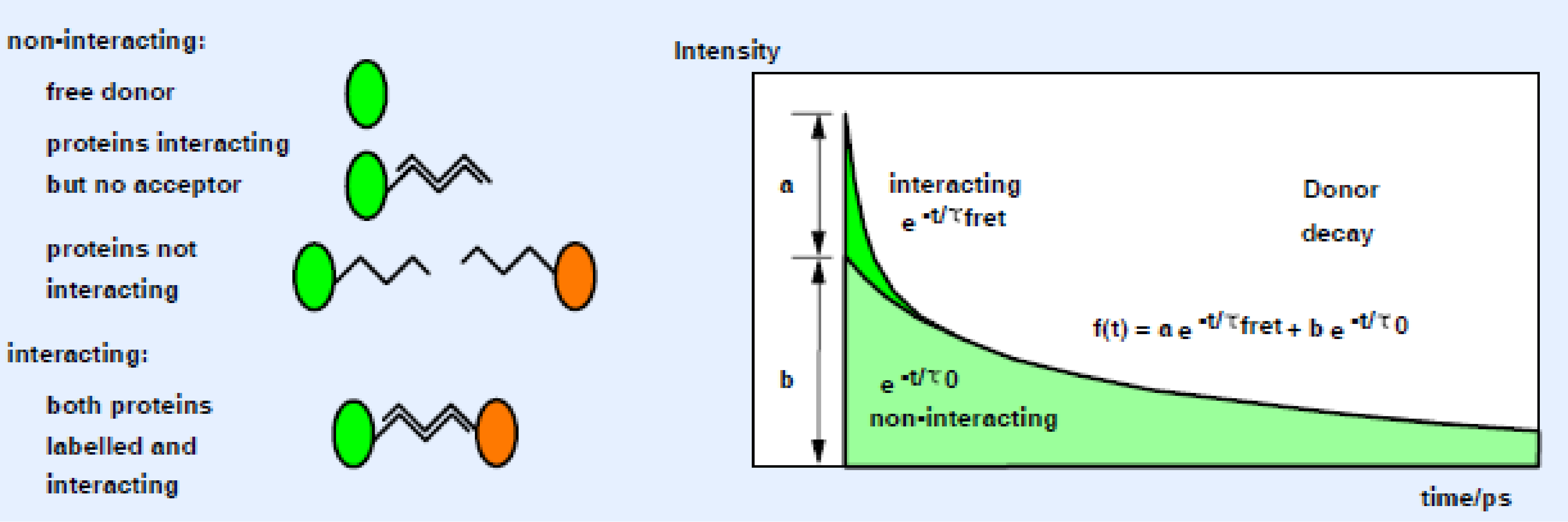


Schematic of the operational principles



Expected experimental results

Fluoroscence Resonance Energy Transfer (FRET)



Fluorescence decay components in FRET systems

Basics of FRET experiments

Picoseconds time resolution is a crucial factor for FRET experiments

$$E_{fret} = 1 - \tau_{fret} / \tau_0$$

$$(r / r_0)^6 = \tau_{fret} / (\tau_0 - \tau_{fret}) \quad \text{or} \quad (r / r_0)^6 = \frac{1}{E_{fret}} - 1$$

$$N_{fret} / N_0 = a / b$$

Summary and Outlook

- Circular scanning RF deflector working in the range 0.5 - 1 GHz
- Spiral scaning working with 750, 825 MHz
- Average rate of the RF PMT with single MCP plane + MPPC PE detector can reach few GHz
- Wide field of potential applications
- A prototype RF PMT has been designed at Photek Ltd.

  Need additional funding to start small-scale production and quantitative testing of timing precision
- Development is continuing at Yerevan, but the way for fastest application is the organization of R&D in colaboration with EU centres

Thank you for your attention