Fast timing detectors for operation in high magnetic fields

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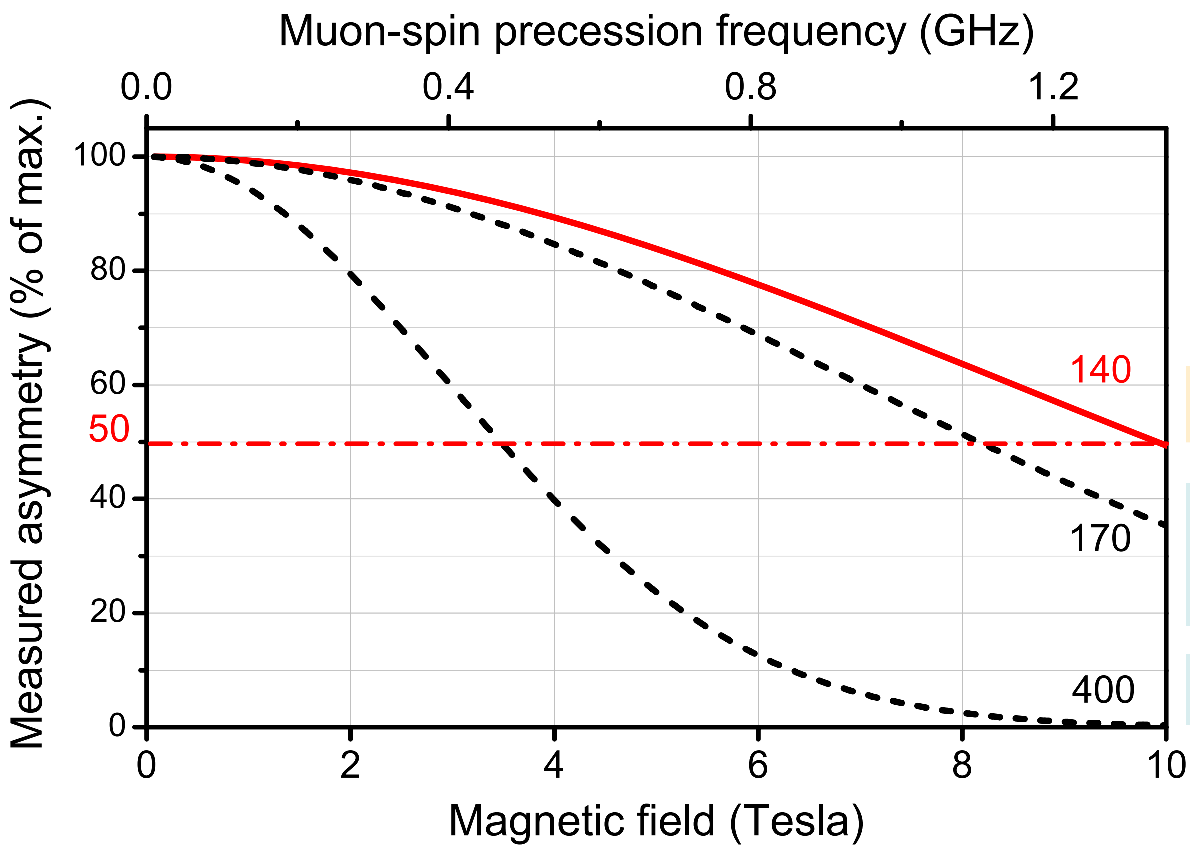
A challenge of muon spin rotation experiments in 10T

Detection of 1.35 GHz muon spin precession signal in 10T ⇨ time resolution $\sigma \leq 140\text{ps}$

Per counter (μ^+ / e^+): $\leq 100\text{ps}$



Upper limit for a 10 T spectrometer

7T *HiTime* instrument at TRIUMF (PMT- based detector system)

"Standard" μSR spectrometer

PMT based scintillation counters:

- in high magnetic fields the time resolution is limited due to attenuation and broadening of the light pulses in the necessary light guides

TF μSR in high fields ➔ no light guides ➔ no PMTs

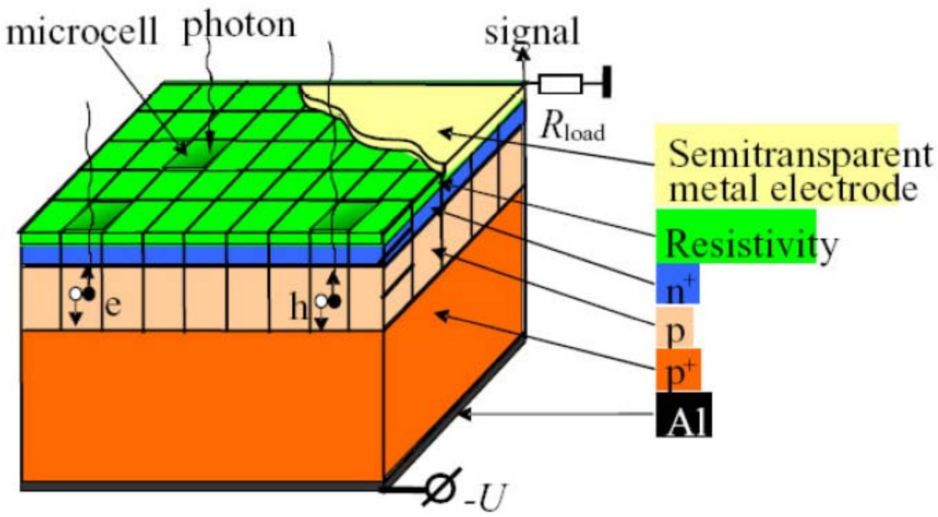
		Potentially promising photosensors				
photosensor / parameter	**PMT**	Avalanche PhotoDiode **(APD)**	Large Area Avalanche Photodiode **(LAAPD)**	Hybrid Photo Detector **(HPD)**	MicroChannel Plate PMT **(MCP PMT)**	Multipixel Geiger-mode Avalanche PhotoDiode **(G-APD)**
active area	> 100 mm^2	≤ 100 mm^2	≤ 400 mm^2	> 100 mm^2	> 100 mm^2	≤ 10mm^2
operation voltage	~ 2 kV	**~ 400 V**	~ 1600 V	~ 8 kV	~ 2 kV	**< 100 V**
gain	$10^5 – 10^7$	≤ 500	≤ 2000	$≤ 8·10^4$	$10^5 – 10^7$	$10^4 – 10^7$
PDE (%, near UV)	30	*	*	30	**15**	**5** (2003) 30 (2007)
fast response (near UV)	yes	yes	no (drift time)	yes	yes	yes
operation in high fields	<< 1T (typ. 0.3T)	**expected** (tested ≤10T)	**expected** (tested ≤5T)	certain orientations	max 2T (certain orient.)	**expected** (tested ≤5T)
compactness	bulky	**compact**	**compact**	bulky	bulky	**compact**
non-magnetic package	no	**yes**	**yes**	no	no	**yes**

* no single phe resolution; QE ~ 70%

good acceptable not acceptable

G-APD – multi-pixel Geiger-mode Avalanche PhotoDiode

G-APD ≡ SiPM, MAPD, SSPM, MPPC …



MRS APD [A. Akindinov, Beaune05]

$$Q_i = C_i \cdot (U - U_0)$$

$$M = Q_i / e$$

$$Q = \sum Q_i$$

G-APD vs. PMT

Advantages:

- insensitive to magnetic field;
- compact, robust;
- low operation voltage (20 – 150 V)

Disadvantages:

- small active area (1 – 10 mm^2)

larger area → G-APD arrays

G-APD: parameters

- Active area (1 – 10 mm^2)
- Number of cells → Dynamic range (100 – 10000 mm^{-2})
- **Photon Detection Efficiency:** $PDE(\lambda, U)$ (≤ 35% at 400 nm)
- Gain: M ($10^4 – 10^7$)
- **One-photon time resolution:** $\sigma_{1ph}(\lambda, U)$ (≥ 100 ps at 400 nm)
- Excess noise factor: $F = 1 + \sigma^2(M) / \langle M \rangle^2$
- Inter-pixel cross-talk: $\alpha(M)$
- Operating voltage: U (15 V – 150 V)
- Dark current: $I_0(T, U)$ (10 nA – 100 μA / mm^2 at RT)
- Dark counts: $N_0(T, U)$ (0.1 – 10 MHz / mm^2 at RT)
- Cell recovery time (10 – 1000 ns)
- Temperature coefficient of gain: $(\Delta M / M) / T$ (0.1 – 10 % / C)
- Radiation hardness

Timing with plastic scintillators: **G-APDs** vs. **PMTs**

time resolution $\boldsymbol{\sigma}$ vs. detected energy $\boldsymbol{E}$

PMT

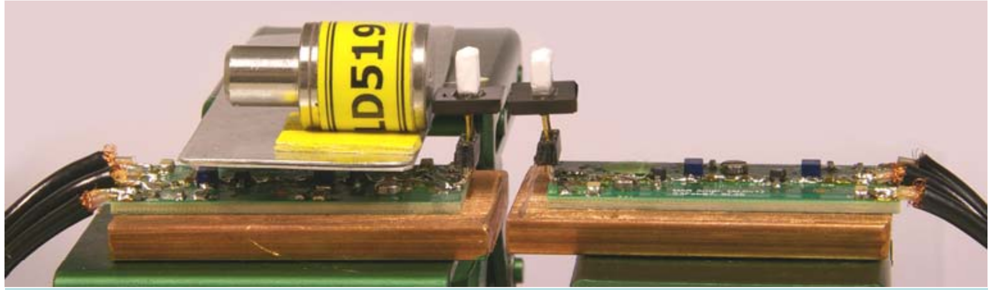
$\sigma E^{0.5} = \mathbf{19\ ps \cdot MeV^{0.5}}$ -- best time resolution (NE111 + XP2020UR-M)

[M.Moszynski, NIMA 337 (1993) 154]

G-APD

$\boldsymbol{\sigma(E)}$ – to be measured …

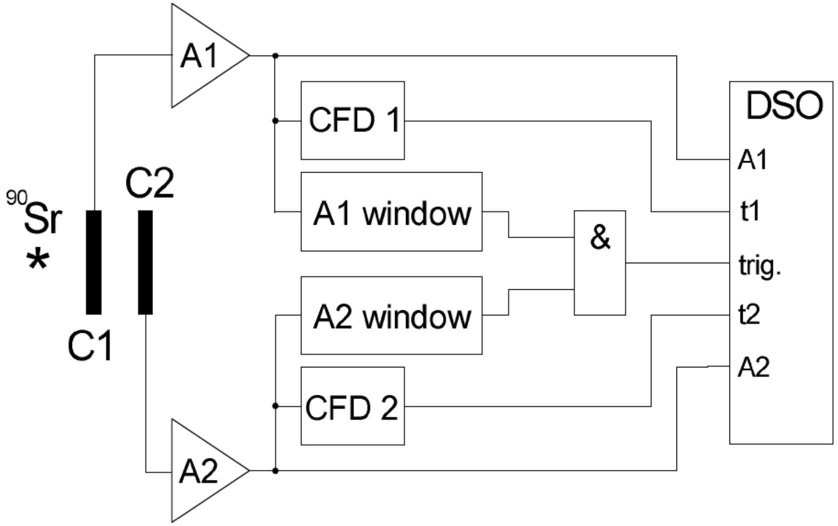
σ(*E*) : measurement setup



Scint.: BC422 (3x3x2 mm³) readout via 3x2 mm² face

G-APDs: MPPC 33-050 (3x3 mm², 400 pixels/mm²)

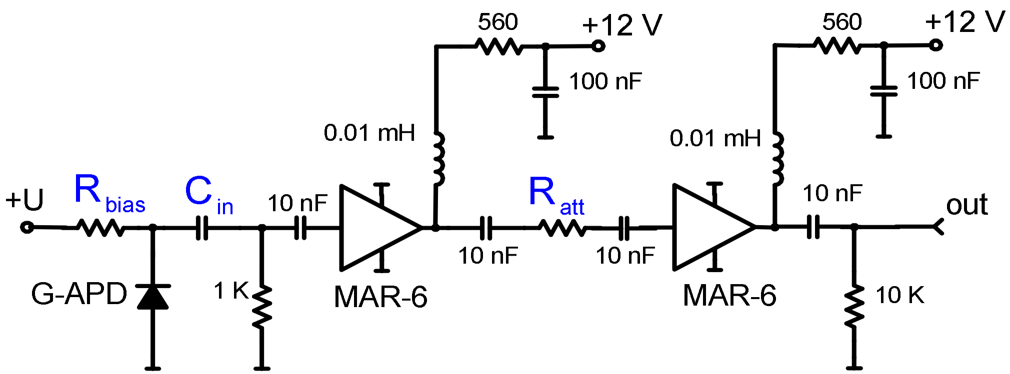
$U \sim 70$ V, $I_0 = 1.0$ µA, $T = 22\,^0$C

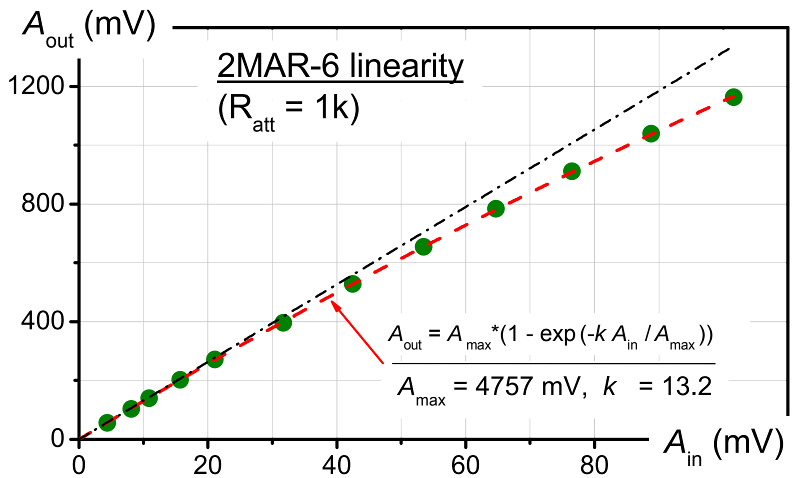


A – MAR—amplifier;

CFD – PSI CFD-950;

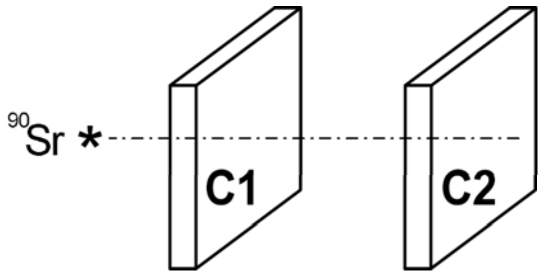
DS0 – LeCroy WavePro 960 (2 GHz).





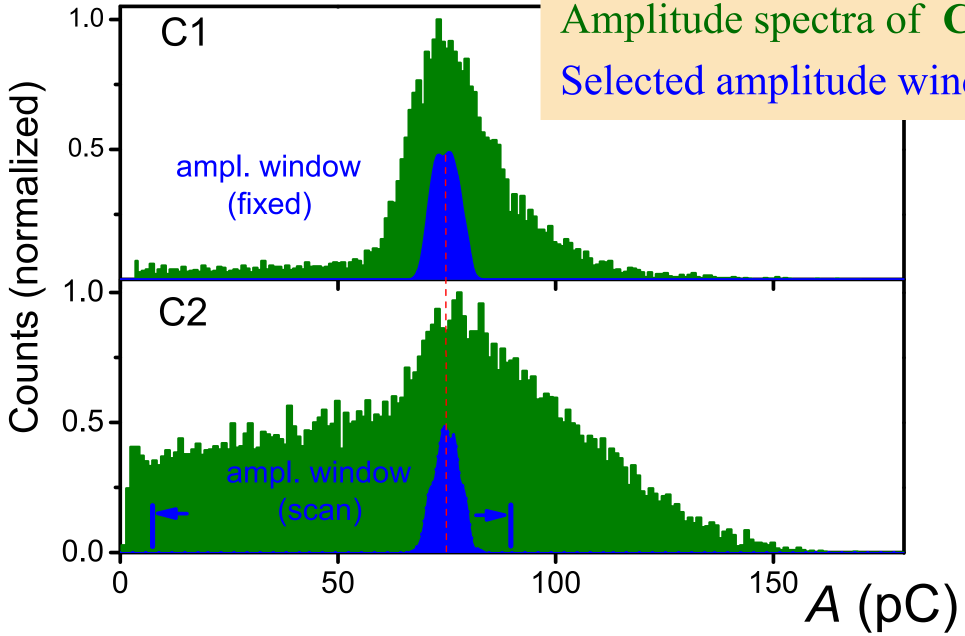
MAR-6 amplifier ($R_{bias} = 1$k, $C_{in} = 56$pF, $R_{att} = 1$k) : Gain = 13, bw ≈ 600 MHz

σ(*E*) : raw data



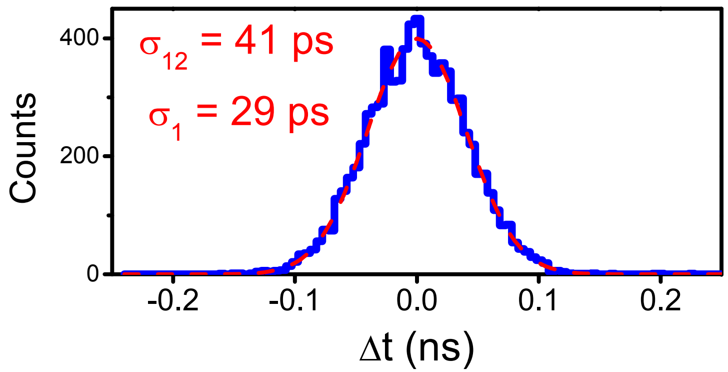
Amplitude spectra of **C1,C2**

Selected amplitude windows



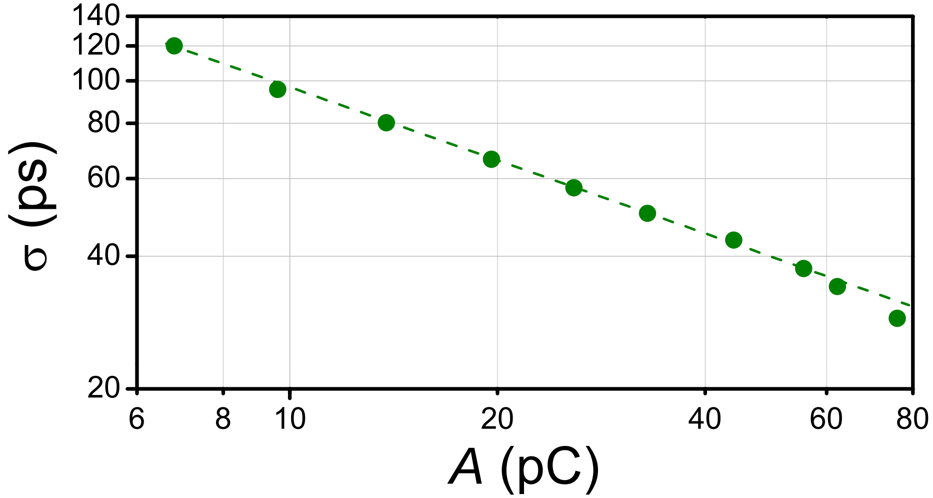
Time difference **t1 – t2**

(A1, A2 in selected windows)



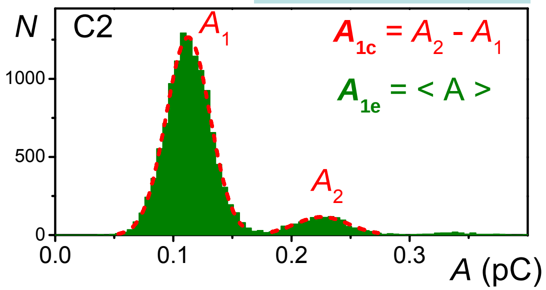
Time Resolution of **C2** vs. Amplitude

(win1 – fixed, win2 – scan)



$\sigma(E)$: $A \rightarrow N_{phe} \rightarrow E$

1e-spectrum C2



1. Correct for non-linearity of the amplifier: $A \rightarrow A_{lin}$

2. Calculate number of firing cells: $N_{cell} = A_{lin} / A_{1c}$

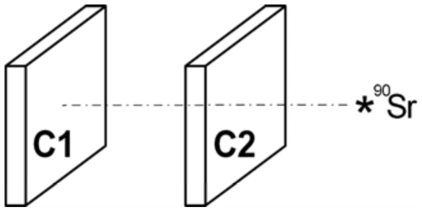
3. Calculate the number of photoelectrons: $N_{phe} = (m / \alpha) \ln (1 - N_{cell} / m)$

$m = 2400$ (cells per 6 mm^2); $\alpha = A_{1e} / A_{1c} = 1.12$

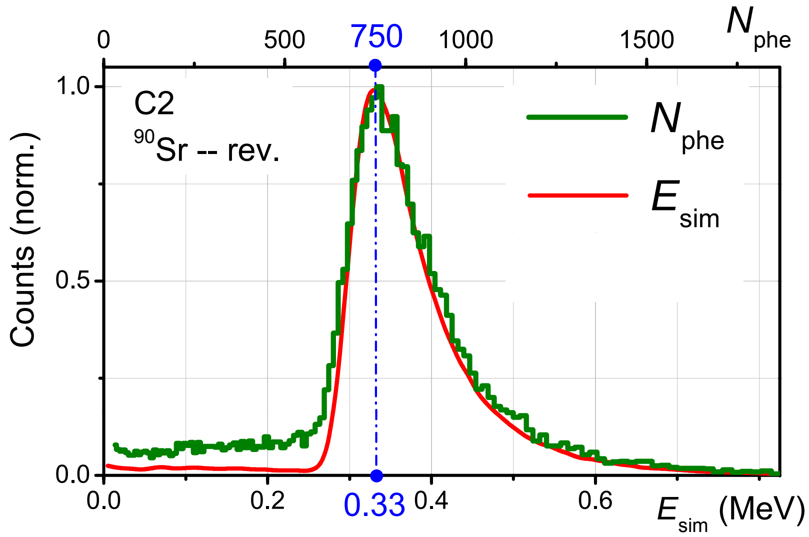
4. Establish the correspondence between N_{phe} and E: $N_{phe} = 2270\, E$

$n\,(N_{phe})$ – experimental data (C2, ^{90}Sr reversed) after the corrections;

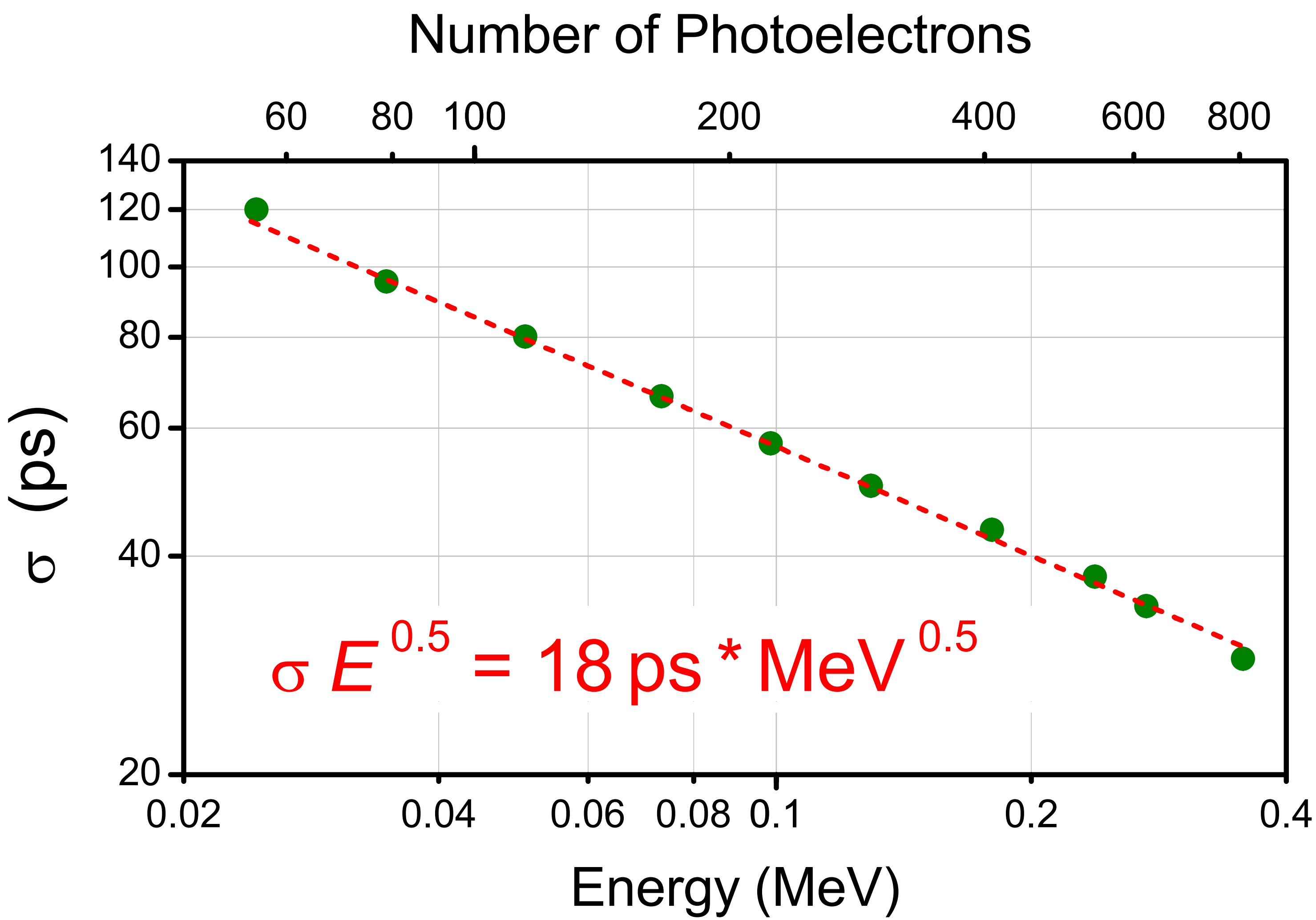
$n\,(E_{sim})$ – spectrum of deposited energies simulated in GEANT4.



^{90}Sr – ``reversed''



$\sigma(E)$: results | BC422 + MPPC 33-050 | 2270 phe/MeV | *PDE* ≥ 27%



PMT: 19 ps · MeV $^{0.5}$

best time resolution [M.Moszynski, NIMA 337 (1993) 154].

NE111 (d25 x 10 mm, Teflon reflector) + **XP2020UR-M**

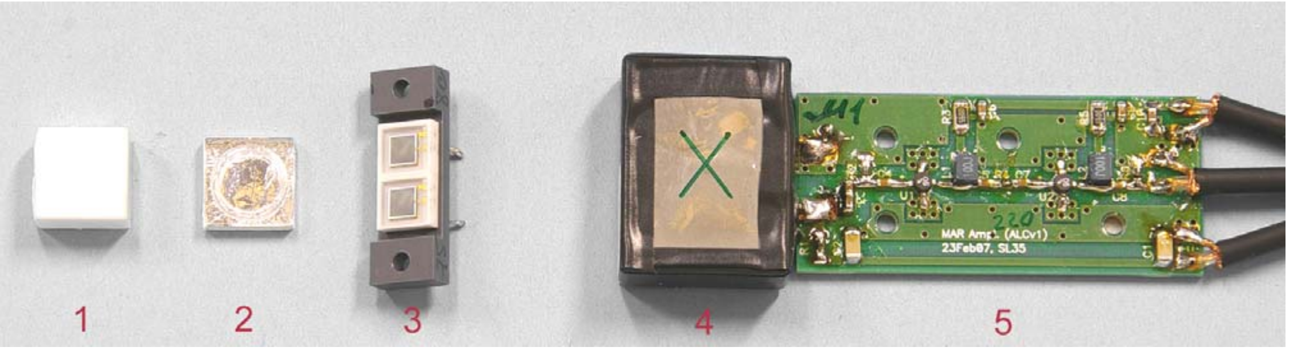
BC422 ≡ NE111

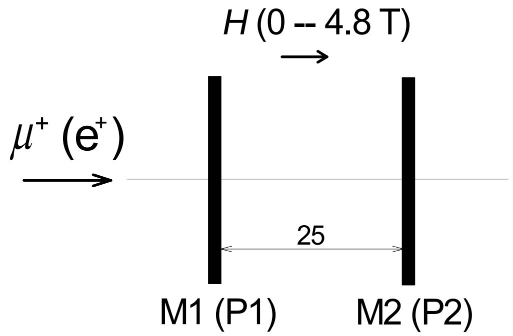
fastest plastic

8400 phe/MeV, 370 nm

Muon and positron counters for 10T spectrometer (prototypes)

***H* = 4.8 T**





(1) Positron counter: **EJ-232** 10x10x5mm;

(2) Muon counter: **EJ-232** ø8x0.3mm in 10x10x2mm frame (BC-800);

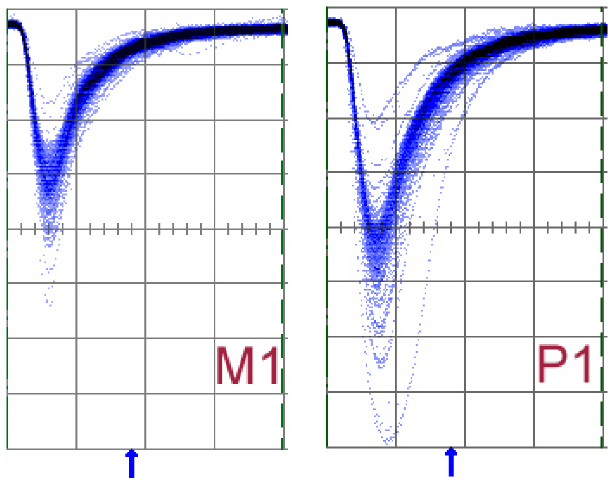
(3) two G-APDs type **Hamamatsu MPPC S10362-33-050 (3x3 mm^2)**;

(4) scintillator + photosensor in a light tight box;

(5) broad band amplifier (gain ~13, bw ~ 600 MHz).

Test setup:
the muon (positron) counters are assembled on a supporting plate inserted into the warm bore of a 5T solenoid. The muon (positron) beam momentum is 28 MeV/c.

4.8T, scale: 5ns, 200mV



Detection of muons (M1) and positrons (P1) in 4.8 T

Signal **rise / fall** times

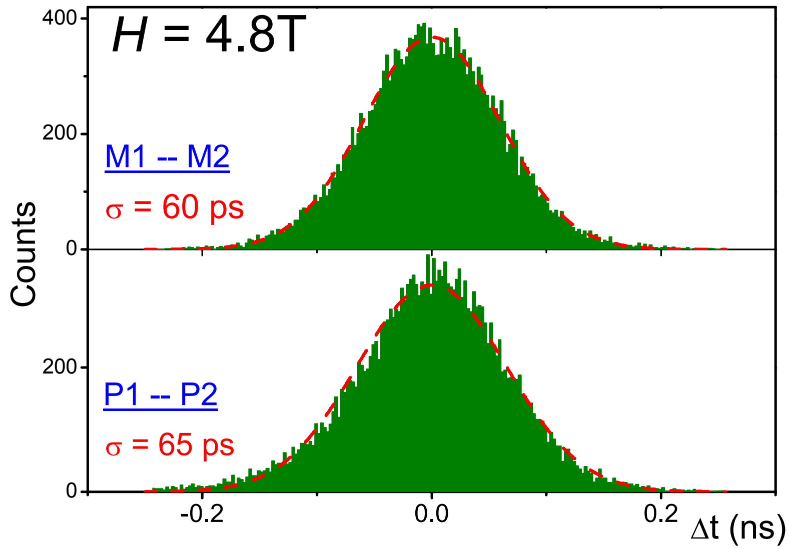
M1 -- **1.24 / 7.2 ns**

P1 -- **1.48 / 8.0 ns**

Muon and positron counters for 10T spectrometer (prototypes)

***H* = 4.8 T**

Time resolution M1-M2 (P1-P2)



Per counter (M / P)	**46 ps**
Spectrometer (M + P)	**65 ps**

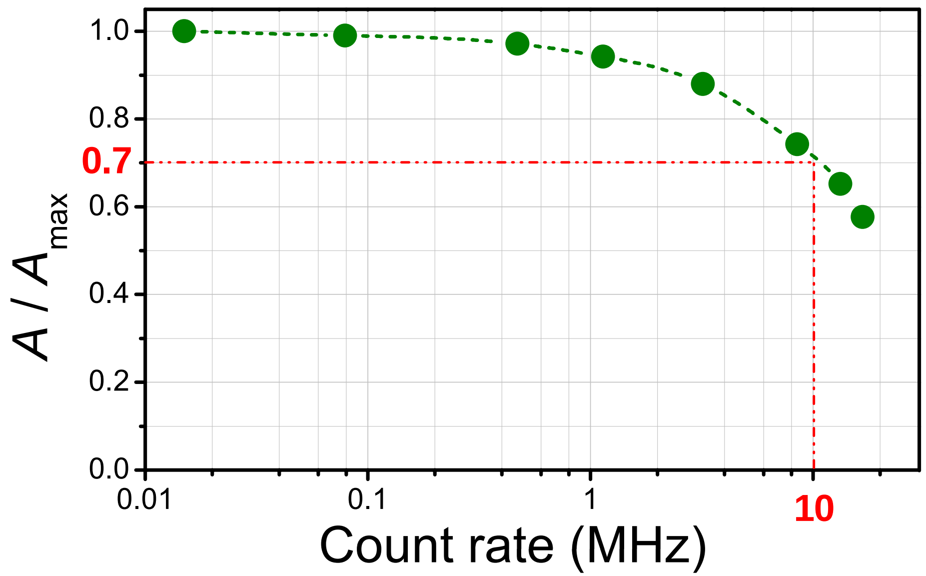
P1: $\sigma E^{0.5} \approx 25$ ps·MeV$^{0.5}$

detected energy ***E* ≈ 0.3 MeV**

E = (actual deposited energy) *

(ratio of photodetector to scint. area)

P1: Amplitude vs. Rate



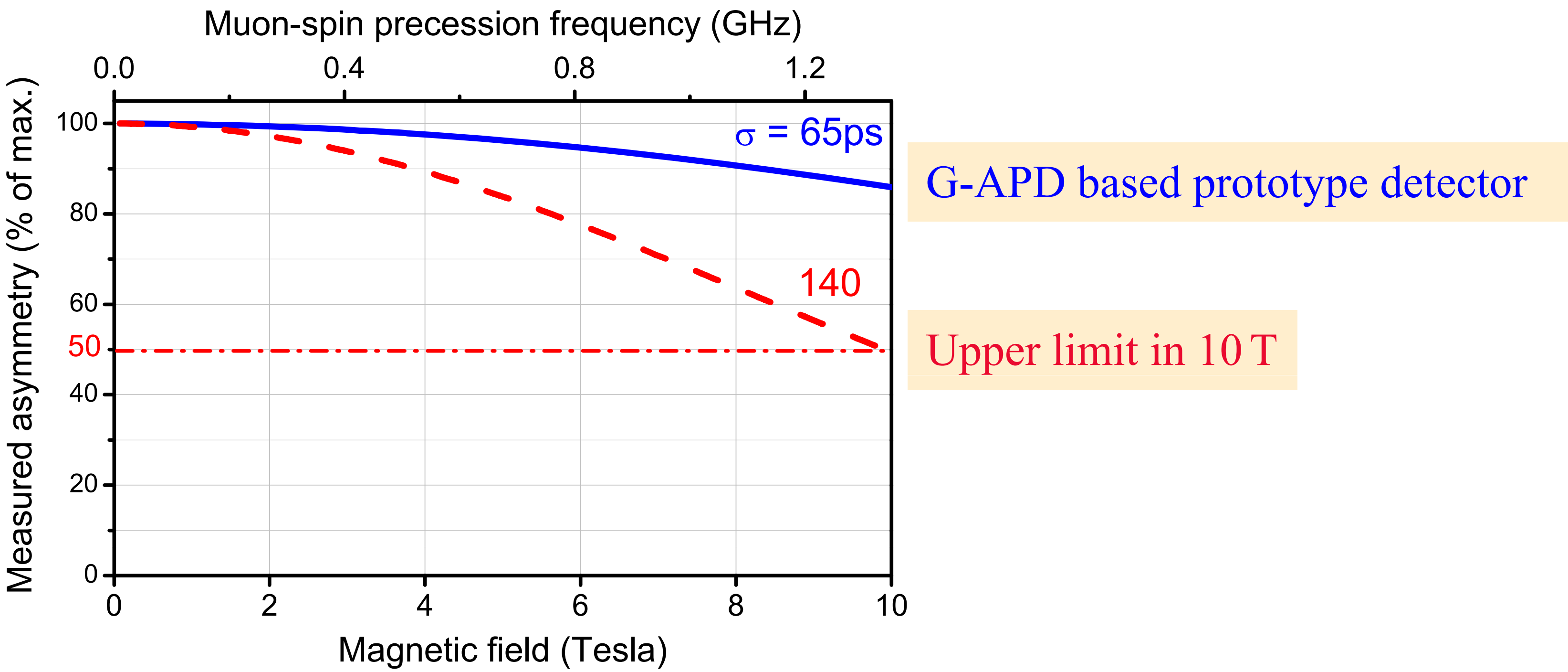
High rate capabilities:

70% signal amplitude at 10 MHz count rate.

Further increase is possible at the expense of time resolution.

Summary

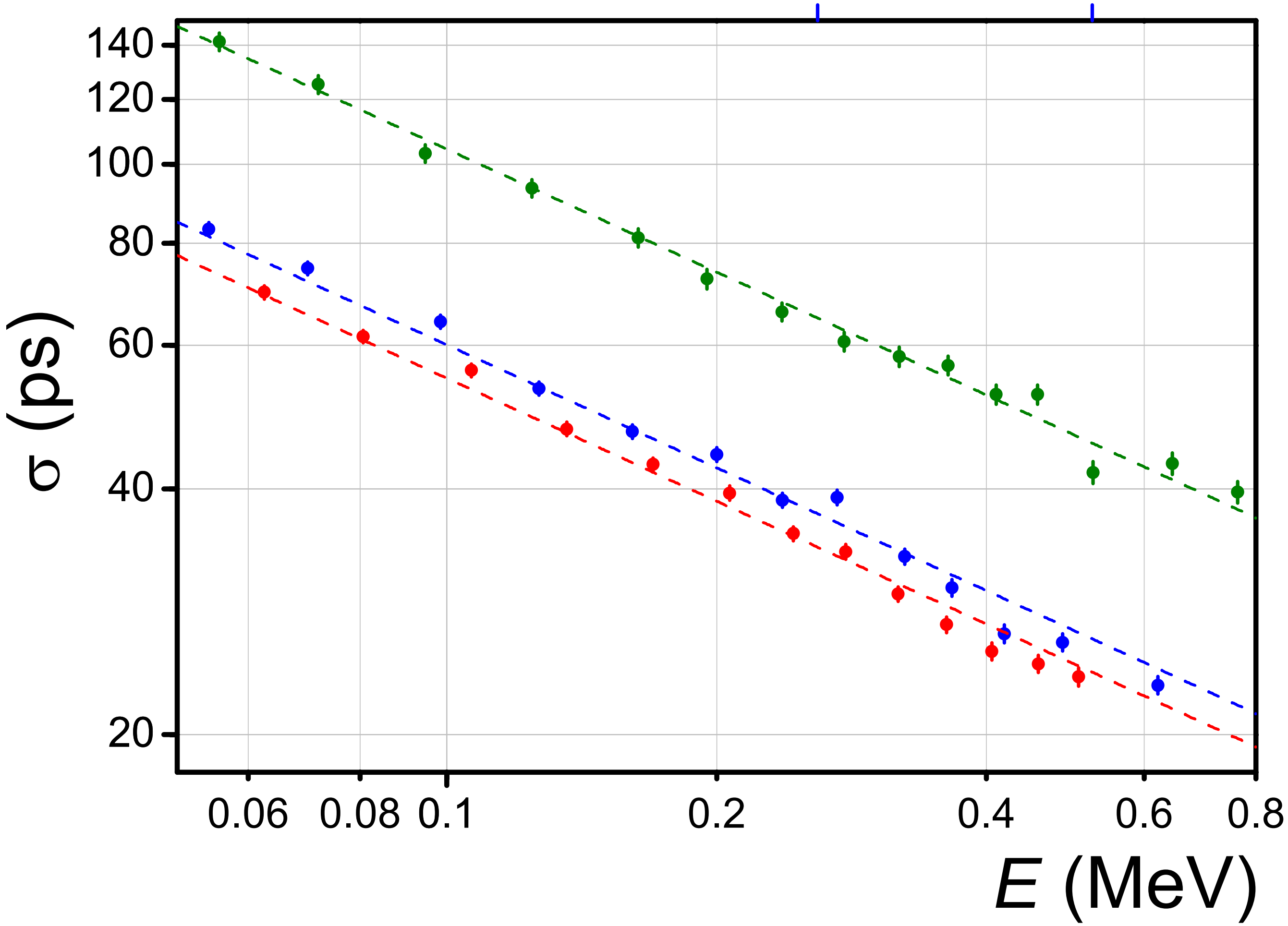
- combined with plastic scintillators G-APDs provide time resolution comparable to that achieved with PMTs: $\sigma E^{0.5} = 18\,\text{ps}\cdot\text{MeV}^{0.5}$
- in contrast to PMTs, the performance of fast-timing G-APD based detectors extends to high magnetic fields
- the use G-APD based detectors in μSR will allow further extending the range of magnetic fields accessible for muon spin rotation studies



Additional slides …

σ(*E*) : some more results …

MPPC 33-100	$N_{cell} = 600$ (per 6 mm^2)	
N_{phe}	~ 600	~ 1200
Saturation factor	1	2



33 ps / $E^{0.5}$

MAPD-3N8

90.80 V, 90 nA

Ampl.

56 pF, 0.11k

19 ps / $E^{0.5}$

MPPC 33-100

70.2 V, 1.6 μA

Ampl.

28 pF, 1k

17 ps / $E^{0.5}$

MPPC 33-50

70.0 V, 0.7 μA

Ampl.

28 pF, 1k