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G-APD + plastic scintillator: fast timing in high magnetic fields

Outline

Scintillation counter consisting of
a plastic scintillator readout by
a Geiger-mode Avalanche Photodiode:

1. what time resolution can be achieved?

   (we try to give an experimental answer)

2. does it work in high magnetic fields?

   (example of application – a 9.5 Tesla μSR spectrometer)

Time resolution vs. Energy: PMTs best result

$$\sigma E^{0.5} = 19 \text{ ps} \cdot \text{MeV}^{0.5}$$

scintillator: **NE111**

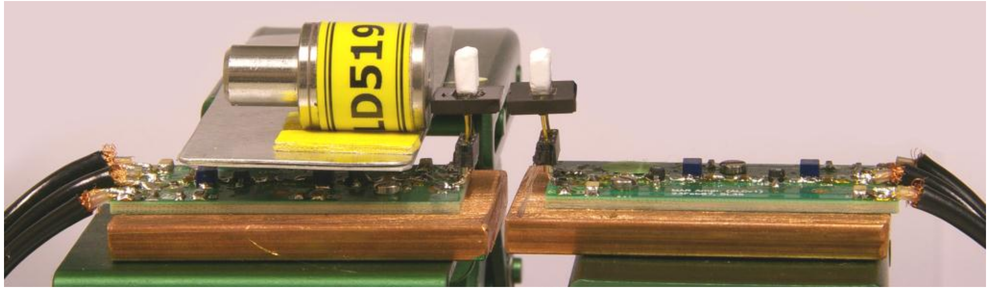
PMT: **XP2020UR-M**

signal processing: **CFD**

References:

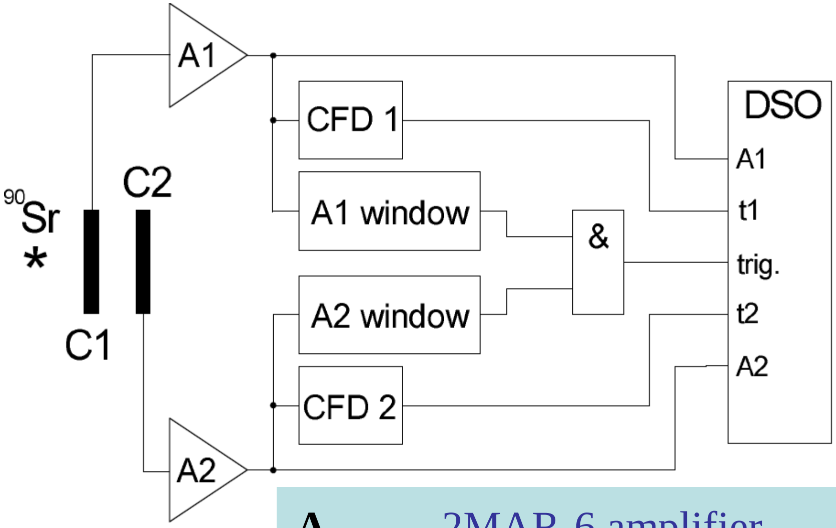
M.Moszynski, B.Bengston, NIMA 158 (1979) 1.
M.Moszynski, NIMA 337 (1993) 154.

σ(E) – measurement with G-APDs



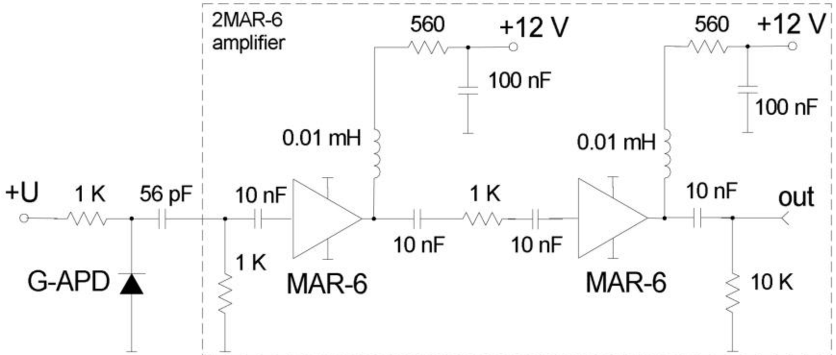
Scint.: BC422 (3x3x2 mm[3]), reflector – Teflon tape, coupling with optical grease via 3x2 mm[2] face

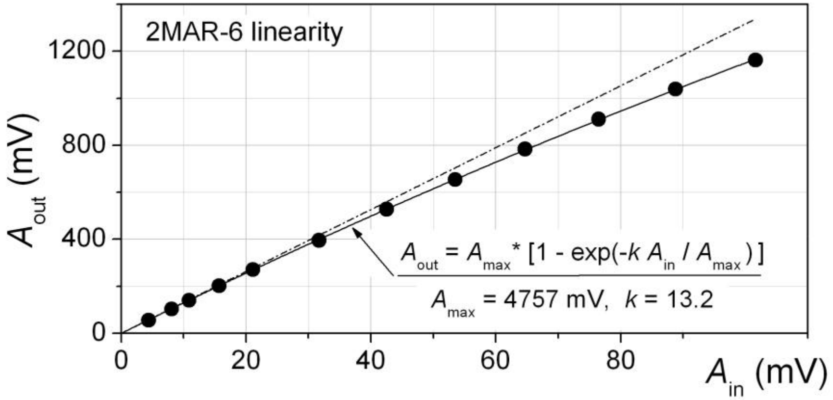
G-APDs: MPPC S10362-33-050 (3x3 mm[2])
U ~ 70 V, I_0 = 1.0 μA



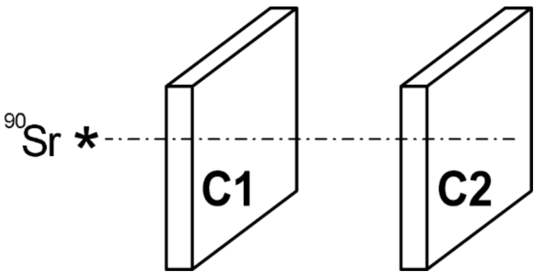
A – 2MAR-6 amplifier
CFD – PSI CFD-950
DS0 – LeCroy WavePro 960 (2 GHz, 16 GS/s)

2MAR-6 amplifier: gain ~ 13, bw ~ 600 MHz

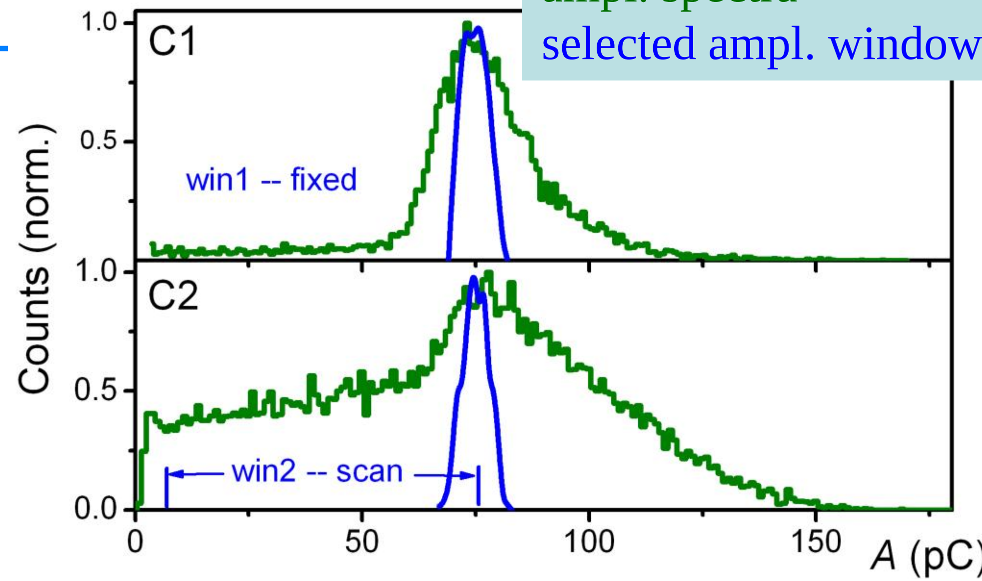




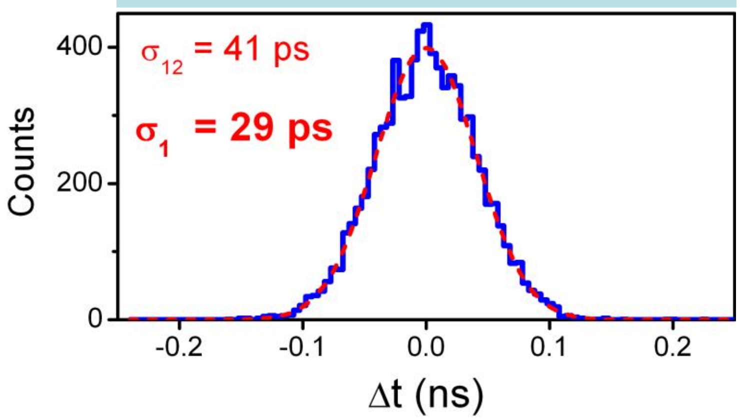
raw data – σ(*A*)



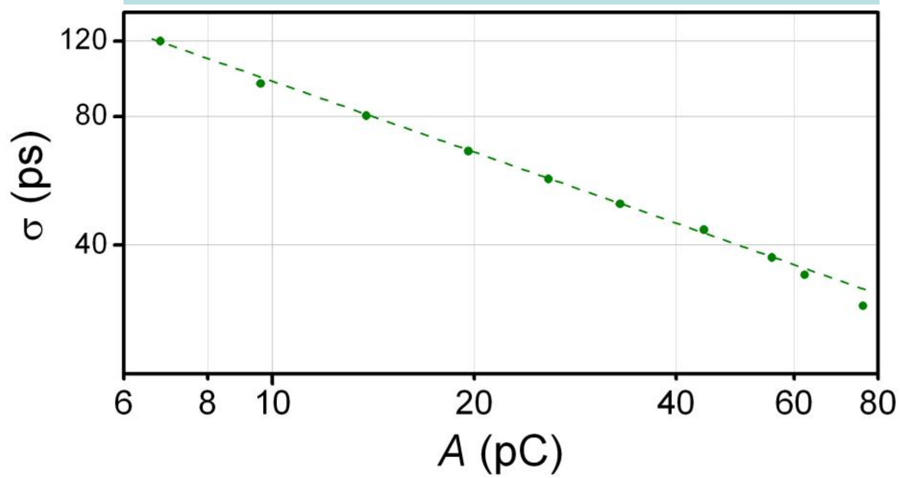
ampl. spectra
selected ampl. windows



Time difference C1 – C2
(signals in selected windows)

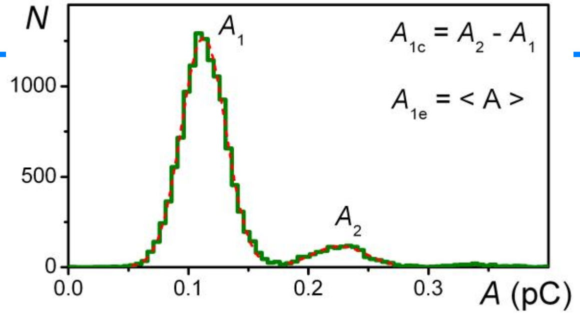


C2: Time resolution vs. Amplitude
(win1 – fixed, win2 – scan)



$\sigma(A) \rightarrow \boldsymbol{\sigma(E)}$

1e-spectrum C2



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

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

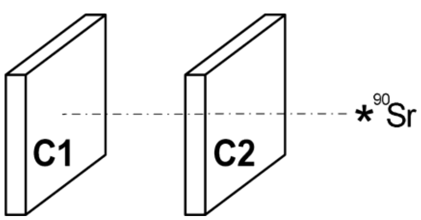
3. Calculate the number of photoelectrons: $N_{phe} = -(m/\alpha)\ln(1 - N_{cell}/m)$

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

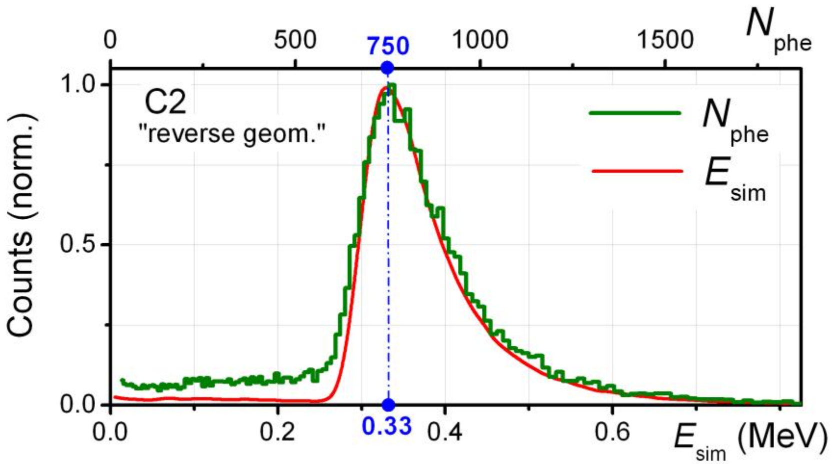
4. Establish the correspondence between N_{phe} and E: $N_{phe} = 2270\,E$

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

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

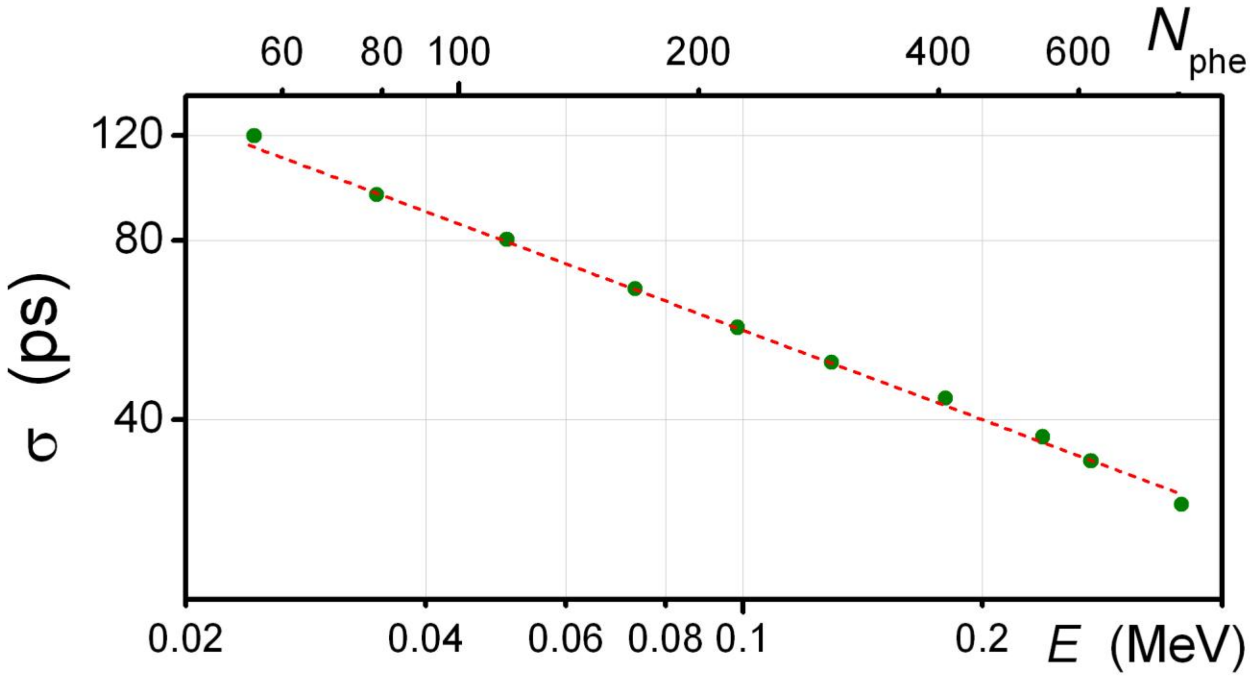


Position of the source – reversed



σ(*E*): results

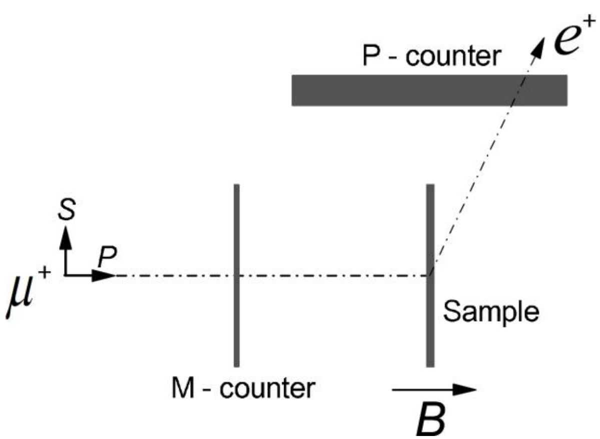
MPPC S10362-33-50 + BC-422



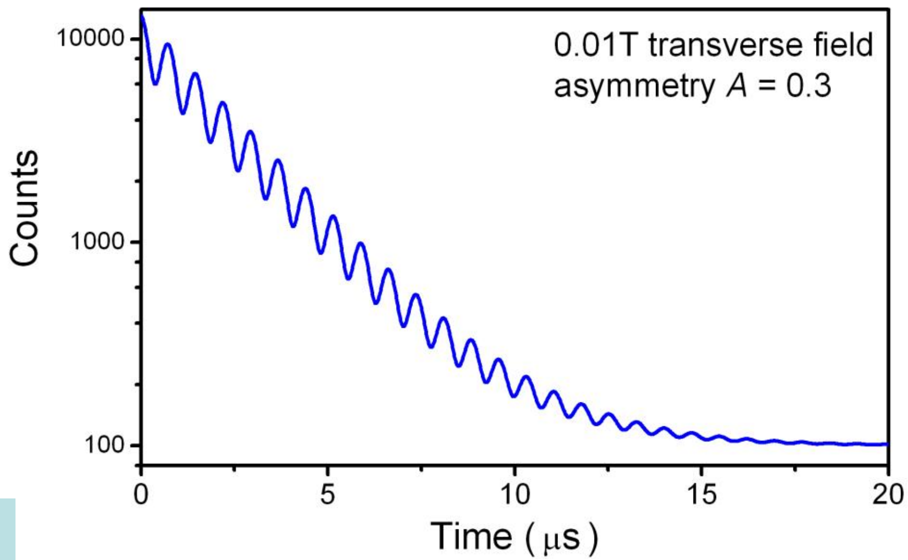
$$\sigma E^{0.5} = 18\ \mathrm{ps} \cdot \mathrm{MeV}^{0.5}$$

Application: Muon Spin Spectroscopy (μSR)

Time-differential μSR: measuring time correlations between muons entering the sample and the positrons from their decay



$$N = N_0 \exp(-t/\tau_\mu)\,[1 + A\cos(\omega t)] + B$$



Experiment in a transverse field – **TF**-μSR

Muon spin ***S*** is rotated by θ = 90 degrees relative to its momentum ***P***. Magnetic field ***B*** is directed along ***P*** and **transverse** to ***S***.

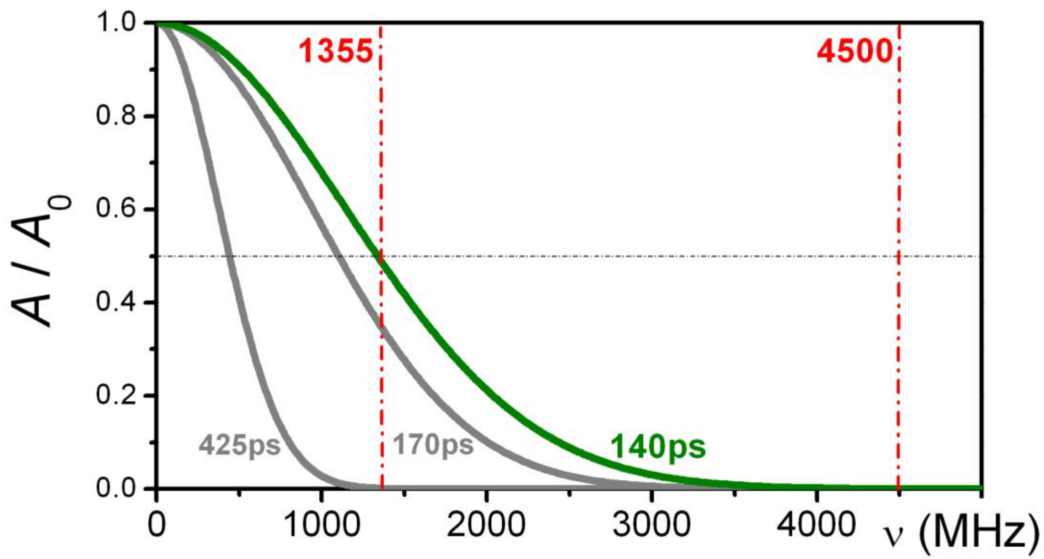
μSR spectrum in a transverse field

muon decay exponent is **modulated** by the muon-spin precession signal (asymmetry ***A*** is the amplitude of the modulation)

A challenge of muon-spin rotation experiments in high fields

$$A / A_0 = \exp[-\,2(\pi\,\boldsymbol{\sigma}\,\nu)^2\,]$$

The apparent asymmetry decreases with increasing the frequency **ν** due to the finite time resolution **σ**.



Characteristic frequencies:

1355 MHz – precession of a free-muon spin in 10 Tesla

4500 MHz – hyperfine splitting in Muonium (**Mu ≡ μ^+ + e^-**)

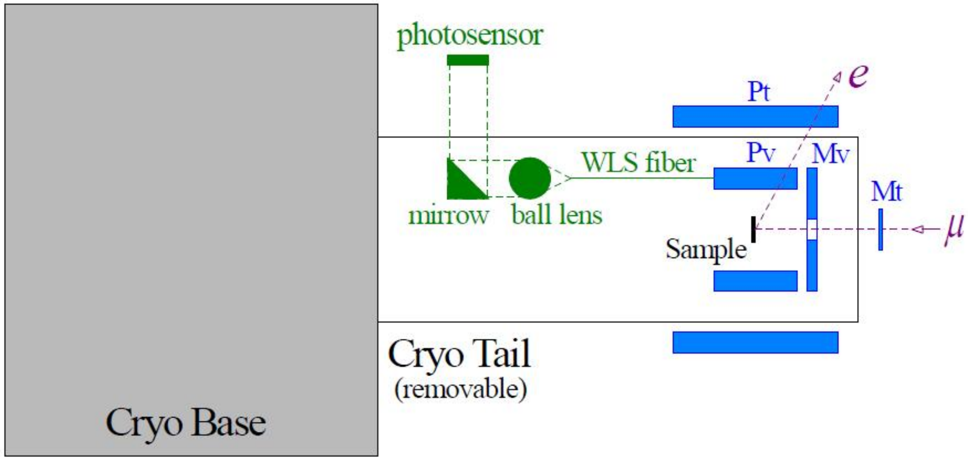
Characteristic σ – values:

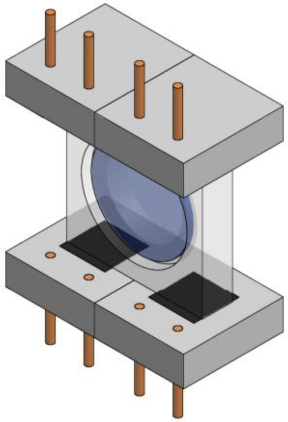
425 ps – time resolution of a “standard” μSR spectrometer (fields below 1 T)

170 ps – 7 T *HiTime* instrument at TRIUMF (PMT– based detector system)

140 ps – accepted upper limit for the **9.5 T *HighField*** instrument at PSI (G-APD – based detector system)

HighField instrument: detector layout





Mt (1x)
scint. EJ-232
Ø6 x 0.3 mm
frame: UVT Plastic
9 x 9 x 2 mm

Double-side readout by two pairs of G-APDs (MPPC S10362-33-050).

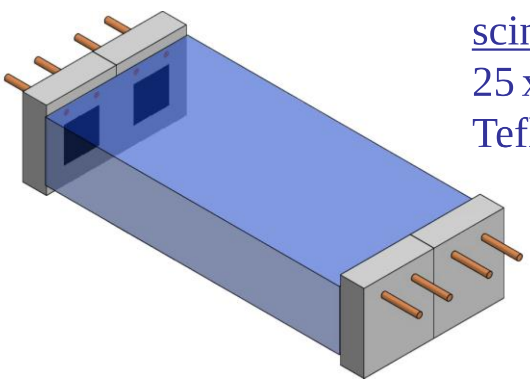
In each pair G-APDs connected in series.

Particle detection time – average value from the two G-APD pairs.

Mt, Pt – muon and positron **timing** counters (scintillators and photosensors at room temp.)

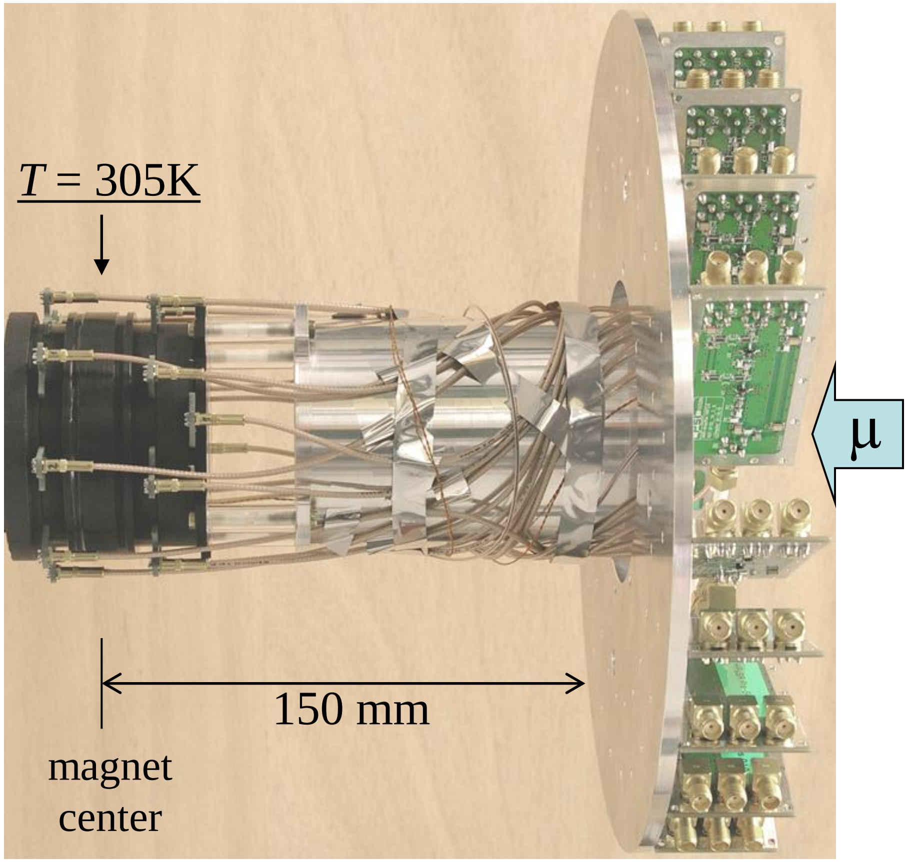
Mv, Pv – muon and positron **veto** counters (scintillators at $T \geq 1$K, photosensors at RT)

- 29 MeV/c muon beam
- $0 \leq B \leq 9.5$T along the beam
- dilution refrigerator or flow cryostat



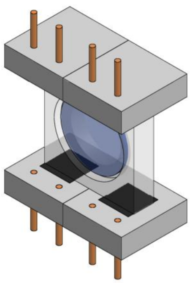
Pt (8x)
scint. EJ-232
25 x 12 x 5 mm
Teflon wrapping

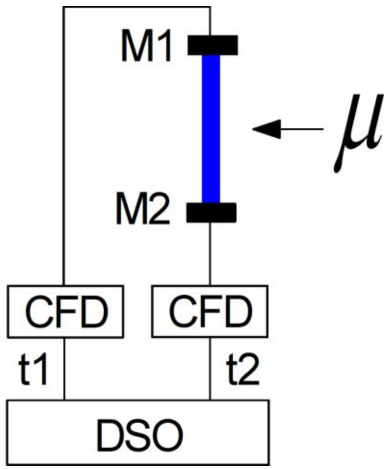
Timing detector (prototype) in 9.5 Tesla magnet

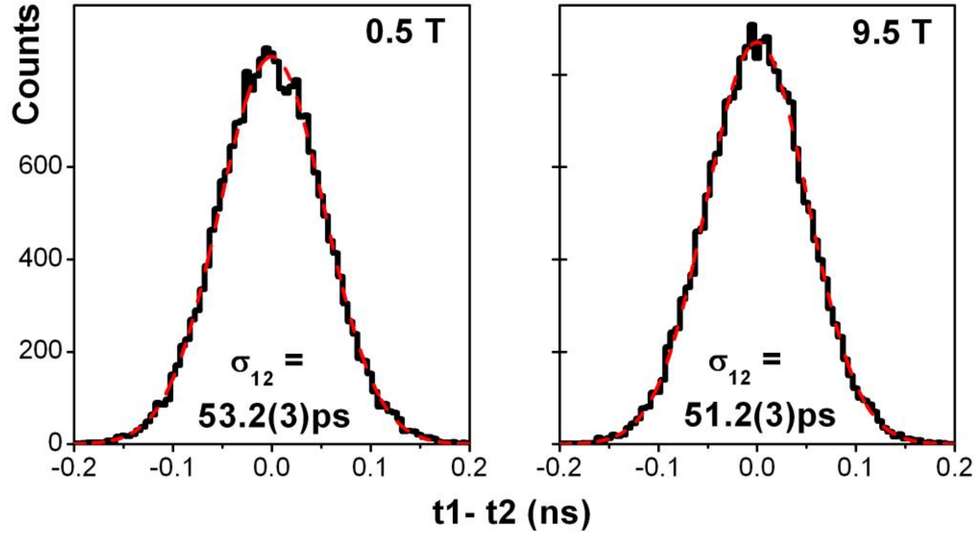


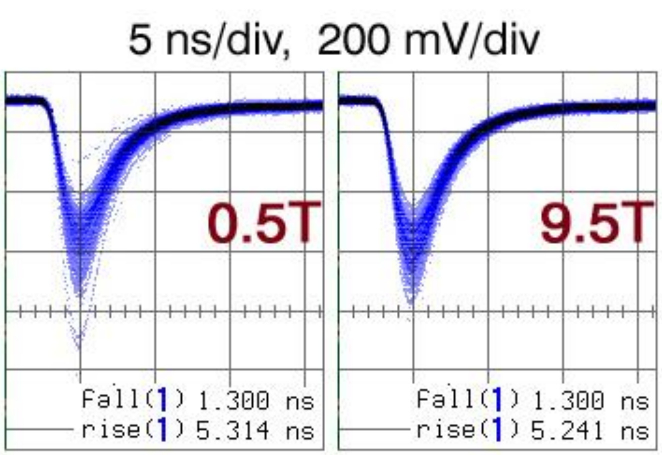
- <u>all components non-magnetic</u>
  homogeneity of the field at the sample should be preserved at the level of 10 ppm
- <u>temperature stabilization</u> – heating above RT

Muon counter









Time resolution

$\sigma_M \approx \sigma_{12} / 2 \approx$ **26 ps**

Mean deposited energy (GEANT4)

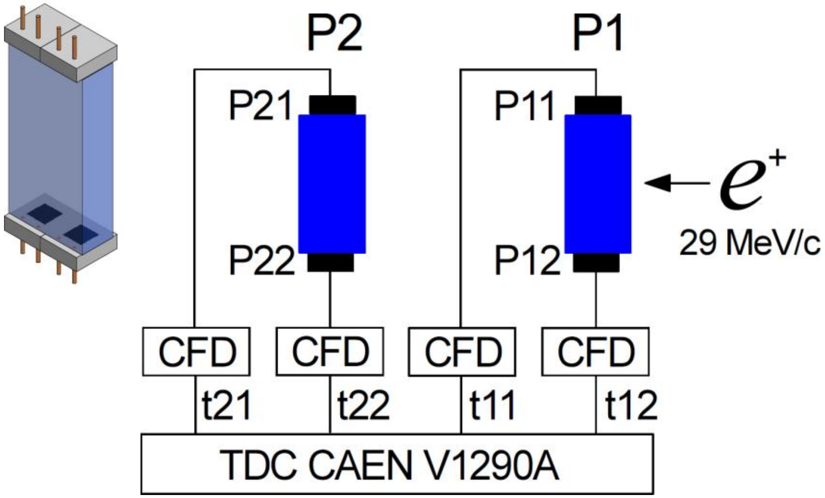
$E \approx 0.6$ MeV

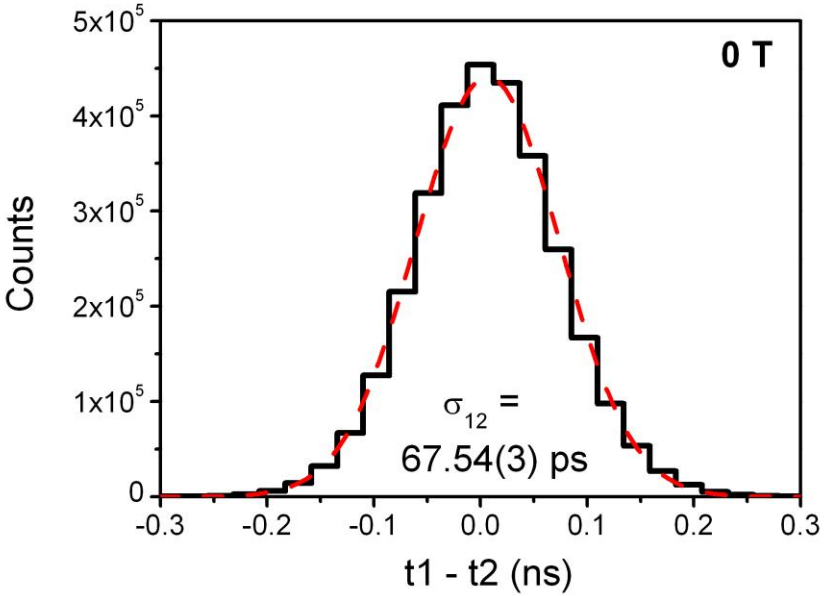
k = area APD / area Scint. = 0.67

$\boldsymbol{\sigma_M \cdot (k E)^{0.5} \approx 17\ \mathrm{ps \cdot MeV^{0.5}}}$

No change in performance up to 9.5 Tesla !!!

Positron counter





t1 = (t11 + t12) / 2

t2 = (t21 + t22) / 2

<u>TDC</u>:

bin width = 24.414 ps

intrinsic time res. σ_{TDC} = 27ps

<u>Time resolution</u>

$\sigma_P \approx [\ (\sigma_{12}^2 - \sigma_{TDC}^2) / 2\ ]^{0.5} \approx$ **44 ps**

<u>Mean deposited energy (GEANT4)</u>

$E \approx 0.9$ MeV

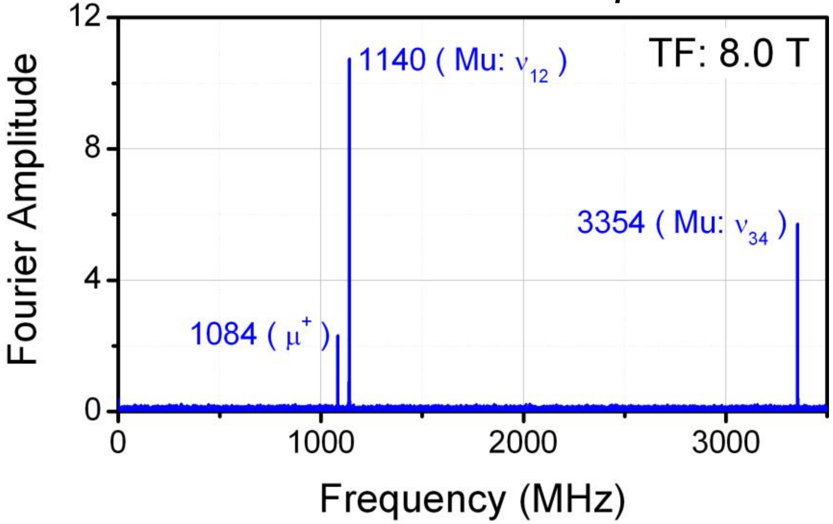
k = area APD / area Scint. = 0.3

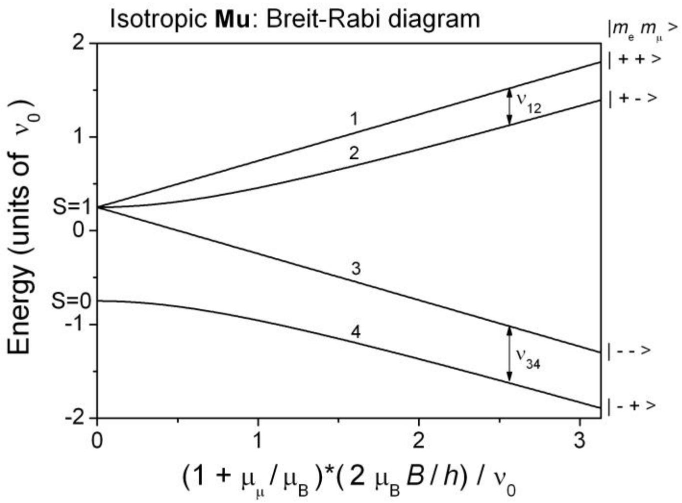
$\boldsymbol{\sigma_P \cdot (\,k\,E\,)^{0.5} \approx}$ **23 ps·MeV$^{0.5}$**

Spectrometer time resolution: Muonium in high transverse fields

Synthetic Quartz crystal in TF 8.0T

Fourier transform of the μSR data





1084 MHz

free-muon spin precession (10% fraction)

1140, 3354 MHz

1-2 and 3-4 transitions in Mu

- 90% fraction
- polarization $P_{12} = P_{34} = 0.5$
- $\nu_0 = 4495$ MHz – hyperfine splitting (isotropic)

Time resolution from μSR-data on Quartz

$$\sigma = 1/\pi \cdot [\, 0.5 \cdot \ln(A_{12} / A_{34}) / (\nu_{34}^2 - \nu_{12}^2)\,]^{0.5}$$

A_{12} , A_{34} – signal amplitudes (asymmetries) from the time-domain fit

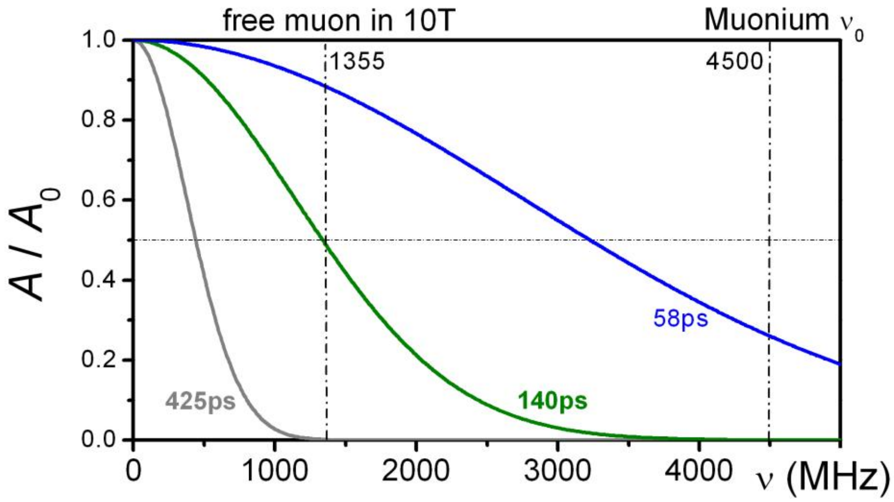
σ = 57.2 (6) ps

Expected from direct measurements

$$\boldsymbol{\sigma} = (\, \sigma_M^2 + \sigma_P^2 + \sigma_{TDC}^2\,)^{0.5} =$$

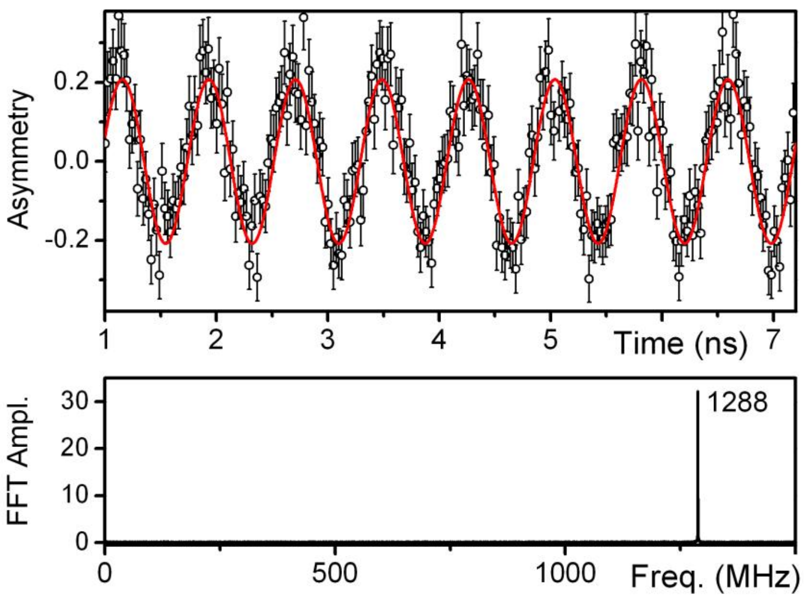
$$= (\, 26^2 + 44^2 + 27^2\,)^{0.5} = \mathbf{58\ ps}$$

High Field μSR-instrument at PSI: performance graphs



Apparent amplitude of the precession signal vs. the signal frequency

With the time resolution of **σ = 58 ps** the reduction of the signal amplitude in **10 Tesla** is only **~ 10%**.



Precession of the spin of a "free" muon in 9.5 T

Measurement on Ag-sample. First 7ns of the 10μs long histogram are shown.

Summary

<u>G-APD + plastic scintillator</u>:

- time resolution: $\boldsymbol{\sigma E^{0.5} \sim 18\,\mathrm{ps} \cdot \mathrm{MeV}^{0.5}}$
- no change of performance up to **9.5 Tesla**

<u>Potential for improvement</u>:

- increase *PDE* for UV light
  (in this work *PDE* ~ 25 % at 390 nm)
- decrease one-photon time resolution
  (in this work $\sigma_{1ph} \sim 100\,\mathrm{ps}$)