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Scintillation Detectors for Operation in High Magnetic Fields: Recent Developments Based on Arrays of Avalanche Microchannel Photodiodes

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Acknowledgements

NMI3 - Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy, JRA8: MUON-S

Key action: Strengthening the European Research Area, Research Infrastructures, Contract no.: RII3-CT-2003-505925

grant
04-78-6839

Outline

- Motivation: The High Magnetic Field μSR project at the Swiss Muon Source at PSI
  - Muon Spin Rotation: principle
  - μSR detector systems: muon counter, positron counter
  - 'standard' systems and their limitations
  - A 10 T μSR spectrometer: challenges
- an AMPD based muon beam profile monitor for high magnetic fields
- AMPD arrays
  - "large" area detectors ($\approx$ 30 cm^2, tile-fiber detector)
  - fast-timing detectors ($\sigma \approx$ 110 ps)

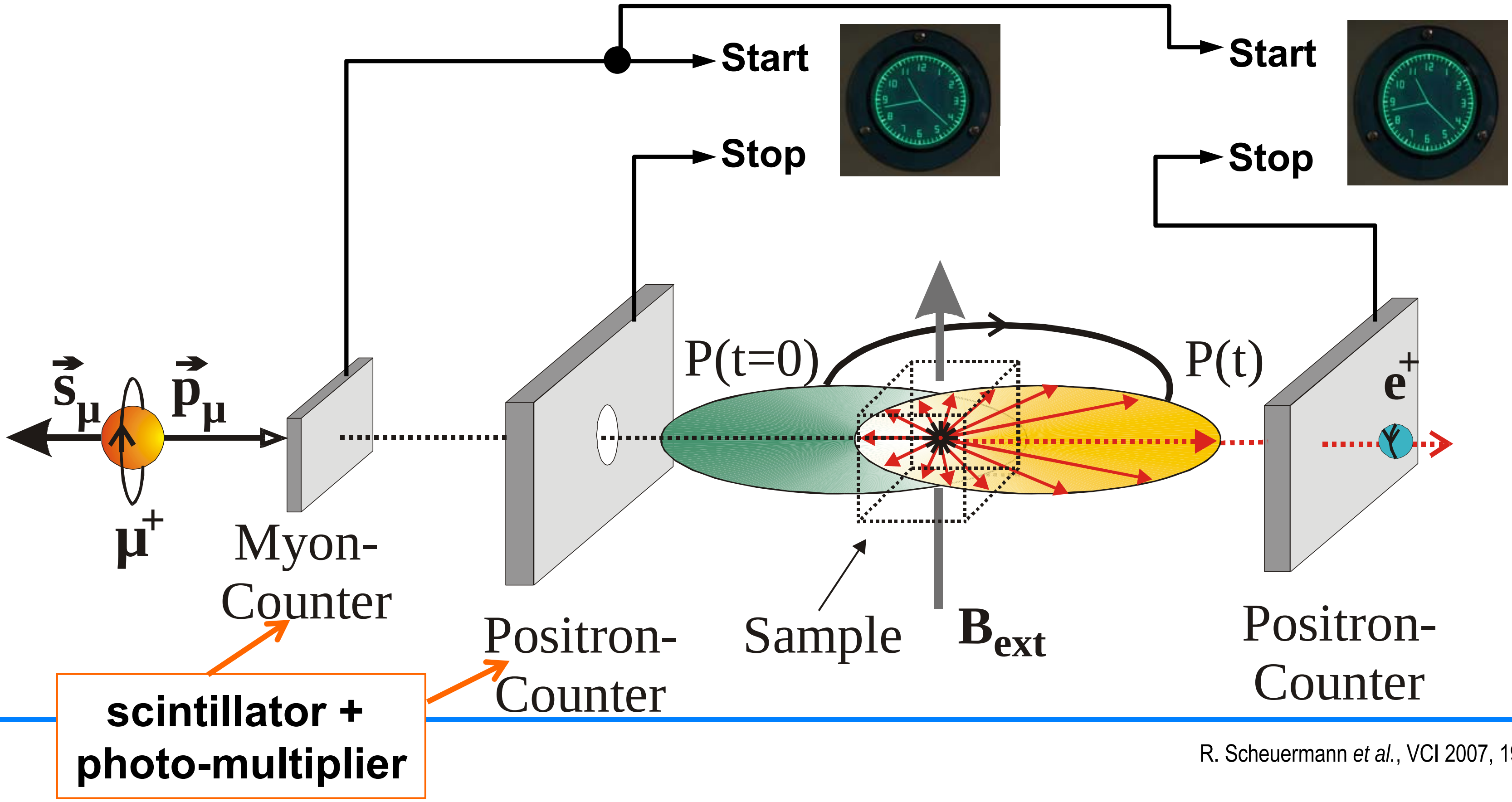
Principle of a Muon-Spin-Rotation (µSR) experiment

µSR = condensed matter research (magnetic resonance) with a fully polarized spin label (the positive muon) probing internal magnetic fields and their distributions

detect the positron from muon decay: $\mu^+ \rightarrow e^+ \, \overline{\nu_\mu} \, \nu_e$

muon spin precession: $\omega = \gamma_\mu \cdot B$, relaxation rate $\sigma^2 = \gamma_\mu^2 \cdot \langle \Delta B^2 \rangle$

γ_μ = gyromagnetic ratio: $2\pi \cdot 135.5$ MHz/T (proton: 42.8MHz/T, electron: 28.1GHz/T)



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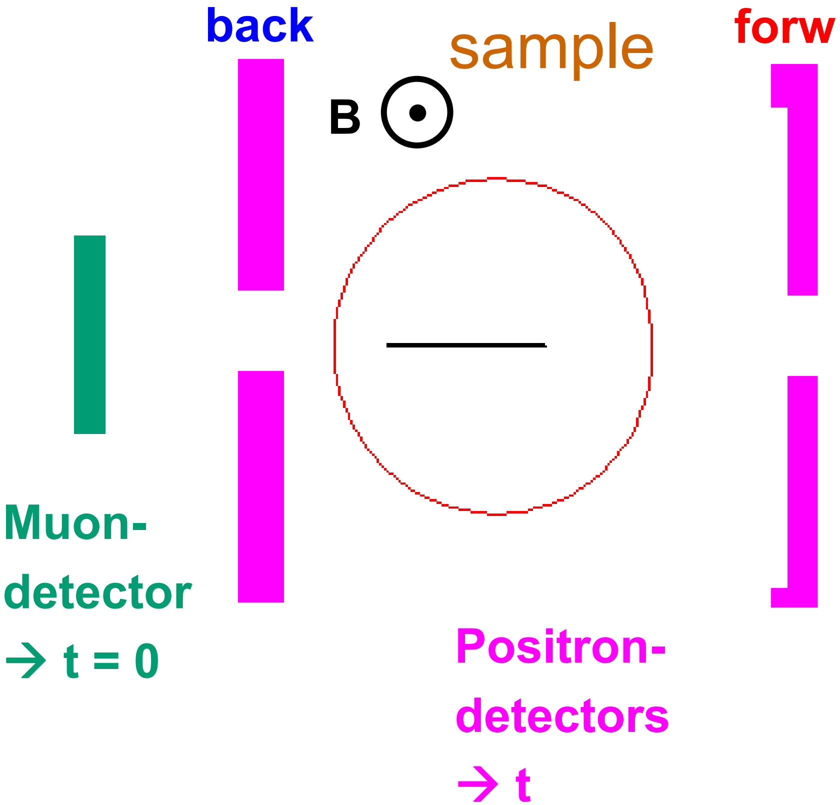
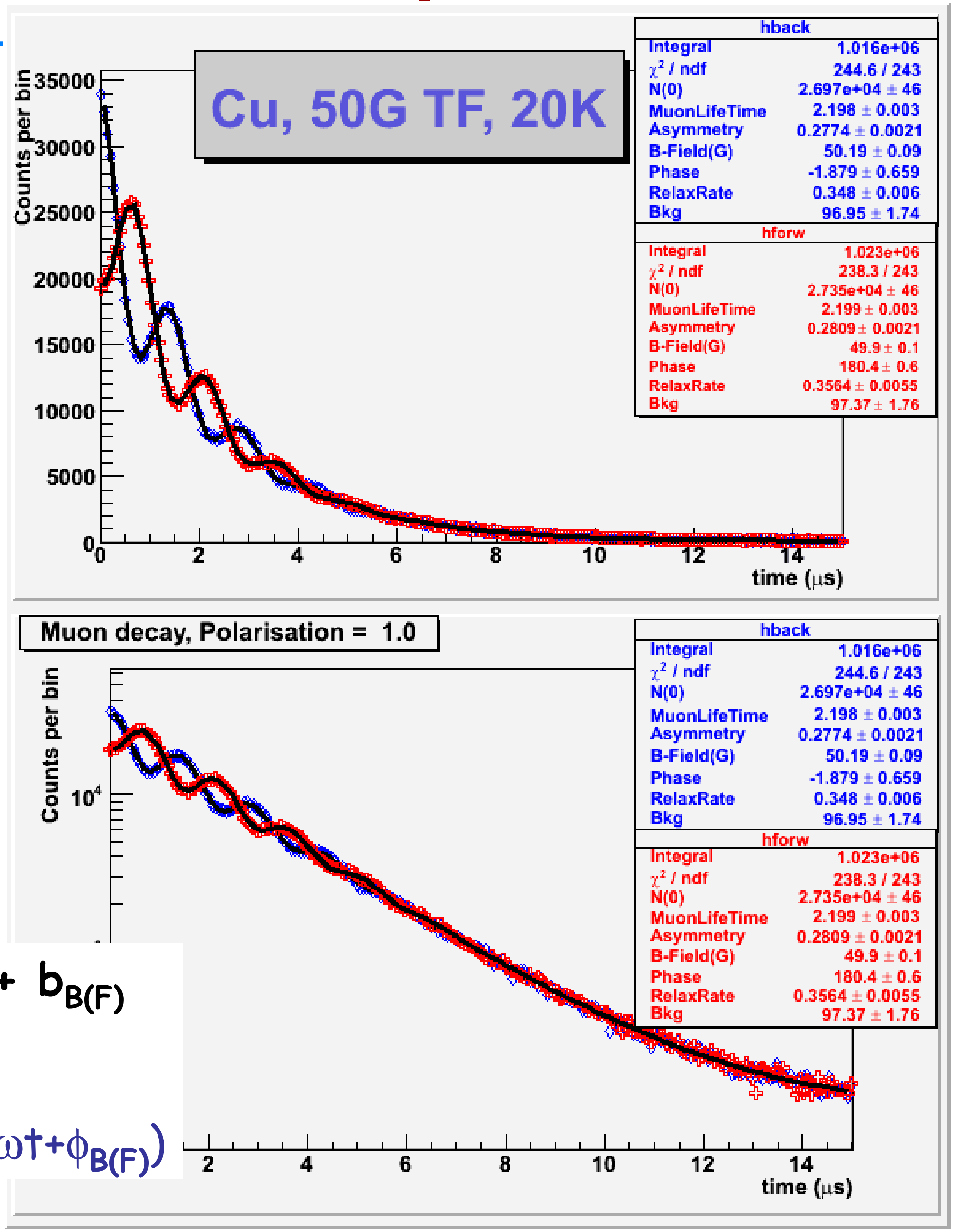
Transverse Field μSR





ensemble average

$$N_{B(F)}(t)=N_{B(F)}(0)\cdot\exp(-t/\tau_{\mu})\cdot(1+A(t)) + b_{B(F)}$$

b: time independent background

$$A(t) = A_0\cdot P(t) = A_0\cdot\exp(-(\sigma_{TF}t)^2/2)\cdot\cos(\omega t+\phi_{B(F)})$$

Present Status of Detector Systems for µSR

MIP energy loss <1 MeV

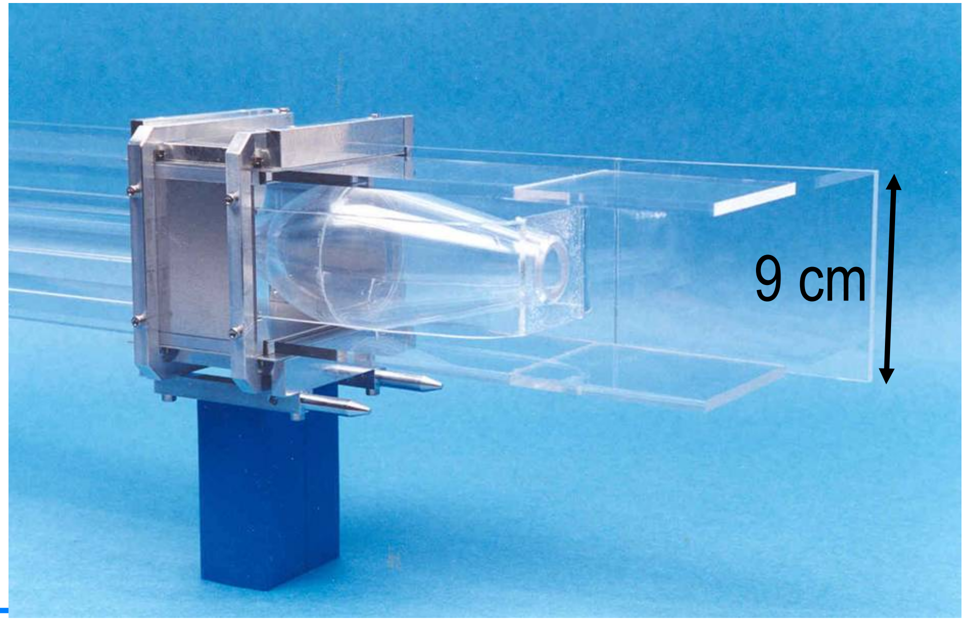
time-correlation µ-e measured,

Present detector system:

fast plastic scintillators (thickness: 200 µm (μ^+) – **5 mm**(e^+))
+ light guides (~ 100 cm)
+ fast photomultiplier tubes (PMTs)
used for µ ‚start' and e ‚stop' counters, ‚veto' counters

⇒ time resolution **δt ≈ 1 ns**

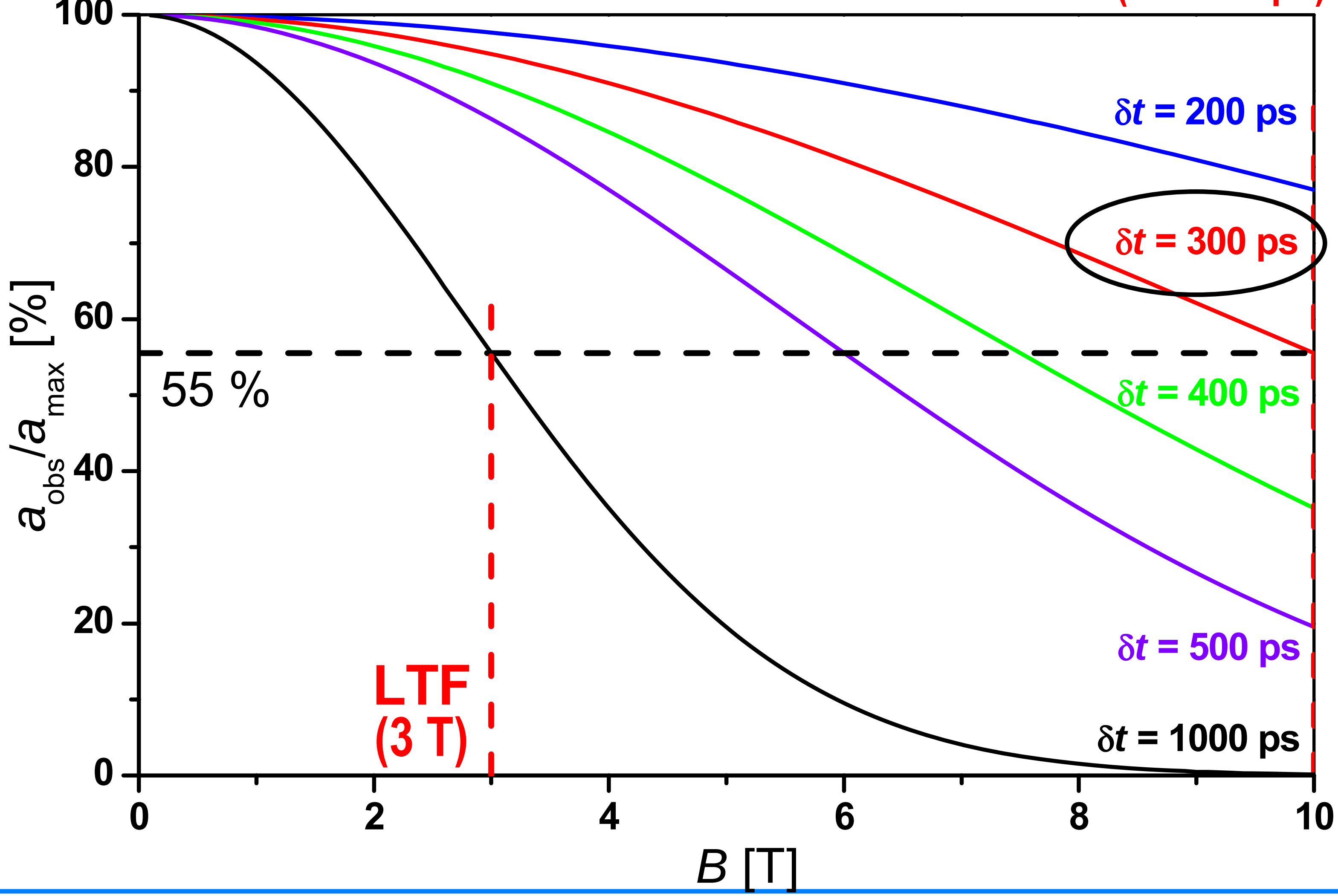
- PMT+scint.: $\delta t \geq$ 150 - 200 ps
- light guides: $\delta t \geq$ 300 ps



Signal height – time resolution (FWHM)

Larmor frequency: 1.35 GHz in 10 T

goal: FWHM δ*t* < 300 ps
(σ < 125 ps)



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SμS Swiss Muon Source

μSR Facilities

ALC
Avoided Level Crossing Resonance Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 4.2 - 600 K
Magnetic Fields: 0 - 5 T

Contact: *A. Stoikov*
alexei.stoikov@psi.ch

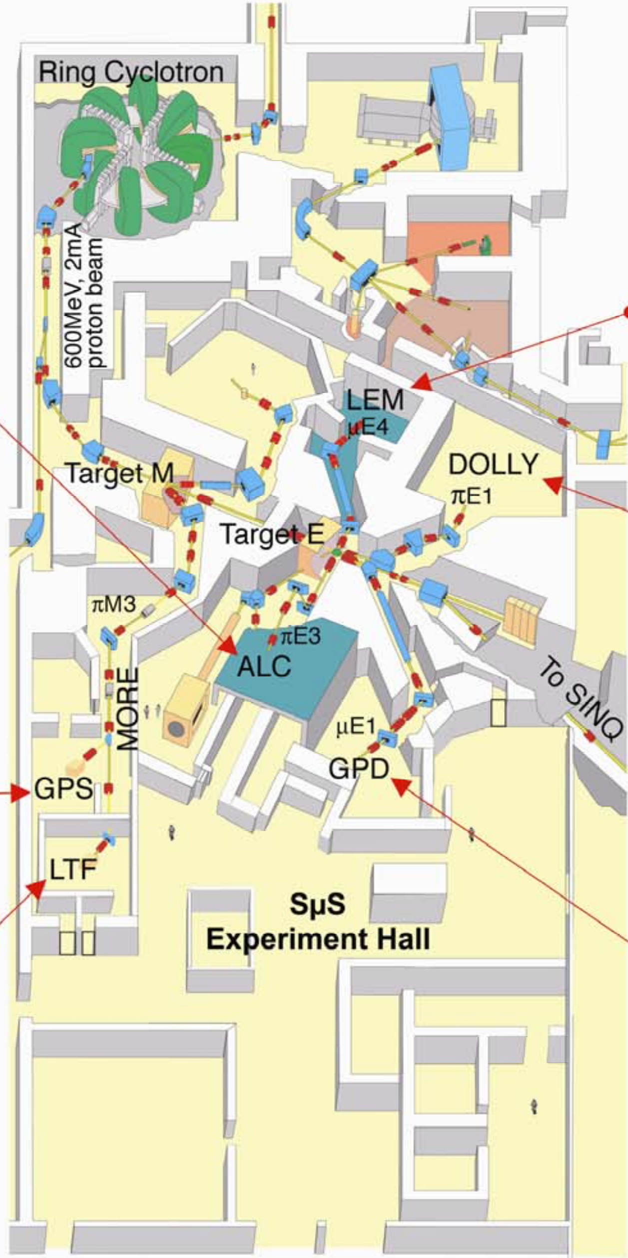
GPS
General Purpose Surface Muon Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 1.8 - 900 K
Magnetic Fields: 0 - 0.6 T
Muons on Request (MORE)

Contact: *A. Amato*
alex.amato@psi.ch

Shared Beam Surface Muon Facility

LTF
Low Temperature Facility
Muon energy: 4.2 MeV (μ^+)
Temperatures: 10 mK - 4.2 K
Magnetic fields: 0 - 3 T
Muons on Request (MORE)

Contact: *C. Baines*
chris.baines@psi.ch

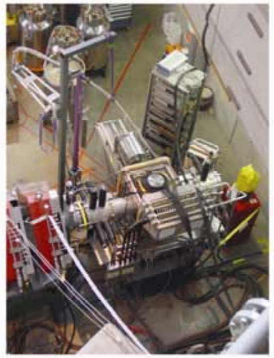


LEM
Low Energy Muon Beam and Instrument
Tunable muon energy: 0.5 - 30 keV (μ^+)
Temperatures: 2.5 - 700 K
Magnetic fields: 0 - 0.1 T perpendicular,
0 - 0.03 T parallel to sample surface

Contact: *E. Morenzoni*
elvezio.morenzoni@psi.ch

DOLLY
General Purpose Surface Muon Instrument
Muon energy: 4.2 MeV (μ^+)
Temperatures: 1.8 - 900 K
Magnetic fields: 0 - 0.5 T

Contact: *R. Scheuermann*
robert.scheuermann@psi.ch



GPD
General Purpose Decay Channel Instrument
Muon energy: 5 - 60 MeV
(μ^+ or μ^-)
Temperatures: 2 - 500 K
Magnetic Fields: 0 - 0.5 T

Contact: *U.Zimmermann*
ulrich.zimmermann@psi.ch

The 10 T High Field Project at the Swiss Muon Source at PSI

http://lmu.web.psi.ch/facilities/PSI-HiFi.html

main challenges: custom designed magnet (min. length) and
fast & compact detector system

Limitations of the present detector systems

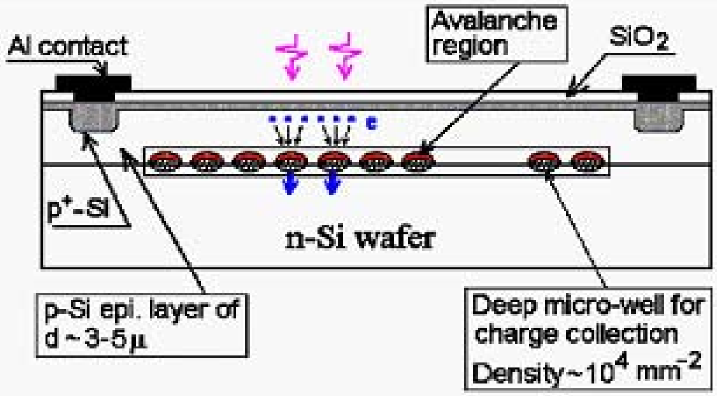
Disadvantages:

- PMTs are bulky, do not allow compact geometries (time resolution!)
- PMTs are sensitive to magnetic fields (few G, kG for mesh dynode PMTs)
  $\Rightarrow$ 'long' light guides needed, deteriorate time resolution
- Spiraling radius of positrons in magnetic fields: 1 cm @ 10 T (30 MeV) requires scintillator close to sample (this presently also restricts the use of higher fields wth reasonable sample size / good event rate...) and the photon detector being placed in the 'high field region'

Number of photons from scintillator: a few thousand only

An AMPD with deep micro-wells

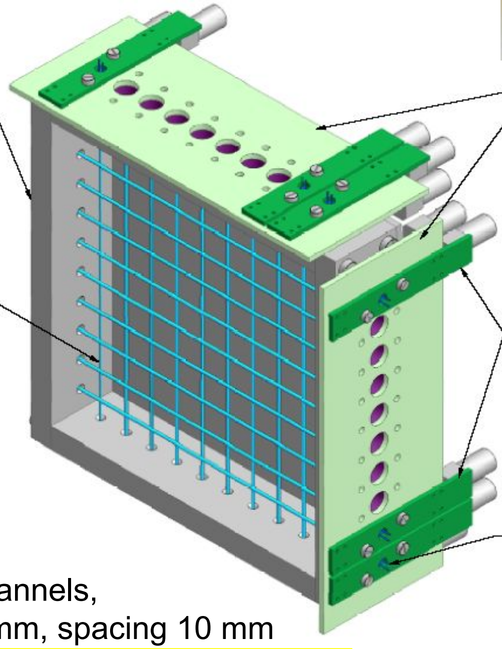
Z. Sadygov *et al.*, NIM A 567 (2006) 70-73

Type	**MW-3, R8** 
	
Photosensitive area	0.75×0.75, 1×1 mm^2 , 3×3 mm^2
Density of microchannels	$\approx 10^4$ mm^{-2}
Photon detection efficiency	≈ 15% at 440 nm
Maximum gain (M_{max})	$\approx 3\times10^4$
Dark current at M_{max}	< 200 nA
Operating voltage	**100-140 V**

Operation in Geiger mode

Muon Beam Profile Monitor for Instrument setup (in 5 T Field)

Dubna R8 AMPD (0.75x0.75 mm^2);
Surface muon beam in area πE3 (ALC solenoid)



Aluminum Frame (100 x 100 mm)

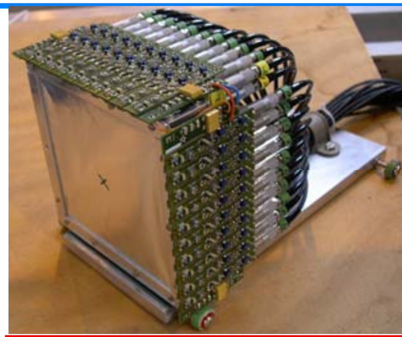
Scint. fibers (POLIFI 0244-10)

Mother Board

Preamplifier
bandwidth ~250 MHz
gain ~250

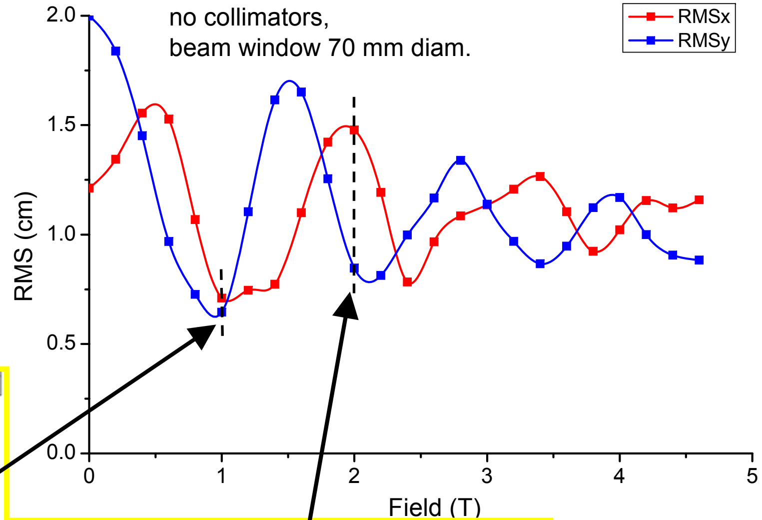
AMPD Dubna R8
active area:
0.75 x 0.75 mm

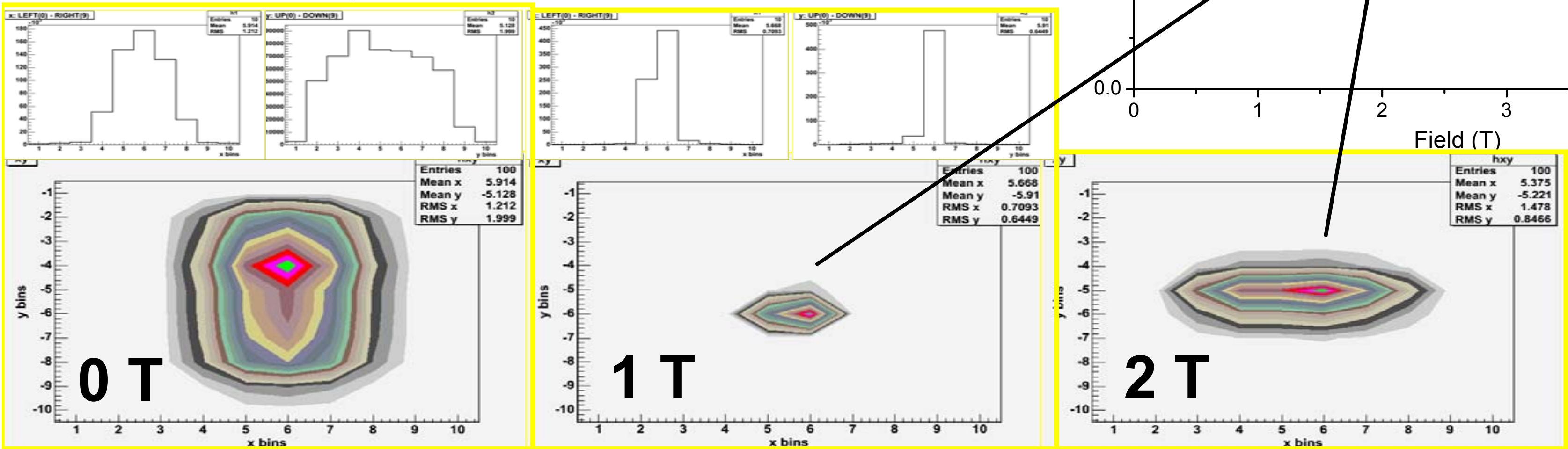
10 x-, 10 y-channels,
fiber diam. 1 mm, spacing 10 mm



A. Stoykov et al., NIM A 550 (2005) 212

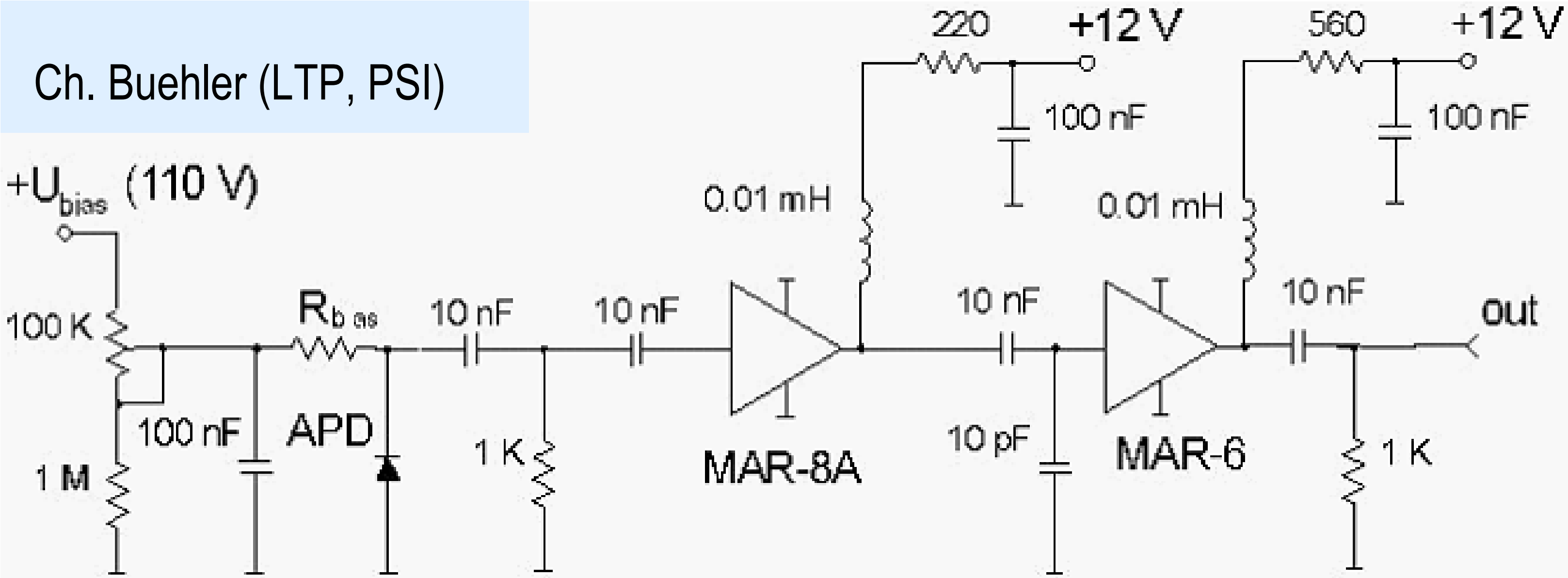
AMPDs and preamps work fine in 5 T!

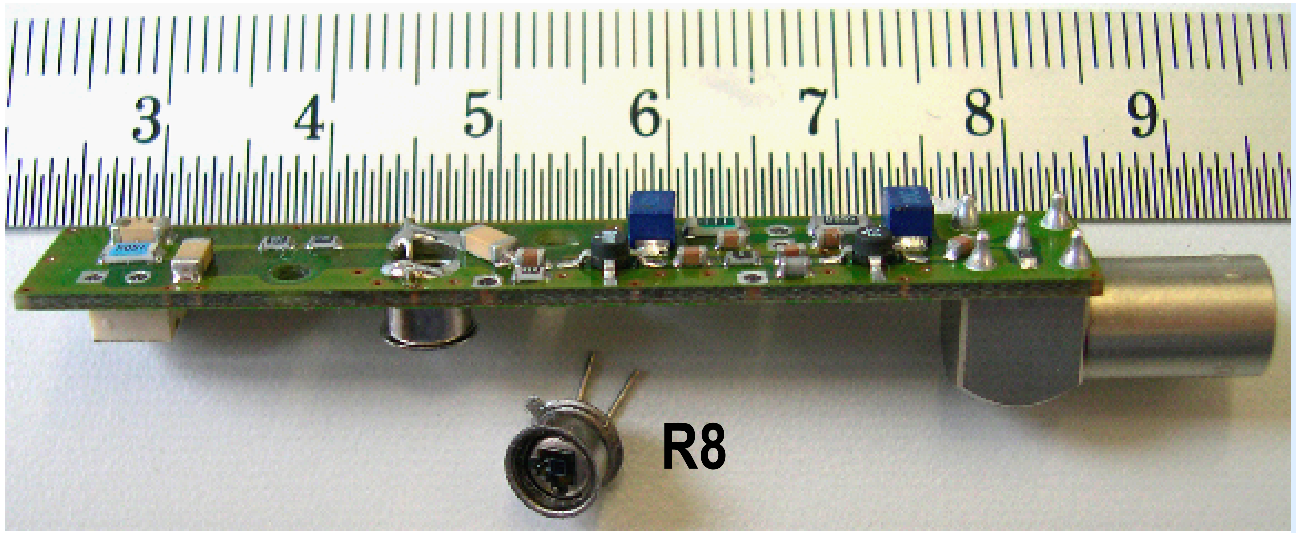




Scintillating Fiber Detector Module

Ch. Buehler (LTP, PSI)





Gain: ≈250

Bandwidth: ≈ 250 MHz

Rate capability:

$\approx 3\times10^6$ μ^+ / s/ channel

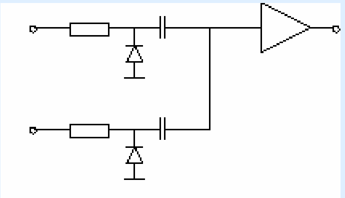
modifications ⇒ 'universal' test board: bandwith > 600 MHz

today's AMPDs: small area (<10 mm^2)

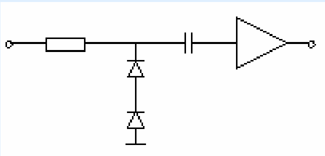
cover larger area: **ARRAY**

connection of APDs into array:

- DC – parallel, AC – parallel;

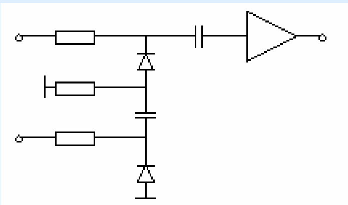


- DC – serial, AC – serial;

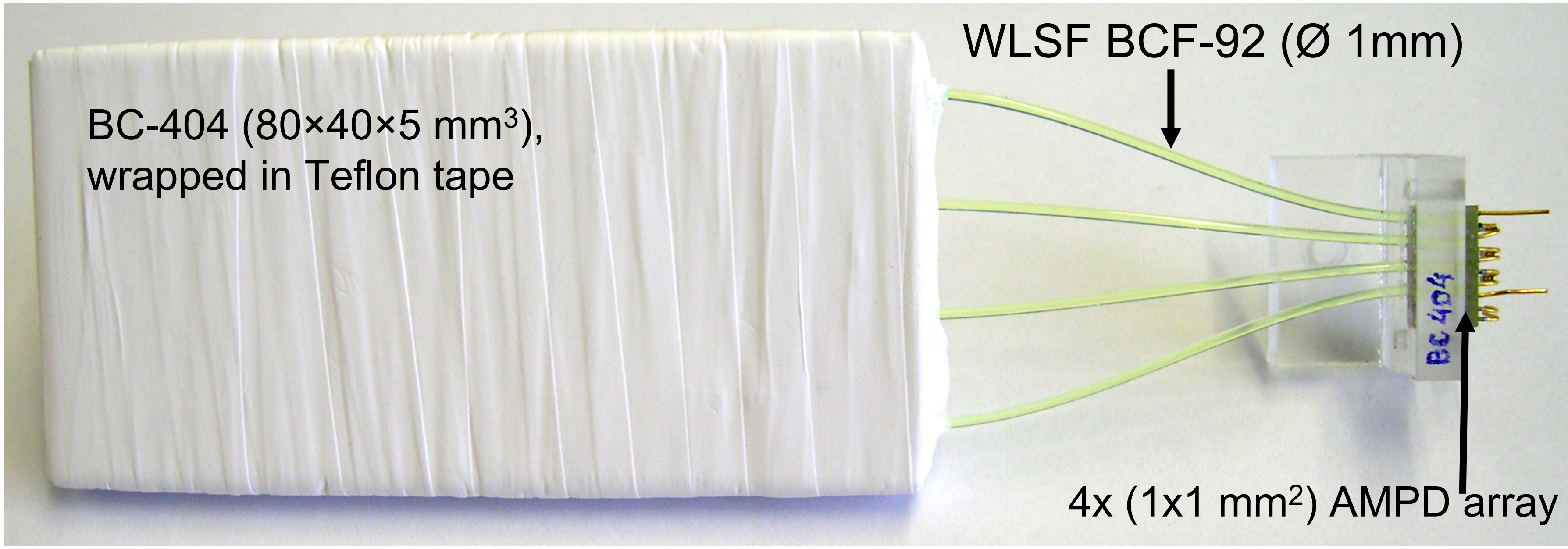


- DC – parallel, AC – serial

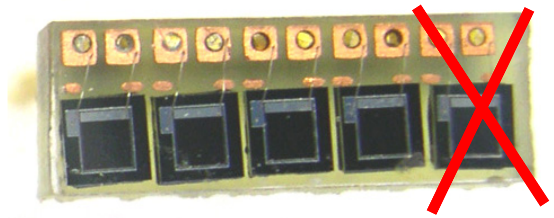
[Y.Benhammou *et al*., CMS TN / 95-122]



A tile-fiber detector with AMPD readout



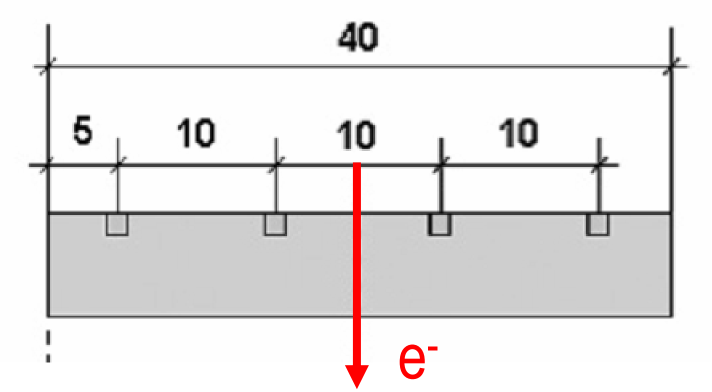
Tested with ^{90}Sr electrons
and 30 MeV/*c* beam positrons

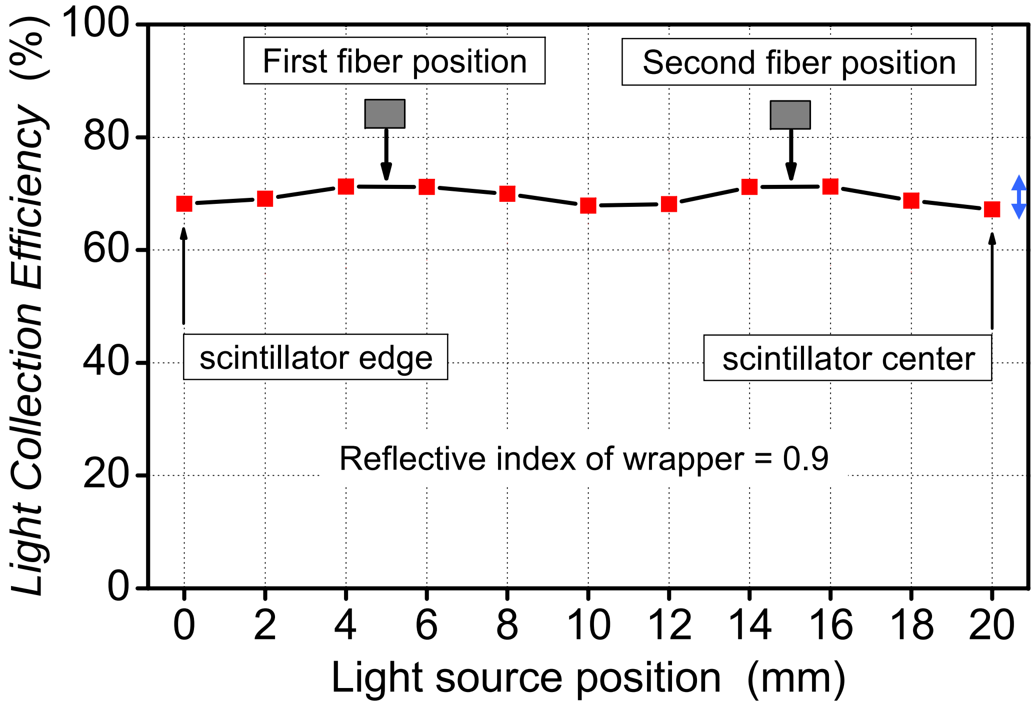


MW-3 array

MC simulations

code: V.A. Baranov et al., NIM A 374 (1996) 335





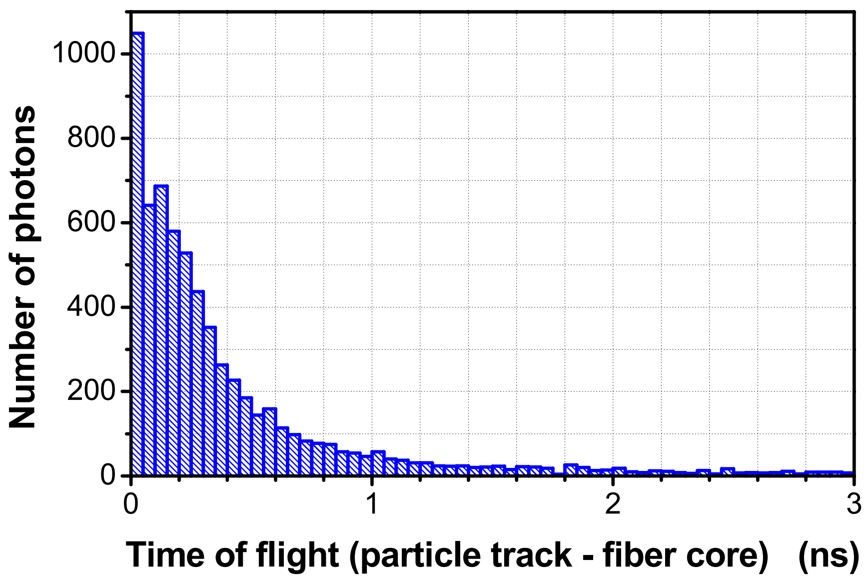
scintillator tile: **$80 \times 40 \times 5$ mm^3**
wrapped in diffuse reflector
absorption length 1.4 m

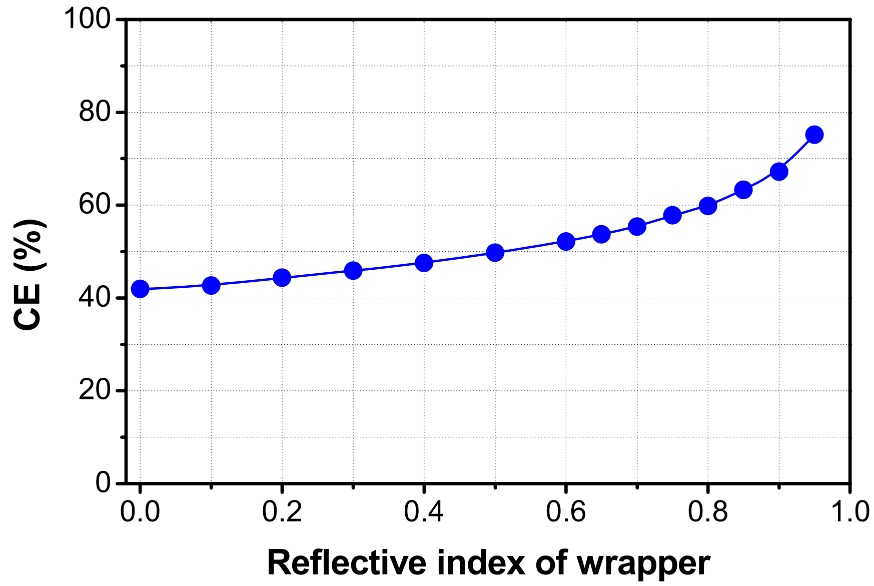
light source = 5 mm long e^- track

fiber:
1×1 mm^2 multiclad, glued into grooves

non-uniformity: < 5%

MC results

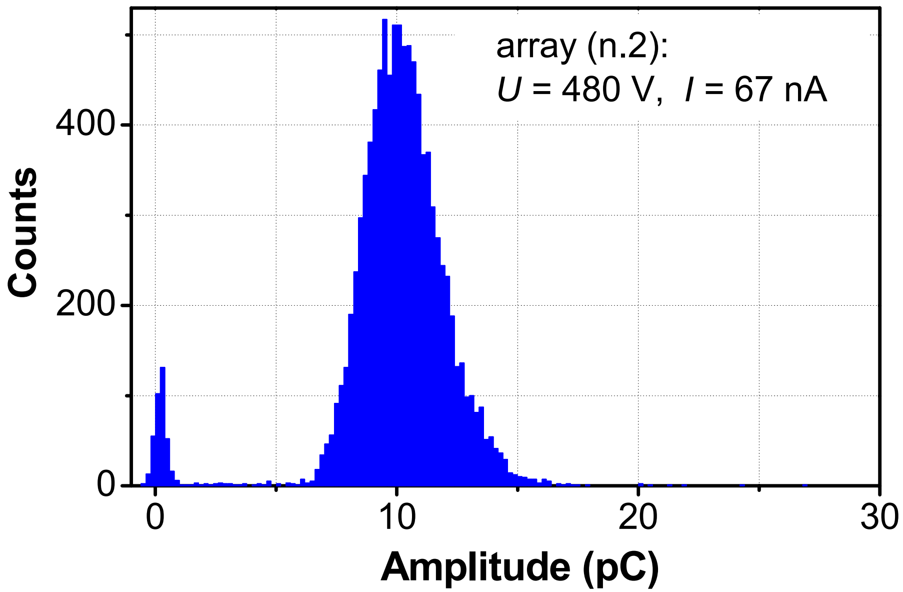


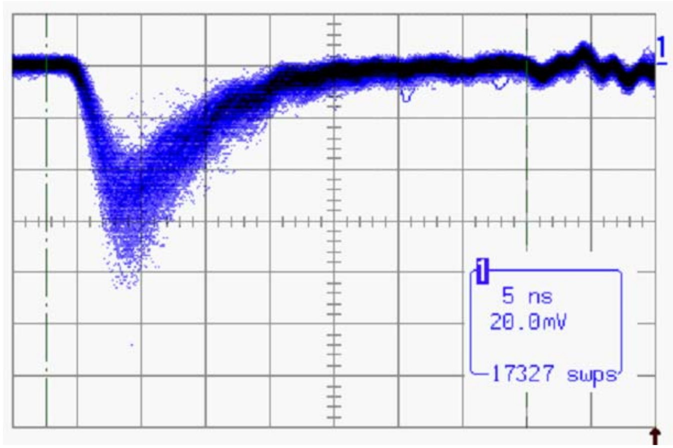


90% of photons are collected in **~1ns**

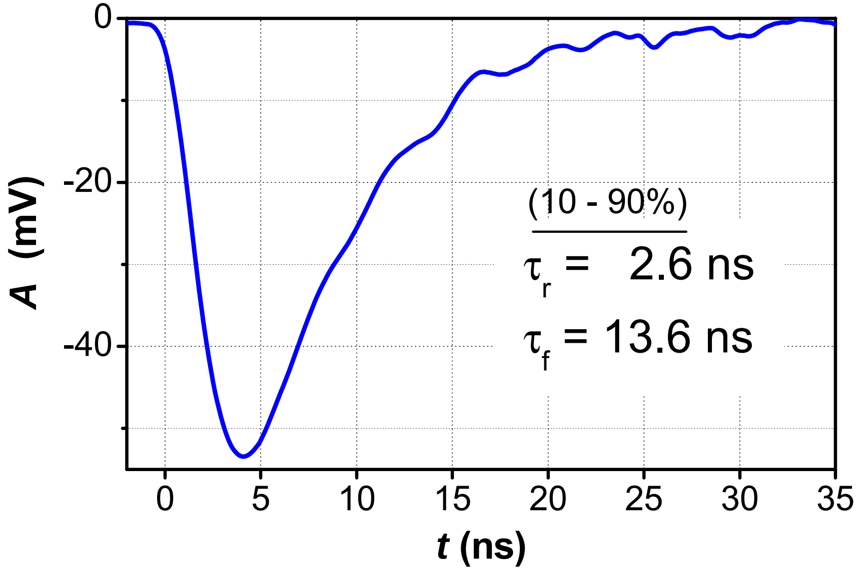
MIP (e^-) from ^{90}Sr

amplitude distribution



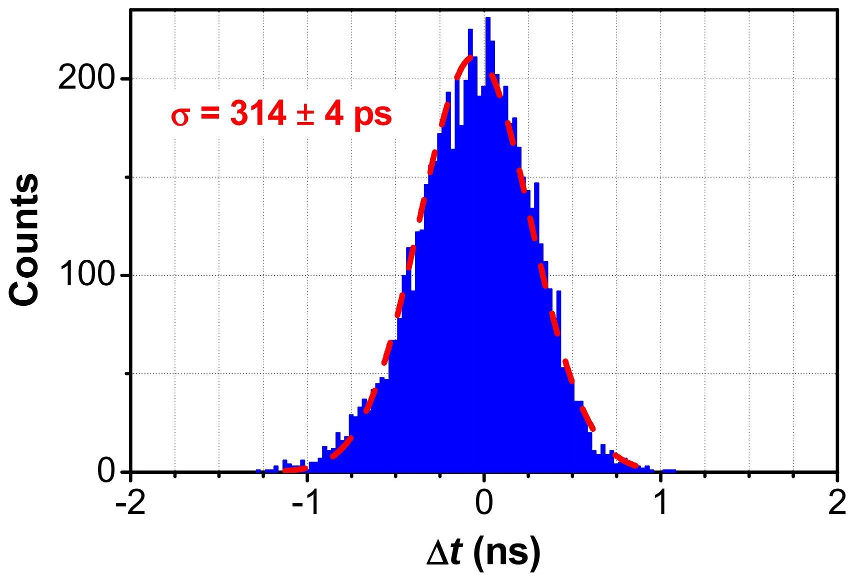


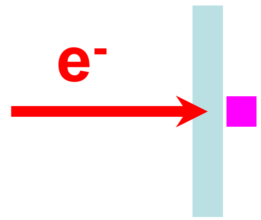
averaged waveform

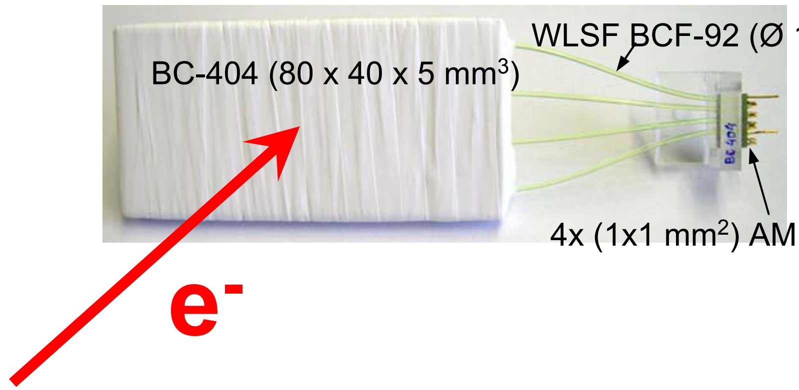


- detection efficiency ≈ **100%**
- variation of signal amplitude over whole area **< 5%**
- detection time variation over whole area **< 100 ps**

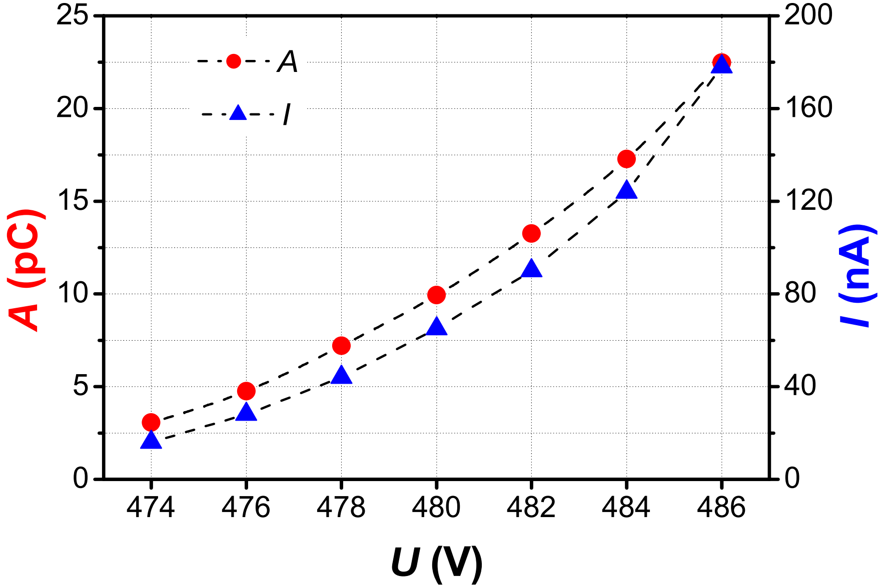
Time resolution

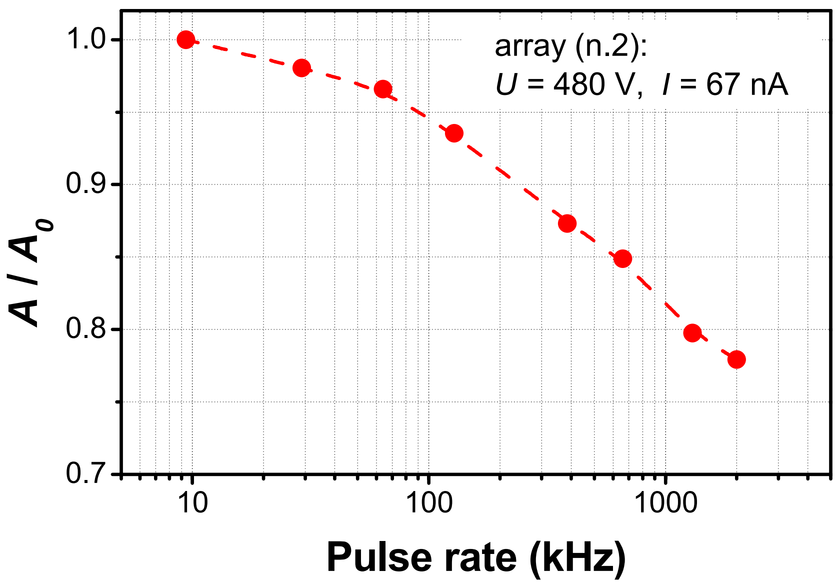






reference detector: σ < 50 ps





ΔU_{bias} = 12 V $\Rightarrow$ factor 8 in *A*

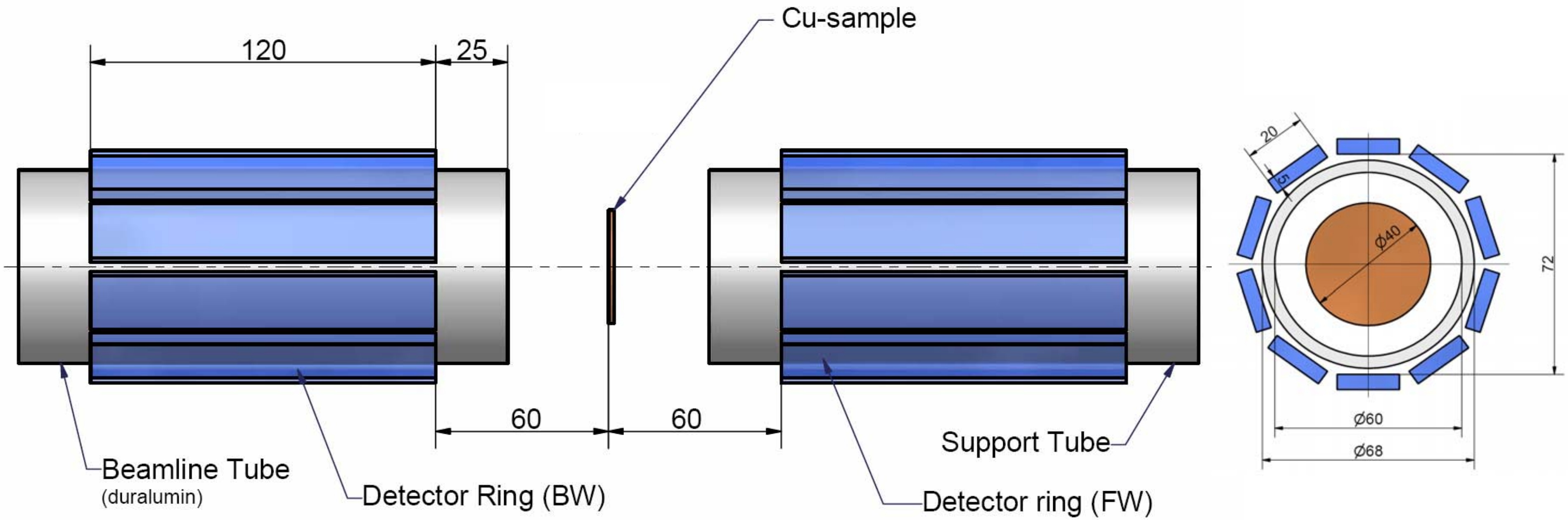
<u>rate capability</u>:

(finite recovery time of a cell after discharge)

29 MeV/c beam e^+ in πE3 (SμS)

1 MHz rate with 20% ampl. loss

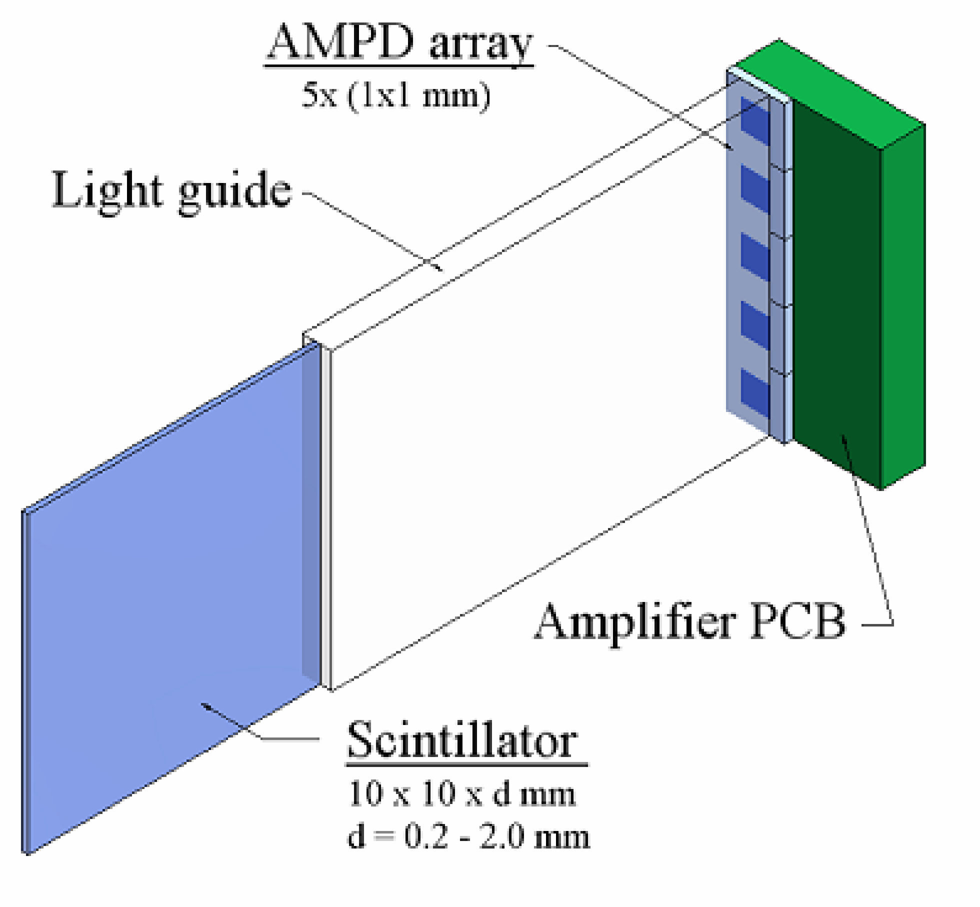
New ALC spectrometer - prototype



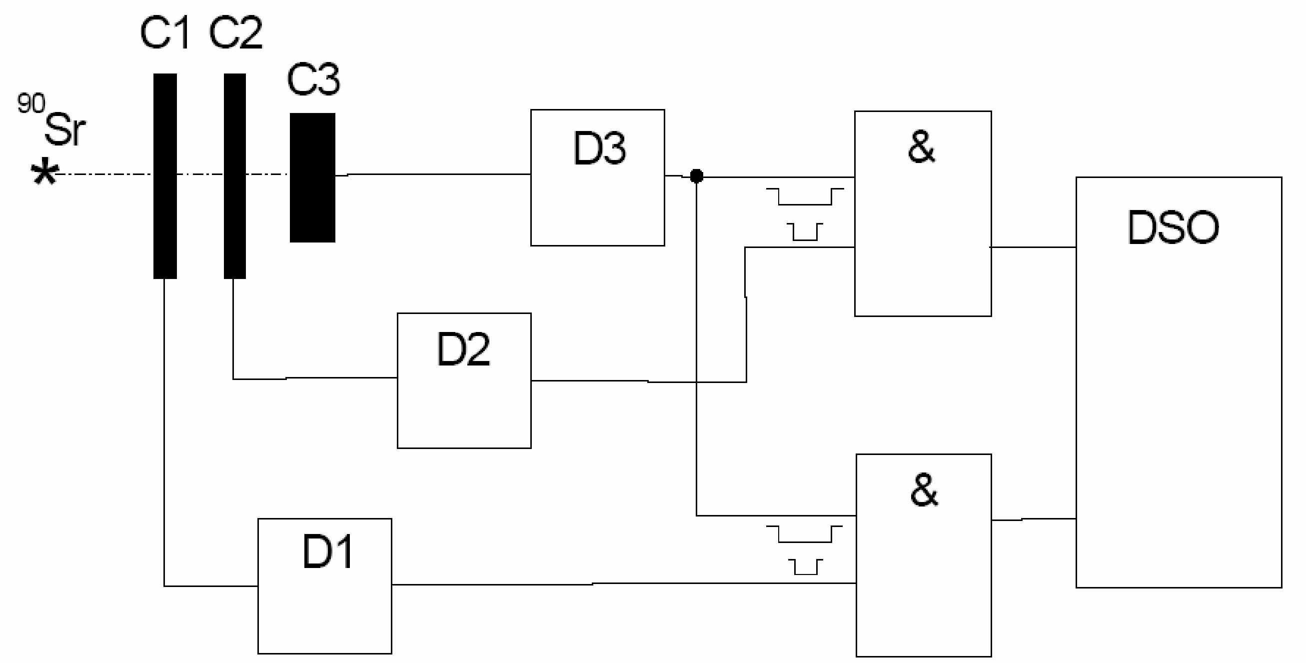
2 × 10 channels FW/BW positron counters
optional: 1 muon counter

under construction, test April 2007

Towards fast timing in high magnetic fields: a concept of an AMPD based scintillation detector



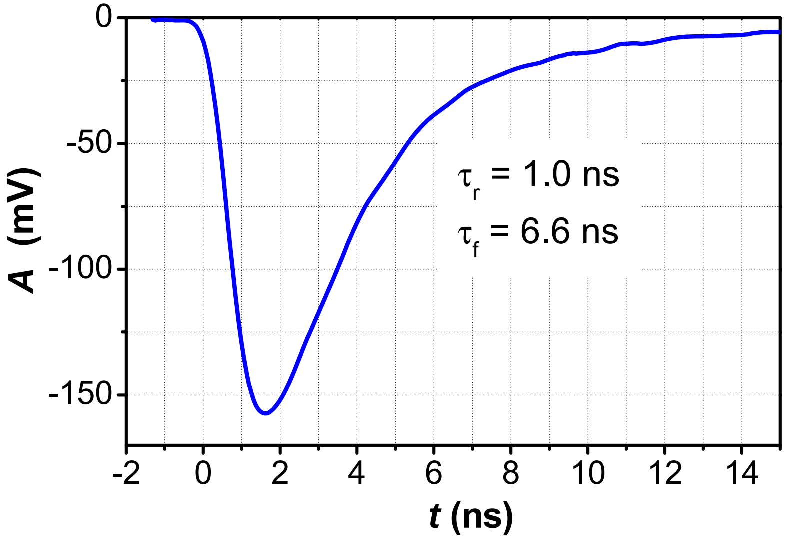
10 x 10 mm^2 active area detector based on 1 x 1 mm^2 AMPDs:
AMPDs are connected to common load.

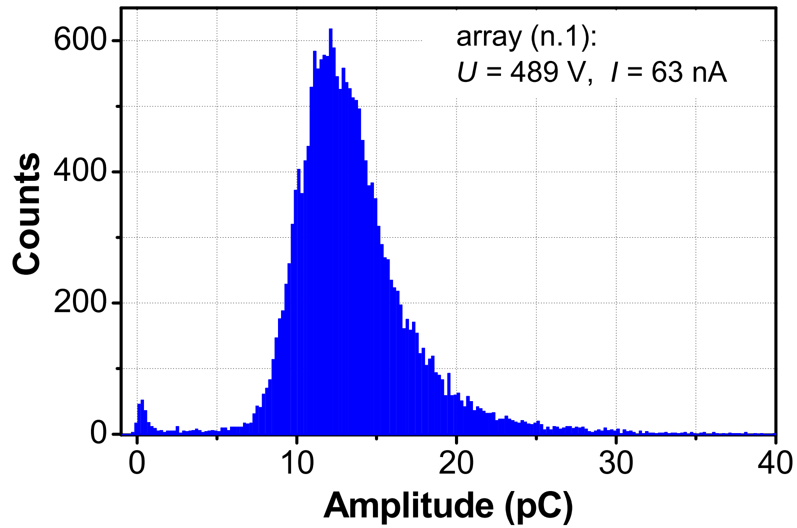


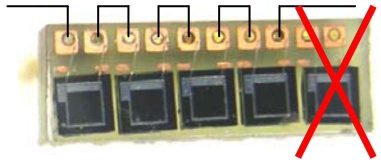
<u>A setup used for the time resolution measurements</u>:

C1, C2 -- two identical detectors under test; C3 is a PMT based detector to identify those electrons from the ^{90}Sr source which passed through C1 and C2;

D1- D3 -- constant fraction discriminators; & -- coincidence schemes; DSO -- LeCroy WavePro 960 digital oscilloscope.

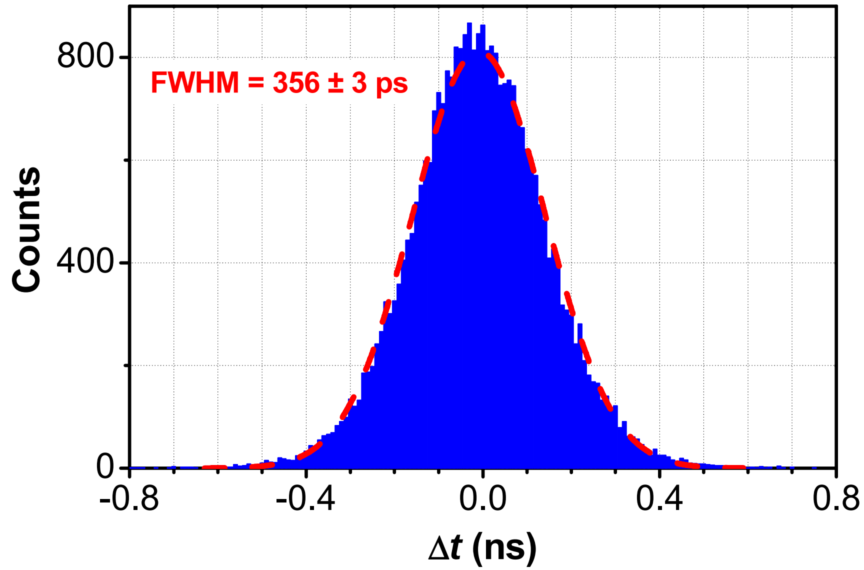






Time resolution

Telescope 2×
(array 4× + 10×10×2 mm BC-422, MIP)



for 1 detector: $\sigma \approx 110$ ps

Scintillator	λ_{max} nm	light yield photons/MeV	pulse charge pC	rise time ns	fall time ns	time res. σ ps
BCF-20	492	8000	15.2	2.10	11.2	**209**
BC-400	423	10000	14.6	1.50	8.3	**160**
BC-404	408	10400	19.3	1.42	7.0	**127**
BC-418*	391	10200	13.5	1.24	6.5	**124**
BC-422	**370**	**8400**	**13.6**	**1.00**	**6.6**	**108**
BC-422Q(0.5%)	370	2900	6.0	0.95	6.1	**145**

* Also tested with an array of 5 AMPDs connected in parallel: **σ ~ 150 ps**.

The deterioration of the time resolution is correlated with the increased rise and fall time of the detector signals (**2.2 ns** and **9.7 ns**) which in turn correlate with the increased capacitance of the detector.

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Summary & Outlook

Detectors based on AMPD arrays:

- μSR „large area" (30 cm^2) tile-fiber positron detector, $\sigma \approx 310$ ps (MIP)
- μSR fast-timing detector, with 2 mm scintillator thickness: $\sigma \approx 110$ ps (MIP)

goal: fast-timing detector with 200 μm plastic scintillator: $\sigma < 50$ ps

AMPDs:

- larger area
- larger gain
- increased sensitivity below 400 nm (fast plastics)

- light output from scintillators & light guides (fibers)
- fast preamps with on-board discriminators