Novel scintillation detectors for μSR-spectrometers

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PSI

12 June 2007

SiPM – Silicon PhotoMultiplier

AMPD (MAPD) – Avalanche Microchannel / Micropixel PhotoDiode

MRS APD – Metal-Resistive layer-Silicon Avalanche PhotoDiode

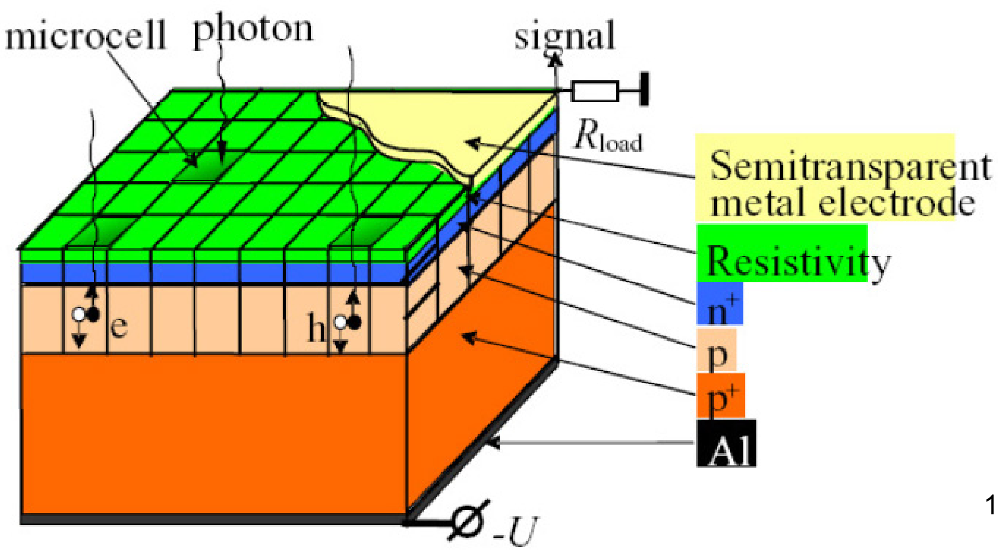
SSPM – Solid State PhotoMultiplier

MPPC – Multi-Pixel Photon Counter

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

G-APD: principle of operation

MRS APD
[A. Akindinov, Beaune05]



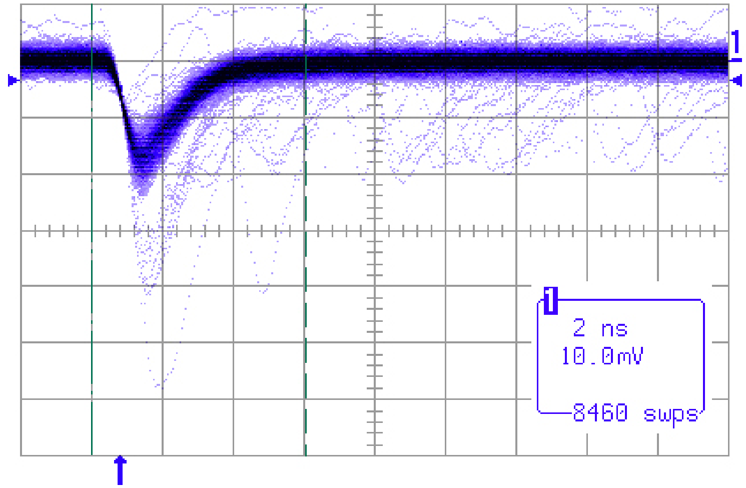
$$Q_i = C_i \cdot (U - U_0)$$

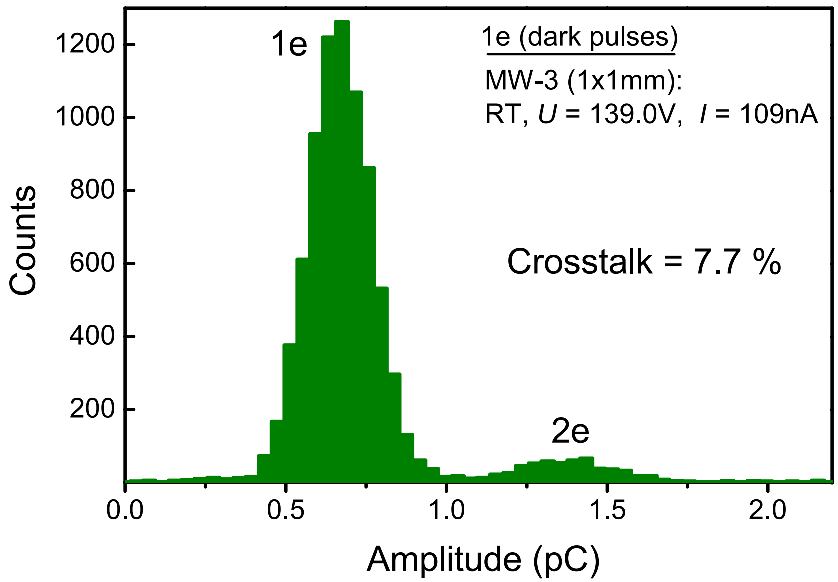
$$M = Q_i / e$$

$$Q = \sum Q_i$$

Signals from the breakdown of single cells:

AMPD MW-3 (1x1 mm^2)
(amplifier: gain ~ 80, bw ~ 600 MHz)





G-APD: parameters

- **Active area** (**typ. 1 mm^2**, max. 25 mm^2)
- **Number of cells → Dynamic range** (100 – 10000 mm^{-2})
- **Photon Detection Efficiency:** $PDE(\lambda, U) = QE(\lambda) \cdot \varepsilon \cdot w(U)$

  QE – quantum efficiency, ε – geometric fill factor, w – avalanche probability
- **Gain:** M (**10^4 – 10^7**)
- **Excess noise factor:** $F = 1 + \sigma^2(M) / \langle M \rangle^2$
- **Inter-pixel cross-talk:** $\alpha(M)$
- **Operating voltage:** U (typ. **15 V** – 150 V)
- **Dark current:** $I_0(T, U)$ (typ. 10 nA – 100 µA, at RT)
- **Dark counts:** $N_0(T, U)$ (typ. 0.1 – 10 MHz, at RT)
- **Cell recovery time** (typ. 0.1 – 10 µs)
- **Temperature coefficient of gain:** $(\Delta M / M) / T$ (typ. 0.2 – 5 %/C)

G-APD vs. PMT

Advantages:

- insensitive to magnetic fields;
- compact, robust;
- low operation voltage

compact, finely segmented detectors and detectors to be used in a high magnetic field environment

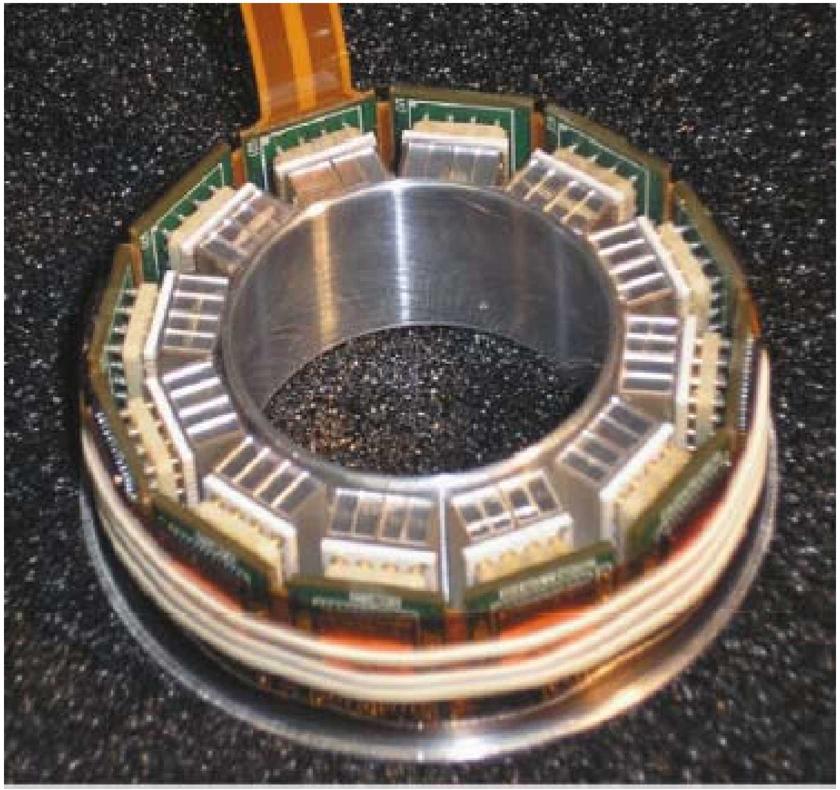
Disadvantages:

- small active area

cover larger area → G-APD arrays

A brilliant example of APD application

C. Woody *et al.*, NIM A 571(2007) 14,
Initial studies using the RatCAP conscious animal PET tomograph



The RatCAP tomograph consisting of 12 LSO arrays with APDs and associated readout electronics

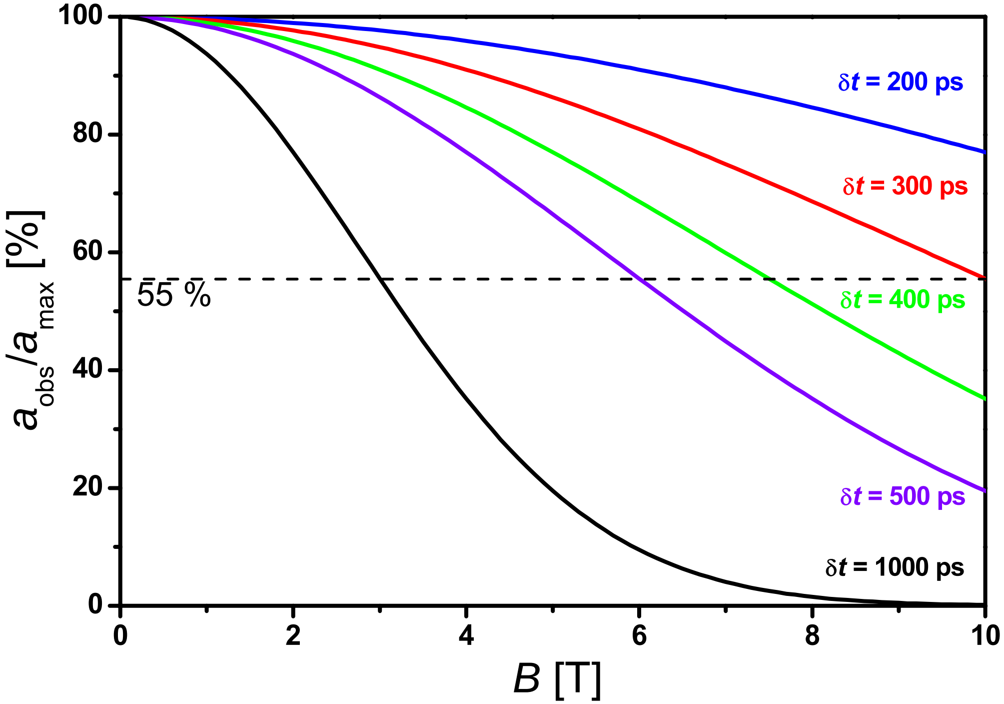
Awake rat wearing the RatCAP that is supported by the tether and mechanical counterbalance system

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

Larmor frequency: 1.35 GHz in 10 T



Muon + positron counter

δt < 300 ps (FWHM)

σ < 125 ps

Per counter

σ < 90 ps

Development of fast timing detectors for the HF-spectrometer:

- research in the field of G-APD based detectors
- experience in the detector design for high fields

↓ ↑

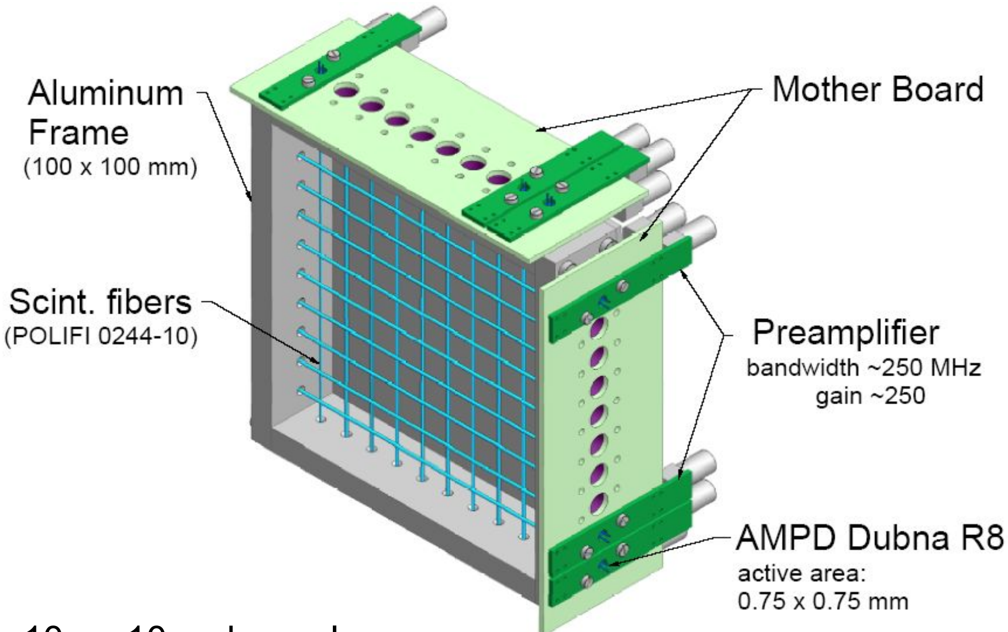
Detector development for ALC, understanding and optimization of its performance:

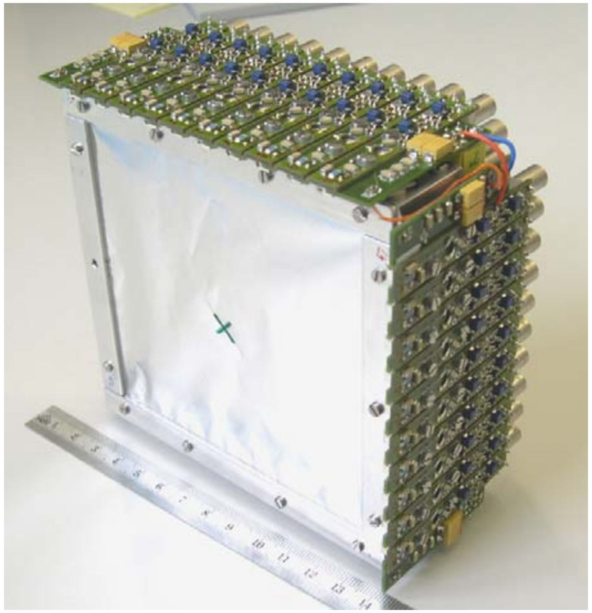
1. position sensitive detector to study the muon beam dynamics in high fields;
2. upgrade of the ALC detector system.

Muon Beam Profile Monitor (BPM)

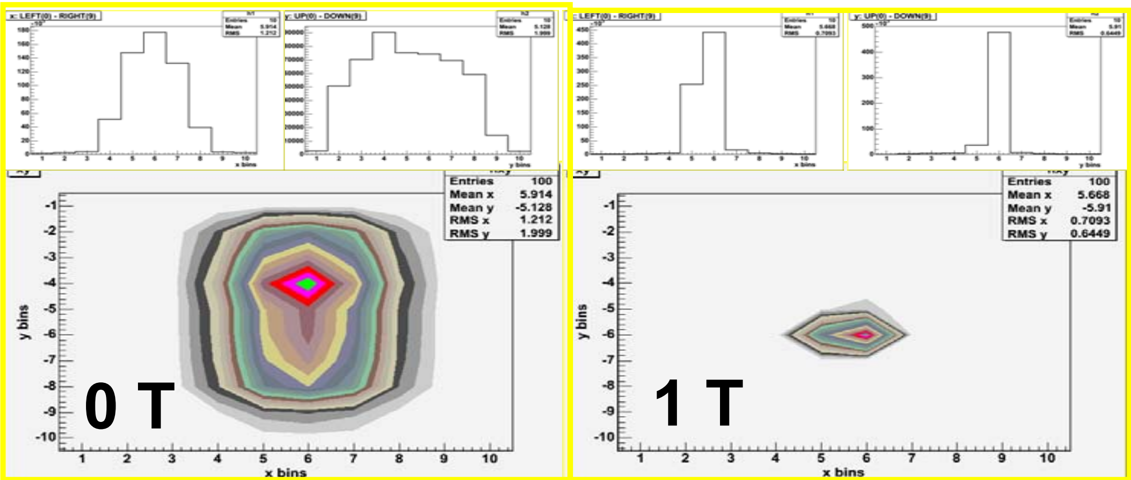
for ALC instrument (28 MeV/c muon beam, up to 5 T field)

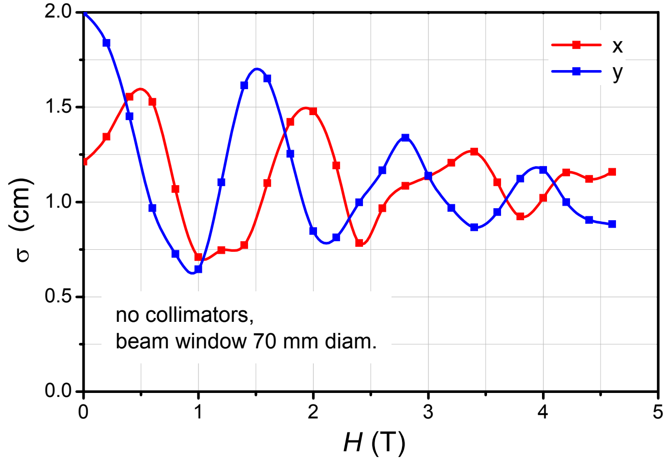
August 2004





10 x-, 10 y-channels,
fibers Ø 1mm, spacing 10 mm





The impact of the BPM:

- the profile of the muon beam in the center of the 5 Tesla solenoid of ALC was measured as a function of $\boldsymbol{H}$;
- stimulated Monte-Carlo simulations (by T. Lancaster) on the muon beam dynamics in high fields;
- muon beam dynamics in high magnetic fields is understood.

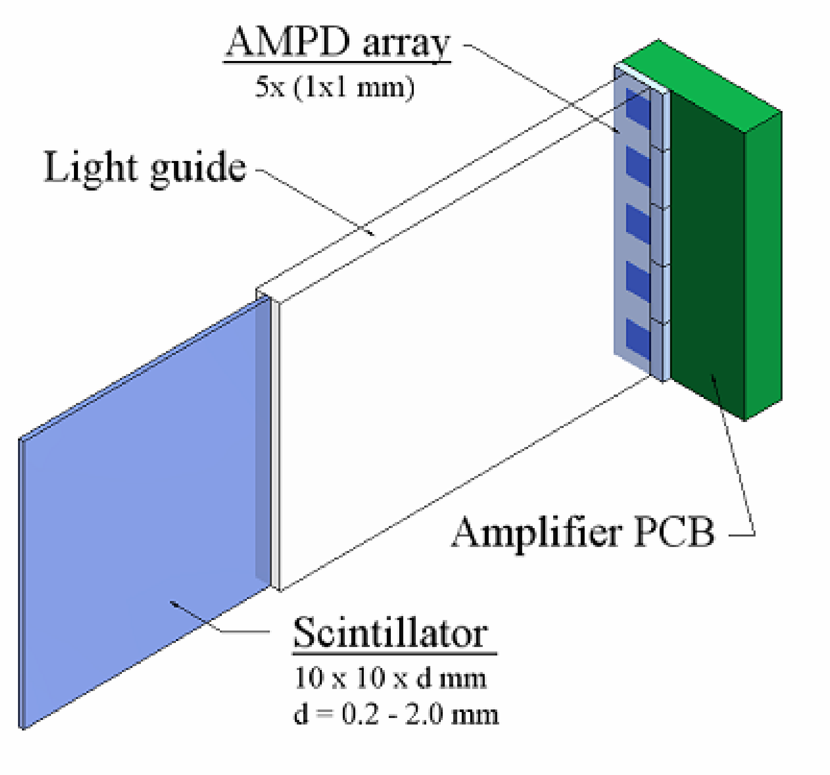
3 years of operation:

- no change in the performance;
- being used for setup of ALC and DOLLY.

Perspectives:

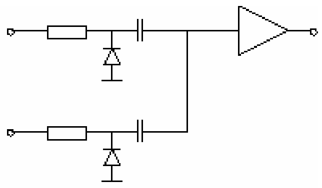
- real two-dimensional mode of operation;
- detection of minimum ionizing particles.

A compact high time resolution detector (concept)

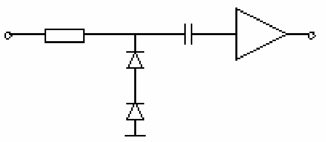


connection of G-APDs into array:

- DC – parallel, AC – parallel

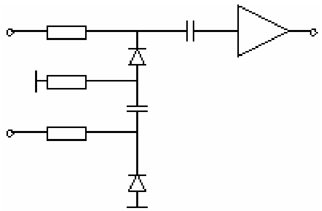


- DC – series, AC – series



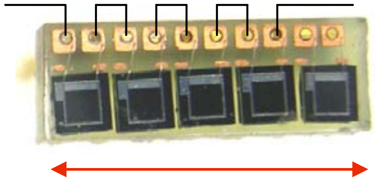
- DC – parallel, AC – series

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



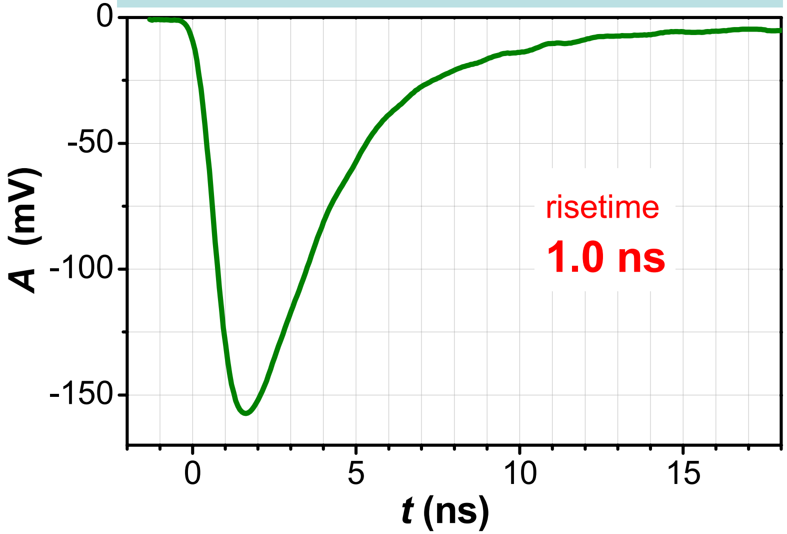
10 x 10 mm^2 active area detector based on 1 x 1 mm^2 AMPDs: AMPDs are connected to a common load.

Array 4 × MW-3 + 10×10×2 mm^3 BC-422, MIP

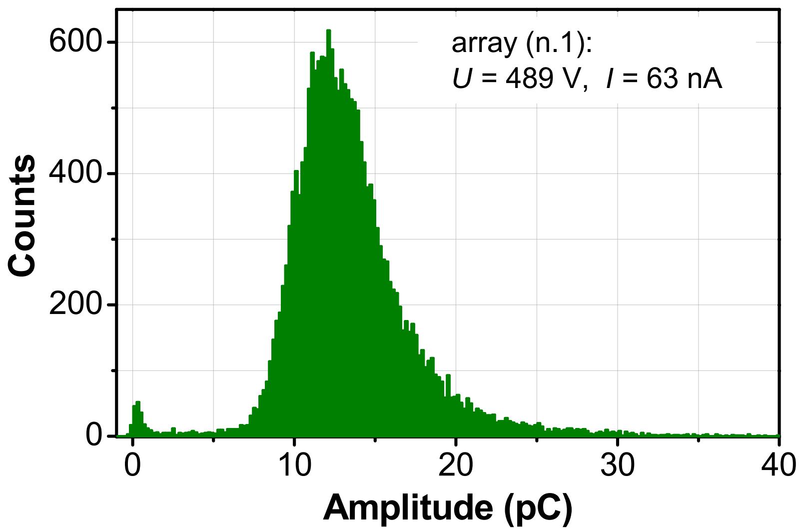


Feb. 2006

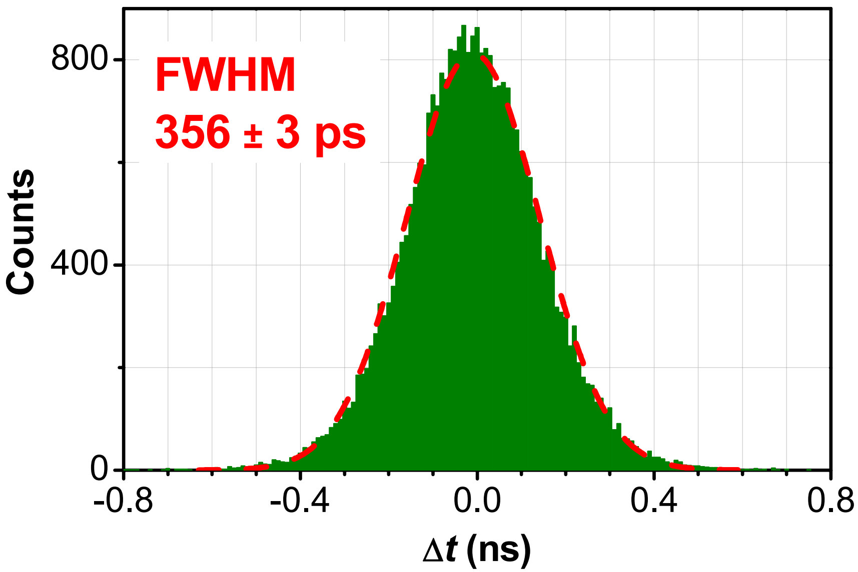
Averaged waveform



Amplitude spectrum



Time resolution (telescope 2x)



1 detector: σ ≈ 108 ps

Array 4 × MW-3 + 10×10×2 mm^3 scintillator, MIP

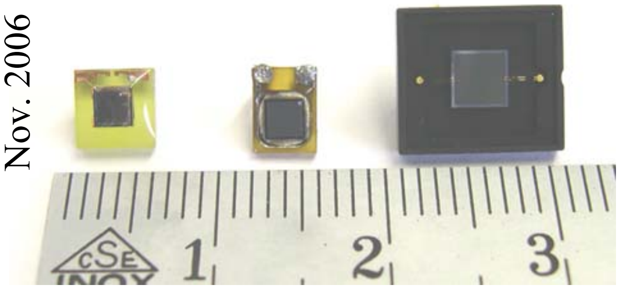
Scintillator	λ_{max} nm	light yield photons/MeV	A / A_{BC-404}	rise time ns	fall time ns	time res. σ ps
BCF-20	492	8000	0.79	2.10	11.2	**209**
BC-400	423	10000	0.76	1.50	8.3	**160**
BC-404	408	10400	1.00	1.42	7.0	**127**
BC-418	391	10200	0.70	1.24	6.5	**124**
BC-422	370	8400	0.70	1.00	6.6	**108**

The time resolution improves towards the fastest UV scintillators (even at some expense of the signal amplitude).

Perspectives: new larger area UV-sensitive G-APDs

Nov. 2006

1	2	3

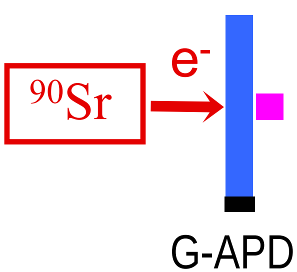


1: AMPD n-INT-1e
1.8 x 1.8 mm^2

2: SSPM 0609B4
2.1 x 2.1 mm^2

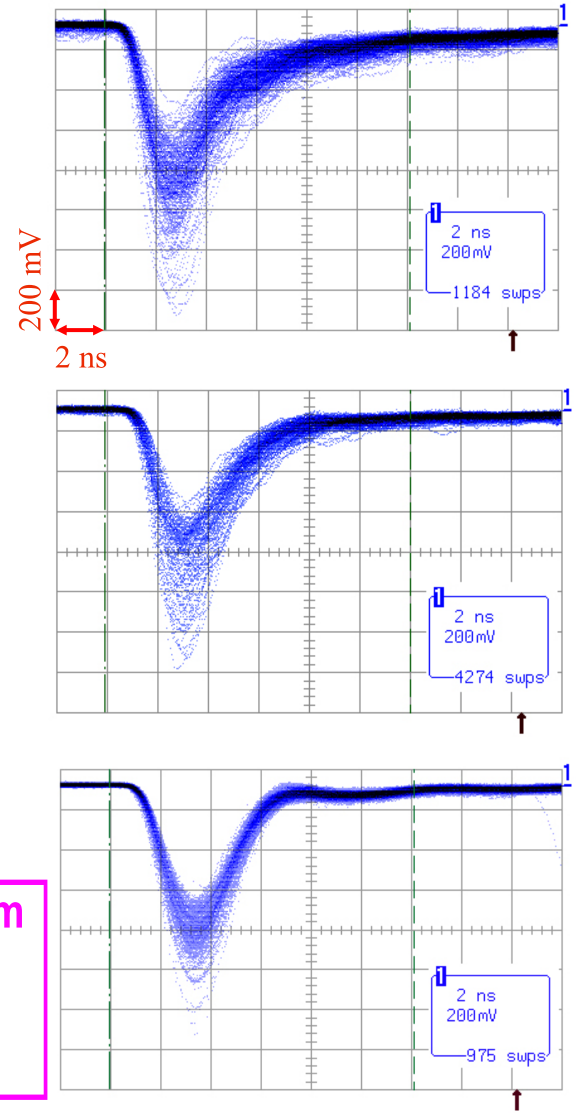
3: MPPC PSI-33-050C
3 x 3 mm^2

BC-418 10x10x2 mm



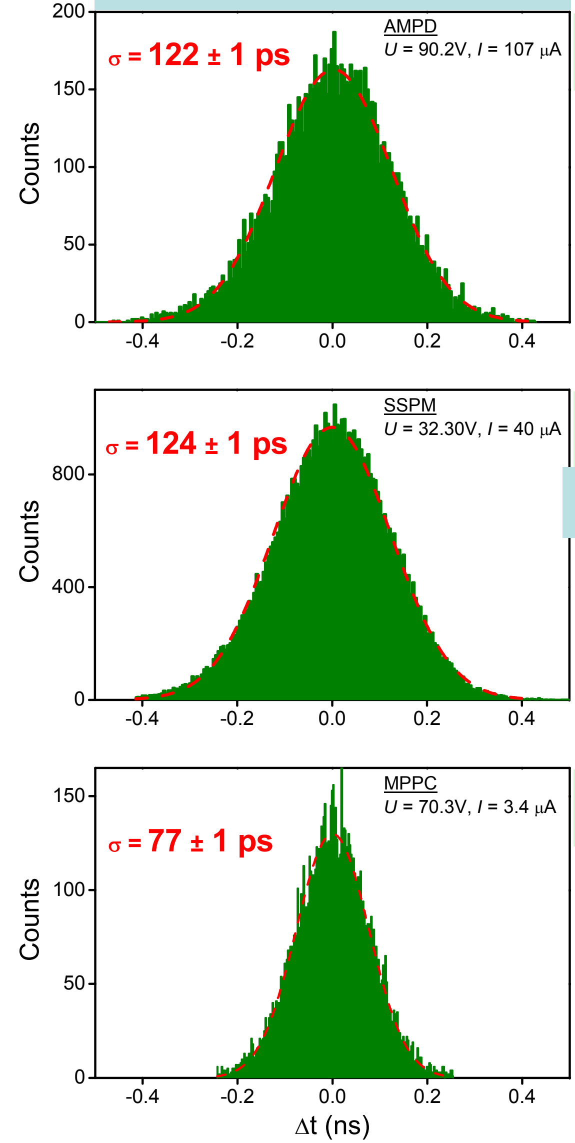
BC-418 Ø8×5 mm
+
PMT R5505-70
σ ≈ 50 ps

Waveforms (MIP)



Time resolution (1x vs. ref.)

ref. det.: **σ ≈ 50 ps**

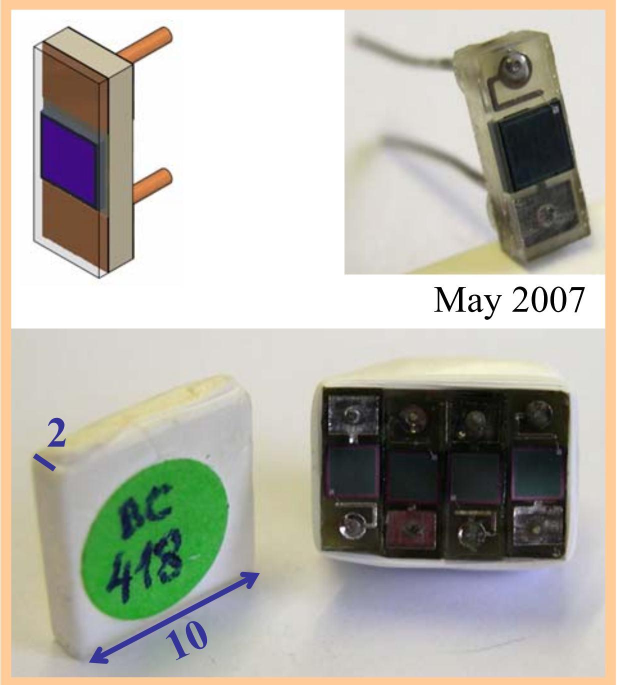


20*

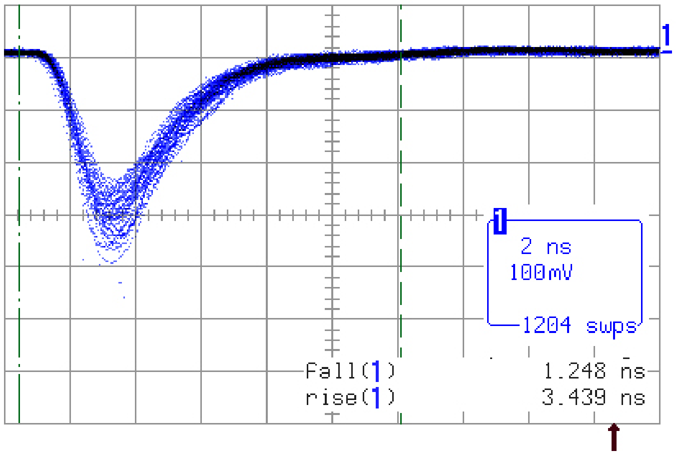
* PDE (%) at 400 nm (producer's data).

SSPM 0609B4 (custom designed package)

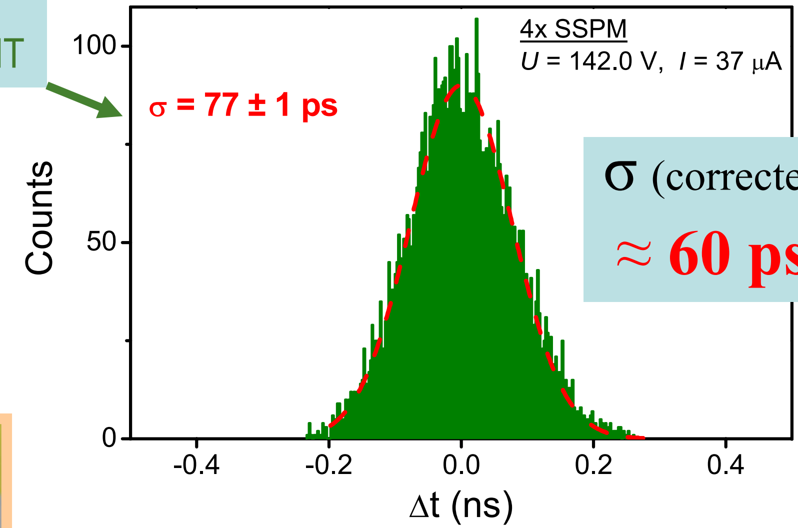
Photonique SA : www.photonique.ch



Waveforms (MIP)
trigger -- PMT

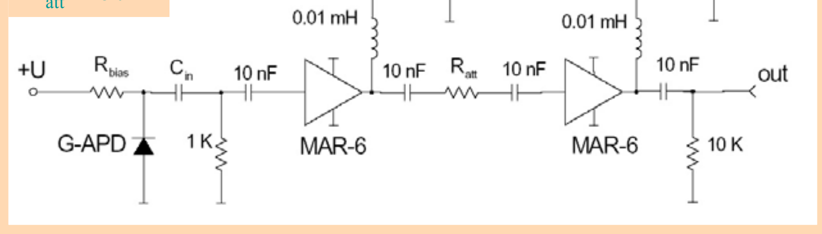


Time resolution
SSPM array + PMT



σ (corrected)
≈ 60 ps

R_{bias} = 1K
C_{in} = 5pF
R_{att} = 50Ω



Detector for the HF-spectrometer: current status

1. G-APDs comparable with PMTs in performance already exist.
2. The required time resolution (< 90 ps) is achieved for a G-APD based positron detector (on table).

Real conditions → problems to study and solve:

- light losses in the light guides (limited space and cryogenic environment);
- additional light losses for the muon counter (200 μm thick scintillator).

The light collection (***CE***) from a 200 μm thick (10x10 mm^2) plastic scintillator: [V.V.Zhuk et al., PSI TM-35-05-01 (2005) 1-7].

CE strongly depends on the scintillator quality:

- maximum *CE* achieved on test samples – **20%**;
- maximum possible *CE* (Monte-Carlo simulations) – **45%** .

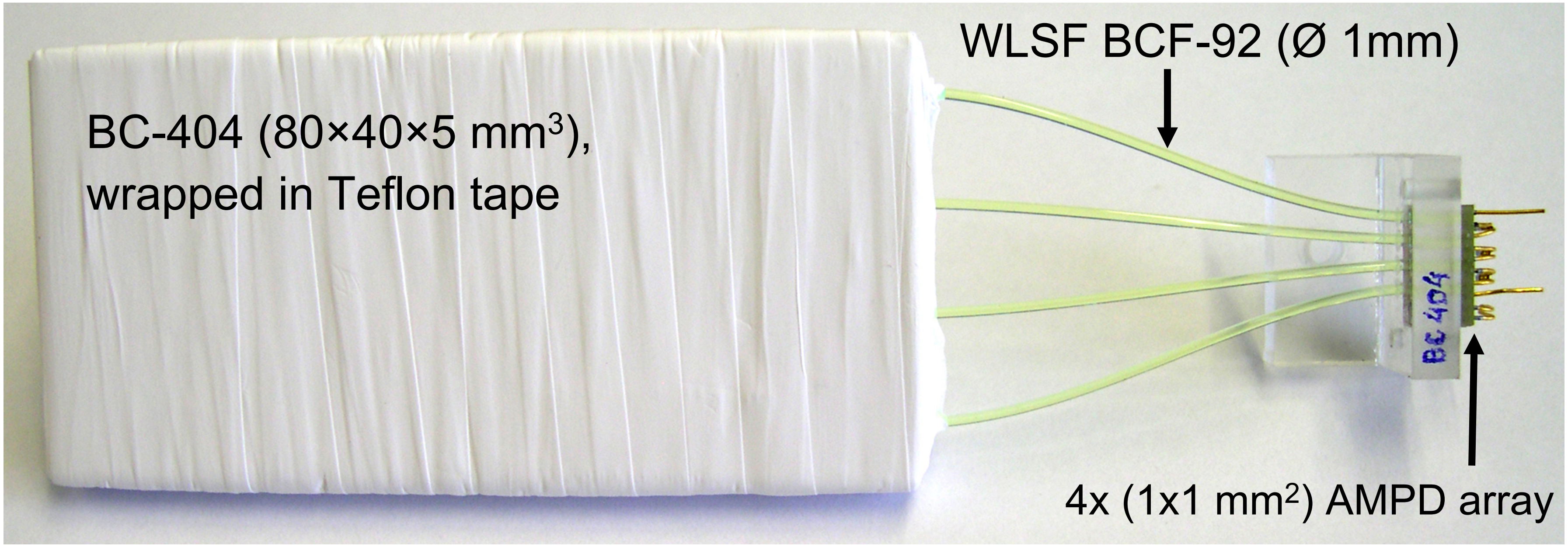
Detector for the 10 T μSR-spectrometer:

- **area:** $\leq 1\ cm^2$
- **time resolution:** $\sigma < 90\ ps$

Detectors for "standard" μSR-spectrometers:

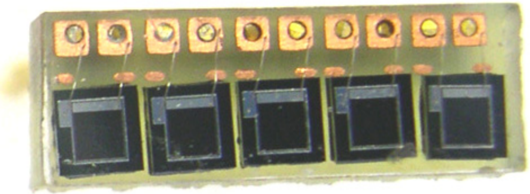
- **area:** $10 - 100\ cm^2$
- **time resolution:** $\sigma \leq 1\ ns$

A tile-fiber detector with AMPD readout



Goal – MIP detection with:

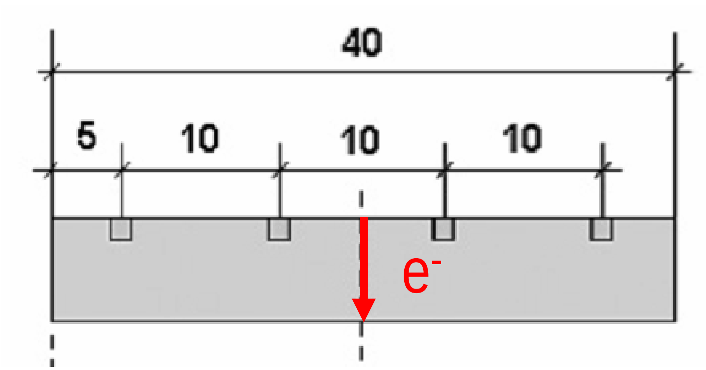
- **100% efficiency**
- **time resolution ≤ 1 ns**



MW-3 array

MC simulations by V. Zhuk

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



scintillator tile: **80×40×5 mm³**

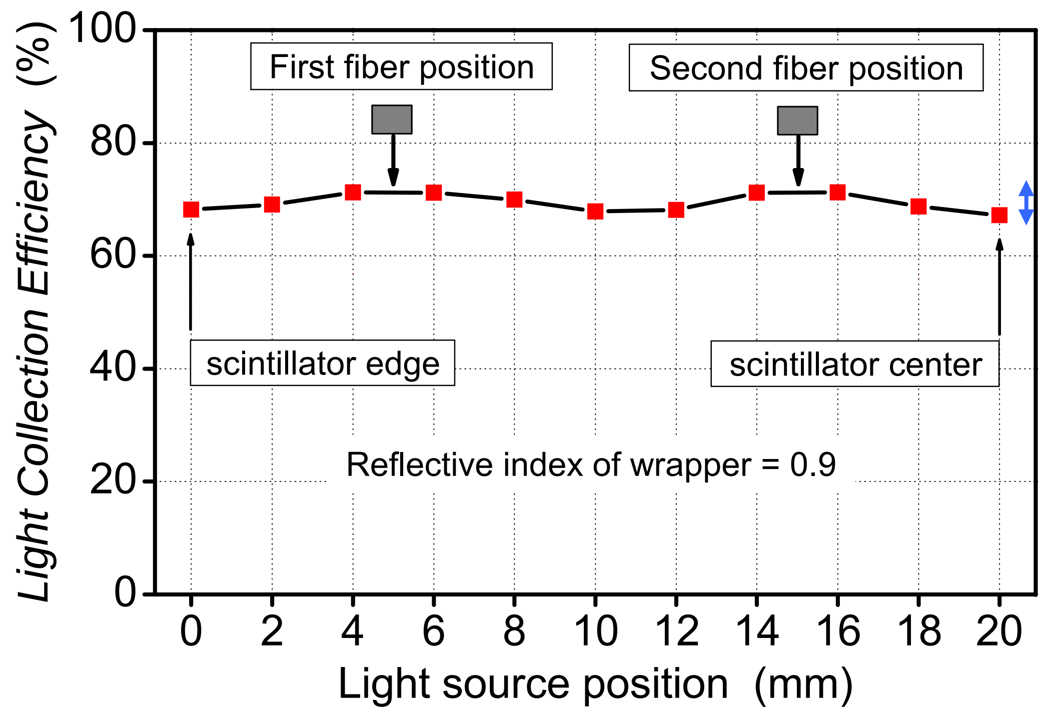
wrapped in diffuse reflector
absorption length 1.4 m

light source:

5 mm long e⁻ track

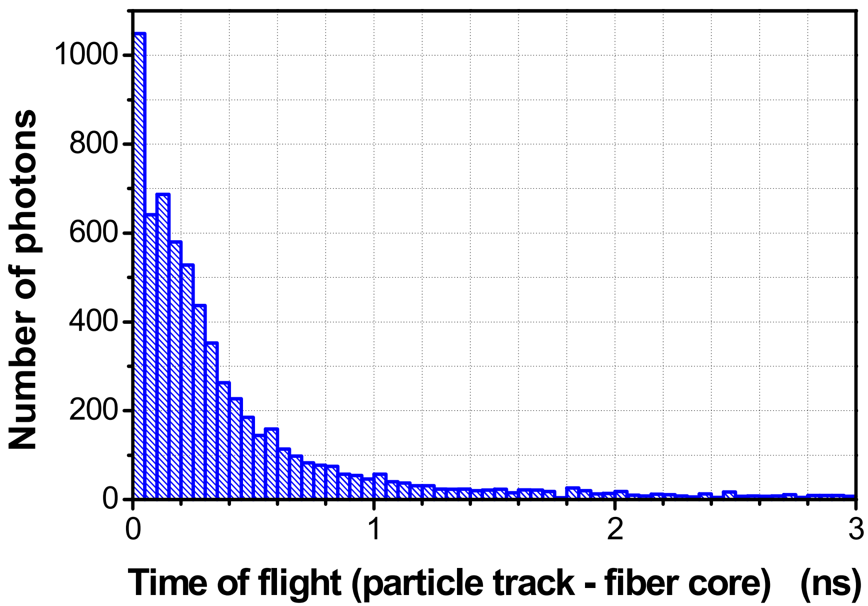
fiber:

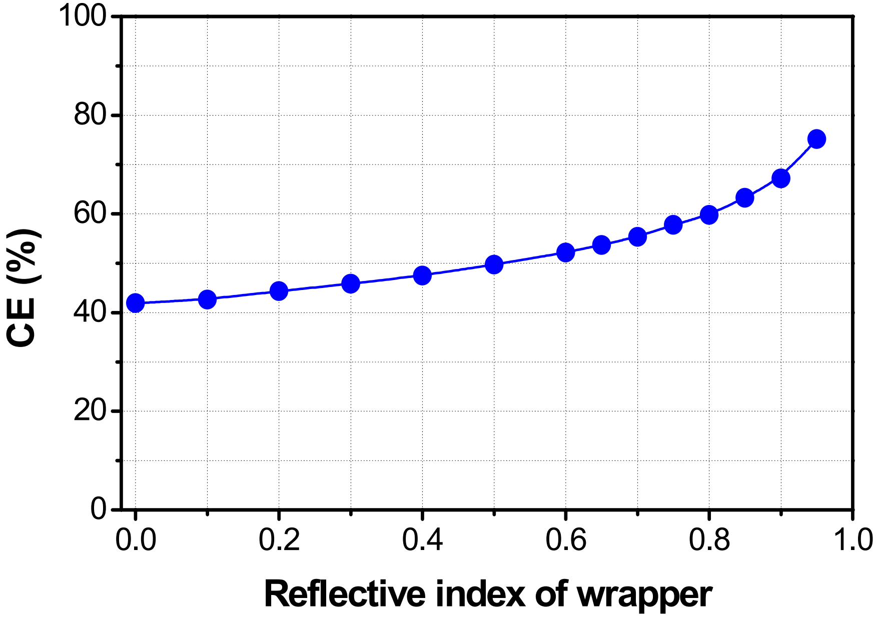
1×1 mm² multiclad,
glued into the grooves



non-uniformity: < 5%

MC results

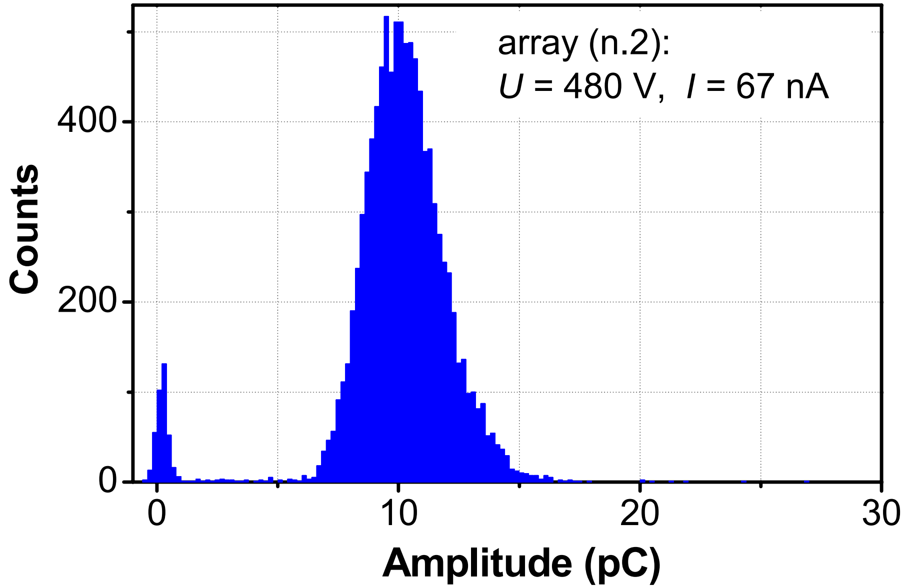




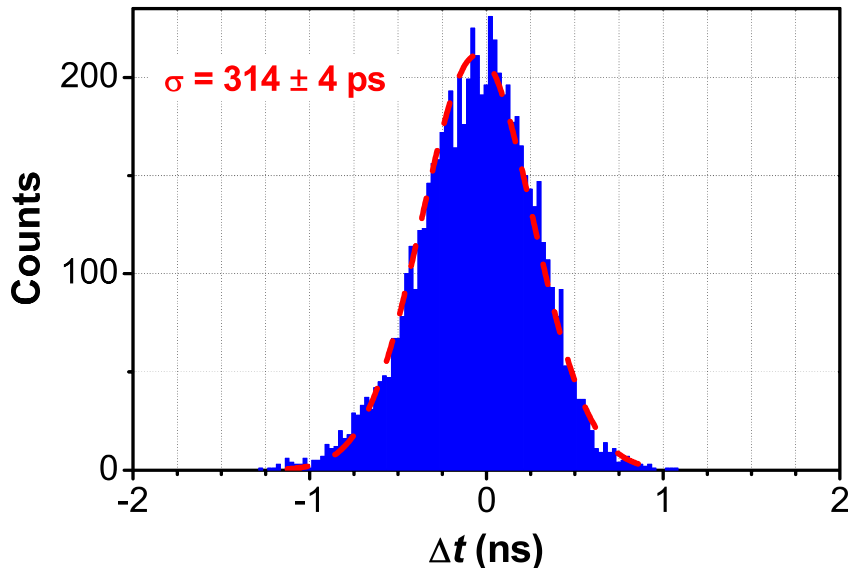
Photon lifetime in the scintillator **< 1ns**

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

Amplitude spectrum



Time resolution (ref. det.: **σ ≈ 50 ps**)



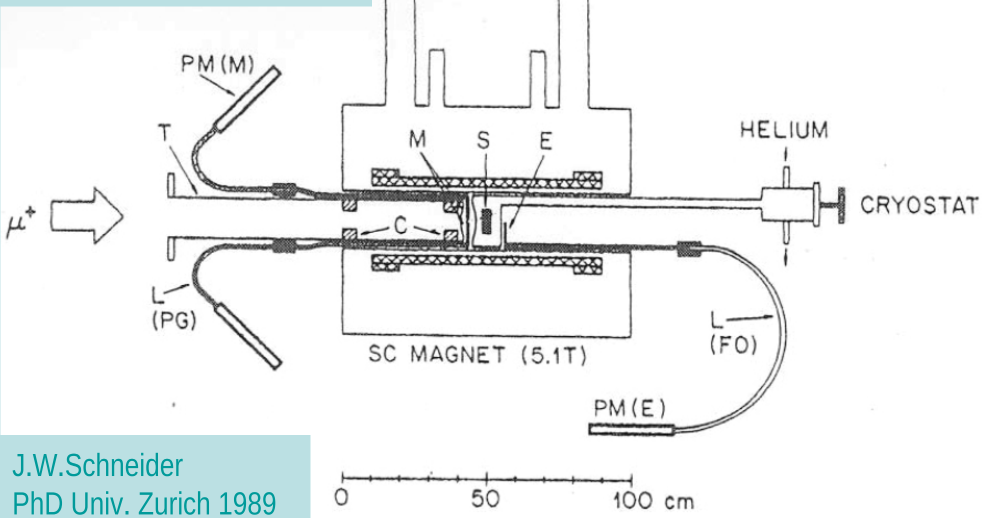
- **detection efficiency ≈ 100%**
- **time resolution < 350 ps**

Uniformity:

- signal amplitude variation **< 5%**
- detection time variation **< 100 ps**

ALC spectrometer in πE3

ALC spectrometer



J.W.Schneider
PhD Univ. Zurich 1989

Time-integral mode:

$$A(H) = (B - F) / (B + F)$$

B, F – BW and FW integral counts;
A – asymmetry.

***H_0* – resonant loss of integral muon spin polarization**

$$B_0 = B - \Delta B \qquad F_0 = F + \Delta F$$

$$A_0 = A - \Delta A$$

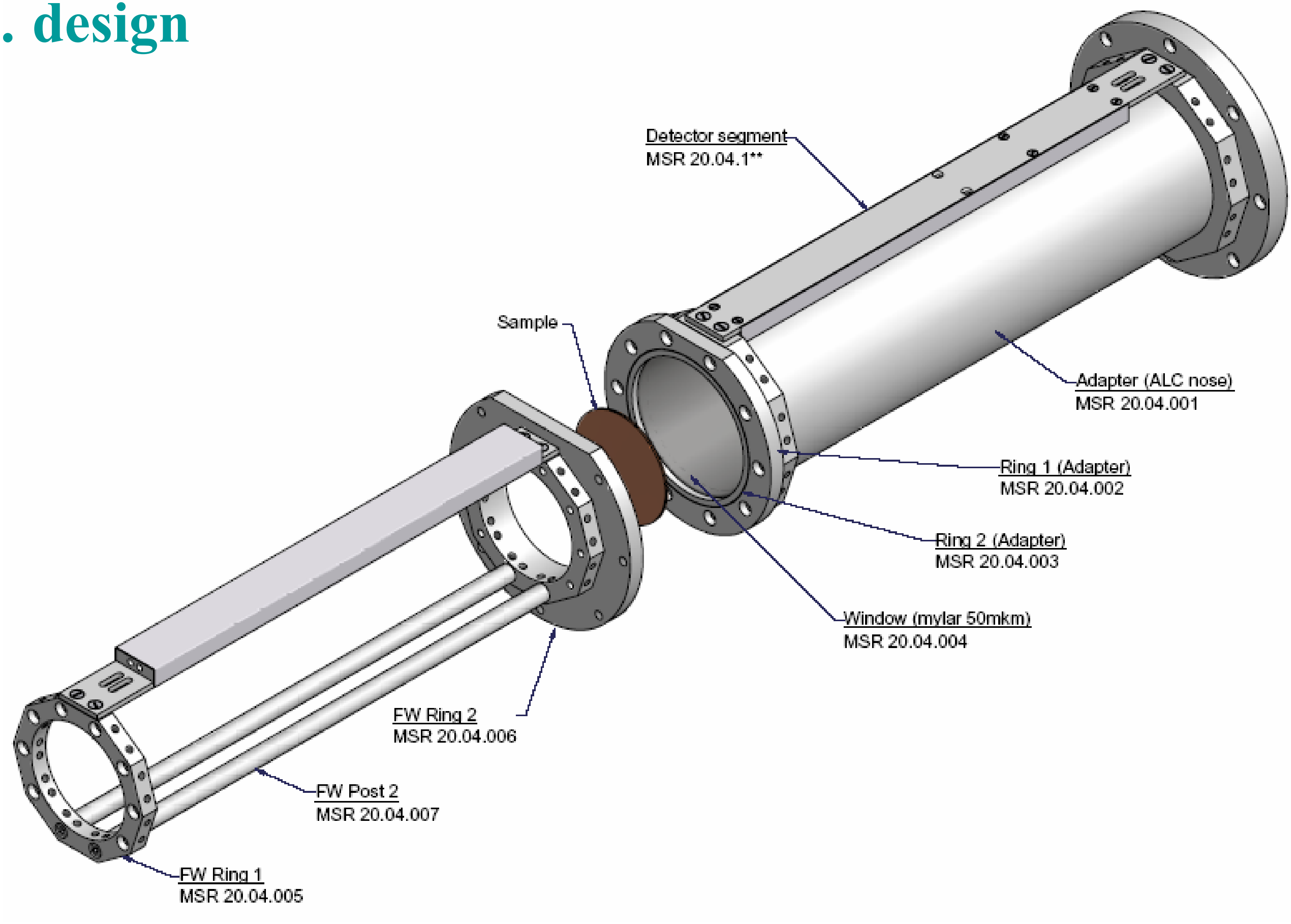
Field dependence of B and F not related to the resonance conditions:

- **variation of the PMT gain;**
- **muon beam spot movement and oscillations (studied by BPM);**
- variation of the counters solid angle due to the altered positron trajectories → to study (and possibly improve): **a versatile detector system is needed !!!**

Flexibility in the detector design → G-APD based detector technology

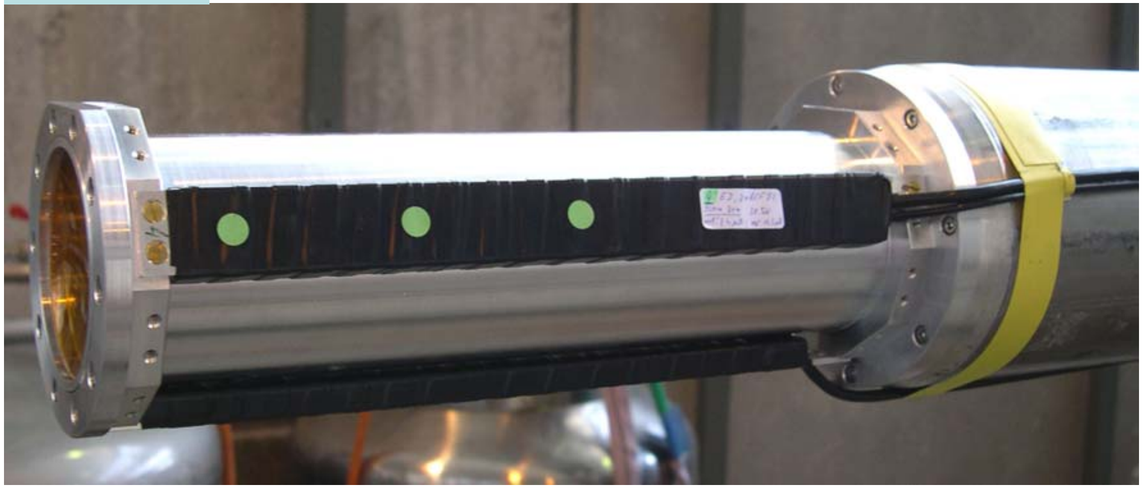
Prototype of the new ALC detector

… design

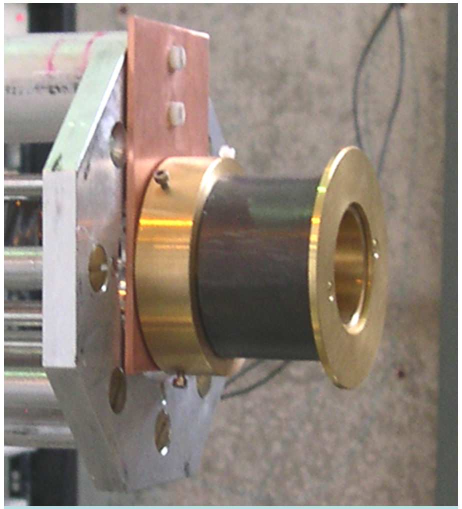


… implementation

BW ring



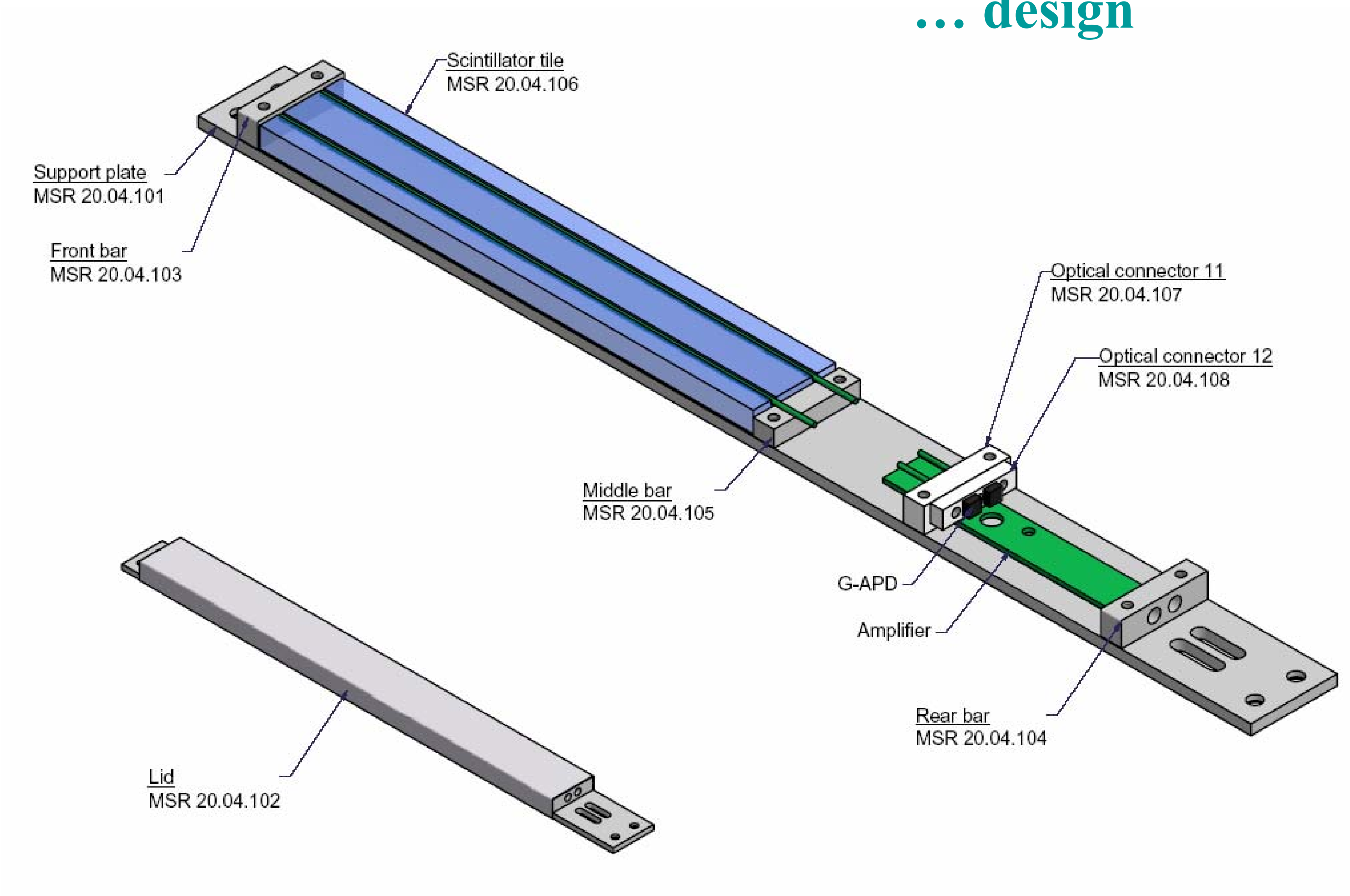
FW ring, sample



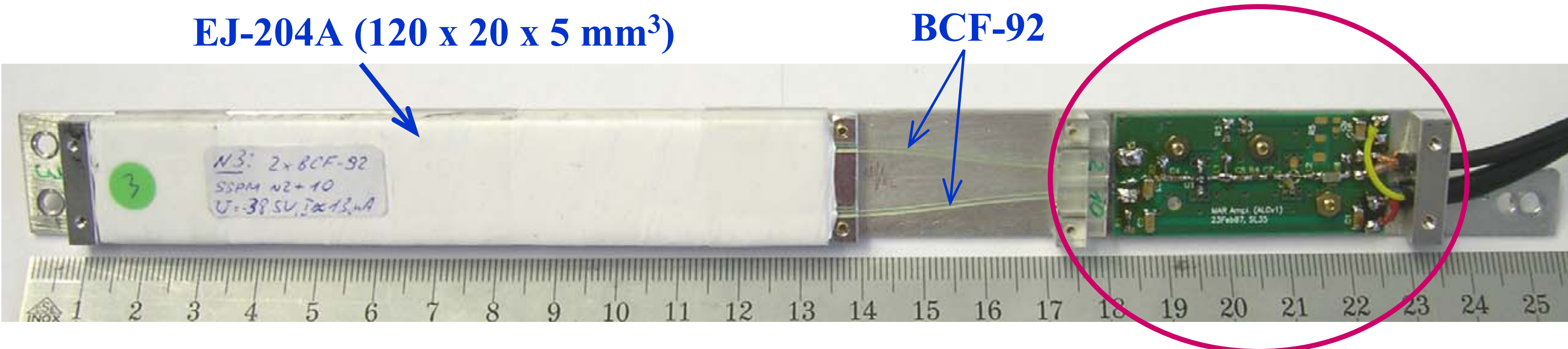
“BW collimator”

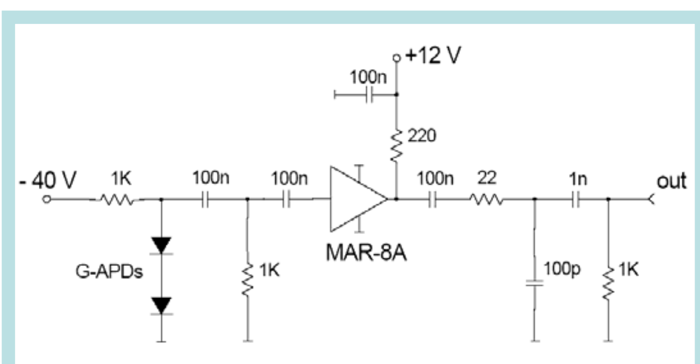
Detector module

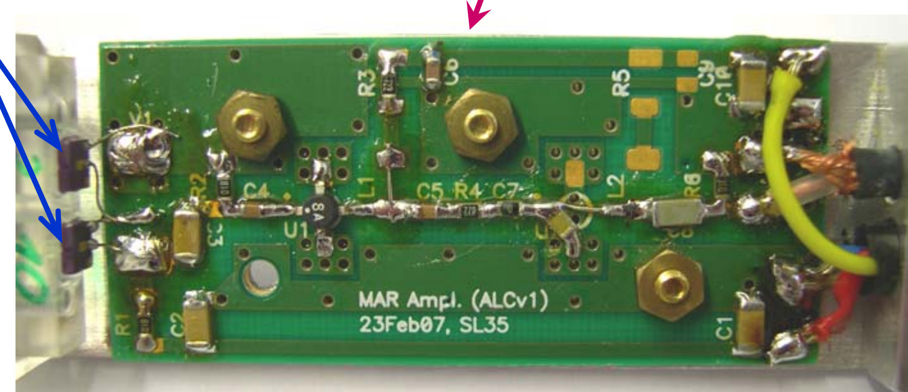
… design



…implementation





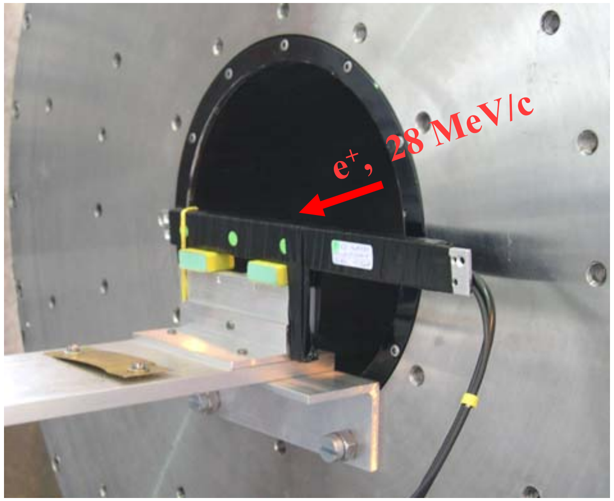


Amplifier: gain ~ **20**, bw ~ **100 MHz**

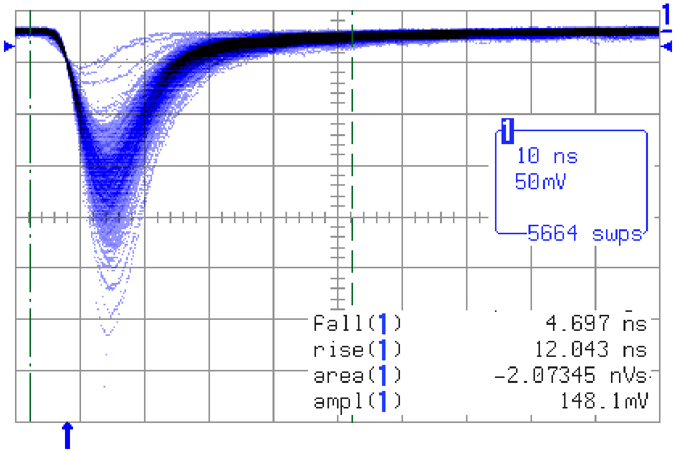
Response to MIPs, rate capabilities

(measured with 28 MeV/c beam positrons)

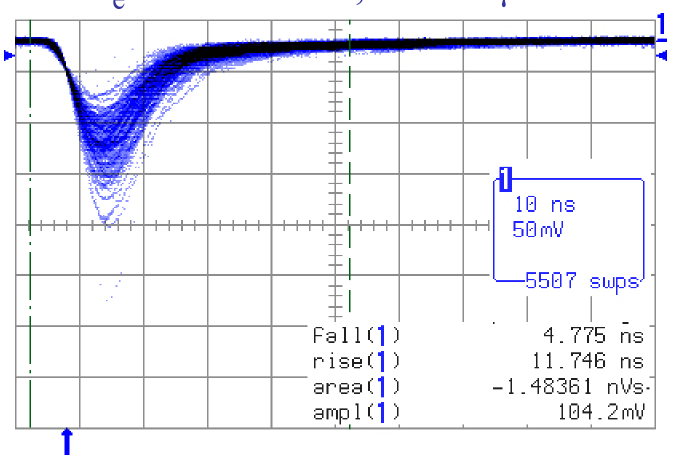
Depend on: 1) recovery time a single G-APD cell;
2) number of cells in the G-APD (576);
3) signal amplitude (~100 phe).



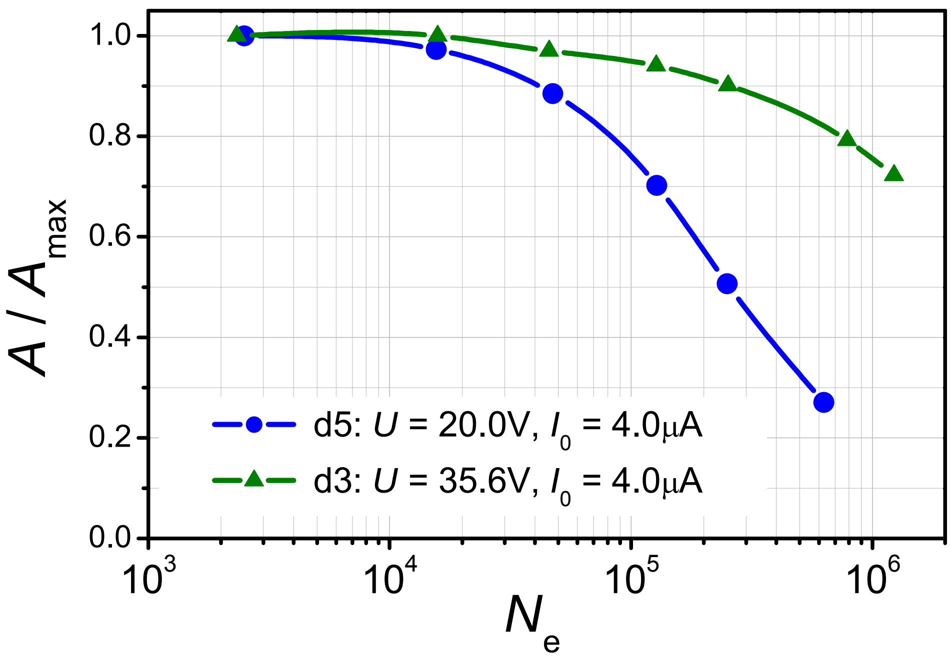
d5: N_e = **$2.3 \cdot 10^3$ s^{-1}**, I = 4.0μA



d5: N_e = **$1.3 \cdot 10^5$ s^{-1}**, I = 6.2μA



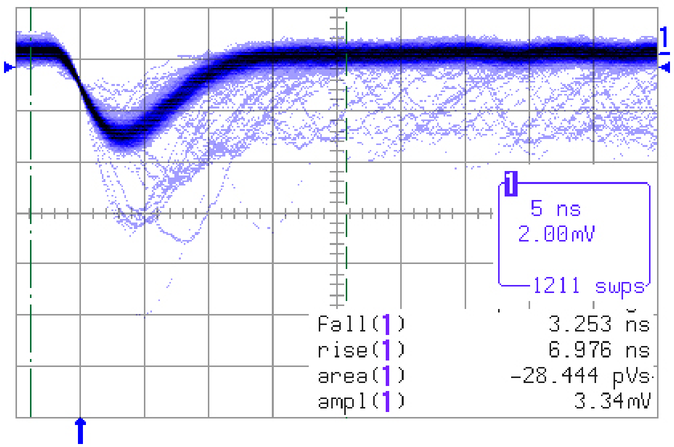
d5 (**1** fiber + **1** SSPM) **d3** (**2** fibers + **2** SSPMs)



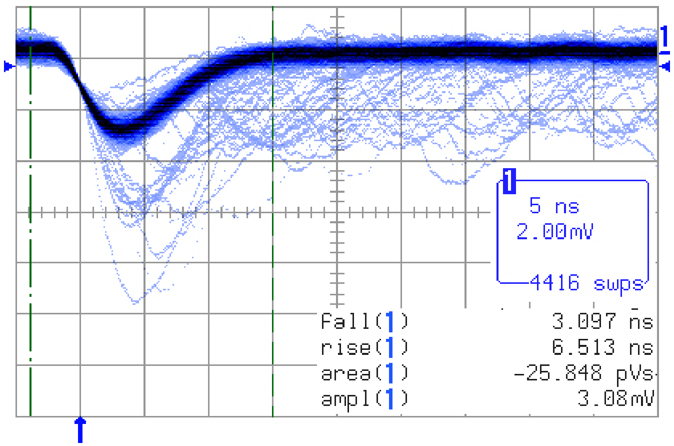
Gain vs. magnetic field

G-APD + amplifier gain -- 1e- signals

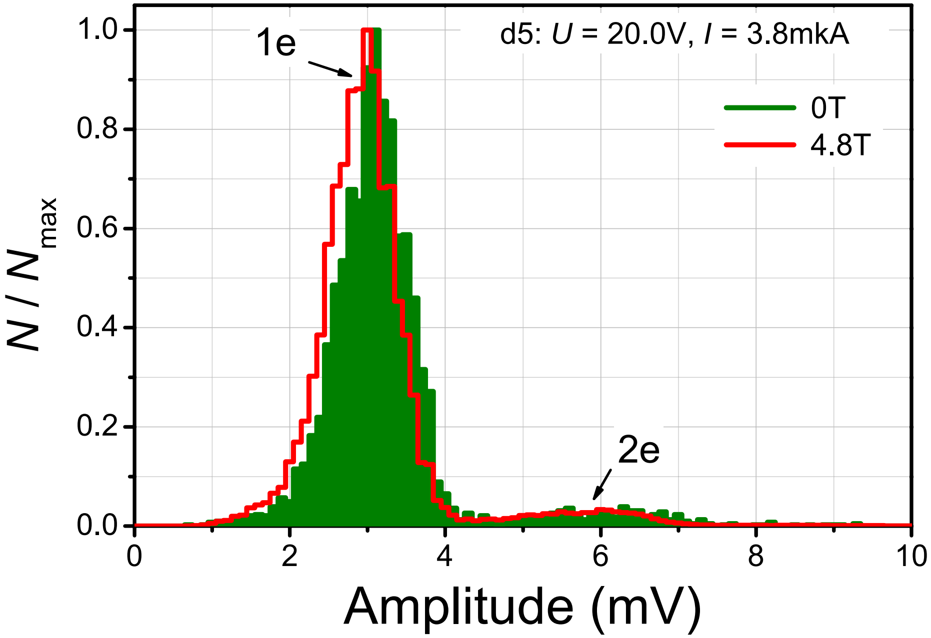
H = 0 T



H = 4.8 T



d5: 1 x SSPM, 20.0V, 3.8μA



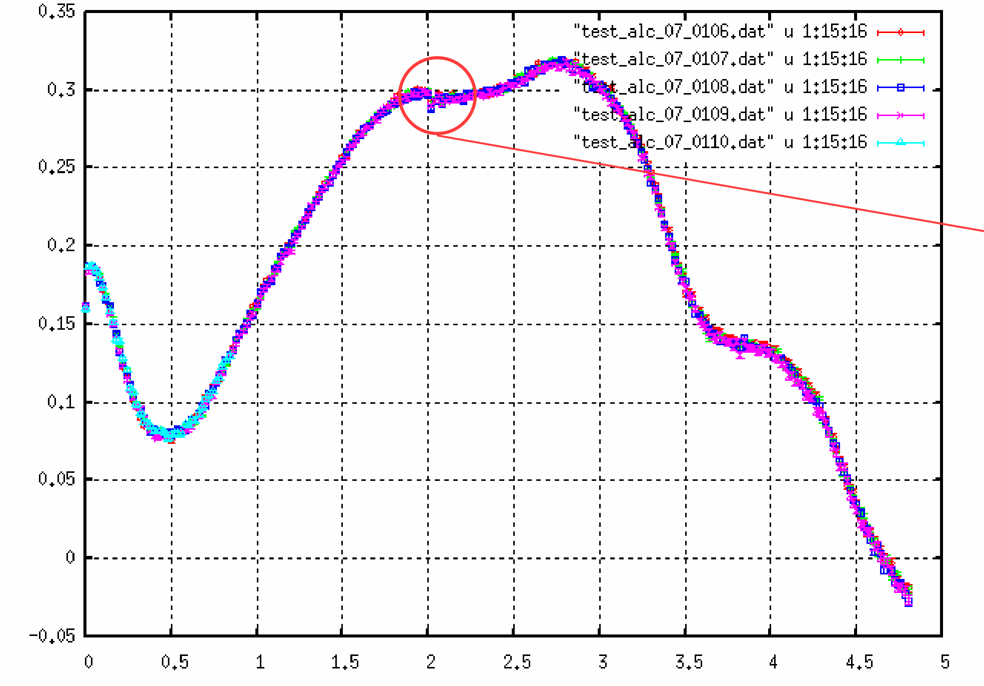
<10% change of the detector gain at H = 4.8 T is determined by the amplifier

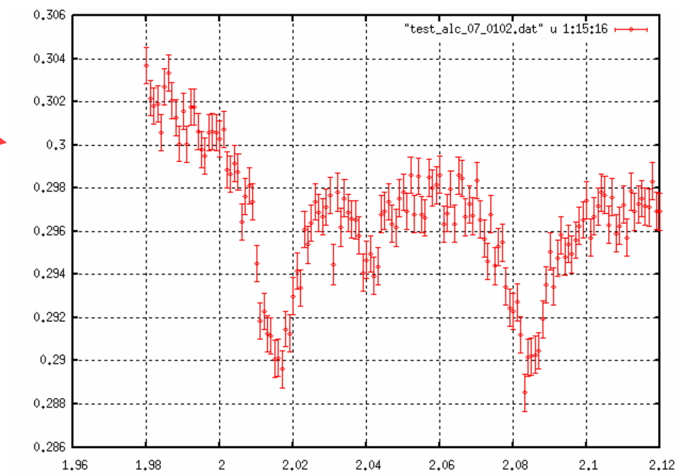
[NIM A 567 (2006) 246]

Performance stability and reproducibility of the data

PEA/Water with “BW collimator”

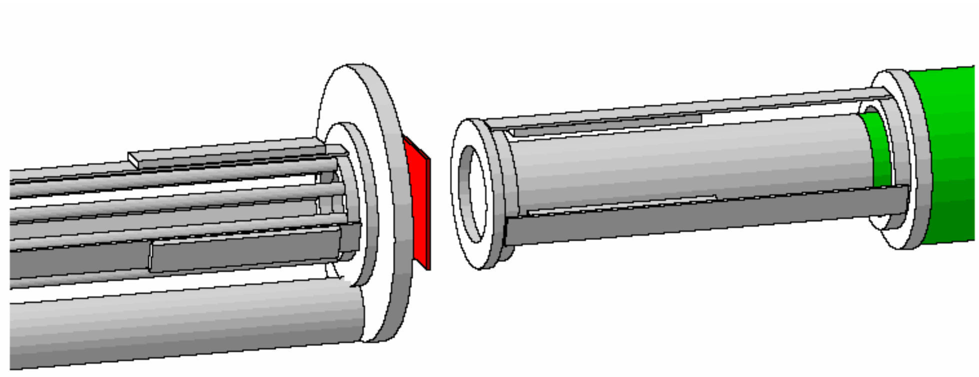
5 scans, ~ 12 hours

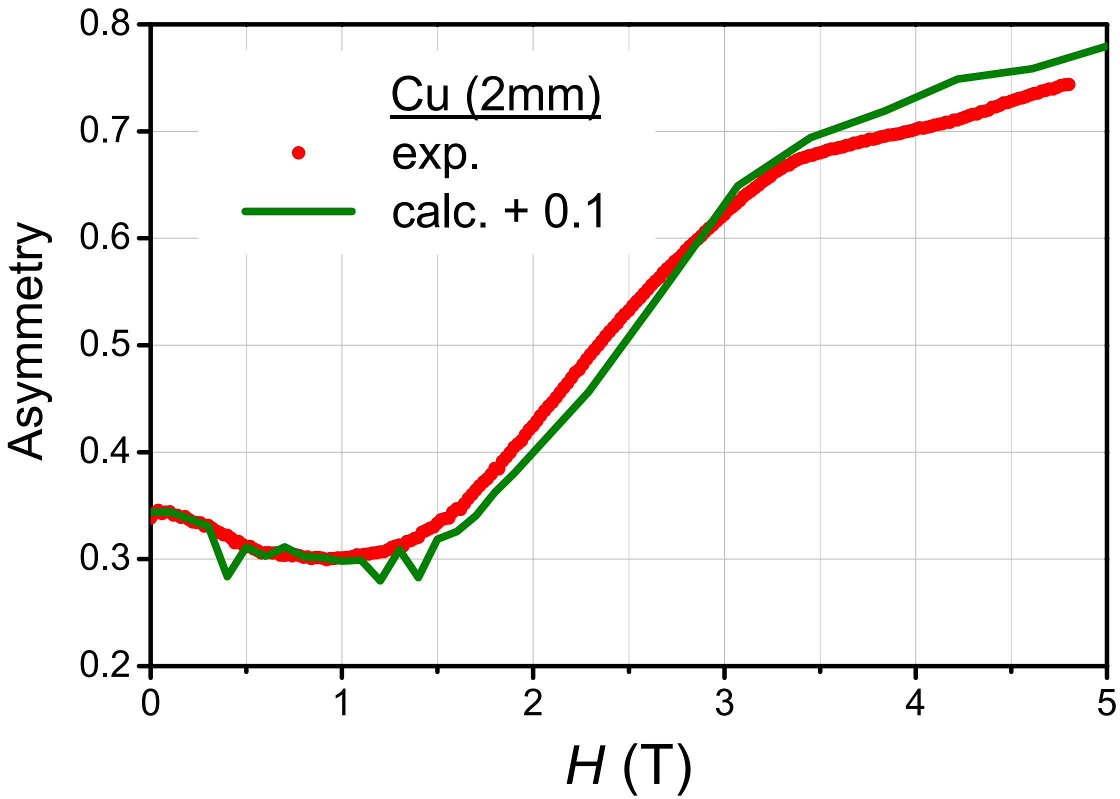




Experimental data vs. GEANT-4 simulations

T. Shiroka & K. Sedlak





Summary (new detector for ALC)

1. A prototype of the new ALC detector consisting of 6 detector modules with G-APD readout was build and tested under the real experimental conditions.

The G-APD based detector module shows performance satisfying the requirements to the ALC detector in terms of:

-- signal-to-noise ratio;

-- operation in high magnetic fields;

-- rate capabilities;

-- stability of the response vs. temperature variations;

-- long term stability and reliability.

2. The effect of the magnetic field on the ALC spectra (dependent on the geometry of the detector) is almost understood thanks to GEANT-4 simulations by **T. Shiroka** and **K. Sedlak**.

From the prototype to the new ALC detector:

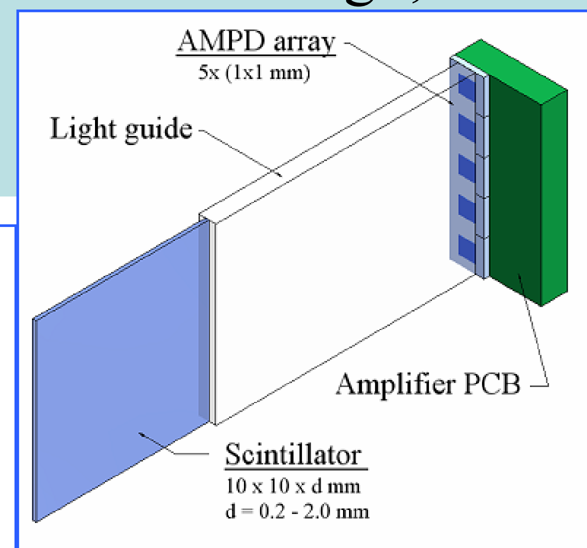
1. GEANT-4 simulations to find an optimal detector geometry (two rings: diameter, length, gap between the rings) – July 2007;
2. Detector design – August 2007;
3. Production of the components and assembly of the detector modules – December 2007 – April 2008;
4. Tests – December 2007, April 2008;
5. Operation – Summer 2008.

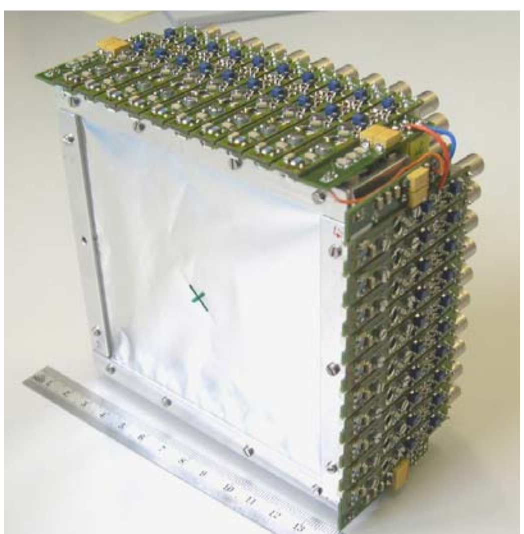
Summary (G-APD based detectors)

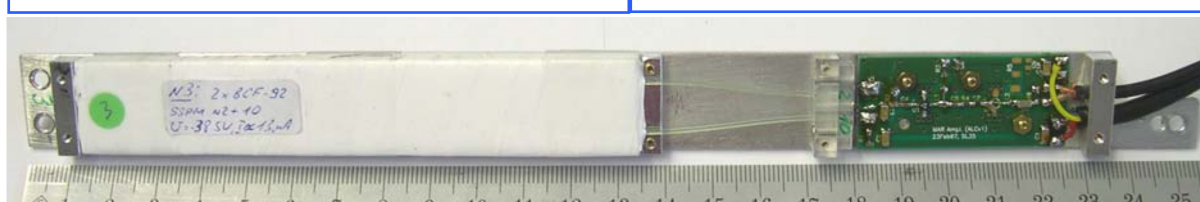
The novel G-APD based technology allows building a wide spectrum of scintillation detectors comparable in performance with the ones based on PMTs.

The main advantages of the G-APD vs. PMT based detectors are:

- compact size and higher flexibility in the detector design;
- operation in magnetic fields;
- low operation voltage.







Acknowledgements

NMI3 – Integrated Infrastructure Initiative for Neutron Scattering and Muon Spectroscopy,
Joint Research Activity (JRA8): MUON-S

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

PSI – ISIS – Univ. Oxford – Univ. Parma

grant
04-78-6839

Ultrafast position-sensitive detectors on the basis of new avalanche micropixel photodiodes with single photon detection efficiency and with high amplitude resolution for visible and UV light

Project leader: Dr. D. Renker

Acknowledgements

AMPD : **Z. Sadygov** (JINR)

SSPM : **D. McNally** (Photonique SA)

MPPC (prototypes, Hamamatsu) **:** **D. Renker** (PSI)

Consultations on G-APDs: **D. Renker,**
Yu. Musienko (CERN)

DAQ: **T. Prokscha,** **K. Gritsay** (JINR)

Electronics: **Ch. Buehler,** **U. Greuter**

Detector development & Measurements: **V. Zhuk** (JINR)

Measurements: **A. Werner** (PSI, summer student – March 2006)

Mechanical work: **M. Elender,** **R. Venturi**

Simulations of the new ALC detector: **T. Shiroka**
K. Sedlak

Publications:

[1] A.Stoykov, R.Scheuermann, T.Prokscha, Ch.Buehler, Z.Ya.Sadygov, ***A scintillating fiber detector for muon beam profile measurements in high magnetic fields***, **NIM A 550 (2005) 212.**

[2] A.Stoykov, R.Scheuermann, T.Prokscha, Ch.Buehler, Z.Ya.Sadygov, ***Study of avalanche microchannel photodiodes for use in a scintillating fiber muon beam profile monitor***, **NIM A 567 (2006) 246.**

[3] I.Britvitch, E.Lorenz, A.Olshevski, D.Renker, Z.Sadygov, R.Scheuermann, A.Stoykov, A.Werner, I.Zheleznykh, V.Zhuk, ***Study of avalanche microchannel photodiodes for use in scintillation detectors***, **JINST 1 (2006) P08002.**

[4] I.Britvitch, E.Lorenz, A.Olshevski, D.Renker, Z.Sadygov, R.Scheuermann, A.Stoykov, A.Werner, I.Zheleznykh, ***Development of scintillation detectors based on avalanche microchannel photodiodes***, **NIM A 571 (2007) 317.**

[5] R.Scheuermann, A.Stoykov, D.Renker, Z.Sadygov, V.Zhuk, R.Mehtieva, A.Dovlatov, ***Scintillation detectors for operation in high magnetic fields: recent developments based on arrays of avalanche microchannel photodiodes***, talk at the 11th Vienna Conference on Instrumentation, Feb19-24 (2007), **submitted to NIM A.**

[6] Y.Musienko, D.Renker, S.Reucroft, R.Scheuermann, A.Stoykov, J.Swain, ***Radiation damage studies of multipixel Geiger-mode avalanche photodiodes***, poster at the 11th Vienna Conference on Instrumentation, Feb19-24 (2007), **submitted to NIM A.**

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[1] A.Stoykov, R.Scheuermann, T.Prokscha, Ch.Buehler, Z.Ya.Sadygov, ***A muon beam profile monitor with scintillating fiber readout by avalanche microchannel photodiodes (AMPDs)***, **TM-35-04-01 (2004) 1-11.**

[2] V.V.Zhuk, A.V.Stoykov, R.Scheuermann, ***Light collection efficiency from thin plastic scintillators***, **TM-35-05-01 (2005) 1-7.**

[3] A.V.Stoykov, R.Scheuermann, Z.Ya.Sadygov, V.V.Zhuk, ***Study of avalanche microchannel/micropixel photodiodes (AMPDs) as photodetectors for μSR spectrometers***, **TM-35-05-02 (2005) 1-6.**