NMI3 - Integrated Infrastructure Initiative for
Neutron Scattering and Muon Spectroscopy

NMI3 Meeting 26.-29.9.05
JRA8 MUON-S

WP1: Fast Timing Detectors – High Magnetic Field µSR Spectrometer Project at PSI
Status Report

R. Scheuermann & A. Stoykov

Laboratory for Muon Spin Spectroscopy, Paul Scherrer Institut, Villigen, Switzerland

Outline

- PSI high-magnetic field project
- AMPDs – properties
- Scintillating fiber module
- Muon beam profile monitor (µBPM)
  – measurements in high magnetic fields
- Commercially available fast timing detectors tested
- Thin scintillators

PSI HMFμSR - Design Specifications

Maximum magnetic field (TF): $H_{max} \sim 10$ T

Field homogeneity / stability: $\Delta H / H \leq 10^{-5}$

(over sample volume $10 \times 10 \times 2$ mm^3 for typ. 4 hrs.)

compact, max. length: $l_{max} \leq 30$ cm ?

$\Rightarrow$ split coil (warm bore, $\varnothing \approx 100$ mm)

solenoid ?

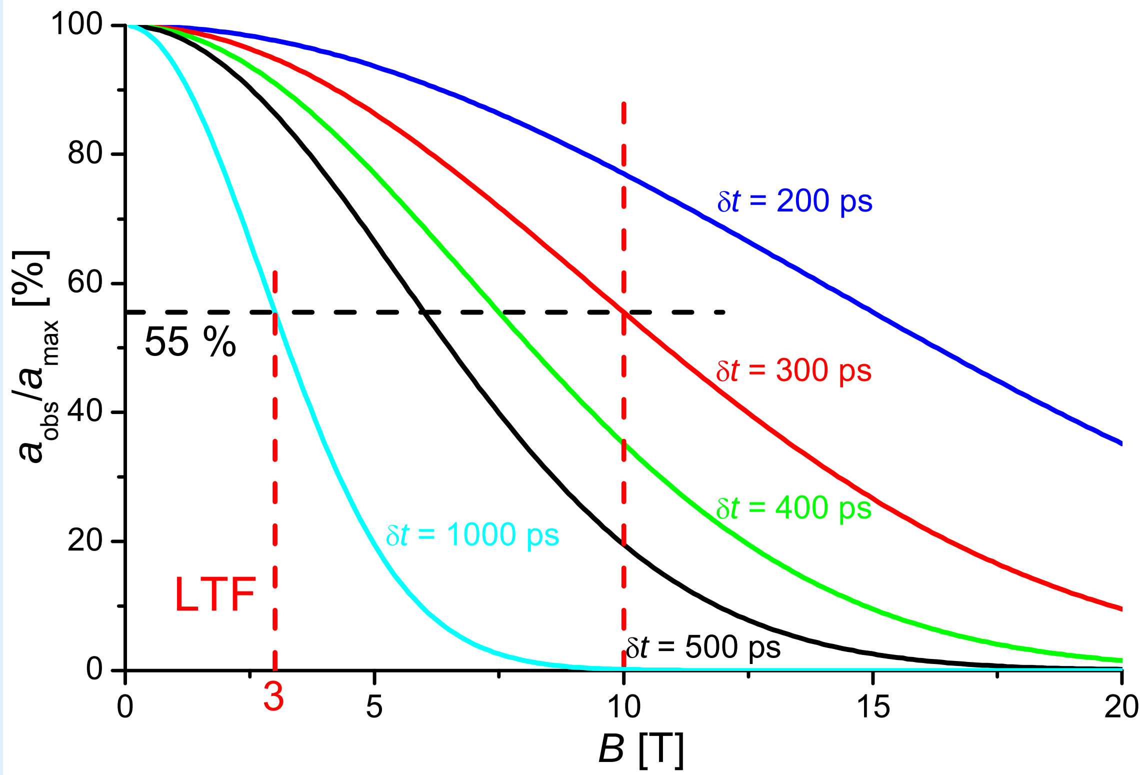
PSI HMFμSR – Time Resolution

μ^+, E_{kin} = 4.2 MeV

TF: 90° spin rotation

time resolution:
$\delta t \leq$ 300 ps (FWHM)

compact detector system: AMPDs ?
(Avalanche Microchannel Photodiodes)



PAUL SCHERRER INSTITUT

Problems / Challenges

Magnet design: length, field homogeneity & long-term stability

Stray field minimization (spin phase coherence)

Muon phase space / momentum bite

Muon beam collimation

Detector system (fast & compact)

Sample environment (incl. scintillators)

The 'real' advantages of APDs:

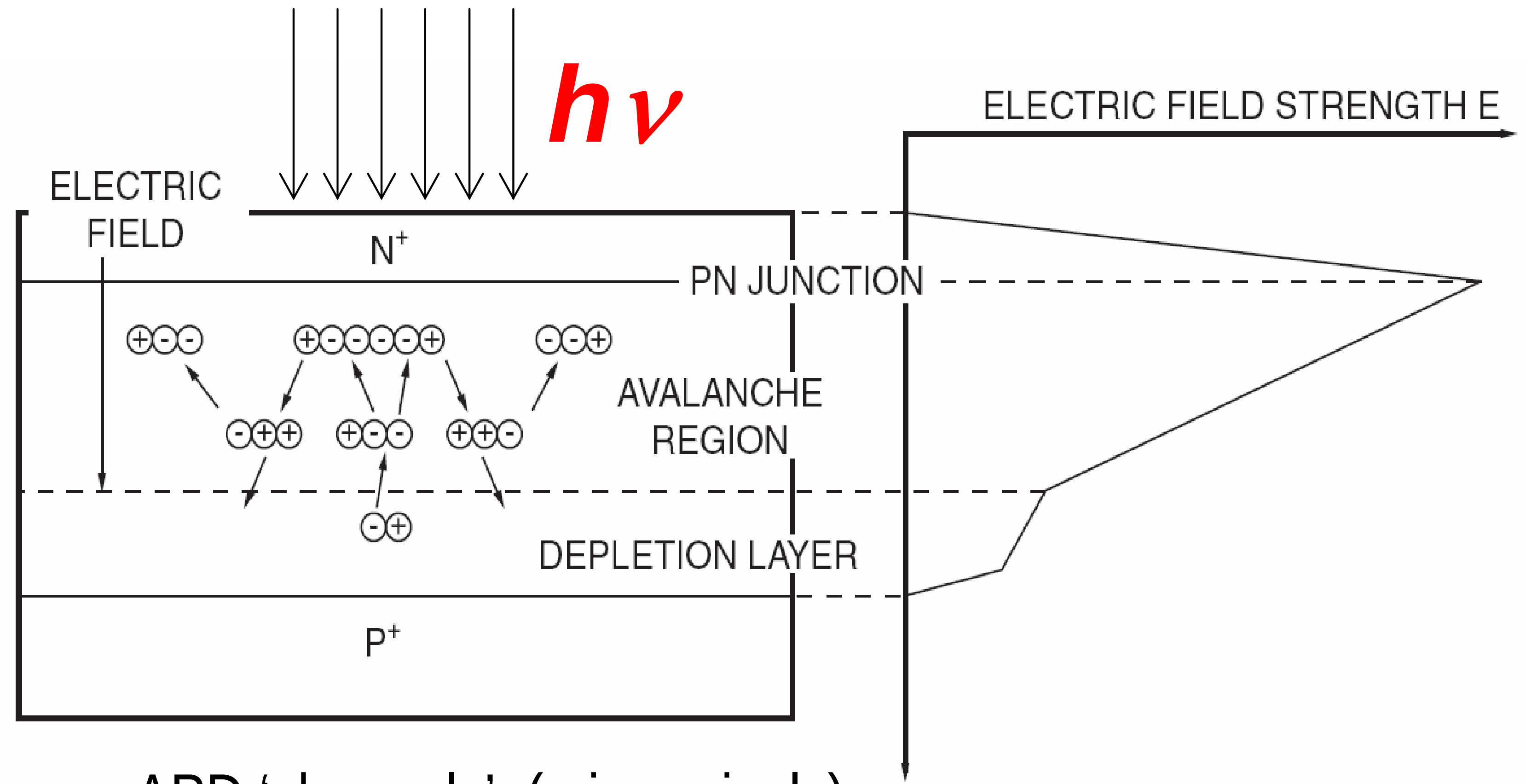
- 'cheap' (multi-segment detectors)
- 'compact'
- insensitive to magnetic fields

⟹ photodetector close to sample with best time resolution (High Magnetic Field Spectrometer)

commercially available APDs: expensive, magnetic housing, OEM, ...

- new development necessary for 'dedicated' devices:
  Protocol PSI – JINR Dubna (24/11/2004): Joint Research in the field of "Development of scintillation detectors on the base of new microchannel avalanche photodiodes" (Z. Sadygov)

APD operation principle

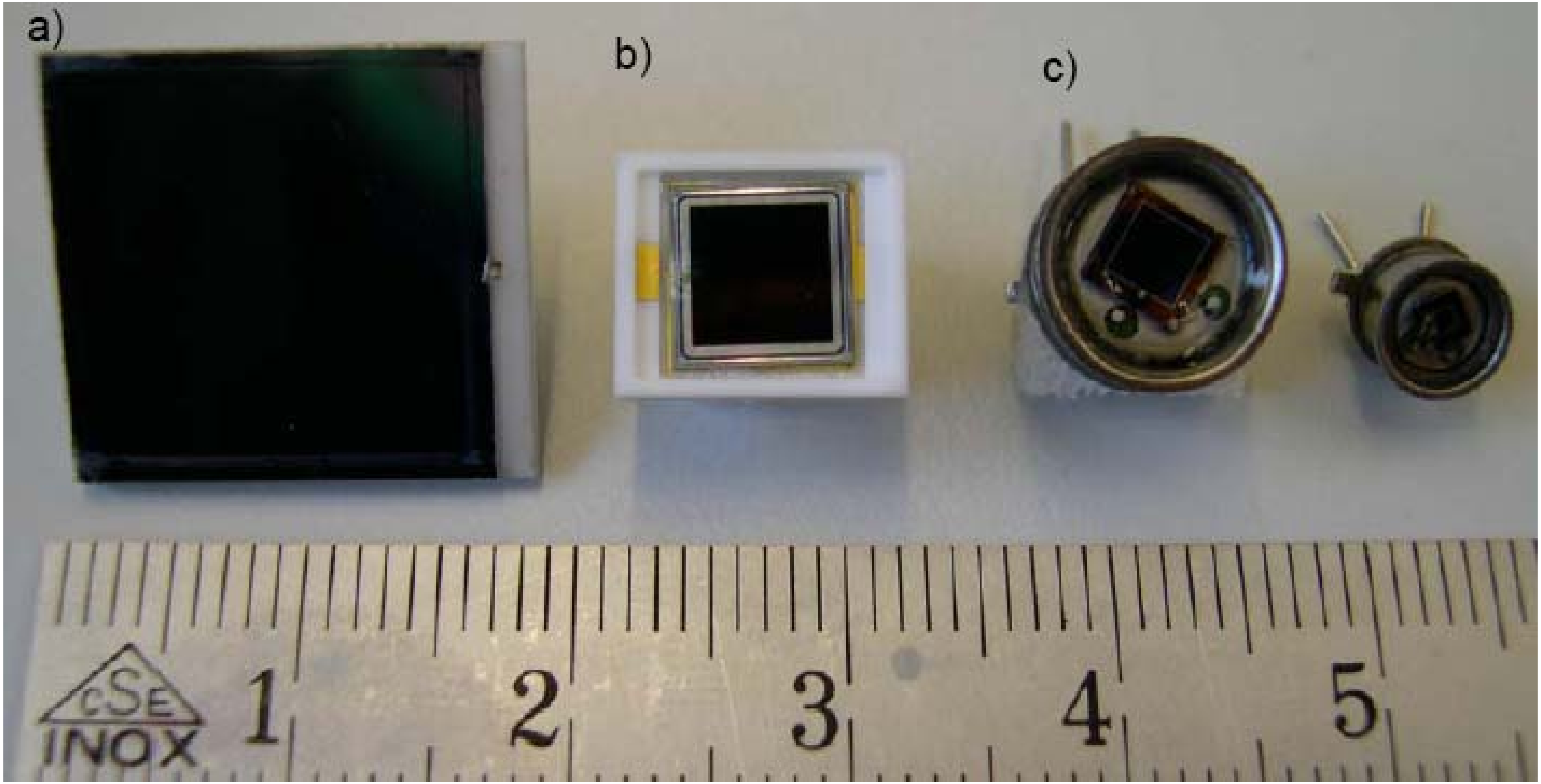


AMPD = $n \times$ APD ‘channels’ (micro-pixels)

Geiger mode (saturation, $U > U_{breakdown}$): reduction of excess noise factor at high gain

Examples of some state-of-the-art APDs:

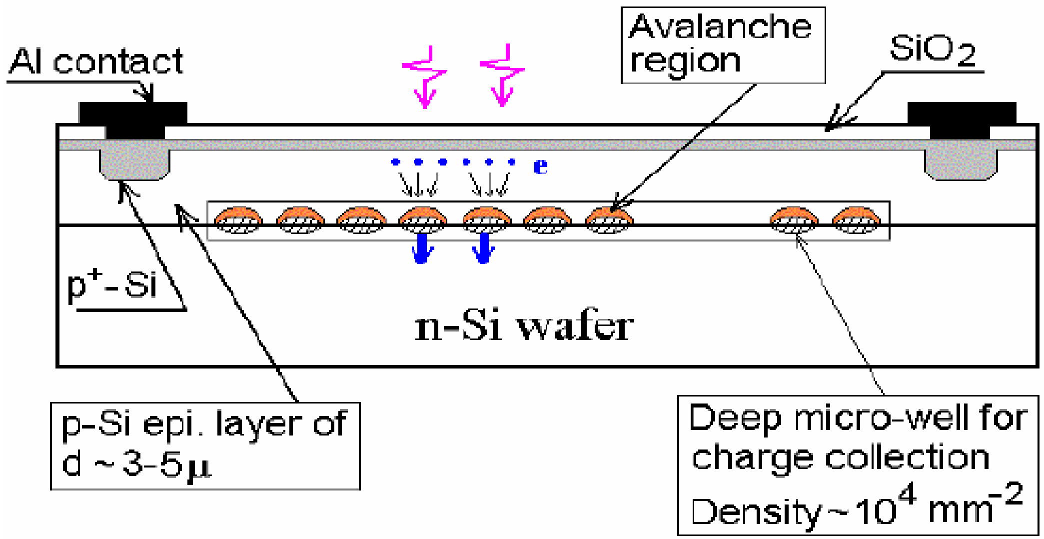
a) RMD S1315 (13 x 13 mm^2); b) Hamamatsu S8148 (5 x 5 mm^2);
c) Dubna R8 AMPDs (2.75 x 2.75 mm^2 and 0.75 x 0.75 mm^2).

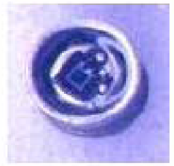


AMPD type Dubna R8

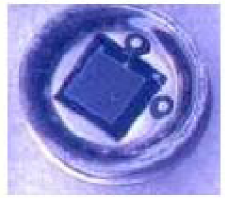
(Z. Sadygov, JINR Dubna)

An AMPD with deep micro-wells. Version # 3.





0.75mm * 0.75mm



2.8mm * 2.8mm

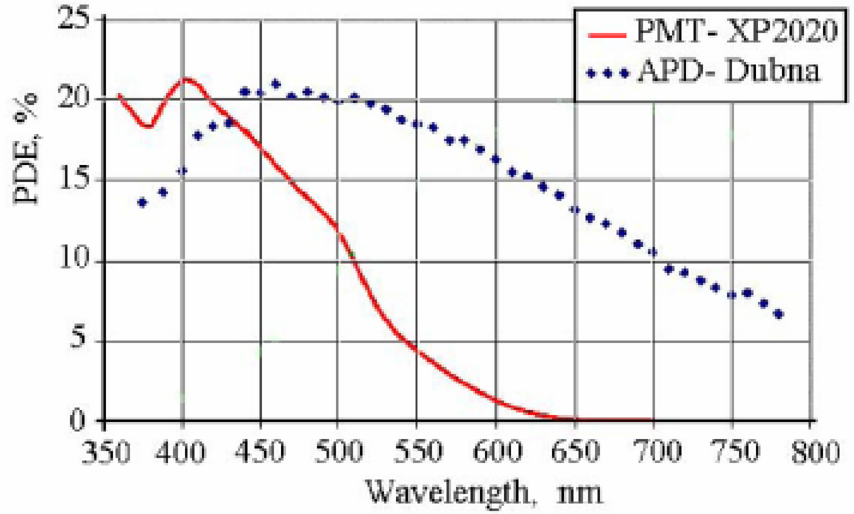
This version of AMPDs demonstrates the unique parameters:

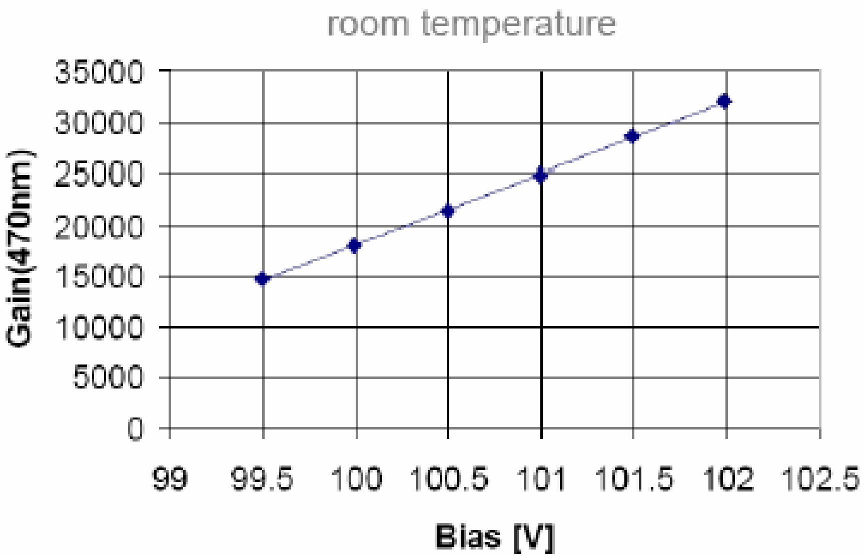
- **Geometrical transparency/active area ---------- 100%;**
- **Quantum efficiency ---------------------------------- 80%;**
- **Max. gain (today)--------------------------------------- 20 000**
- **Equivalent density of pixels ---------------------- 10 000 per mm sq.**
- **Excess noise factor ---------------------------------- 1**

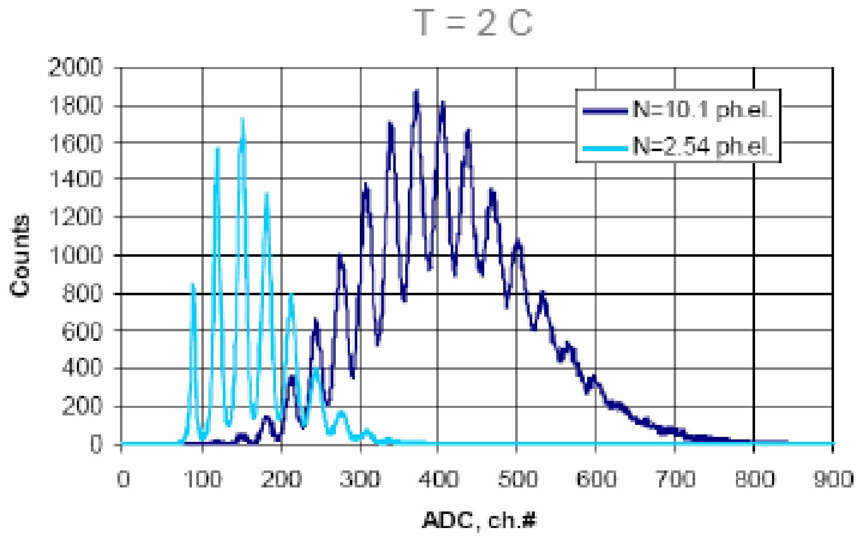
Publication: **A patent application # 2005108324 dated 24.03.2005**

Dubna R8 APD

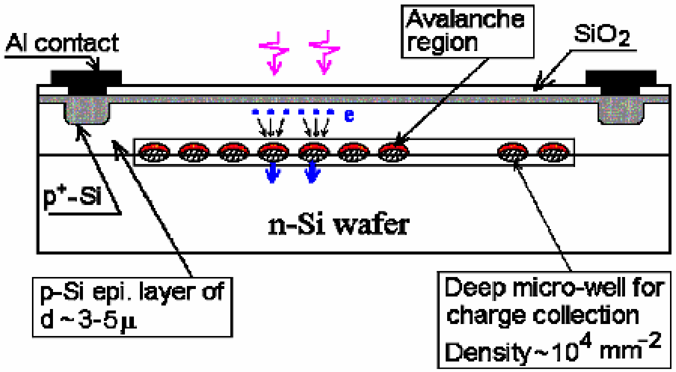
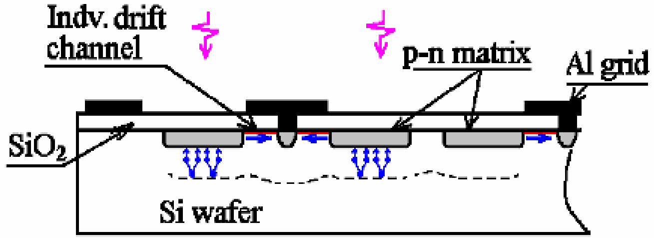
Active area:	0.75 x 0.75 mm^2
Operating voltage:	96 - 100 V
Gain:	20 000 - 30 000.
Dark Current:	20 - 30 nA (M=20 000)
Capacitance:	9 pF
Excess noise factor:	1 - 1.1







courtesy of Yu. Musienko (CERN)

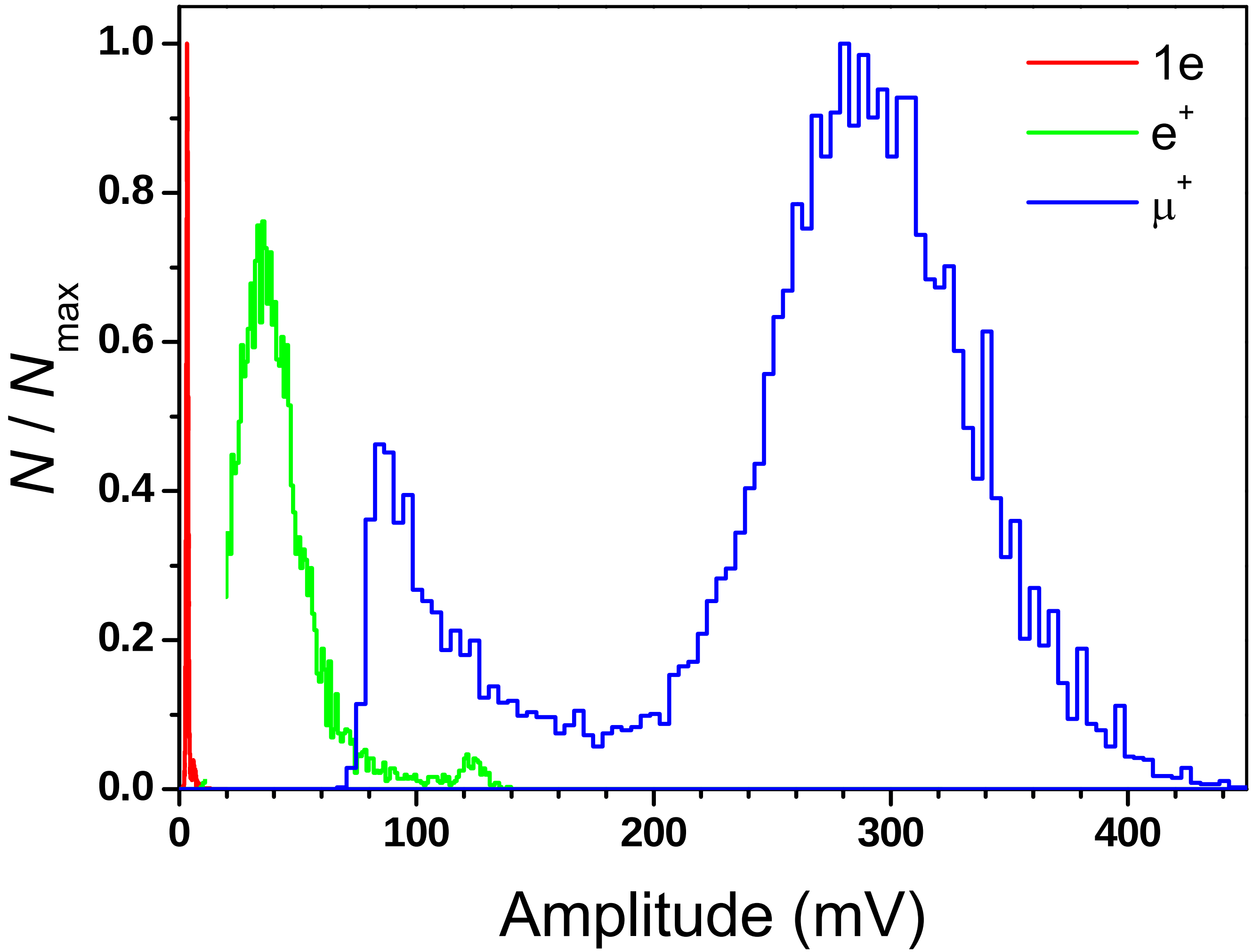
Type	Dubna R8 	Dubna ZS-2 
		
Photosensitive area	0.75 × 0.75 mm^2	1 × 1 mm^2
Density of microchannels	≈ 10^4 mm^{-2}	≈ 10^3 mm^{-2}
Photon detection efficiency	≈ 15% at 440 nm	≈ 3-5% at 380 nm
Maximum gain (M_{max})	≈ 3×10^4	≈ 2×10^6
Dark current at M_{max}	< 200 nA	≈ 1000 nA
Operating voltage	≈ 100 V	≈ 70 V

Readout from thin scintillators

(200 µm; M-counter: start signal)

EJ- 230 (Pilot U), 1 ×1 mm^2,
coupled to ZS-2

AMPD gain ~ 2×10^6
no amplifier !!!

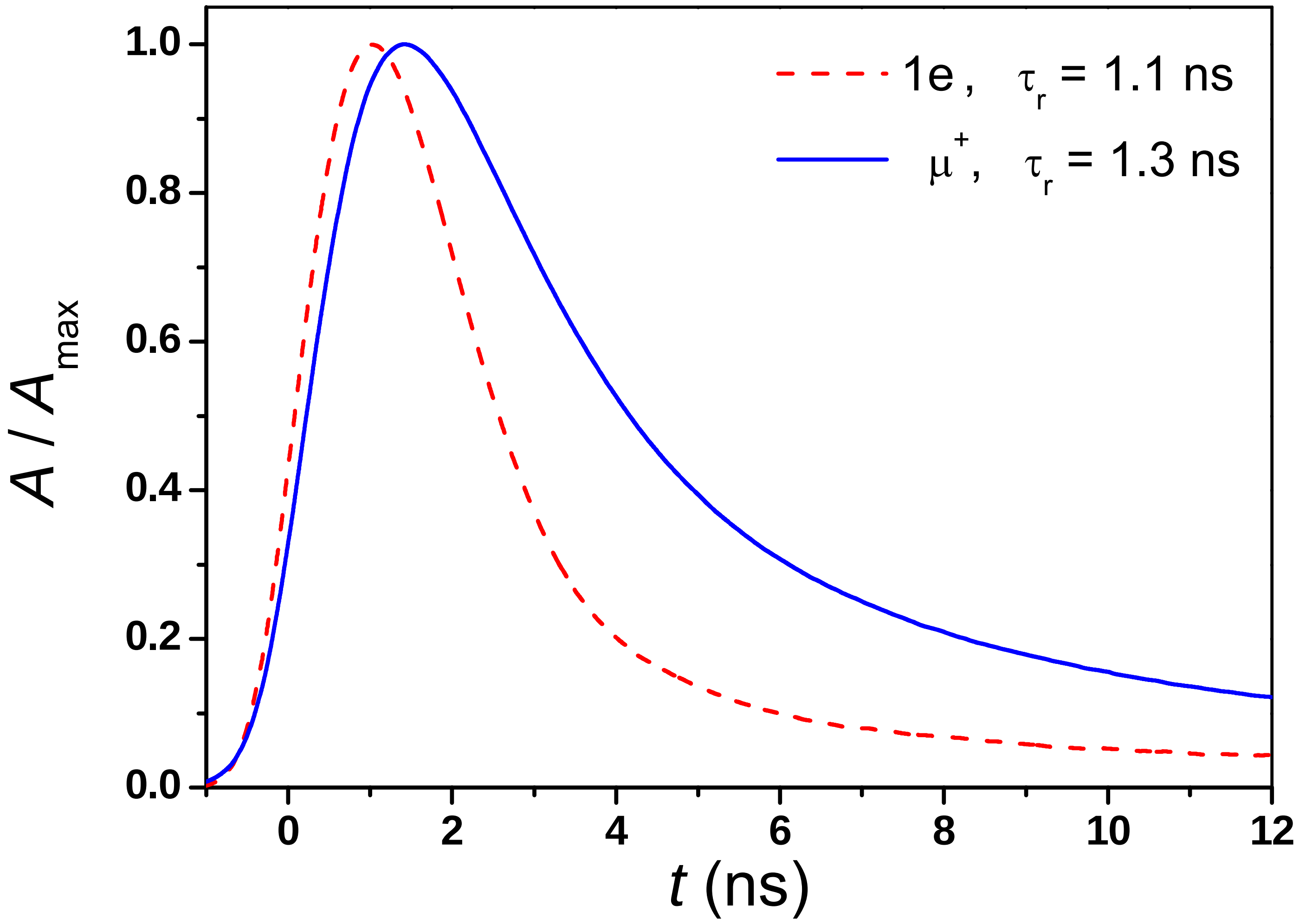


signals from µ$^+$ and e$^+$ well separated

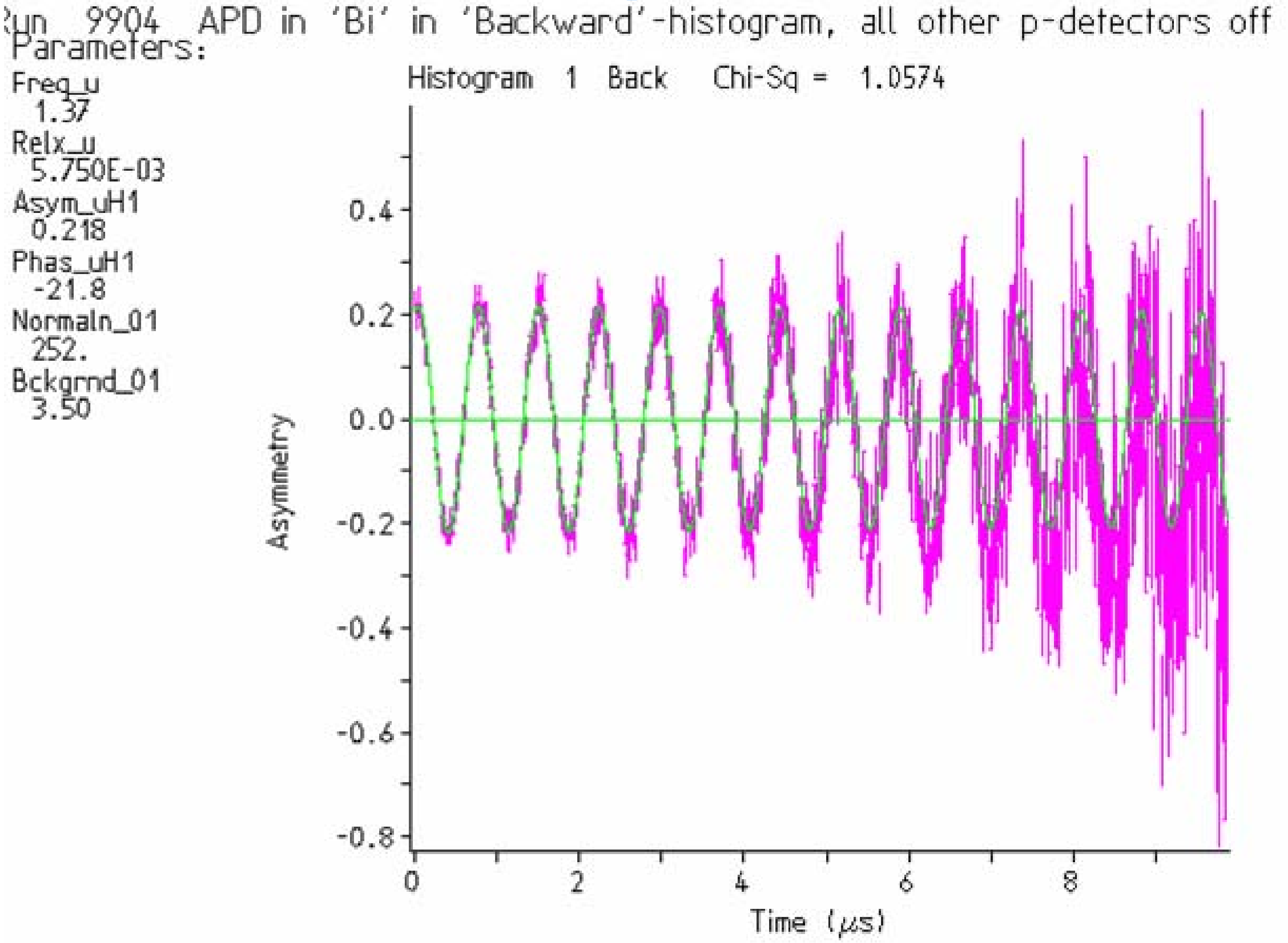
Timing properties (ZS-2)

EJ-230 specs:

τ_{rise} = 0.5 ns, τ_{fall} = 1.5 ns



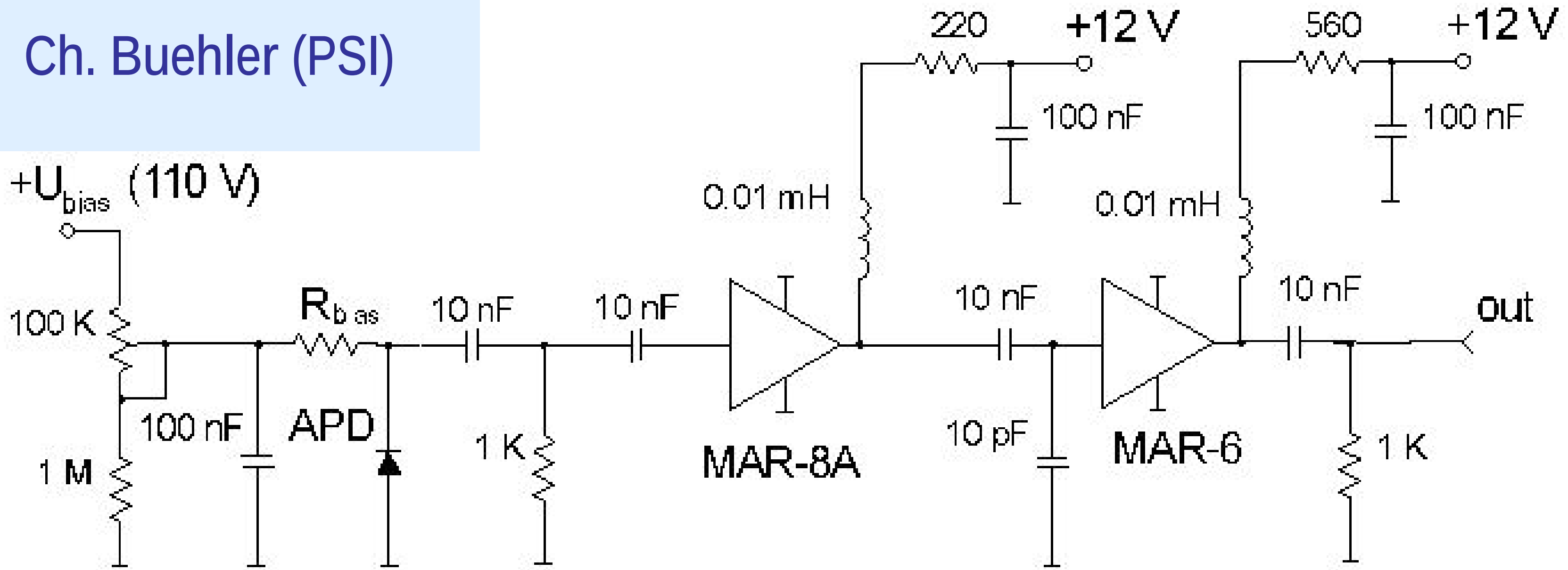
APD Hamamatsu S8148 on NE102A scintillator as positron detector:

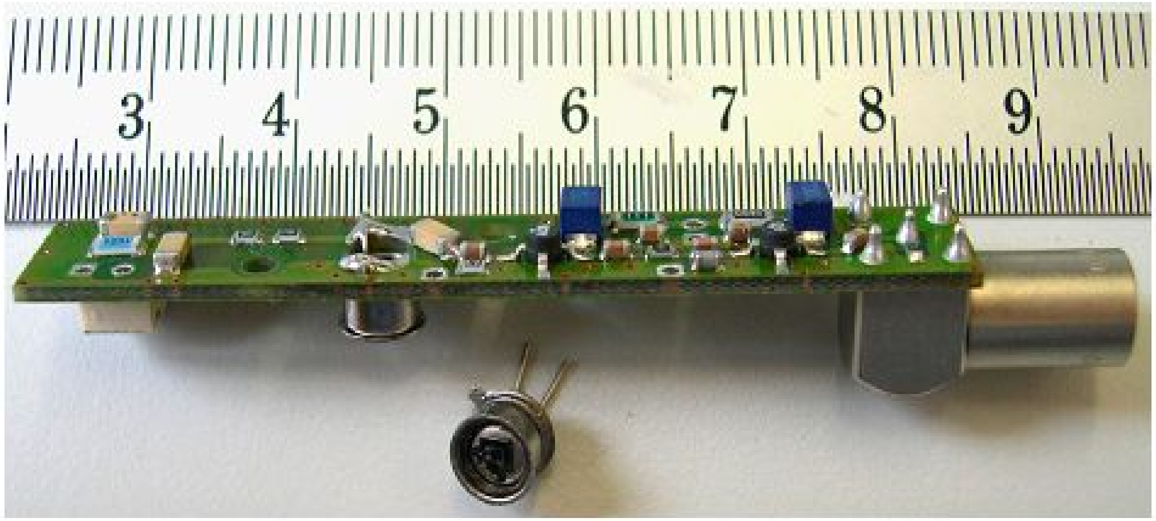


no problem to achieve 'standard' time resolution ≤ 1 ns

Scintillating Fiber Detector Module

Ch. Buehler (PSI)



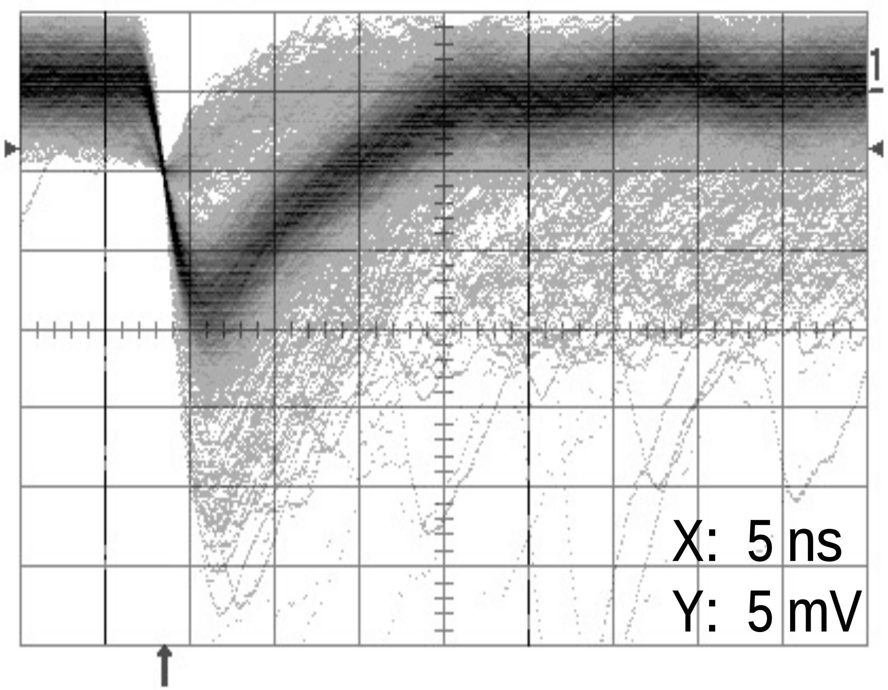


Gain: ≈250

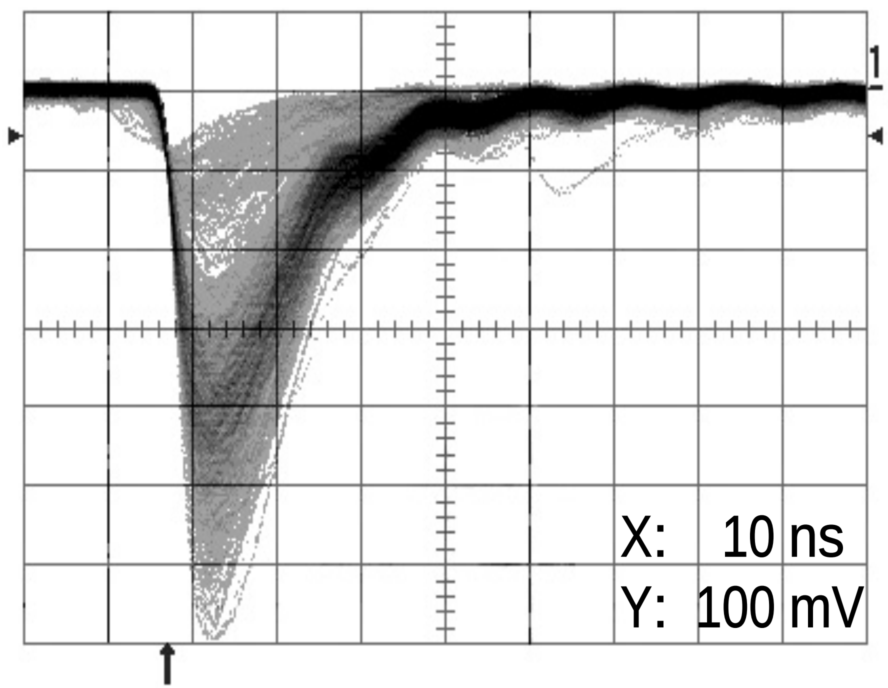
Bandwidth: ≈ 250 MHz

Rate capability:
≈ $3\times10^6\ \mu^+$ / s /channel

Scintillating Fiber Detector Module



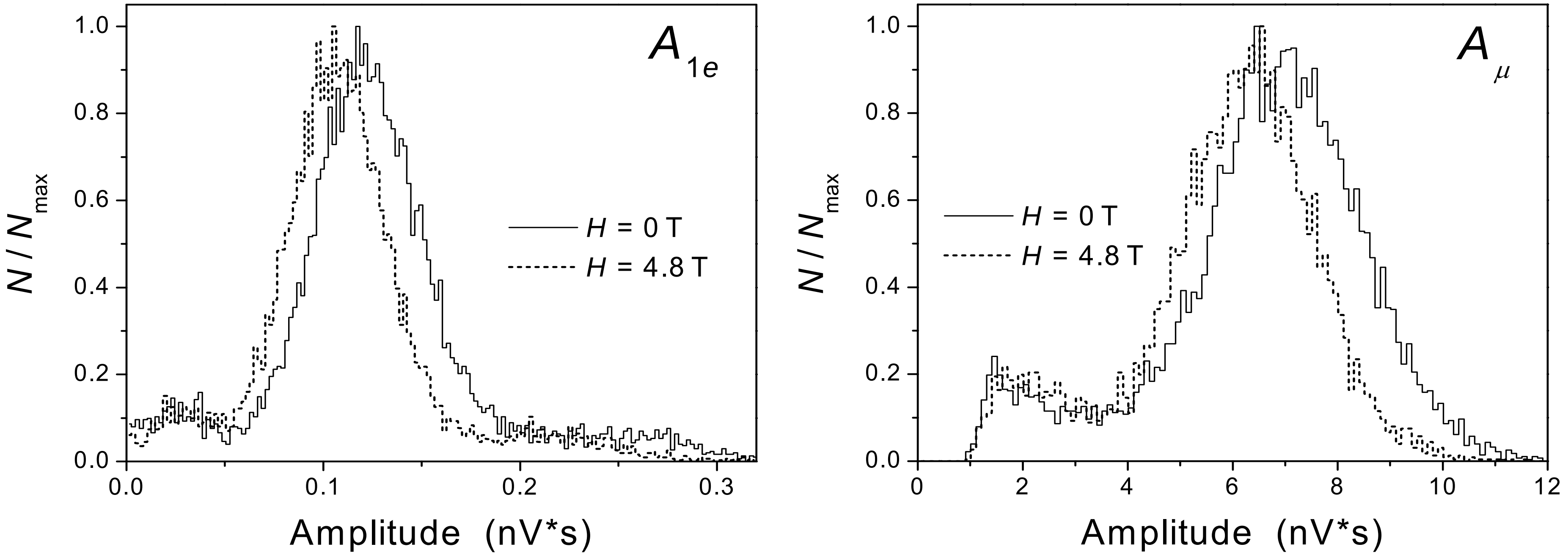
1-electron (dark) signals



Signals from 29 MeV/c muons in 1×1 mm^2 BCF-10 fiber

Scintillating Fiber Detector Module

Amplitude distributions

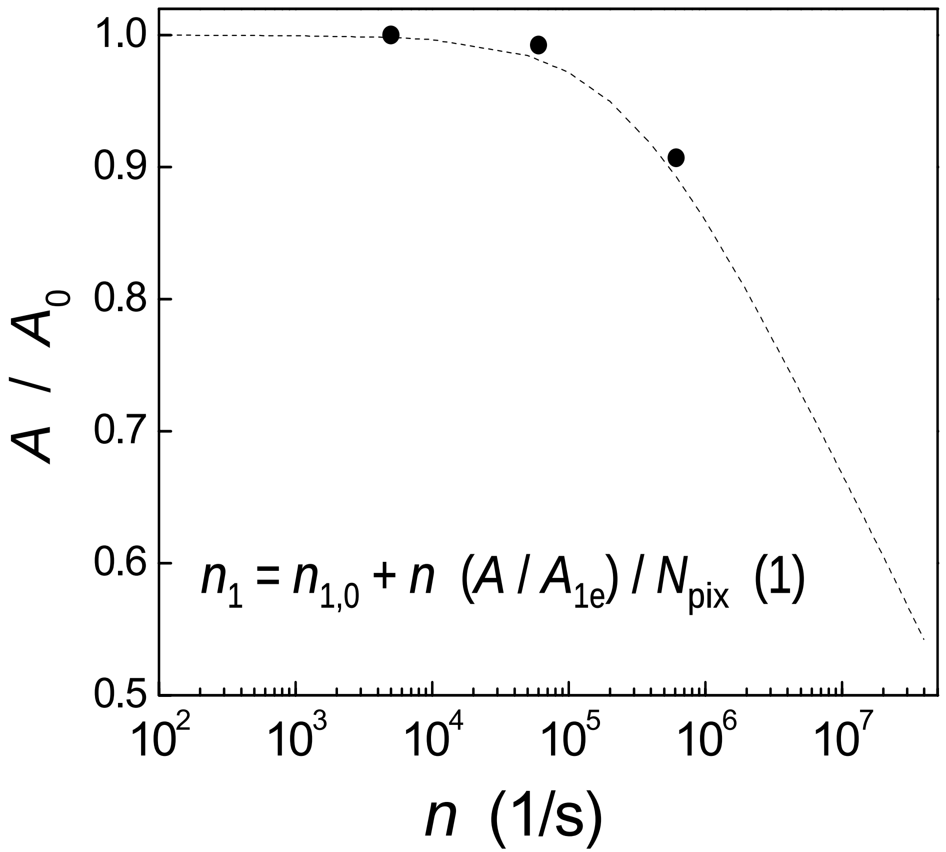


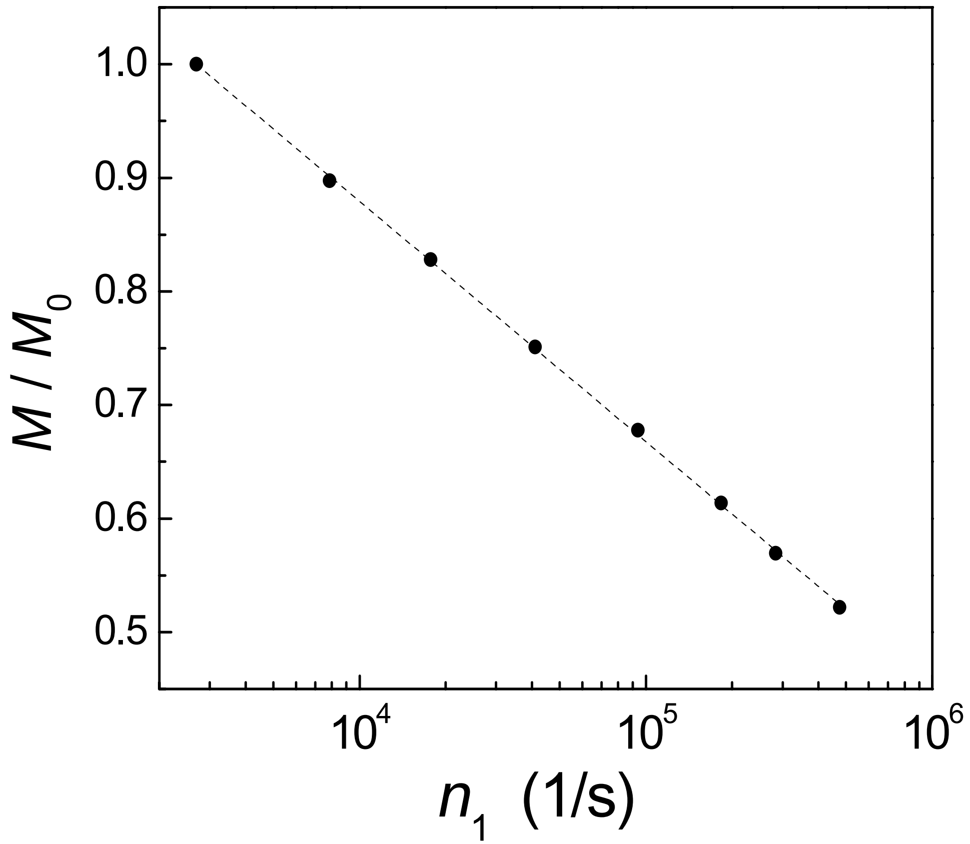
1-electron signals / muon signals

in magnetic fields of zero and 4.8 T.

The decrease (~10 %) of the signal amplitude at *H* = 4.8 T is due to the change of the ***amplifier*** performance in the magnetic field (confirmed by measurements using a pulser signal to feed the amplifier input)

Scintillating Fiber Detector Module





Muon pulse **amplitude** A as a function of **muon rate** n (A_0 = amplitude at dark count rate $n = 5{\cdot}10^3\ s^{-1}$)

Dashed line: prediction of $A(n)$ at higher rates, calculated based on eqs. (1) and (2).

Dependence of the AMPD **gain** M on the **rate per pixel** of 1e-pulses. Dashed line:

$$M / M_0 = 1 - q \ln (n_1 / n_{1,0}), \qquad (2)$$

with $n_{1,0} = 2.7{\cdot}10^3\ s^{-1}$, $q = 0.092$.

Detector Development

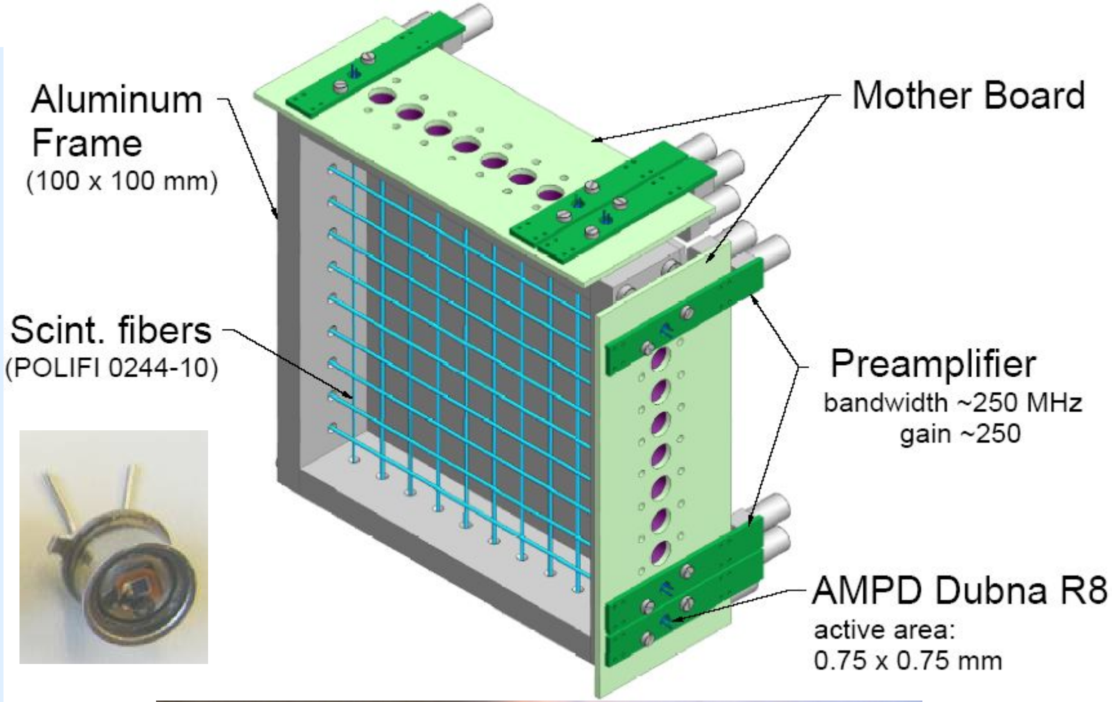
Muon beam profile monitor:

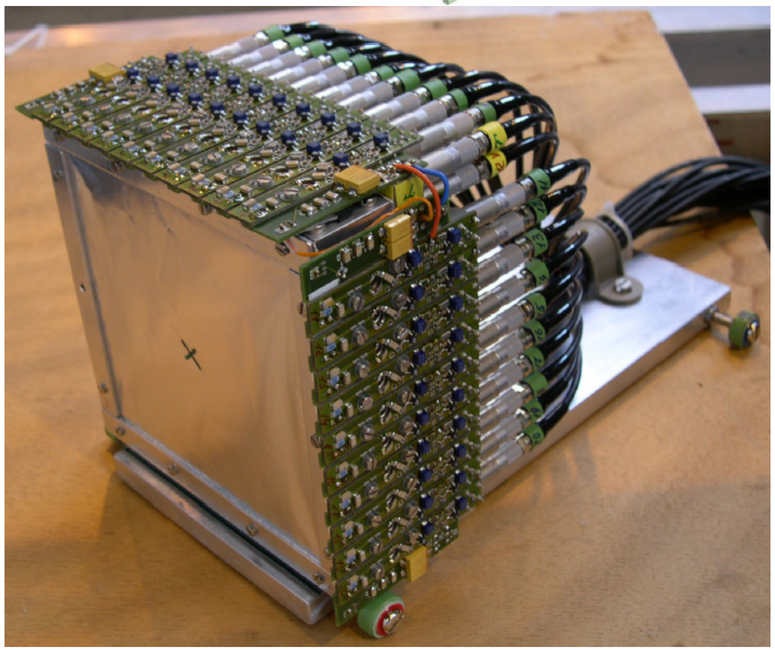
A. Stoykov *et al.*

[NIM A 550 (2005) 212]

Muon beam profile measurement
in center of ALC solenoid:

AMPDs and preamps
work fine in 5 T!



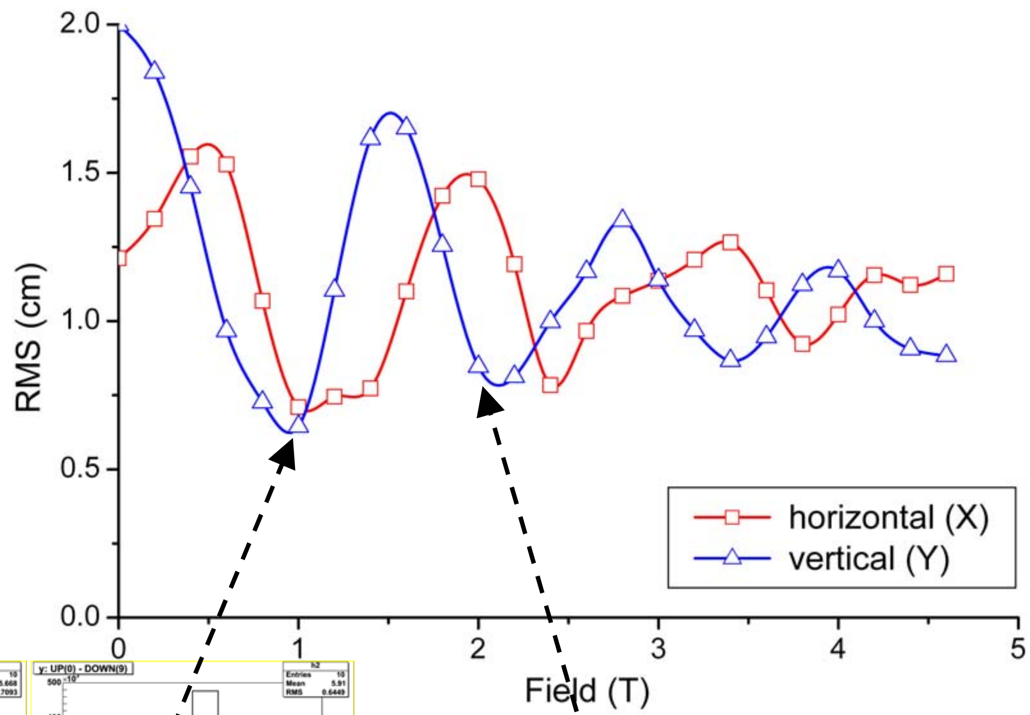


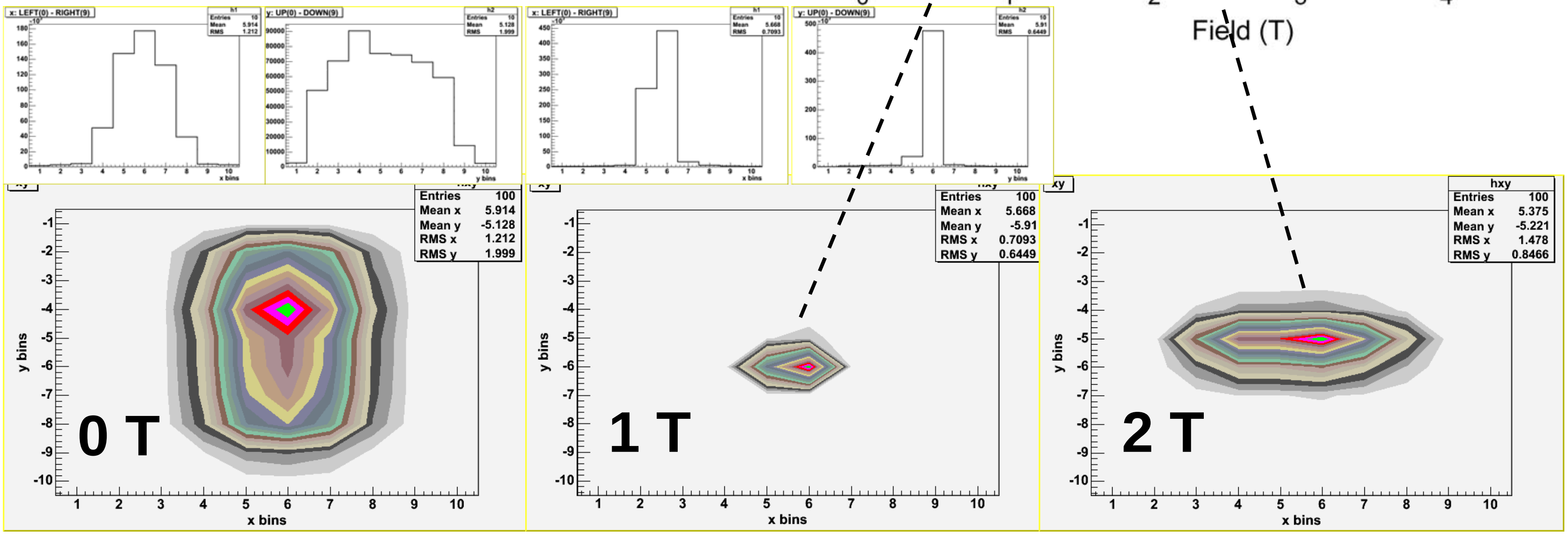
Beam Profile Measurements

Variation of muon spot size on sample

⇒ different trajectories of decay e^+ in high magnetic fields (spiraling), this affects the F-B asymmetry!

⇒ Simulations (T. Lancaster, WP2)





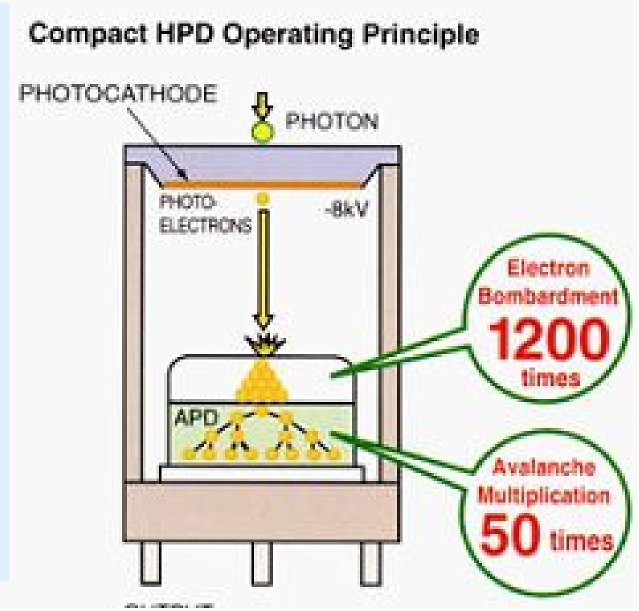
Fast-Timing Detector Development

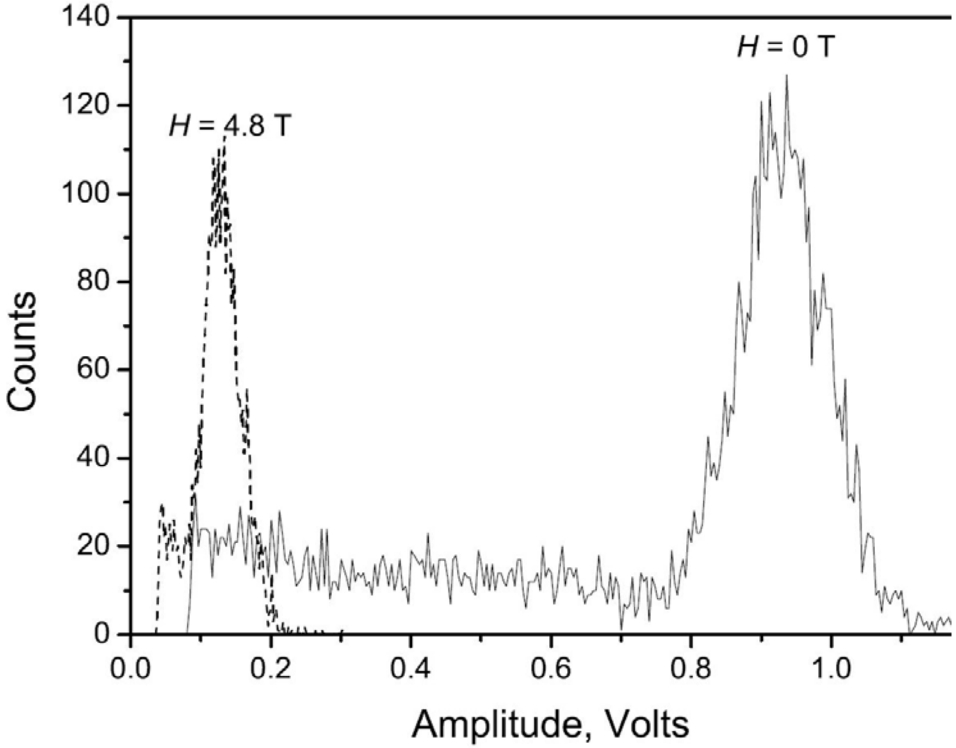
Hybrid Avalanche Photodetector Hamamatsu R7110U-07:

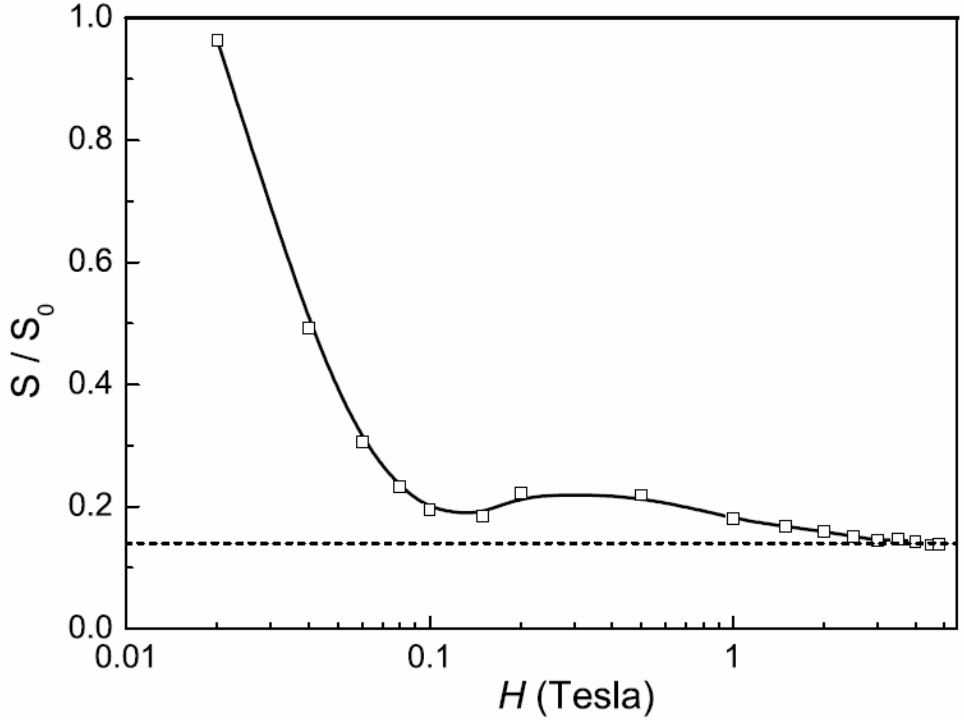
combination PMT+APD

electrostatic focussing lost above 1 kG // axis: decrease of signal amplitude

excellent timing properties (rise time): no change !







Multianode-MCP PMTs

BURLE PLANACON™ 85001-501

4 channels

good timing properties, but severe cross-talk, bulky, not user-friendly

quantum efficiency × collection efficiency ≈ 10% (PMT XP2020: 28%)…

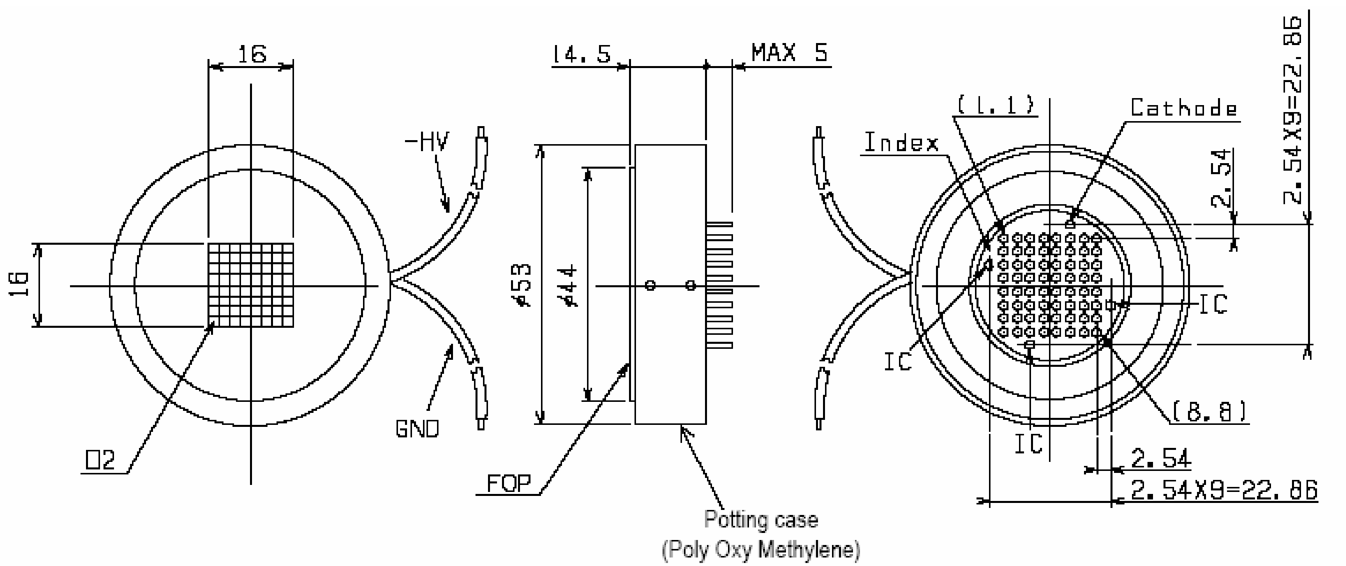
insufficient gain: only 5×10^5

Multipixel HPD

Hamamatsu R9503U-04-M064

8x8 pixels, 16x16 mm^2 eff. area
– (25 kSFr…)

Tests planned 12/2005



Thin scintillators

Study the light collection from thin plastic scintillators

Motivation

One of the most important issues in fast timing experiments is efficient collection of light from the scintillator to the photosensor (significant light losses might occur in the scintillator itself and in the light guides).

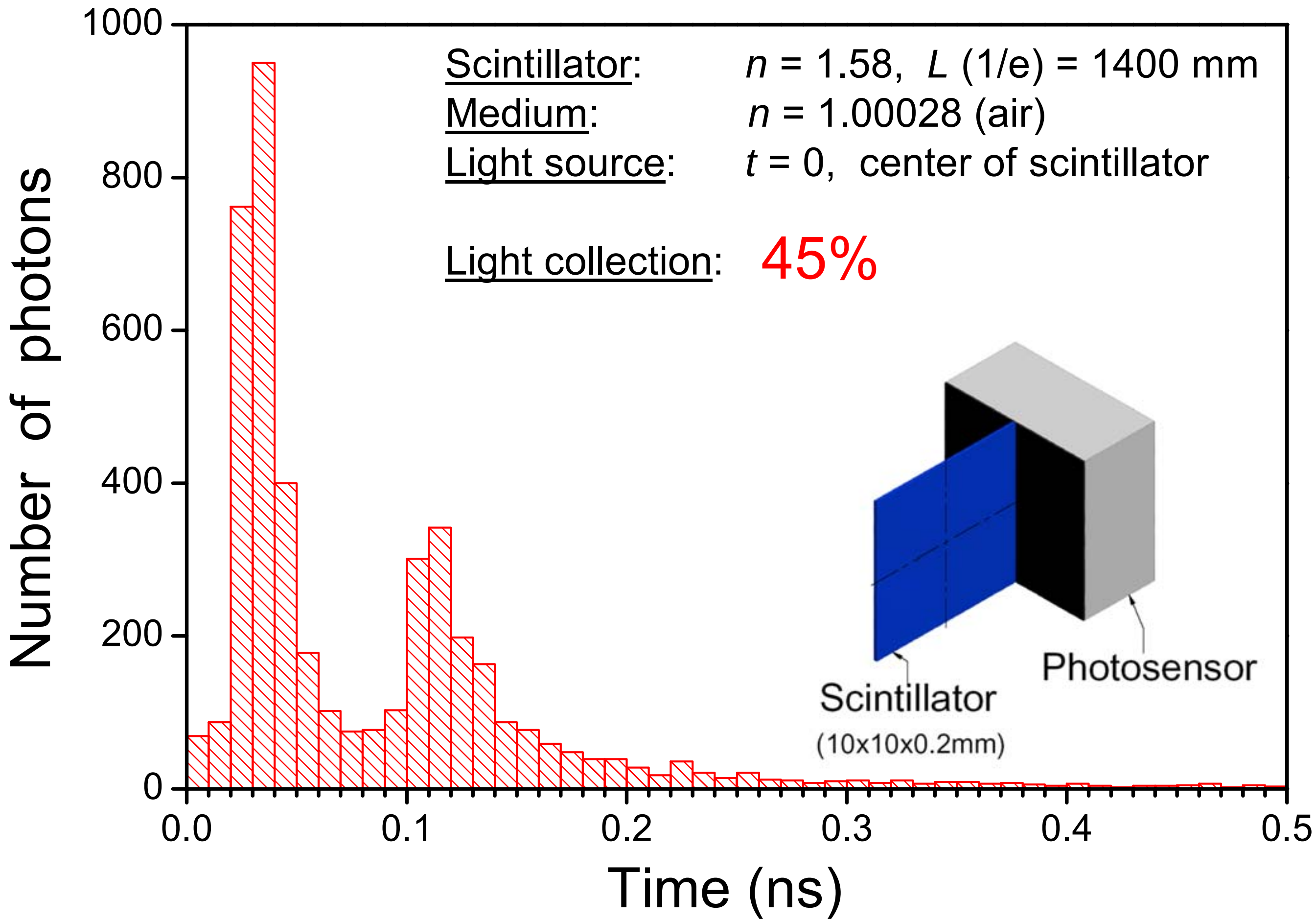
Muon counters of μSR spectrometers are based on ~200 μm thick plastic scintillators. The number of reflections each photon undergo in a thin scintillator is very large and the quality of the scintillator strongly effects the light collection.

Goal

Find out the upper limit for the light collection from a thin 10 x 10 x 0.2 mm^3 scintillator via one of 10 x 0.2 mm^2 faces.

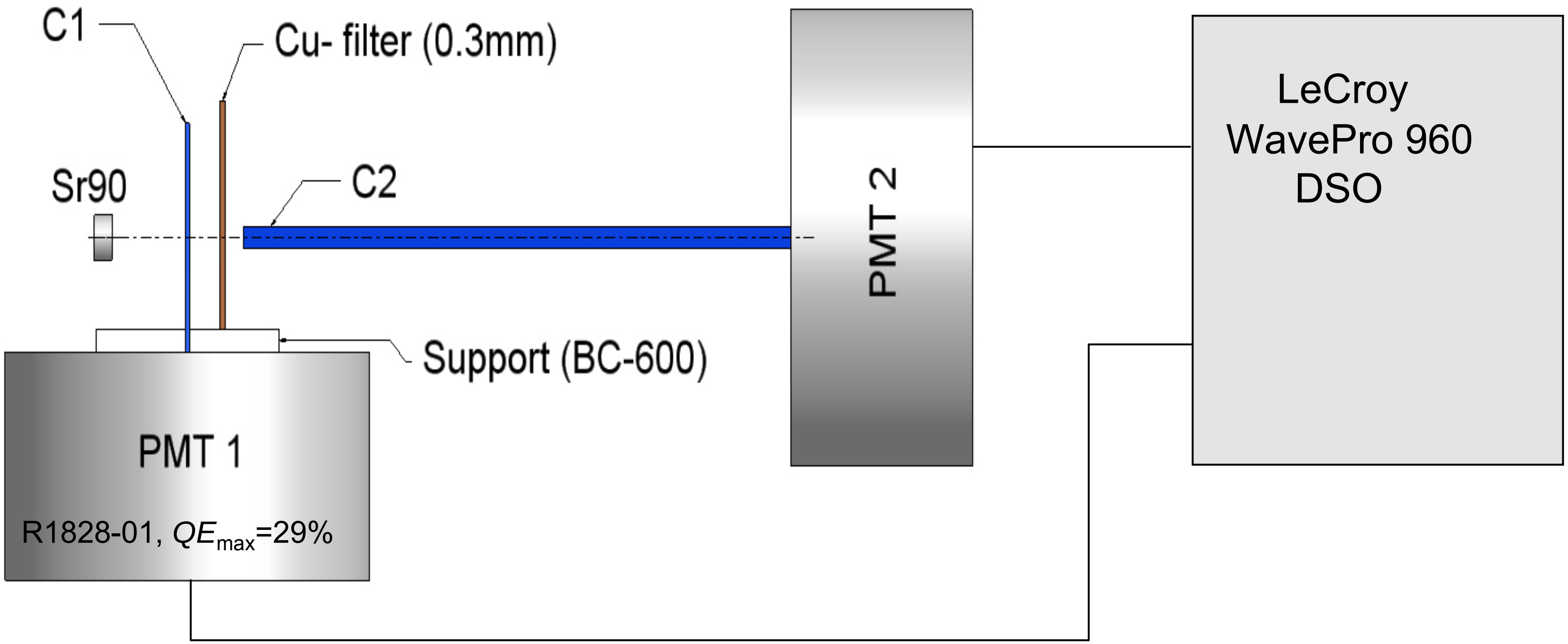
Monte-Carlo simulations

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



Time histogram for the photons collected from a 10 x 10 x 0.2 mm^3 plastic scintillator via one of the 10 x 0.2 mm^2 faces (absorbs all incident photons). About **45%** of photons are collected **within 0.2 ns.**

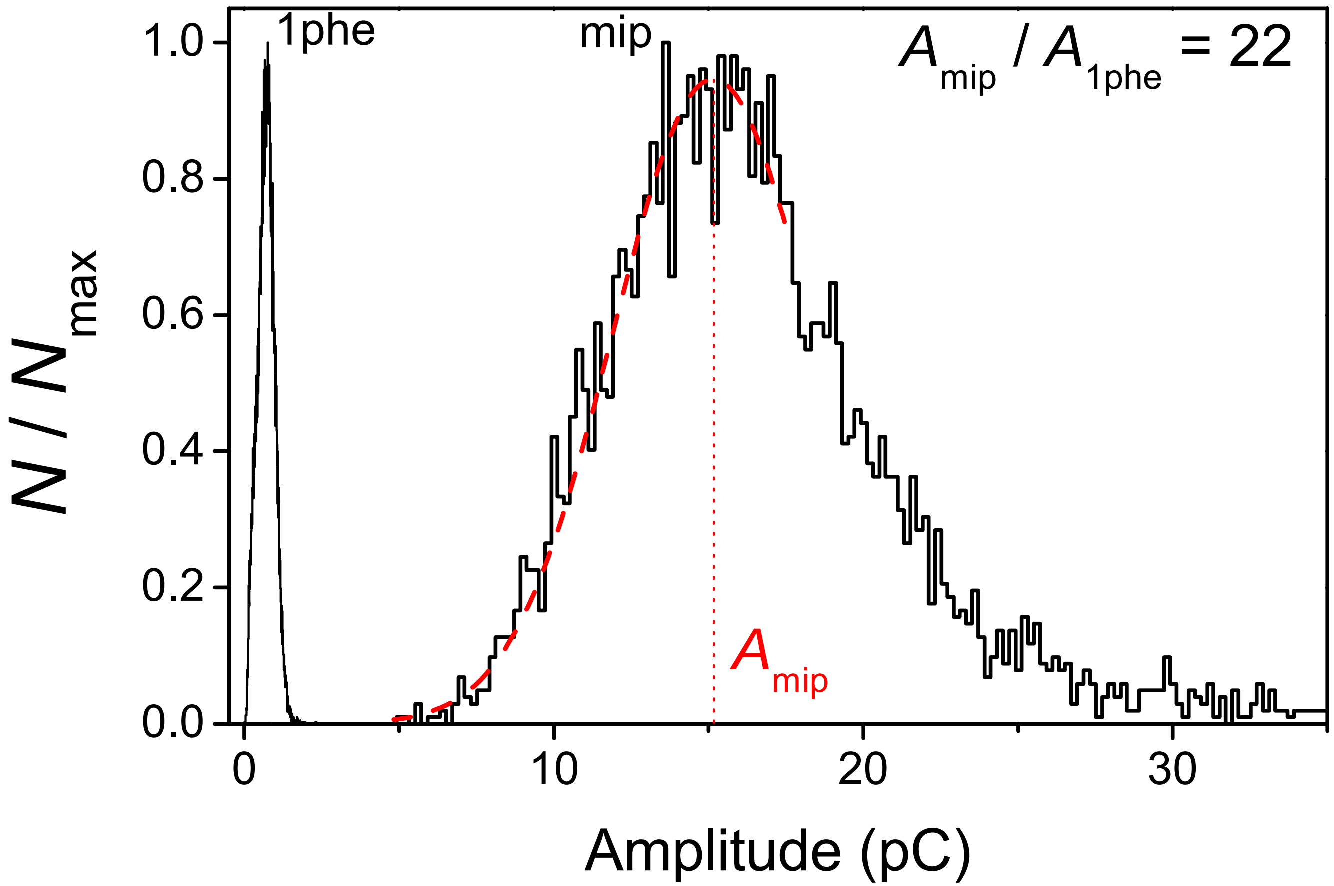
Experimental setup



C1: test scintillator 10 x 10 x d mm^3, d ~ 0.2 mm;

C2: BCF-10 scint. fiber (1 x 1 mm^2);

Cu-filter: cuts off electrons with energies < 0.7 MeV.

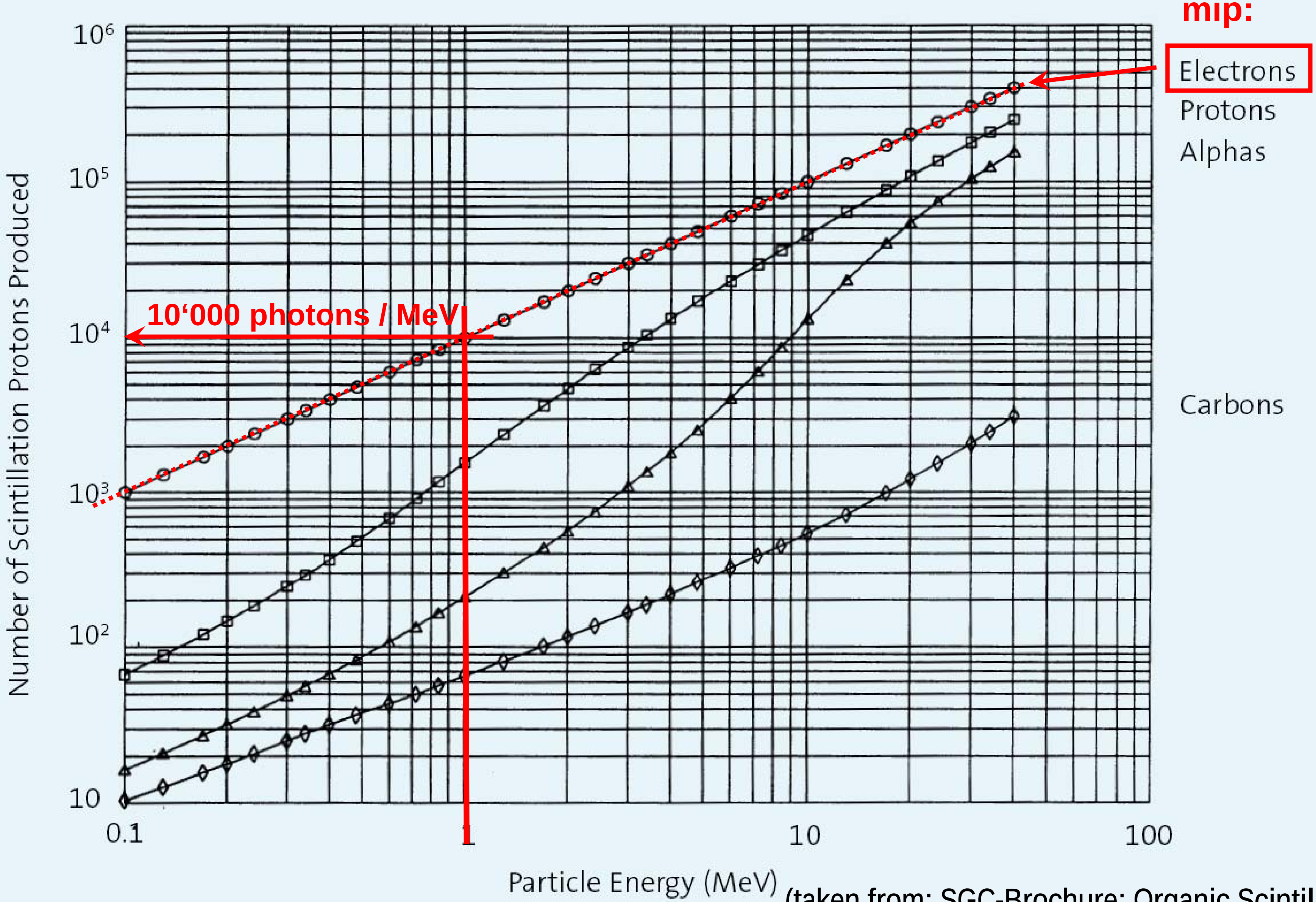


Amplitude distributions for one-photoelectron PMT signals (1phe) and signals from relativistic electrons (mip) passing through scintillator C1 (sample no.10: 230 µm BC-400).

A_{1phe} -- the mean amplitude of 1phe-signals, measured by shining weak continuous light onto C1 ($n \sim 10^5\ s^{-1} \gg n_{dark}$);

A_{mip} -- the most probable amplitude from relativistic electrons emitted by ^{90}Sr.

Response of BC-400 (light output: 65% anthracene)
Scintillation Light Produced vs. Particle Energy



(taken from: SGC-Brochure: Organic Scintillators)

Scintillators studied

Scintillator	*LE*, ph/MeV	*QE*, %	$N_{phe,max}$ (200 µm)
EJ-204 / BC-404	10400	26	108
EJ-230	9700	28	108
EJ-232	8400	27	90
EJ-212 / BC-400	10000	25	100
EJ-232Q / BC-422Q (0.5%)	2900	27	31

PAUL SCHERRER INSTITUT

$N_{phe} = A_{mip} / A_{1phe} \times 200 / d$ – measured number of photoelectrons per mip scaled to 200 μm

$CE = N_{phe} / N_{phe,max}$ – efficiency for the light collection

$N_{phe,max} = (dE/dx)_{mip} \times \rho \times 200\ \mu m \times LE \times QE$

$(dE/dx)_{mip} = 2\ MeV \times (cm^2/g)$, $\rho = 1\ g / cm^3$,

LE: light yield of the scintillator

QE: quantum efficiency of the PMT averaged over the emission spectrum of the scintillator

The quality of the samples was estimated visually with marks from 1 (poor) to 5 (excellent) -- the table gives the group characteristic quality estimates.

* The samples were obtained from Eljen cut to the specified dimensions. No microcracks are seen in the scintillator bulk but the larger faces look wavy. Smaller faces were not polished and look rugged.

** The samples were cut from scintillator sheets using a diamond saw. Microcracks appeared due to pressing the scintillator when cutting.

*** The samples were cut from scintillator sheets. The smaller faces were hand-polished. Microcracks appeared due to pressing the scintillator when polishing.

PAUL SCHERRER INSTITUT

Sample			Sample quality		N_{phe}	*CE*, %
Nn	Scint. type	d, μm	faces 10x10mm + bulk	faces 10xd mm		
1	EJ-204	190	4.5*	1	15.2	14.1
2	EJ-230	200			12.3	11.4
3	EJ-232	160			12.5	13.9
4	EJ-232Q	180			4.4	14.2
5	BC-400	230	3**	2.5	12.3	12.3
6	BC-422	210			3.7	4.1
7	BC-422Q	250			3.2	10.3
8	BC-422	210	3.5***	4.5	9.3	10.3
9	BC-422Q	250			4.0	12.9
10	BC-400	230			18.9	18.9
11	EJ-212	300			18.9	18.9

Thin scintillators

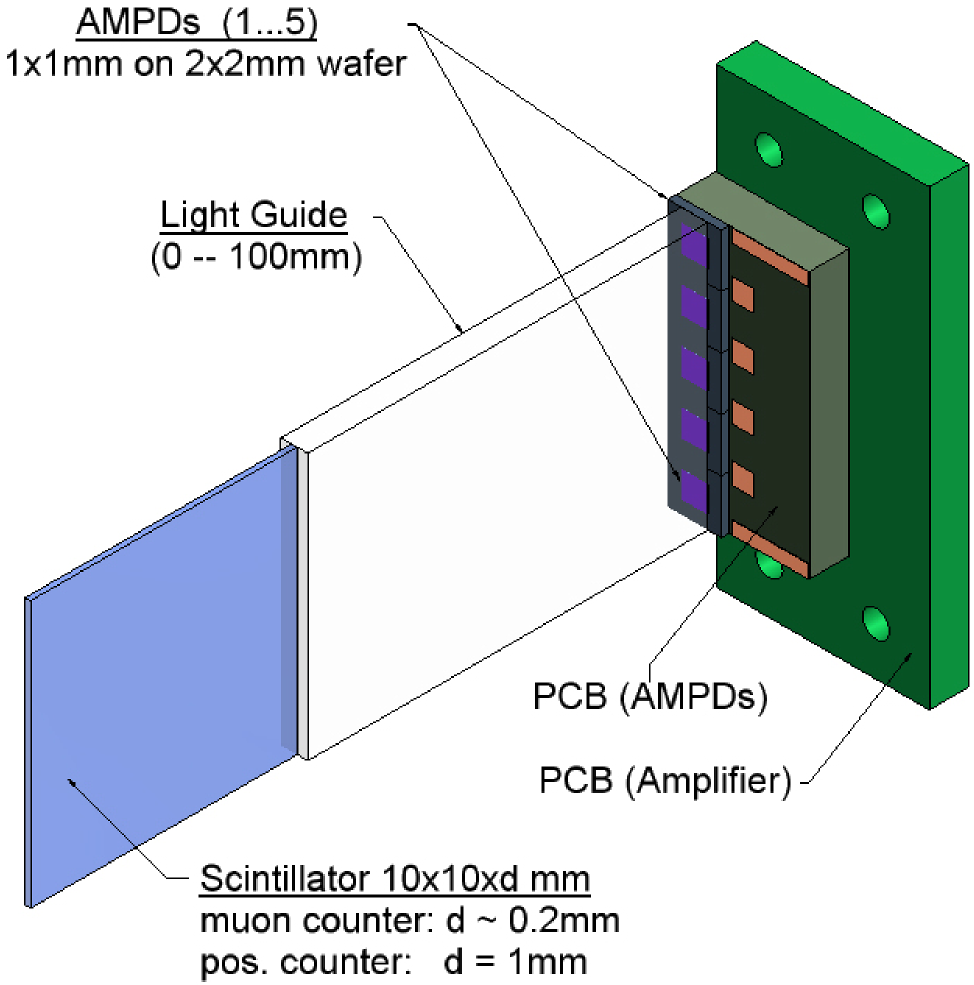
Summary

1) Very high values (up to **20%**) for the light collection efficiency (***CE***) were obtained with thin 10 x 10 x *d* mm^3 (*d* ~ 0.2 mm) plastic scintillators. The maximum possible efficiency of **45%** predicted in Monte-Carlo simulations is proven to be realistic.

2) The **quality of a scintillator** has a strong effect on the light collection. Fine polishing of the smaller 10 x 0.2 mm^2 faces is important (simulations show that full absorption on the three 10 x 0.2 mm^2 faces leads to a decrease by a factor of 4 in *CE*).

3) With *CE* > 20% **the development of a prototype of a magnetic field insensitive detector based on a fast plastic scintillator and today available AMPDs (area 1 x 1 mm^2, *PDE* = 3 – 5% at 380 nm) becomes feasible.**

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



Expected performance (with ZS-2mp)

LC ~ 20% (200 μm), 20 – 40% (1 mm)

K_g = 0.5 (geometry factor)

PDE (ZS-2mp) = 3 – 5% for EJ-230

EJ-230 (200 μm): **12 phe** / μ^+ (29 MeV/c)

EJ-230 (1mm): **6 – 12 phe** / e^+ (mip)

Sufficient for feasibility tests !!!

Summary

Fast-timing detectors available on the market: tested (& rejected...)

- fast-timing spectrometer requires special development: AMPDs

next generation of AMPDs:
larger area, larger gain,
increased sensitivity below 400 nm,
AMPD array for readout of thin scintillators

- can be used in future muSR spectrometers

Collaboration PSI-JINR (Z. Sadygov, V. Zhuk):
AMPD development / light guides & fibers

Full spectrometer simulation (detector arrangements, secondary beam, ...): WP2

PSI electronics development (?):
fast preamps (matching AMPD impedance, $\neq 50\ \Omega$)
with on-board discriminators