Scintillator strip KLM detector for Super Belle

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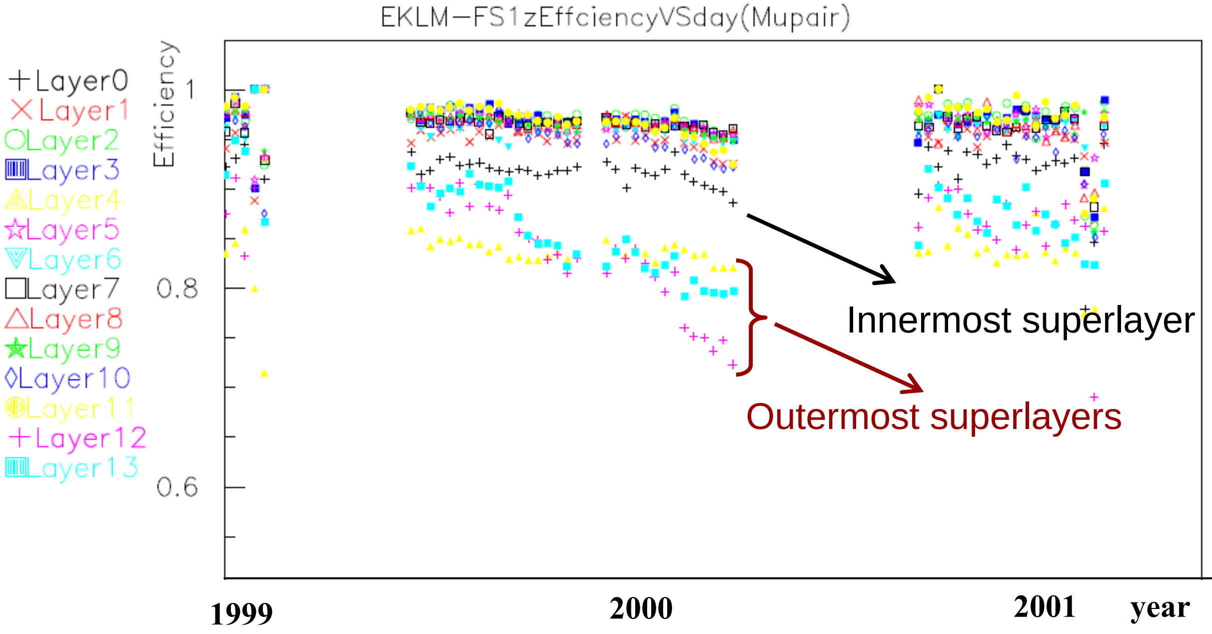
for ITEP group

Outline:
- Motivation for new detector
- Proposed setup
- Geiger APD as photodetector
- Radiation hardness
- Test module
- Physics performance

Motivation for a new KLM design

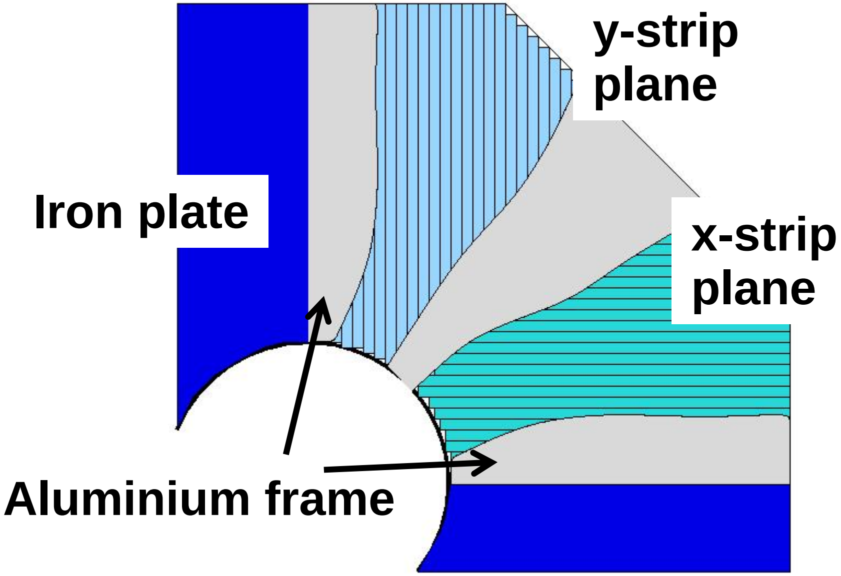
- The present RPC design for KLM demonstrated nice performance at Belle
- However already with the present luminosity the efficiency degradation is observed due to high neutron background and large RPC dead time. The effect is large for the endcap KLM.
- The paraffin shield helps to reduce neutron background just slightly in the outermost endcap superlayers.
- The background rate in the innermost superlayers are only ~2 times smaller and can't be shielded
- With 20 times higher bg occupancy the efficiency becomes unacceptably low (<50%)



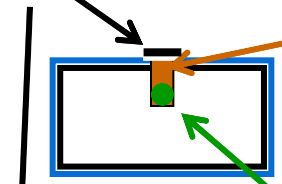
For SuperB new KLM design in endcap is required

Scintillator KLM set up

- The geometry is fixed by the requirement to use the existing 4cm gaps in the iron magnet flux return yoke divided into 4 quadrants. It is also economical to use the existing RPC frames as a support structure.
- Two independent (x and y) layers in one superlayer made of orthogonal rectangular strips with WLS read out
- Photodetector = avalanche photodiod in Geiger mode (*GAPD*)

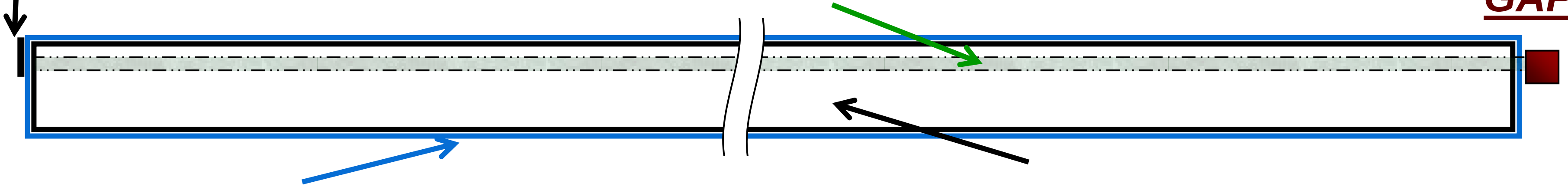


Mirror 3M (above groove & at fiber end)



Optical glue increase the light yield ~ 1.2-1.4)

WLS: Kurarai Y11 ∅1.2 mm



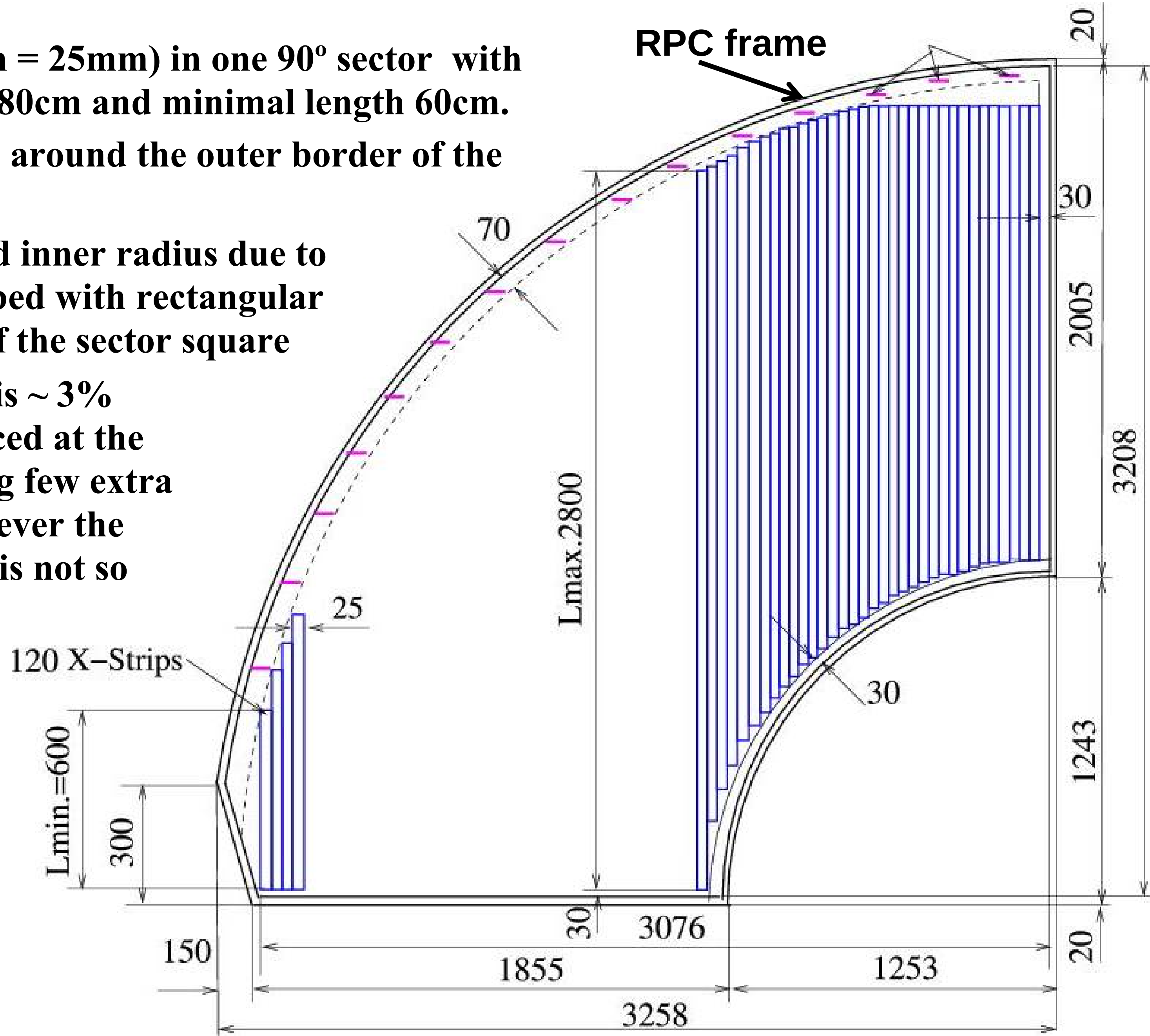
GAPD

Diffusion reflector (TiO_2)

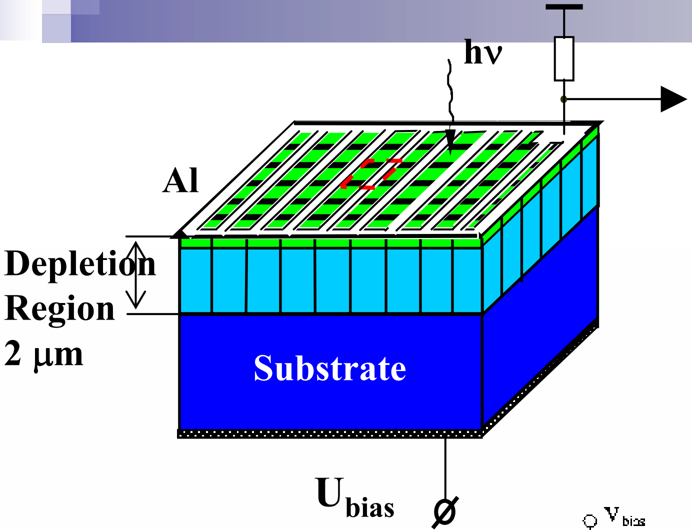
Strips: polystyrene with dye (1.5% PTP & 0.01% POPOP)

Sketch of the KLM set up

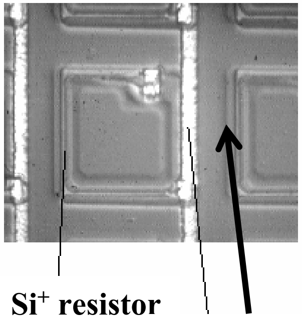
- ~120 strips (width = 25mm) in one 90º sector with maximal length 280cm and minimal length 60cm.
- GAPD are placed around the outer border of the sector.
- Dead zone around inner radius due to circle circumscribed with rectangular strips is ~ 0.2% of the sector square
- Outer dead zone is ~ 3% and may be reduced at the expense of adding few extra short strips. However the outer acceptance is not so much important.
- The total area of dead zones is slightly smaller than RPC case
- 28, 000 read out channels for whole endcap KLM.

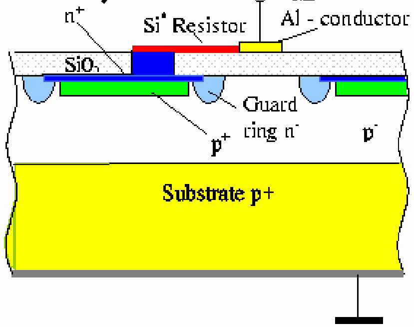


GAPD characteristics: general

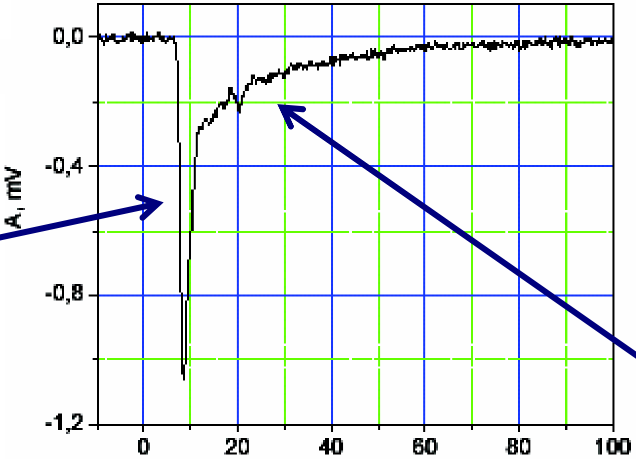


- Matrix of independent pixels arranged on a common substrate. Typical matrix size ~ 1 x 1 mm^2; typical N of pixels ~ 200−2000.
- Each pixel operates in a self-quenching Geiger mode.
- Each pixel produces a standard response independent on number of incident photons (arrived within quenching time
- *GAPD* at whole integrates over all pixels: *GAPD* response = number of fired pixels.
- Dynamic range ~ number of pixels.
- Internal GAPD (one pixel) noise is 100kHz − 2MHz





Short Geiger discharge development < 500 ps

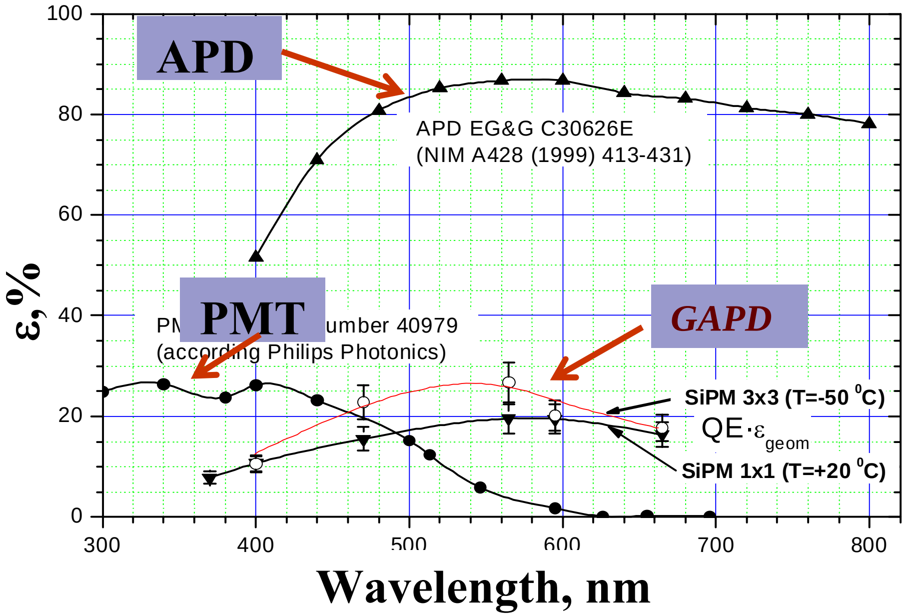


Discharge is quenched by current limiting with polysilicon resistor in each pixel I < 10μA

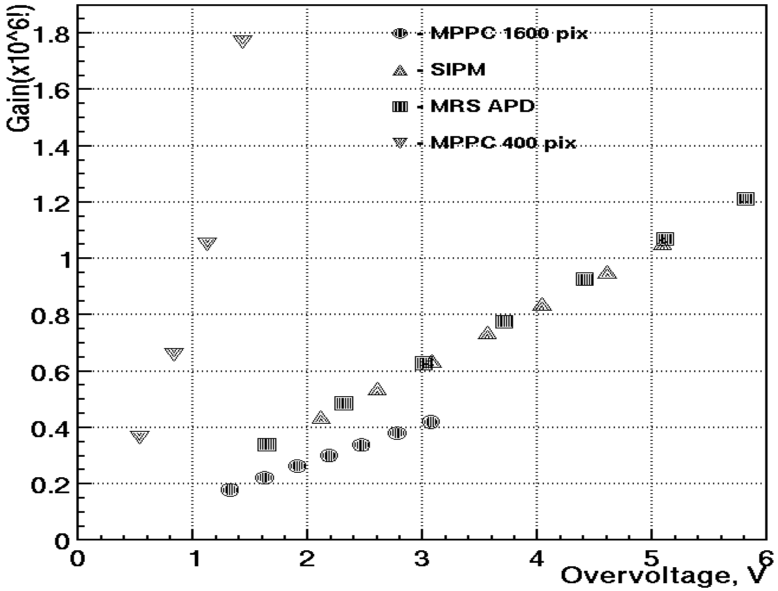
Pixel recovery time ~ $C_{pixel}R_{pixel}$=100-500ns

GAPD: efficiency and HV

- **Photon Detection Efficiency is a product of**
  - **Quantum efficiency > 80% (like other Si photodetectors)**
  - **Geometrical efficiency = sensitive area/total area ~30−50%**
  - **Probability to initiate Geiger discharge ~ 70%**
- **Finite recovery time ⇒ dead time depends on noise rate and photon occupancies**



Working point $U_{bias}=U_{break}+\Delta U$; (≈ 50–60V); overvoltage above breakdown (ΔU) – is a subject of optimization between efficiency, noise rate and cross-talk ≈ 1–3V.



Each pixel works as a Geiger counter with charge $Q = \Delta U\, C$, $C \sim 50$fmF;

$Q \sim 3 \times 50$ fmC ~ 10^6 e – comparable to vacuum phototubes

GAPD production

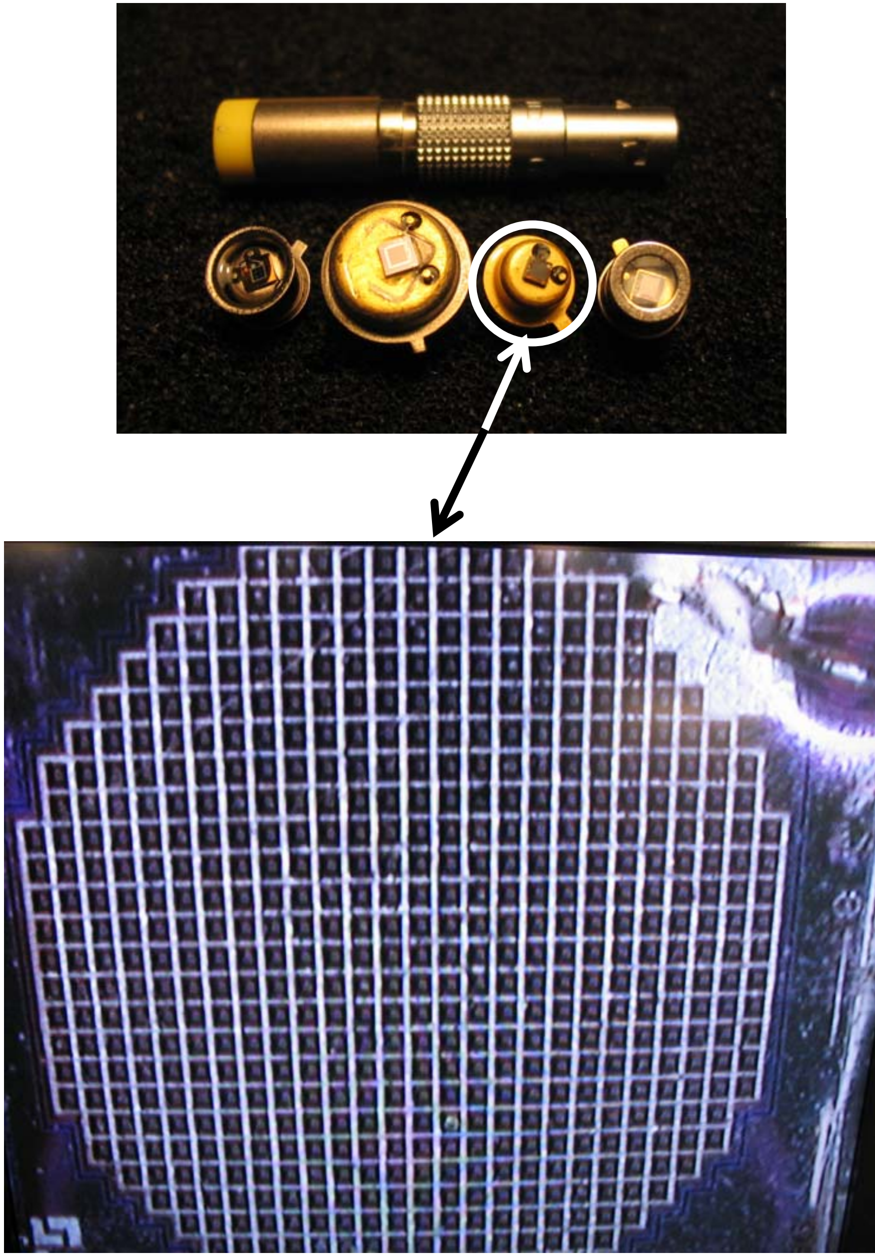
Around 1990 the GAPD were invented in Russia. V. Golovin (CPTA), Z. Sadygov (JINR), and B. Dolgoshein (MEPHI-PULSAR) have been the key persons in the development of *GAPD*s.

Now produced by many companies:

- CPTA Moscow, Russia
- JINR Dubna, Russia
- PULSAR Moscow, Russia
- HAMAMATSU Hamamatsu City, Japan
- And several others in Switzerland, Italy, Island…

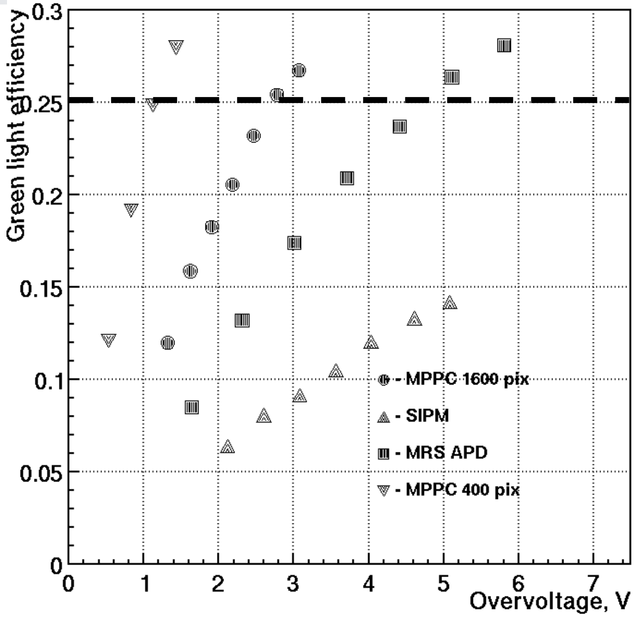
Only MEPHI, CPTA and Hamamatsu have experience of moderate mass production of >1000 pieces working in real experiment.

We work with CPTA (Moscow) where the producer is eager to optimize the *GAPD* for our purposes (the spectral efficiency is tuned to Y11 fiber wl / the *GAPD* shape to match with the fiber)



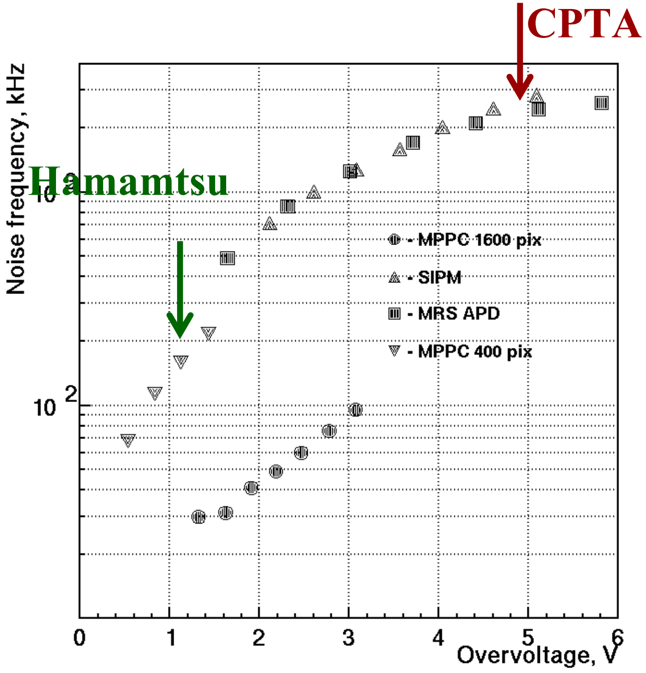
Comparison of different products

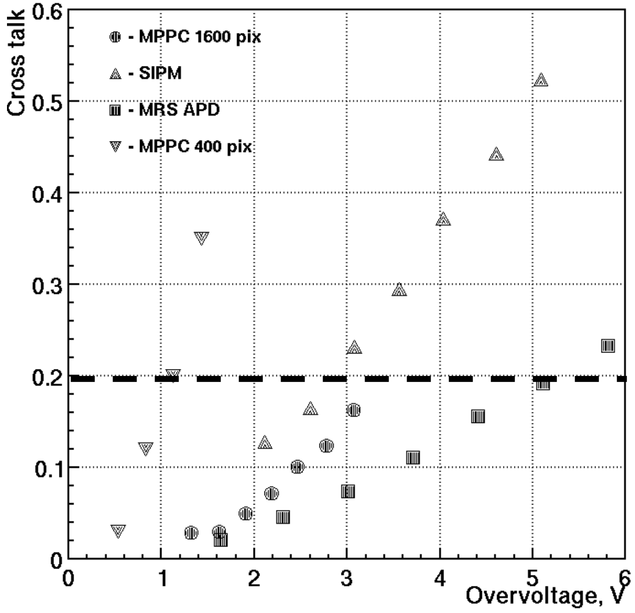
CPTA and Hamamatsu devices have similar efficiency for green light and cross talk and similar radiation hardness. MEPHI‘s GAPD has smaller efficiency with Y11 light



Intitially much smaller Hamamatsu‘s MPPC noise is not a big advantage in our conditions:

- it grows with irradiation and in one-two year of SuperB operation becomes comparable to CPTA‘s
- GAPD noise with reasonable threshold is much smaller than physical background rate



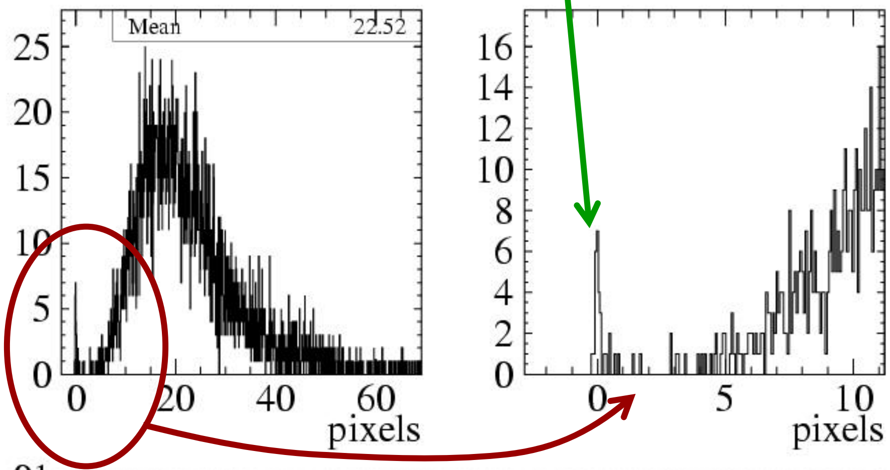


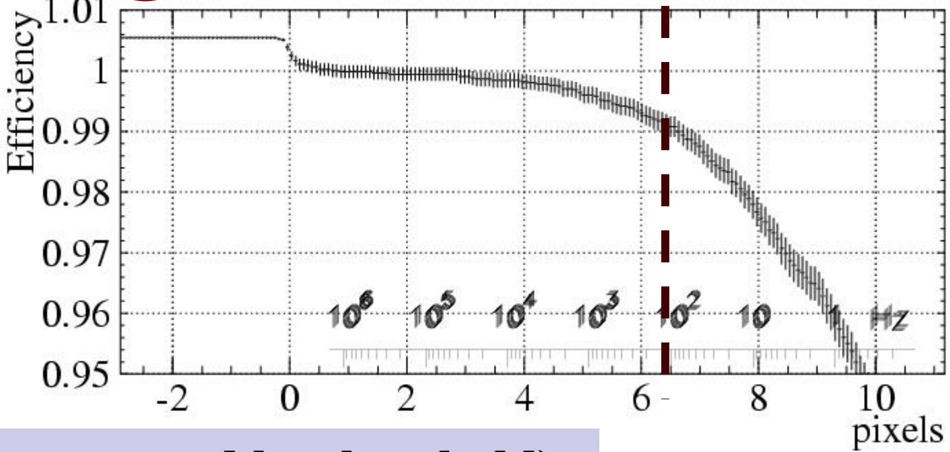
Efficiency and *GAPD* noise

1 m × 40 mm × 10 mm strip

- **Use cosmic (strip integrated) trigger to measure MIP signal and LED to calibrate *GAPD***
- **Average number of photoelectrons from MIP is ~22.**
- **<10% variation of light yield across the strip; ~20% smaller light yield from the far end of the strip**
- **Discriminator threshold at 99% MIP efficiency (6.5 p.e.) results in *GAPD* internal noise of 100 Hz only!**

imperfection of the trigger





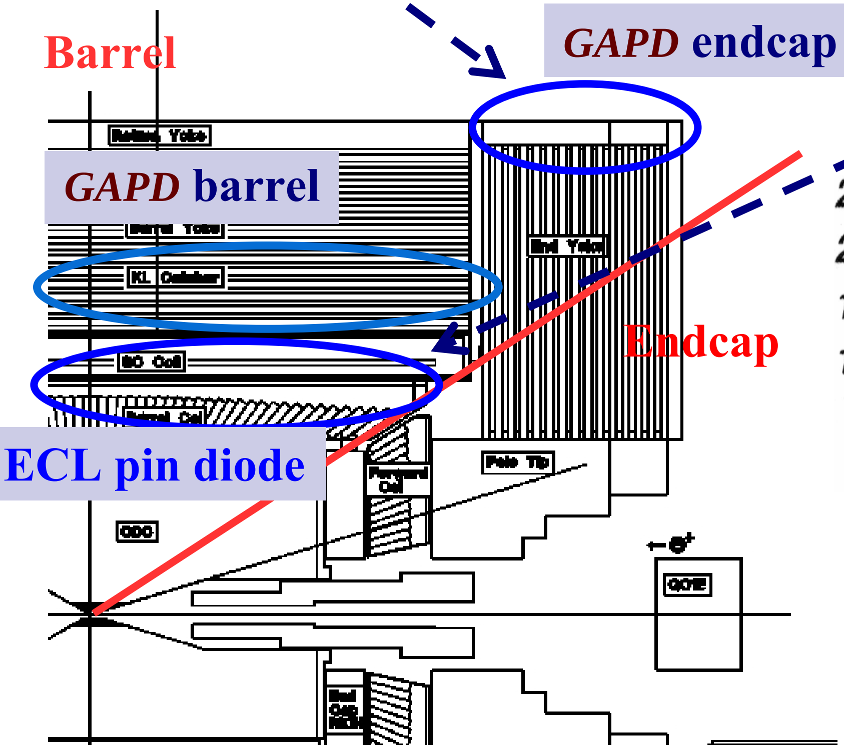
Internal GAPD noise is not a problem (suppressed by threshold), and is much smaller than expected physical background rate

Estimate of neutron dose at SuperB

Now (L=1.4×10^{34}) ~ 1mSv/week → 15mSv/week at SuperB (L=2×10^{35})
→ 3Sv/5 years → conservatively → 9×10^{9} n/cm^{2}/5years

Luxel budges (J type) measure fast neutron dose

Independent method: neutron dose has been measured at ECL via observed increase of the pin-diod dark current: ΔI ~ 5nA



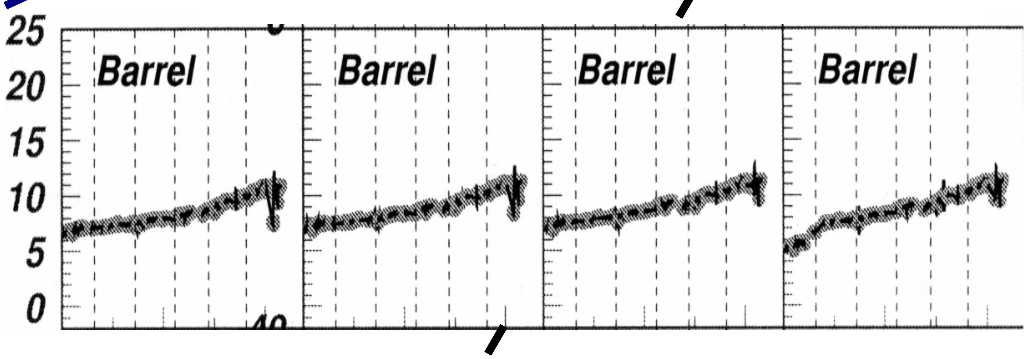
Barrel

GAPD barrel

GAPD endcap

Endcap

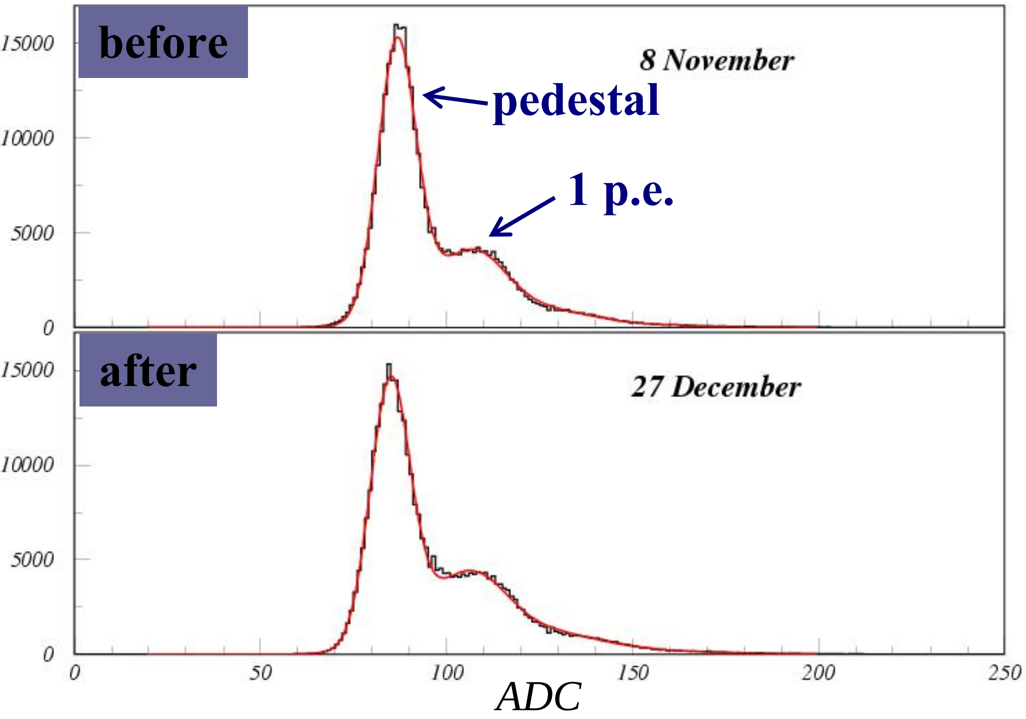
ECL pin diode



Conservatively: 5×10^{8} n/cm^{2}/500fb^{-1}
assuming dose ~ 1/r → 10^{10} n/cm^{2}/5years

Both methods are conservative and give consistent estimates of 10^{10} n/cm^{2}/5years
Neutron dose at barrel KLM can be 1.5 times higher

Radiation damage measurements at KEKB tunnel



The GAPDs have been exposed to neutron radiation in KEKB tunnel during 40 days. The measured neutron dose is 0.3 Sv, corresponding to half year of Super KEKB operation

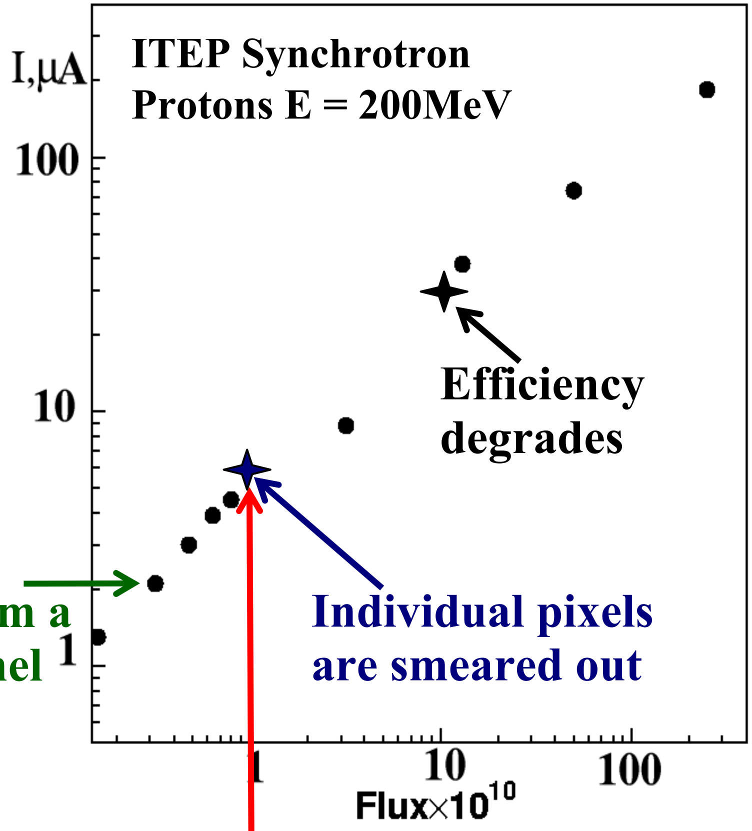
- Increase of dark currents after 40 days in KEKB tunnel
  $I_{after} - I_{before} \sim 0.1\ \mu A$ (within the accuracy of the measurement)
- More accurate estimate of *GAPD* degradation is done using fit to ADC spectra: the 1 p.e. noise has increased by 10% only after 40 days in KEKB tunnel for the *GAPD*s irradiated with the highest dose 0.3 Sv.

Extrapolation to 5 years of operation: I_{dark} will increase by 1 μA;
1 p.e. noise rate will increase twice

The tests go on. By the summer shut down the dose will be equivalent to 2.5 years.

Radiation damage measurements

- Dark current increases linearly with flux Φ as in other Si devices: $\Delta I = \alpha \Phi V_{eff}$ Gain, where $\alpha = 6 \times 10^{-17}$ A/cm, $V_{eff} \sim 0.004$ mm^3 determined fr observed ΔI
- Since initial *GAPD* resolution of ~ 0.15 p.e. is mu better than in other Si detectors it suffers sooner:
- After $\Phi \sim 10^{10}$ n/cm^2 individual p.e. signals are smeared out, while MIP efficiency is not affected
- MIP signal are seen even after $\Phi \sim 10^{11}$ n/cm^2 but efficiency degrades



ITEP Synchrotron
Protons E = 200MeV

Efficiency degrades

Individual pixels are smeared out

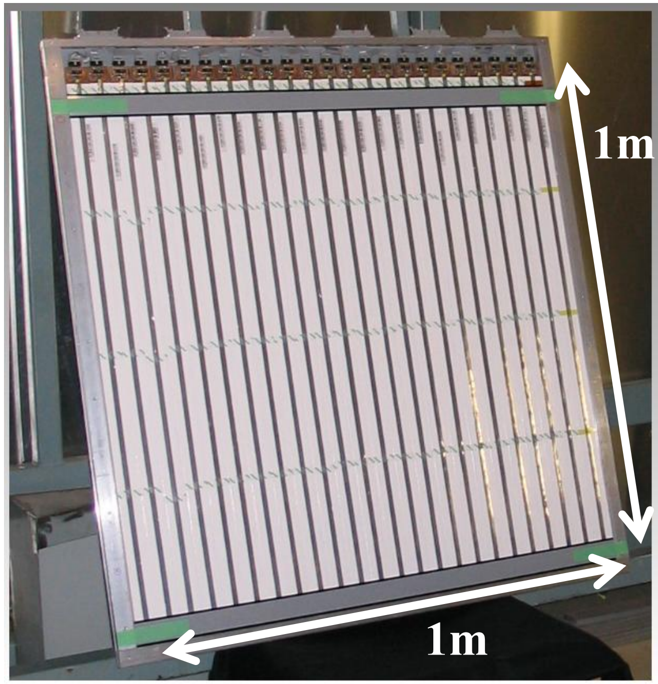
Extrapolated for 5 years at SuperB increase of noise from a measurement in KEKB tunnel

Conservatively estimated neutron flux in 5 years at SuperB assuming neutron energy spectrum causing maximal damage

- Measurements at KEKB in almost real conditions demonstrate ~3 times smaller dam than estimated

Radiation hardness of *GAPD* is sufficient for SuperBelle, but we do not have a large safety margin for more ambitious luminosity plans

Test module in the KEKB tunnel



- We produced one hundred 1m-strips arranged in 4 layers
- Initially supposed to be installed in the iron gap instead of the not working outermost RPC layer. However dismantling of RPC turns out to be a hard job. Finally installed in the KEKB tunnel almost without any shield (2mm lead).
- Tested during 40 days of 2007 run. Tests are continued in 2008.

- **Key issues of the 2007 fall test run**
  - ☐ Study radiation ageing of ***GAPD***:
    1 day dose at the KEKB tunnel equivalent to 7 days dose at the prospective position at SuperB.
  - ☐ Measure background rate needed for a realistic MC simulation.
  - ☐ Test compatibility with Belle DAQ: try to store test module hits on data tapes
  - ☐ Check MIP registration efficiency in a noisy conditions

Electronics

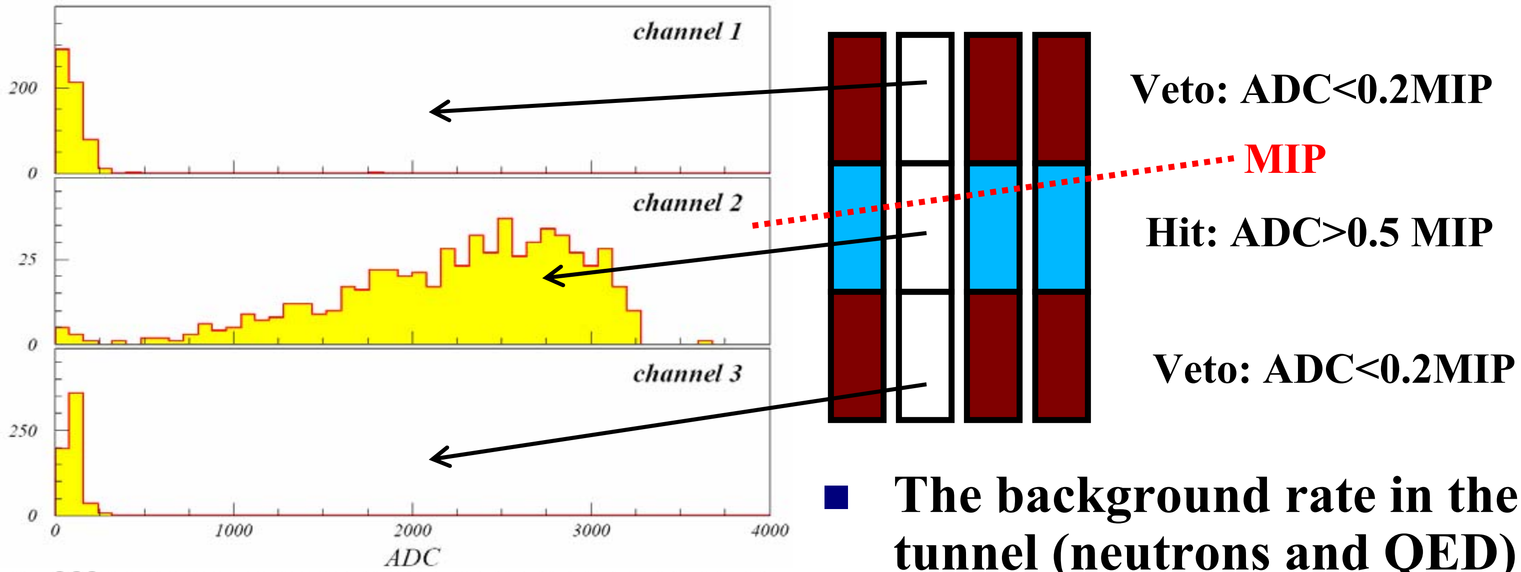
Basic requirements for electronics:

- Need a simple preamplifier since the GAPD signal is relatively large (few mV/50 Ohm for 1p.e.).
- Each *GAPD* has individual optimal HV (spread ~ 5V): HV to be set by microcontoller from a database or tuned online.
- Each *GAPD* has individual gain: individual thresholds required.
- Time resolution of strip+GAPD ~1ns. It is very desirable to transfer time information to DAQ without deterioration to measure the position along strip (20 cm / 1 ns) and to suppress the random backgrounds.
- Usefulness of amplitude measurements or two thresholds per channel to improve K_L reconstruction is under the study using the MC.

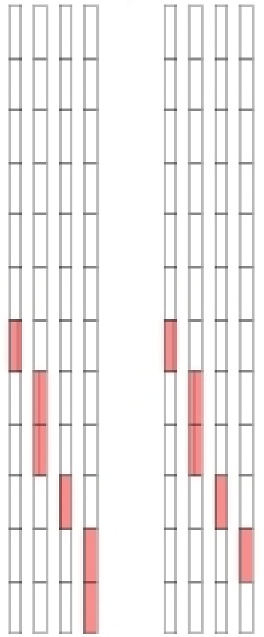
A primitive electronic scheme has been realized for the test module (100 channels) using home made ITEP HV control and NIM discriminators and worked adequately.

VPI and U. Illinois have expressed interest in developing the electronics for KLM. They have a good experience with electronics for present KLM.

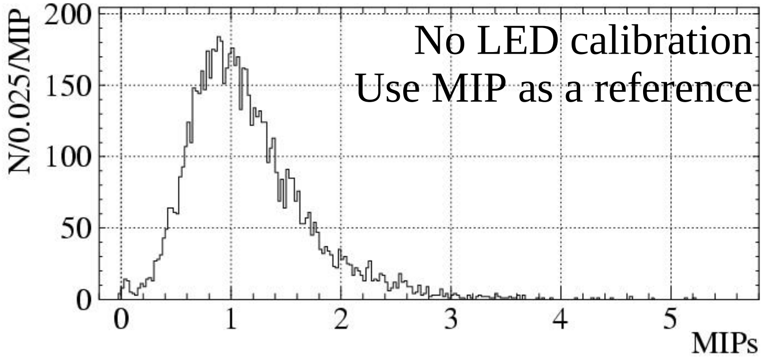
MIP detection in KEKB tunnel

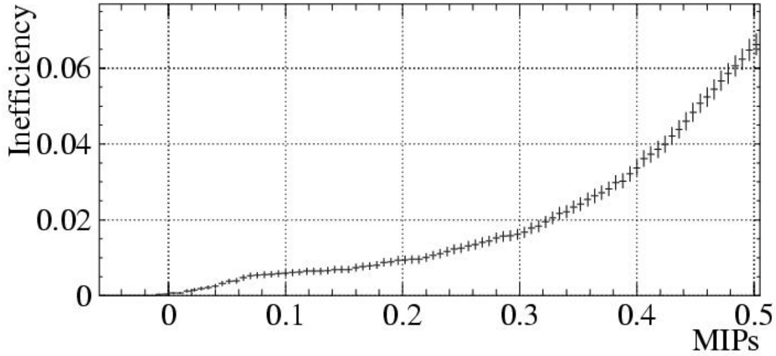


- **The background rate in the tunnel (neutrons and QED) is ~ 2kHz/strip (5Hz/cm^2)**
- **Standalone MIPs is well triggered with bg conditions**
- **The MIP efficiency with noisy conditions vs threshold is similar to those obtained with no beam bg data**



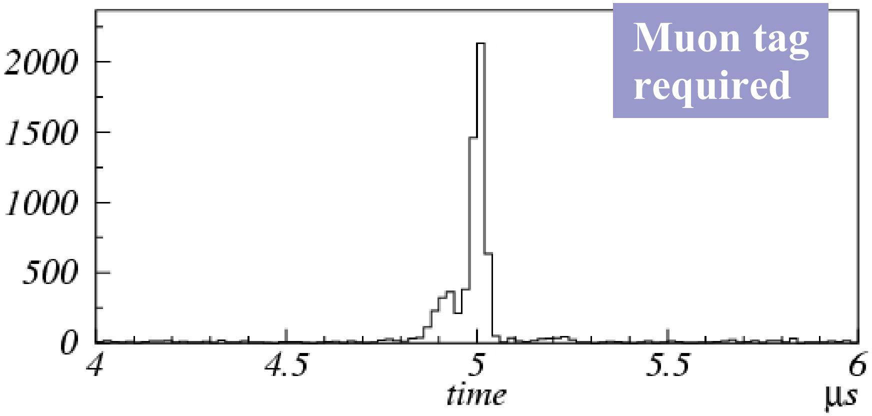
Hit map display (typical events)

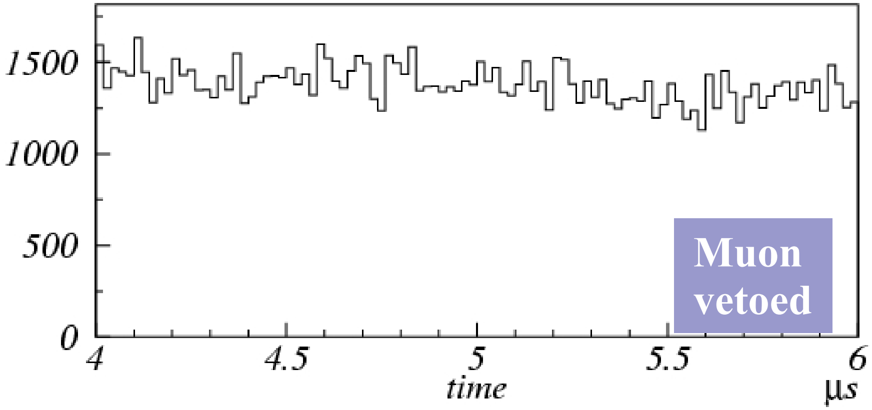


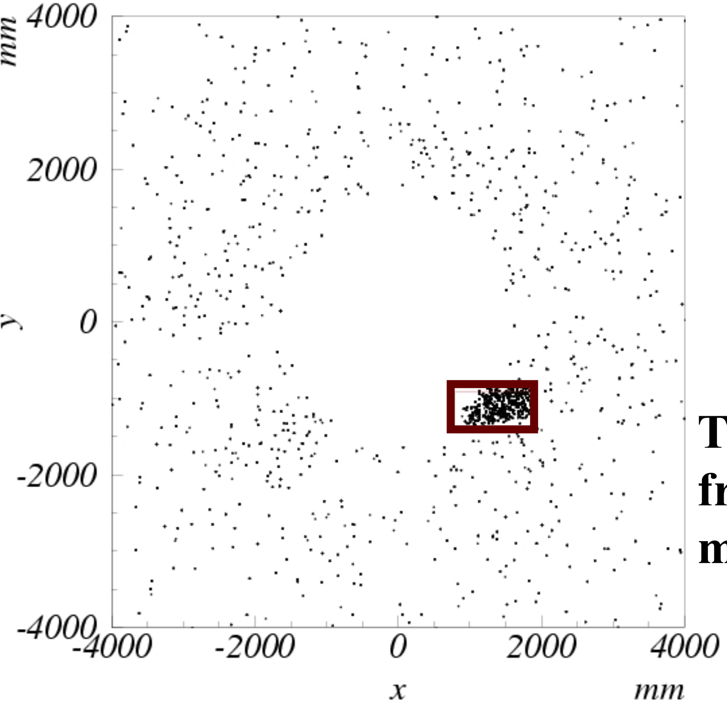


Stored sc-KLM data

- Sc-KLM hits are stored in the data tapes: the raw hit rate is ~10 times higher than RPC hits.
- Muons from $ee \to \mu\mu$ are seen with proper time off line.
- Proper time hits show the position of the test module in the tunnel.







The distribution of the muons hits (x%y) extrapolated from CDC to $z = z_{\text{test module}}$ with the proper time sc-KLM module hits.

Physics performance

- **Scintillator detectors are more sensitive to neutrons (due to hydrogen in plastic). Conservatively the expected neutron bg rate is 10 times higher than at RPC:**

  (0.5 Hz/cm^2 RPC $\Rightarrow$ 5 Hz/cm^2 sc-KLM) @ L=1.4 * 10^{34} $\Rightarrow$ 70 Hz/cm^2 at SuperB

  The tests in the KEKB tunnels show that this estimate is really conservative.

- **Background neutron can produce hits in one strip only (no correlated hits in x and y plane). The probability to detect 2-dimentional hit in the whole endcap KLM due to accidental 2 neutrons x-y hits depends on the integration time: ~ 0.005 * (t / 1 nsec)^2 .**
- **K_L detection**
  - ☐ **The present K_L algorithm: require coincidence of two superlayers hits, consistent in $\theta-\phi$ will certainly work well with negligibly small fake rate due to random bg hits coincidences.**
  - ☐ **Strip+GAPD time resolution is ~1 ns. A possibility to improve K_L detection efficiency (reconstruct K_L using a single superlayer hit) depends on the electronics.**
  - ☐ **A possibility to use amplitude information to improve efficiency (several thresholds) to be studied with GEANT MC.**
- **Muon identification should be better due to better spatial resolution and higher MIP detection efficiency.**

Cost estimate for endcap KLM

Item		price	cost
Scintillator strips	28, 000 pc. (14,000 kg)	20 $/kg	280 k$
WLS fiber	56 km	1.4 $/km	80 k$
Photo-detectors CPTA	28, 000 pc.	20 $/pc.	560 k$
Optical glue			30 k$
Electronics	28, 000 ch.	? $/ch.	? k$
Miscellaneous			70 k$
Transportation			40 k$
Total			1060 k$

* Cost estimate for electronics will be made after the electronics design

** Cost does not include electronics, labor and R&D

*** Changes in $ exchange rate can influence the cost

Summary

- Scintillator KLM design is OK for SuperB:
  - the efficiency of MIP detection can be kept at high level (>99% geometrical; thresholds: compromise between efficiency and neutron bg rate)
  - K_L reconstruction: rough estimates were done for LoI; full MC simulation to be done by TDR using the information from the test module
- Radiation hardness of *GAPD* is sufficient for SuperBelle for endcap and barrel parts, but we do not have a large safety margin for L=10^{36}.
- The test with a real prototype showed a good performance of the proposed design; further optimization is to be done before TDR: compromise between physical properties/cost.

The tests are continued this spring run to see further *GAPD* degradation

Many thanks
to the Belle KLM group for the help in tests
and
D. Epifanov for providing us
the ECL neutron flux measurements