DIRC 2013, September 4-6, 2013

The Belle II PID System

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Contents

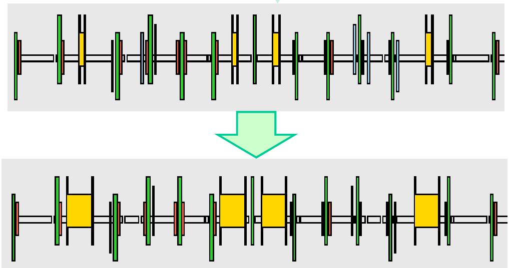
Belle II detector

PID systems

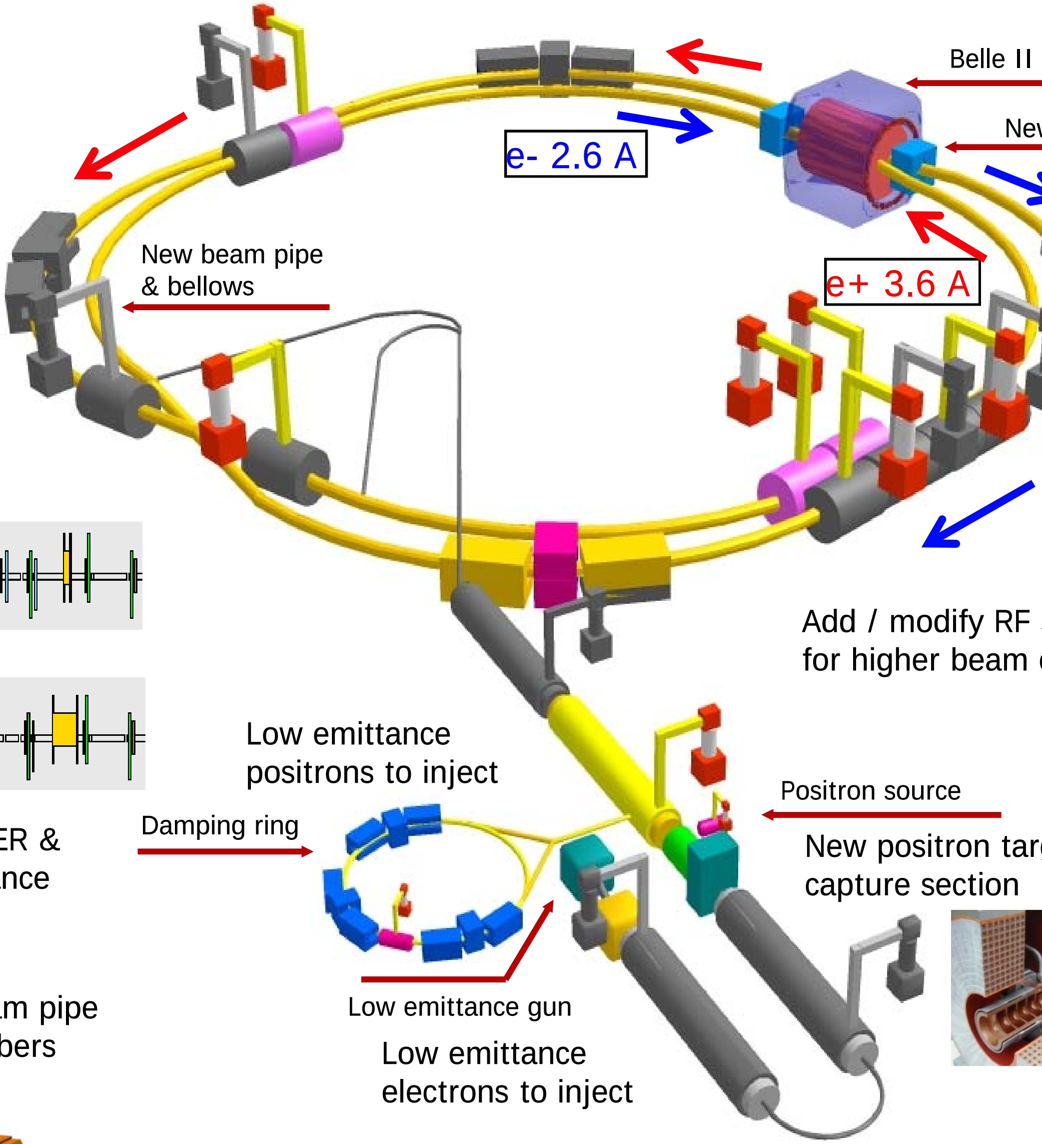
- Barrel: TOP
- Endcap: ARICH

KEKB to SuperKEKB

Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance



Belle II

New IR

New beam pipe & bellows

Damping ring

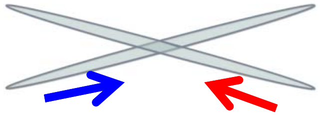
Low emittance positrons to inject

Positron source

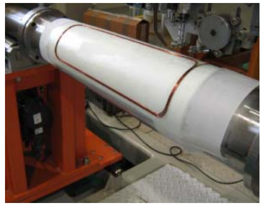
Low emittance gun

Low emittance electrons to inject

Colliding bunches

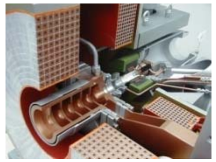


New superconducting /permanent final focusing quads near the IP

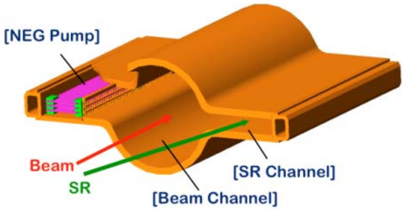


Add / modify RF systems for higher beam current

New positron target / capture section



TiN-coated beam pipe with antechambers

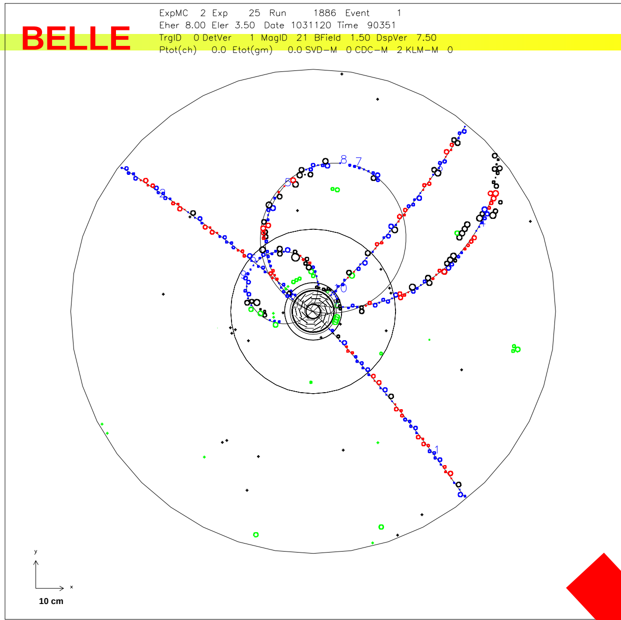


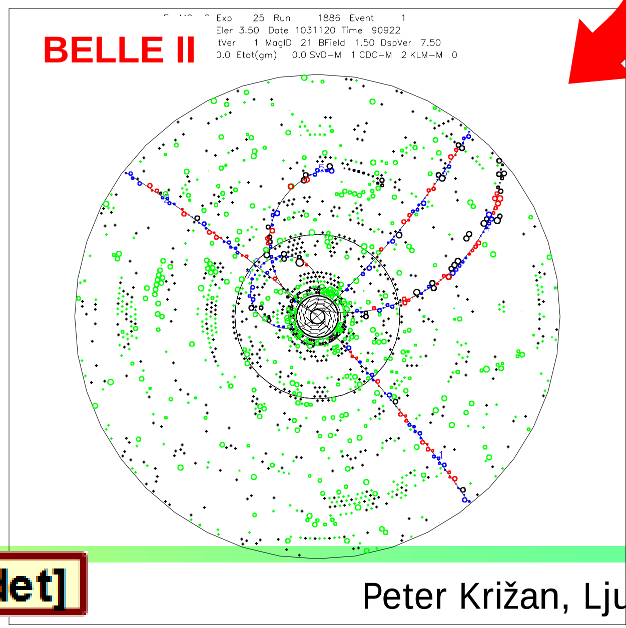
To obtain x40 higher luminosity

Need to build a new detector to handle higher backgrounds

Critical issues at L= 8 x 10^{35}/cm^2/sec

- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing
- **Require special features**
  - low *p* μ identification ← sμμ recon. eff.
  - hermeticity ← ν "reconstruction"



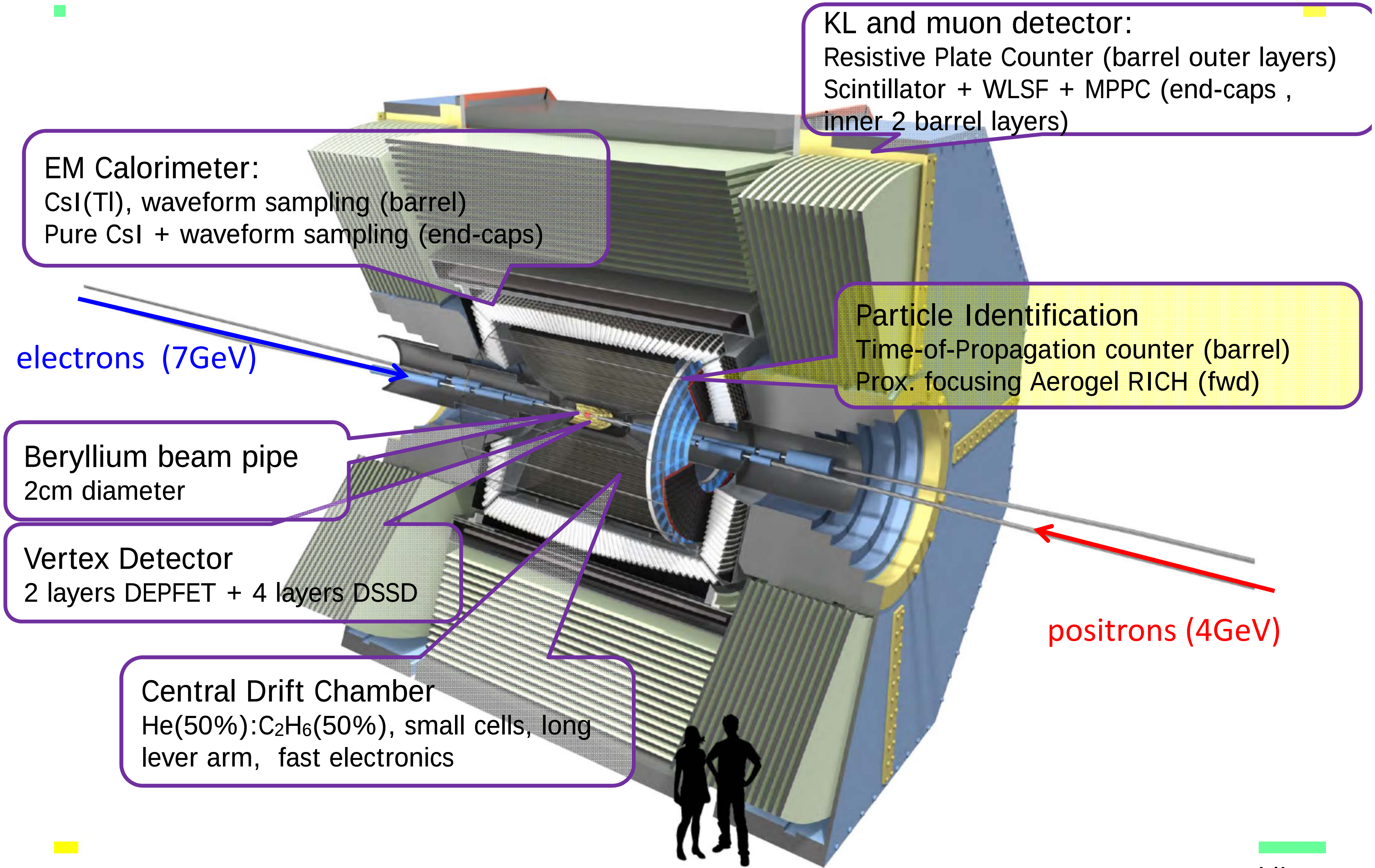


Have to employ and develop new technologies to make such an apparatus work!

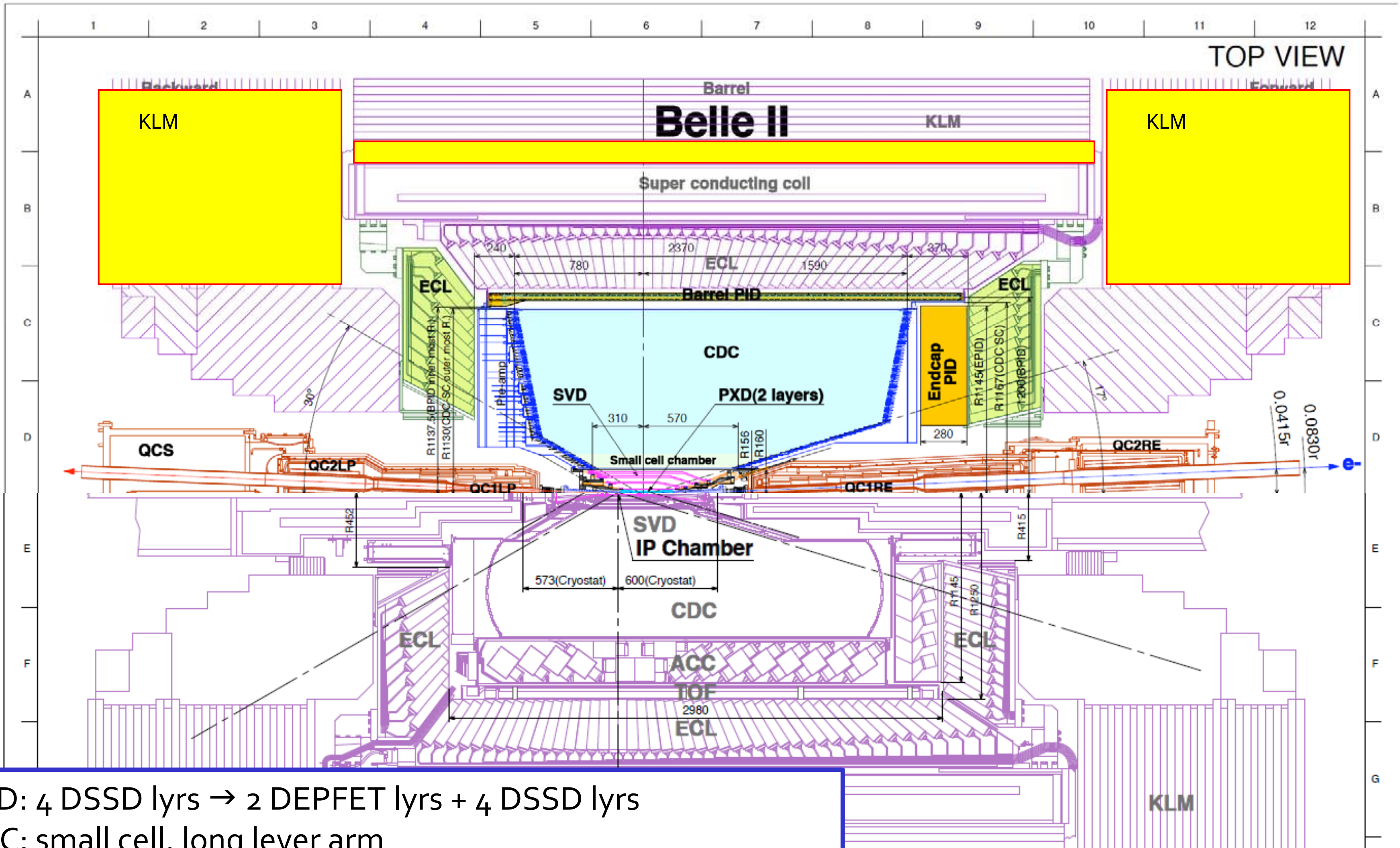
→

TDR published arXiv:1011.0352v1 [physics.ins-det]

Belle II Detector



Belle II Detector (in comparison with Belle)

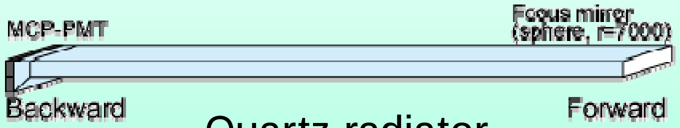


SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling (+pure CsI for endcaps)
KLM: RPC → Scintillator +MPPC (endcaps, barrel inner 2 lyrs)

In colour: new or upgraded components

Particle Identification Devices

Barrel PID: Time of Propagation Counter (TOP)



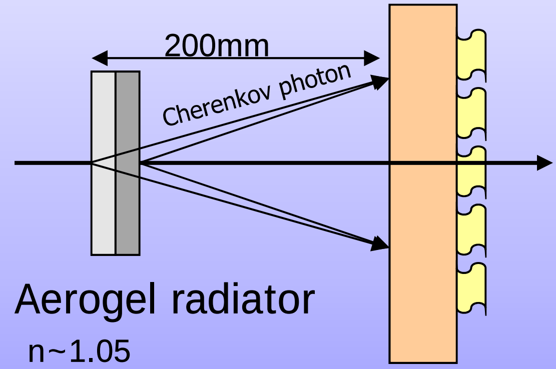
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)

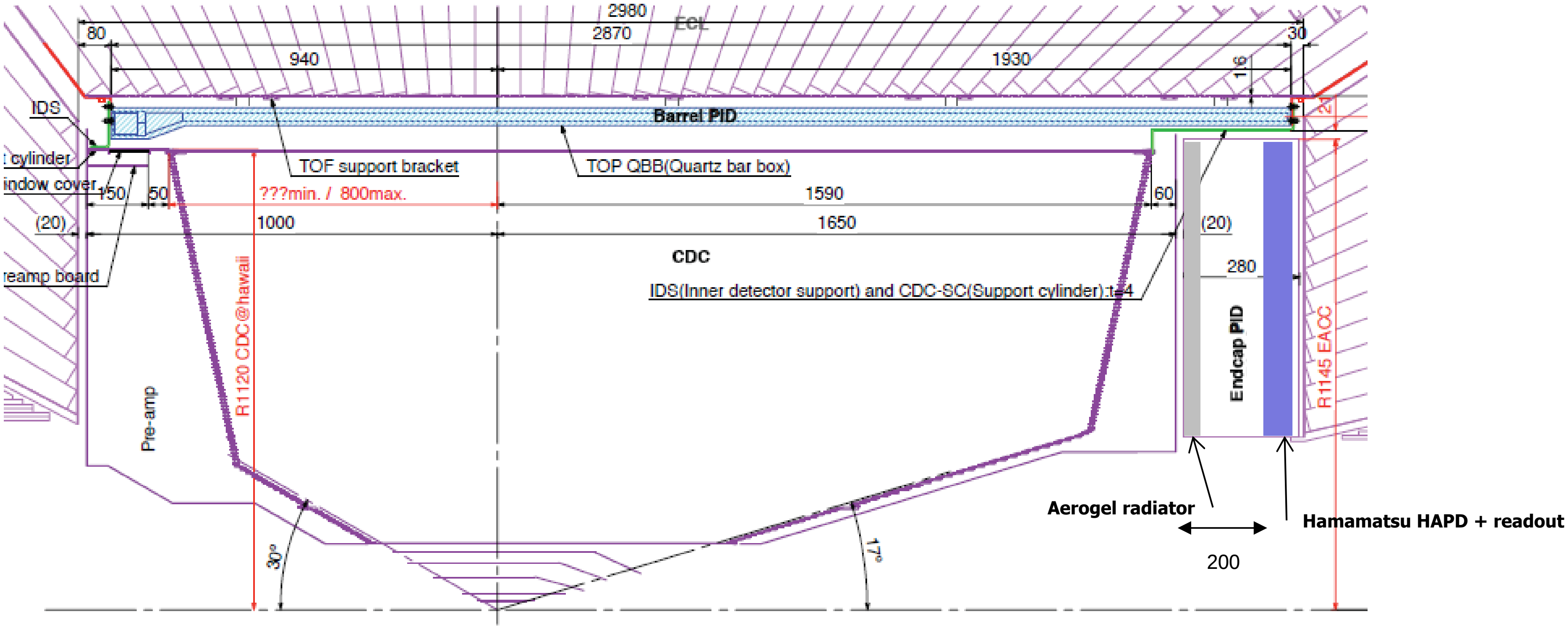


Aerogel radiator

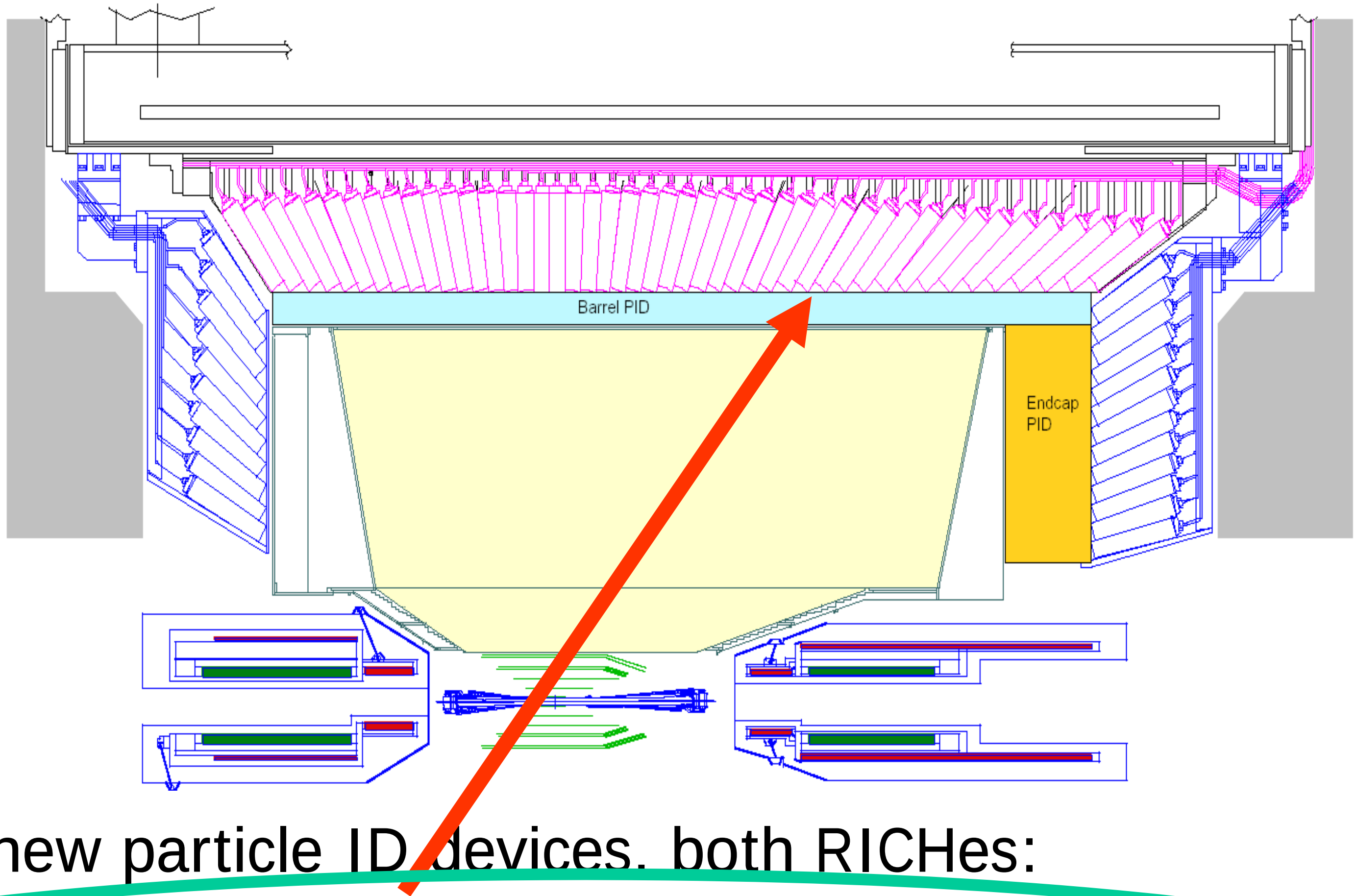
n~1.05

Hamamatsu HAPD

+ new ASIC



Belle upgrade – side view



Two new particle ID devices, both RICHes:

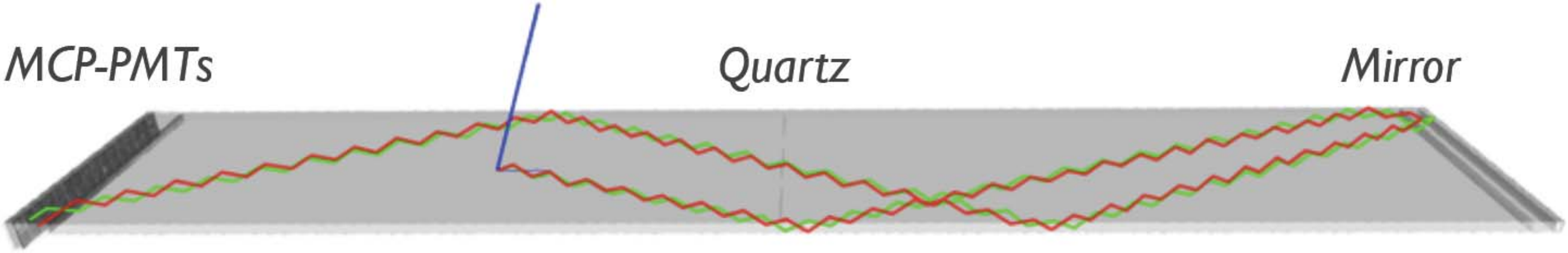
Barrel: Time-of-propagation counter (TOP) counter

Endcap: proximity focusing RICH

Barrel PID: Time of propagation (TOP) counter

Cherenkov ring imaging with precise time measurement.

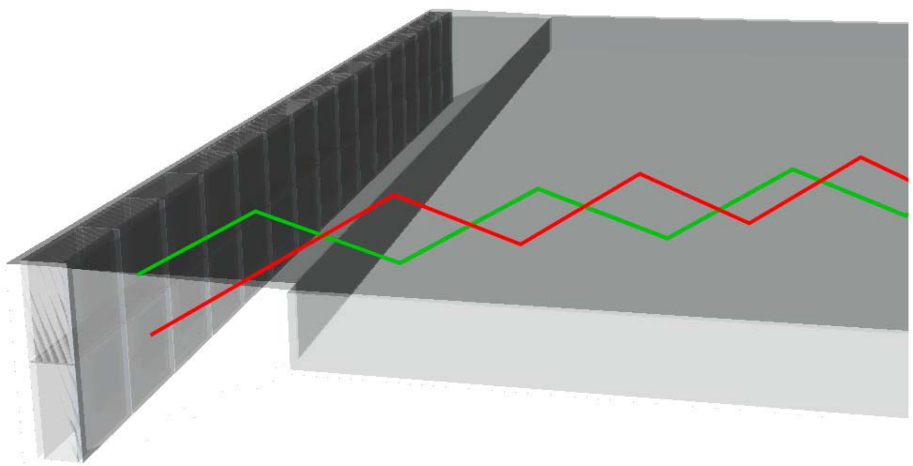
Device uses internal reflection of Cherenkov ring images from quartz like the BaBar DIRC



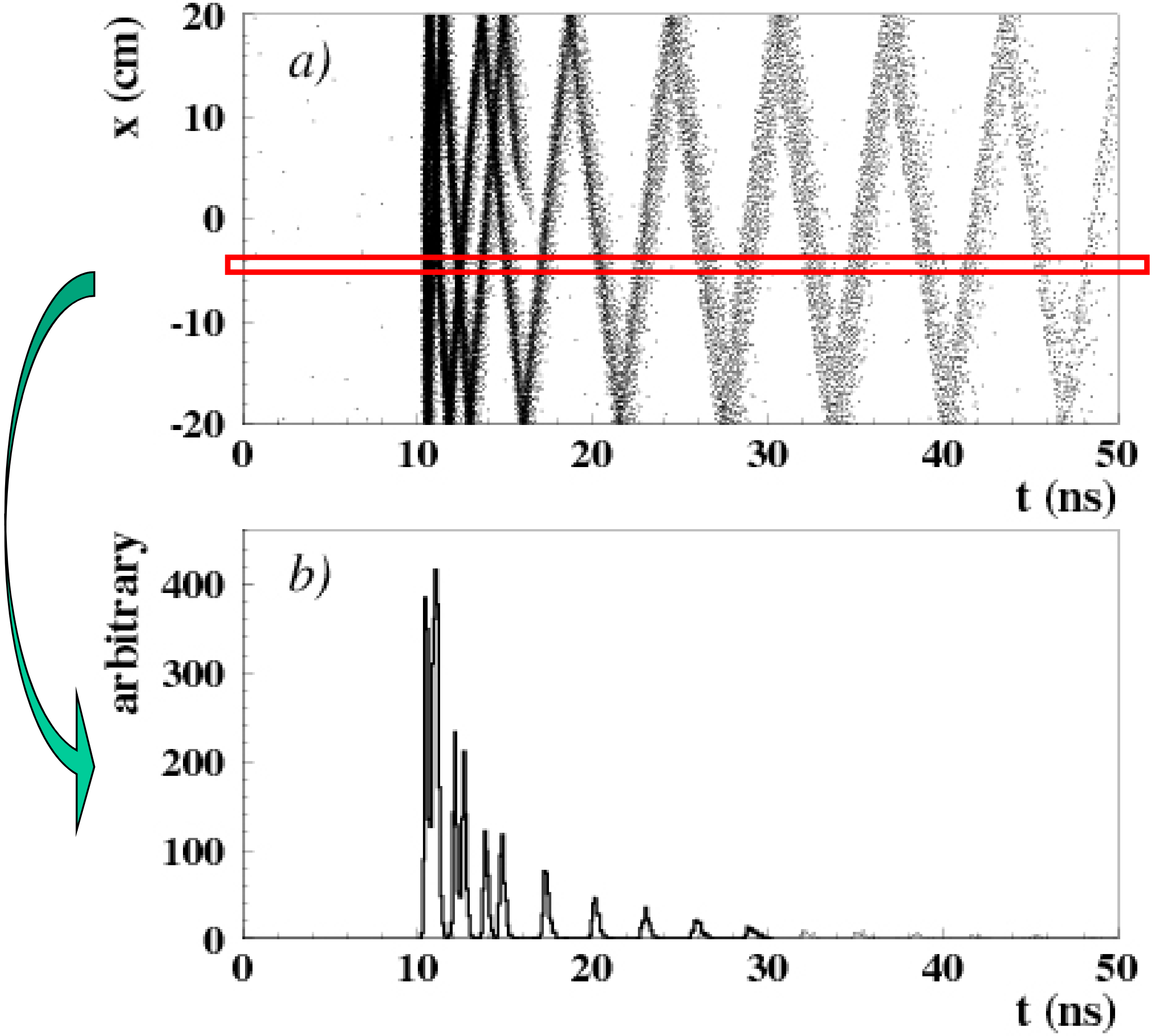
Example of Cherenkov-photon paths for 2 GeV/c $\pi^{\pm}$ and $K^{\pm}$.

Reconstruct Cherenkov angle from two hit coordinates and the time of propagation of the photon

- Quartz radiator (2cm)
- Photon detector (MCP-PMT)
  - Excellent time resolution ~40 ps
  - Single photon sensitivity in 1.5 T
- Fast read-out electronics



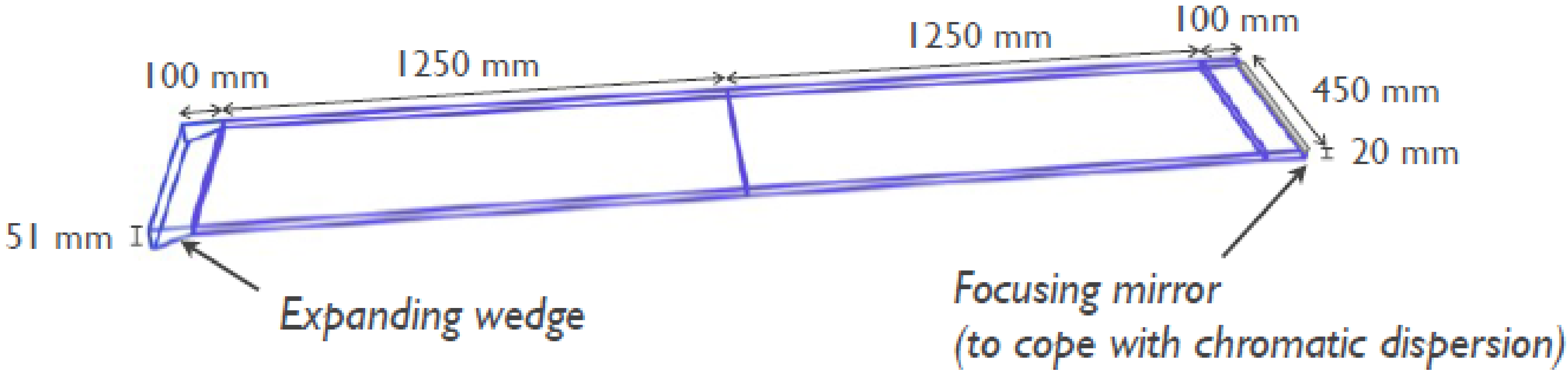
TOP image



Pattern in the coordinate-time space ('ring') of a pion hitting a quartz bar with ~80 MAPMT channels

Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)

Quartz bar

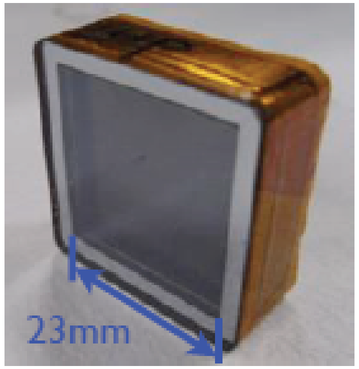


32 quartz bars are needed for the full Belle-II detector, 20x450x1250mm^3, two per module, plus mirror and wedge.

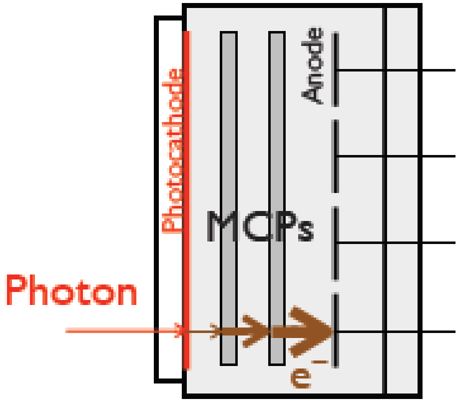
The quartz needs to be of high quality to ensure that photon losses are minimised, and that the Cherenkov photon reflection angles are maintained.

Quartz Property	Requirement
Flatness	<6.3µm
Perpendicularity	<20 arcsec
Parallelism	<4 arcsec
Roughness	< 0.5nm (RMS)
Bulk transmittance	> 98%/m
Surface reflectance	>99.9%/reflection

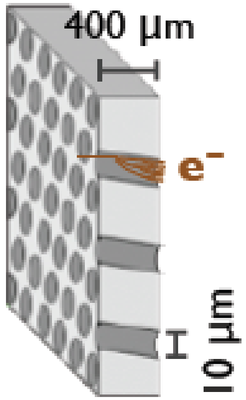
Photon detector: SL10 MCP PMT



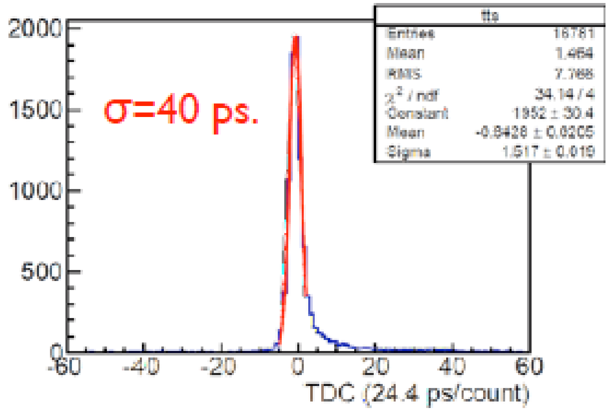
square shape



cross-sectional view

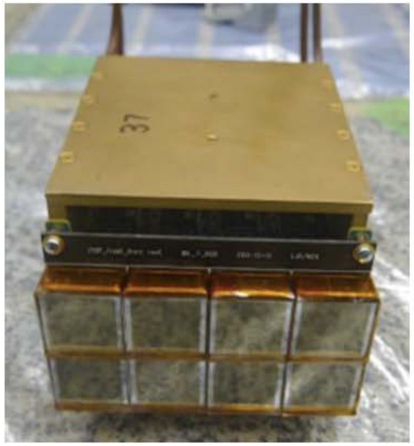


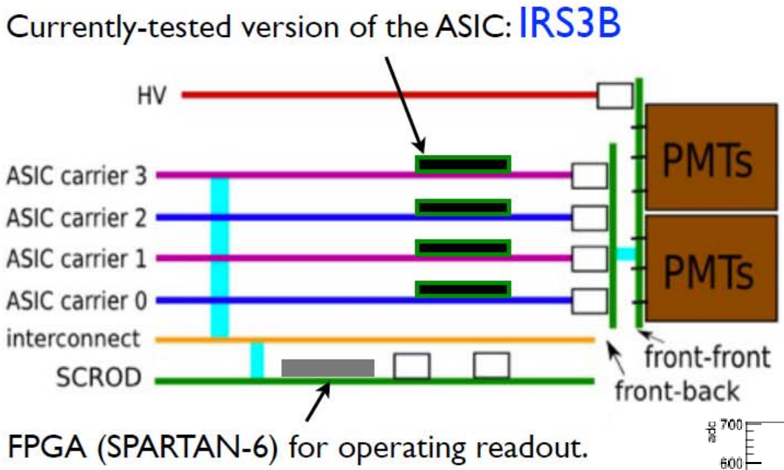
MCP

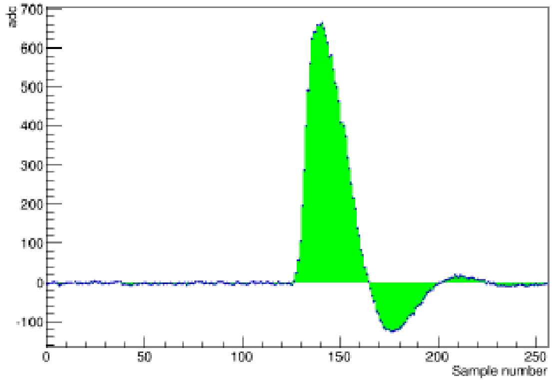


- MCP-PMT has an active area of ~23x23mm^2
- Photocathode: NaKSbCs
- Readout via 4·4 channels – 512 total channels per TOP module.
- PMTs required to have a peak quantum efficiency of >24%, and a collection efficiency of ~55%.
- Intrinsic transit time spread: ~40ps.

Read-out electronics







Based on a waveform-sampling ASIC

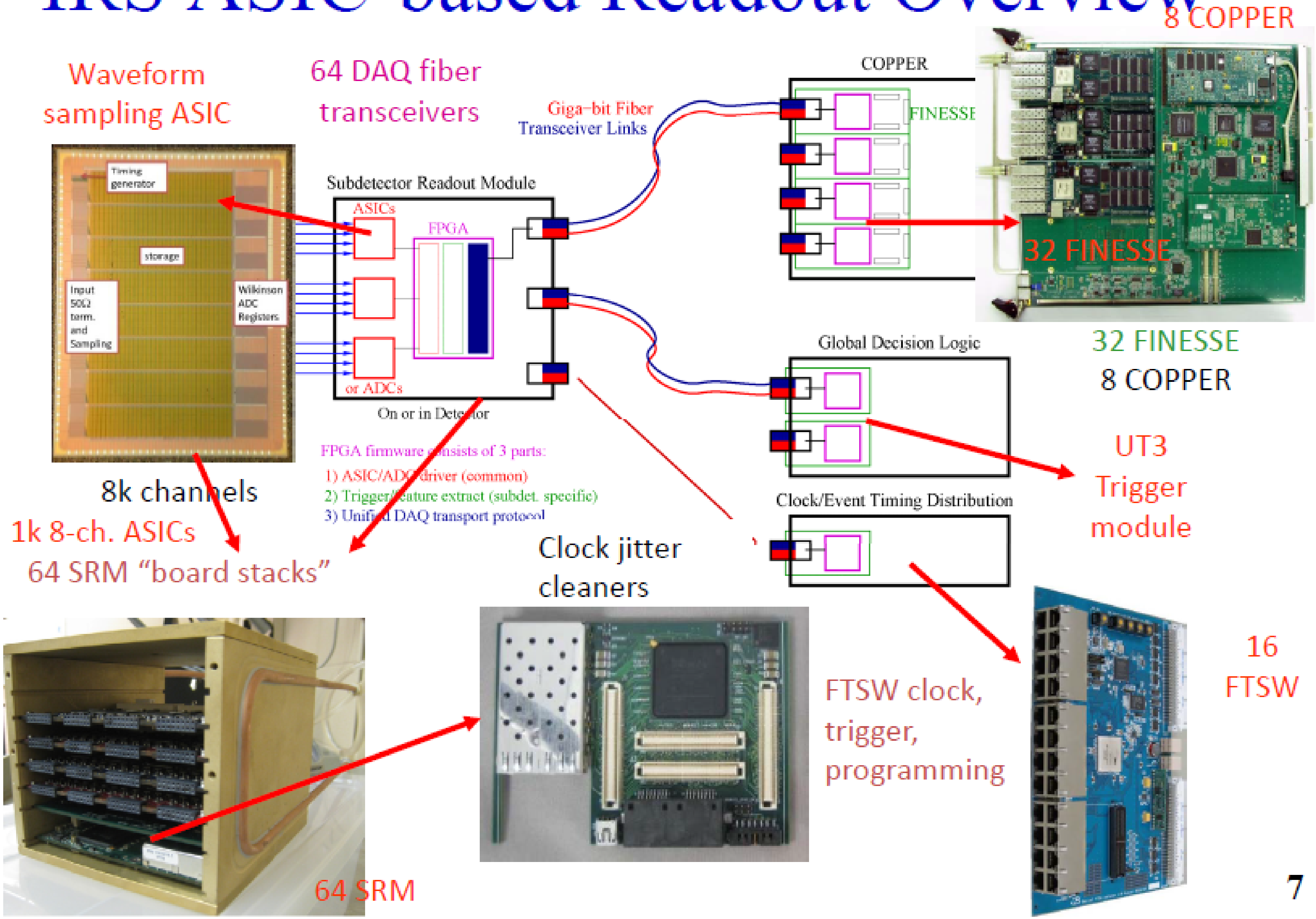
4 × 10^9 samples / sec. Chip intrinsic time resolution of <25 psec.

Calibration of the time and the charge requires a significant learning curve.

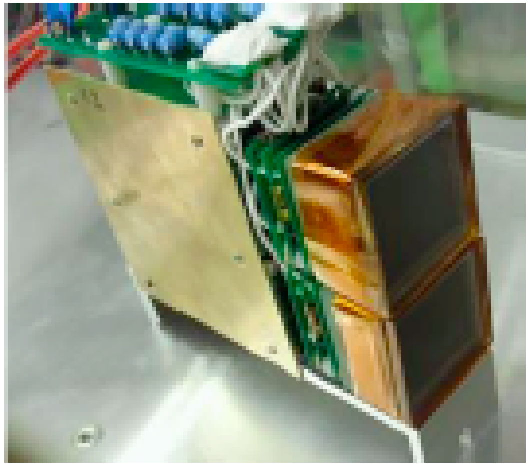
G. Varner, “Experience with the first generation deep sampling ASICs IRS and BLAB3”, Workshop on Timing Detectors: Electronics, Medical and Part. Phys. Appl., Cracow, 2010.

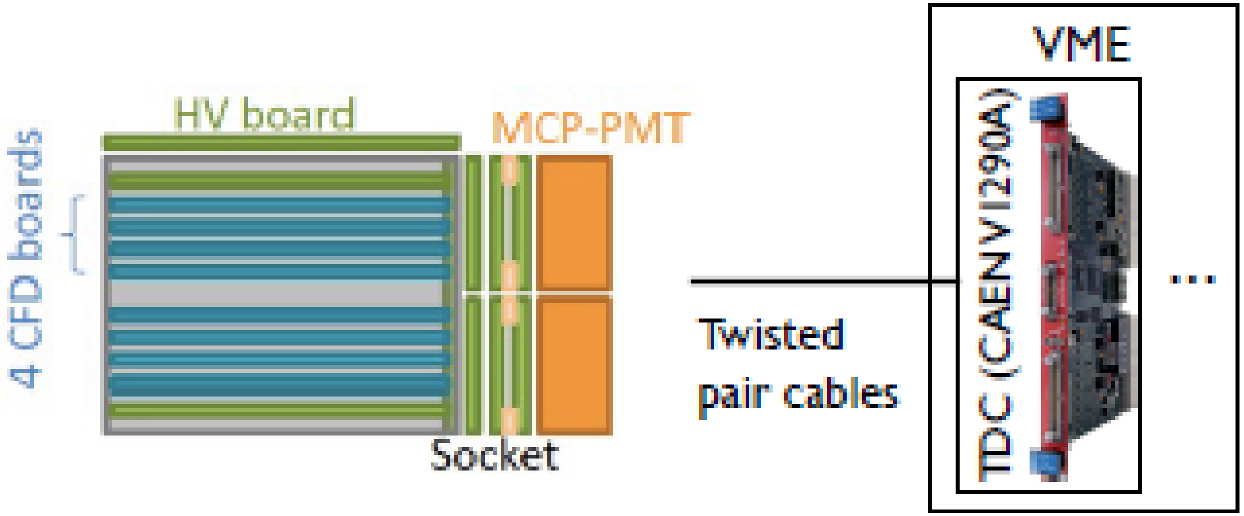
G. Varner, “Deeper Sampling CMOS Transient Waveform Recording ASICs”, TIPP 2011

IRS ASIC-based Readout Overview



Read-out electronics – backup for TOP performance tests

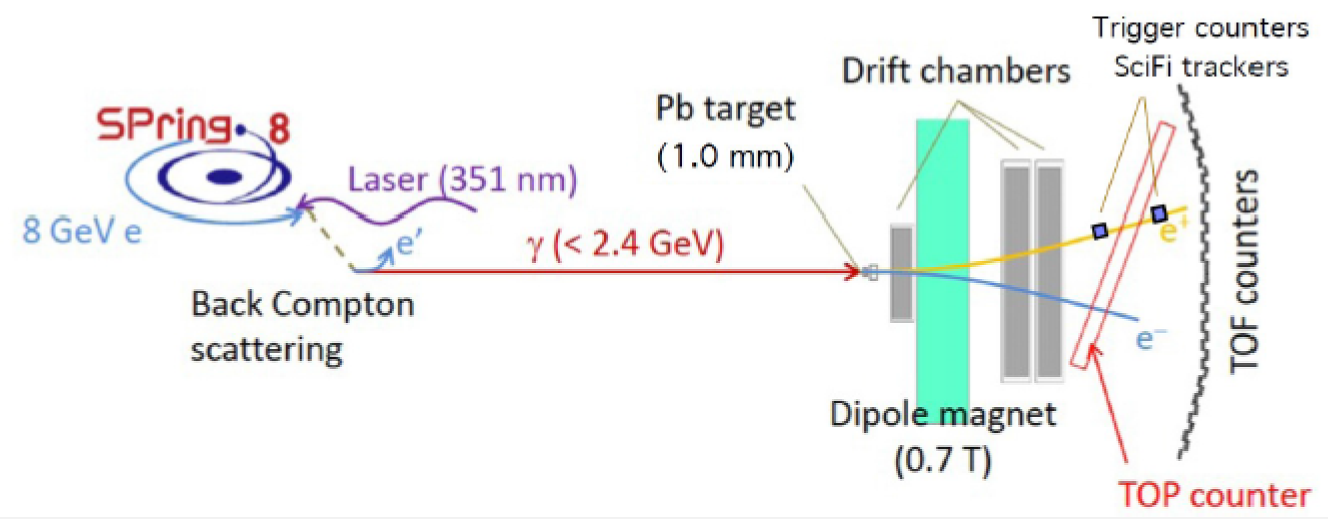




- Based on constant fraction discriminator (CFD).
- MCP-PMT 16 channels are merged into 4 at the MCP-PMT socket.
- Time resolution ~ 50 psec.
- Calibration relatively simpler. Can be used for TOP performance tests

→K. Inami, RICH 2010.

Beam test at SPRING8

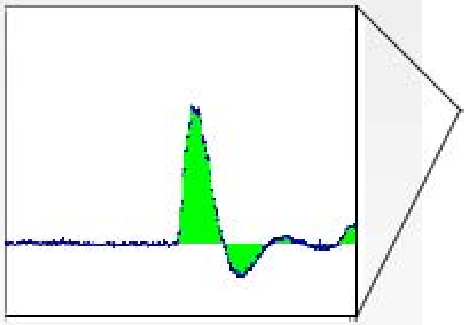


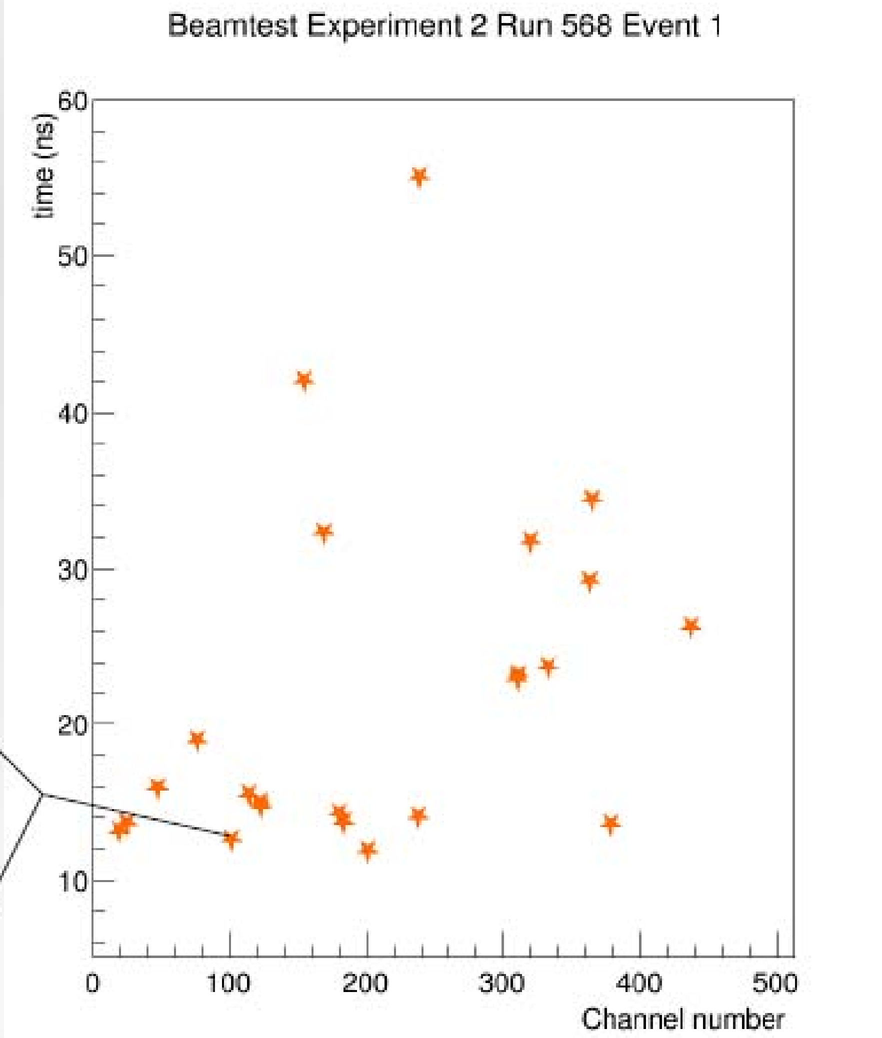
Secondary positron beam, ~2.1 GeV

TOP prototype mounted in the LEPS spectrometer.

Beam Test Event

- Single events have a mean of ~30 Cherenkov photons detected.
  - Each waveform yields a hit time.
  - Multiple events are required in order to see a ring image.

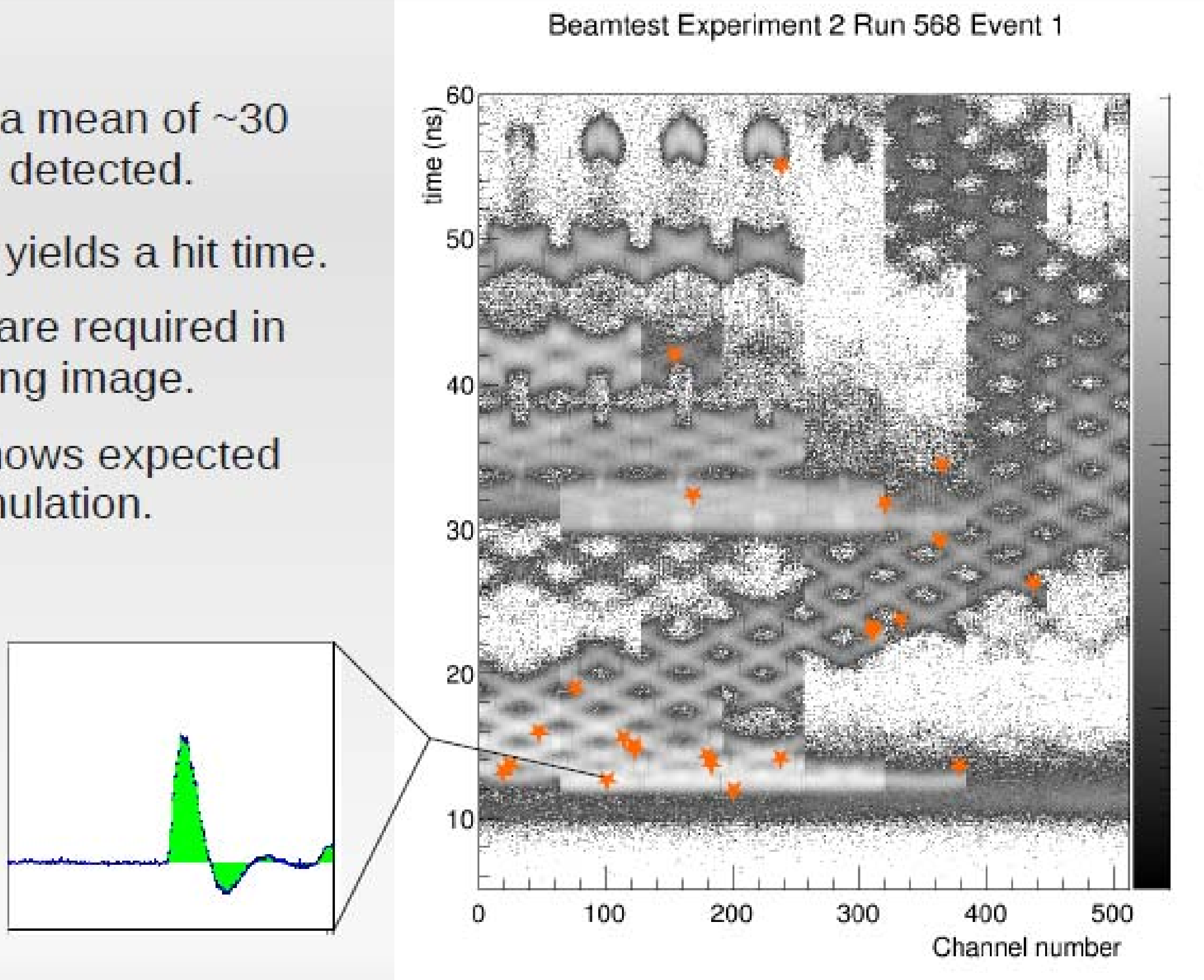




Recorded by the baseline IRS3B waveform sampling read-out.

Beam Test Event

- Single events have a mean of ~30 Cherenkov photons detected.
  - Each waveform yields a hit time.
  - Multiple events are required in order to see a ring image.
- Greyscale image shows expected distribution from simulation.

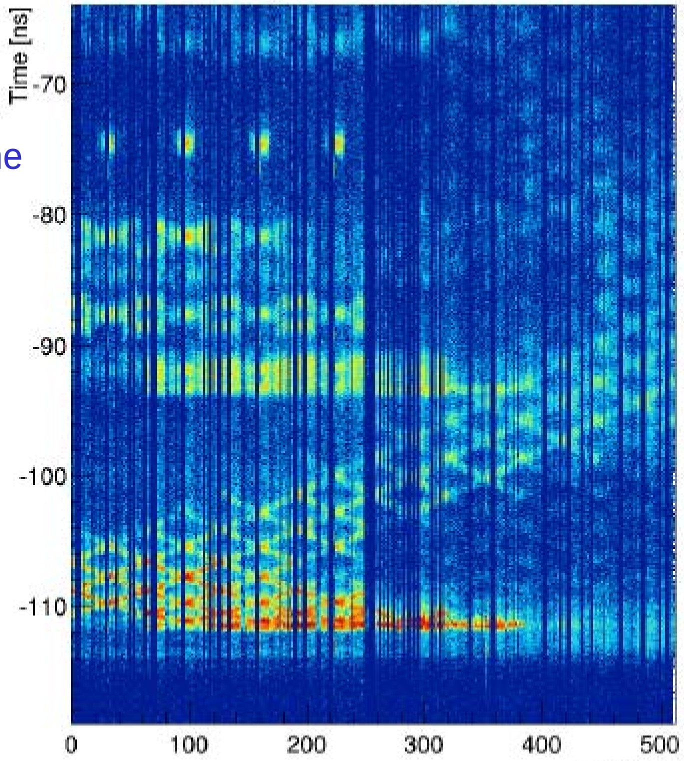


ID of the particle: from a 2D likelihood function

TOP image

Pattern in the coordinate-time space ('ring') – different for kaons and pions.

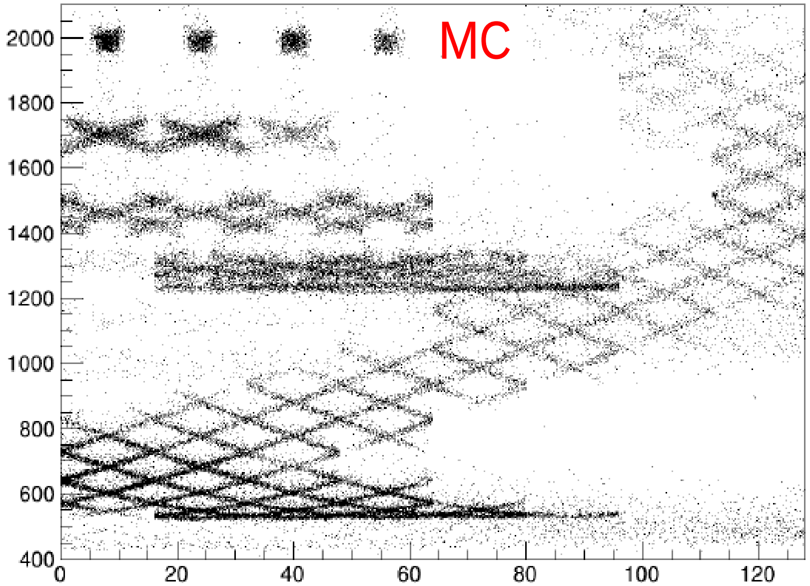
Excellent agreement between beam test data and MC simulated patterns.



time

coordinate

time



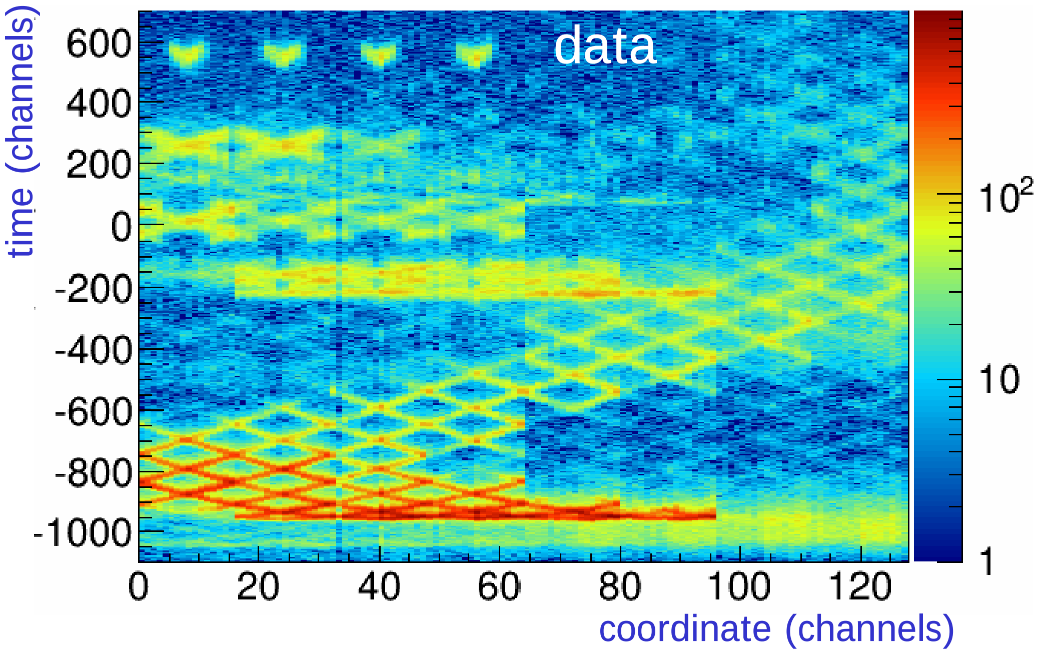
coordinate

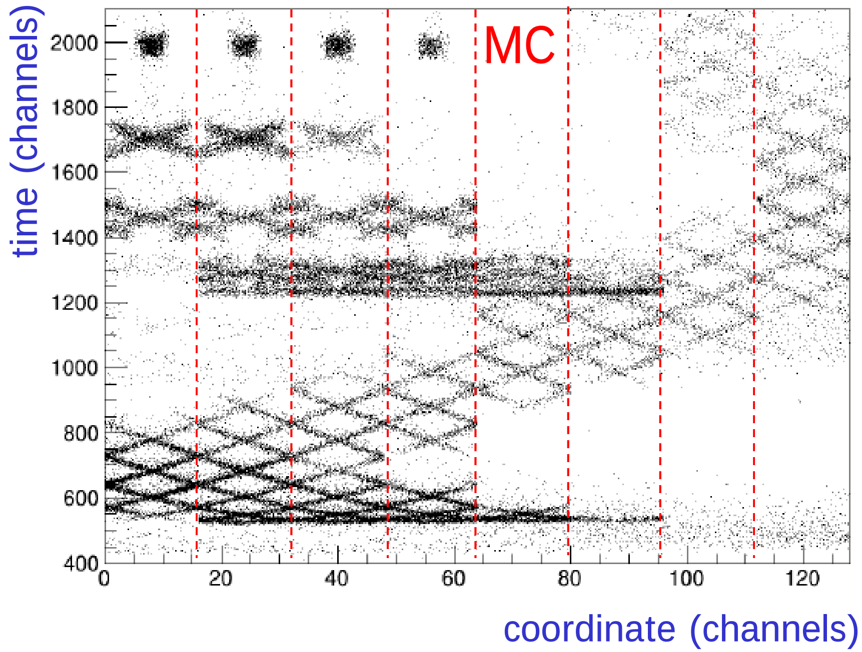
Recorded by the baseline IRS3B waveform sampling read-out.

TOP image

Pattern in the coordinate-time space ('ring') – different for kaons and pions.

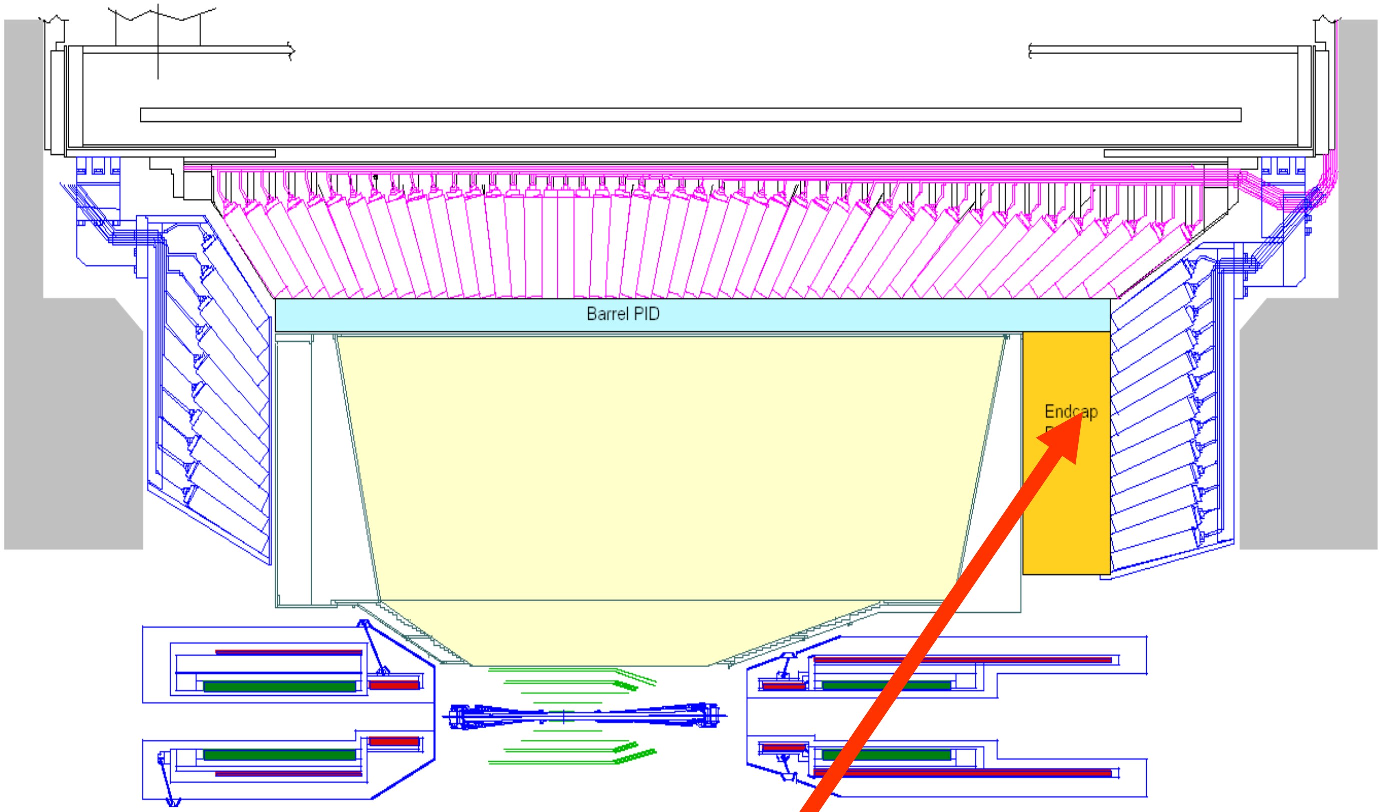
Excellent agreement between beam test data and MC simulated patterns.





Recorded by the CFD-based read-out.

Belle II PID system

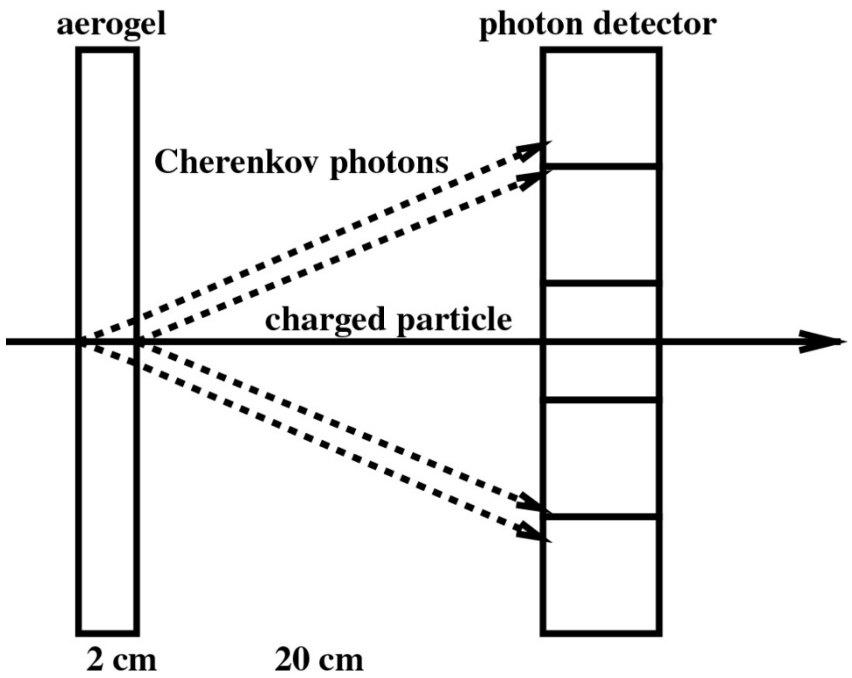


Two new particle ID devices, both RICHes:

Barrel: Time-of-propagation counter (TOP) counter

Endcap: proximity focusing RICH

Endcap: Proximity focusing RICH



K/π separation at 4 GeV/c:

$\theta_c(\pi)$ ~ 308 mrad (n = 1.05)

$\theta_c(\pi) - \theta_c(K)$ ~ 23 mrad

For single photons: $\delta\theta_c(\text{meas.}) = \sigma_0$ ~ 14 mrad,

typical value for a 20mm thick radiator and 6mm PMT pad size

Per track:

$$\sigma_{track} = \frac{\sigma_0}{\sqrt{N_{pe}}}$$

Separation: $[\theta_c(\pi) - \theta_c(K)]/\sigma_{track}$

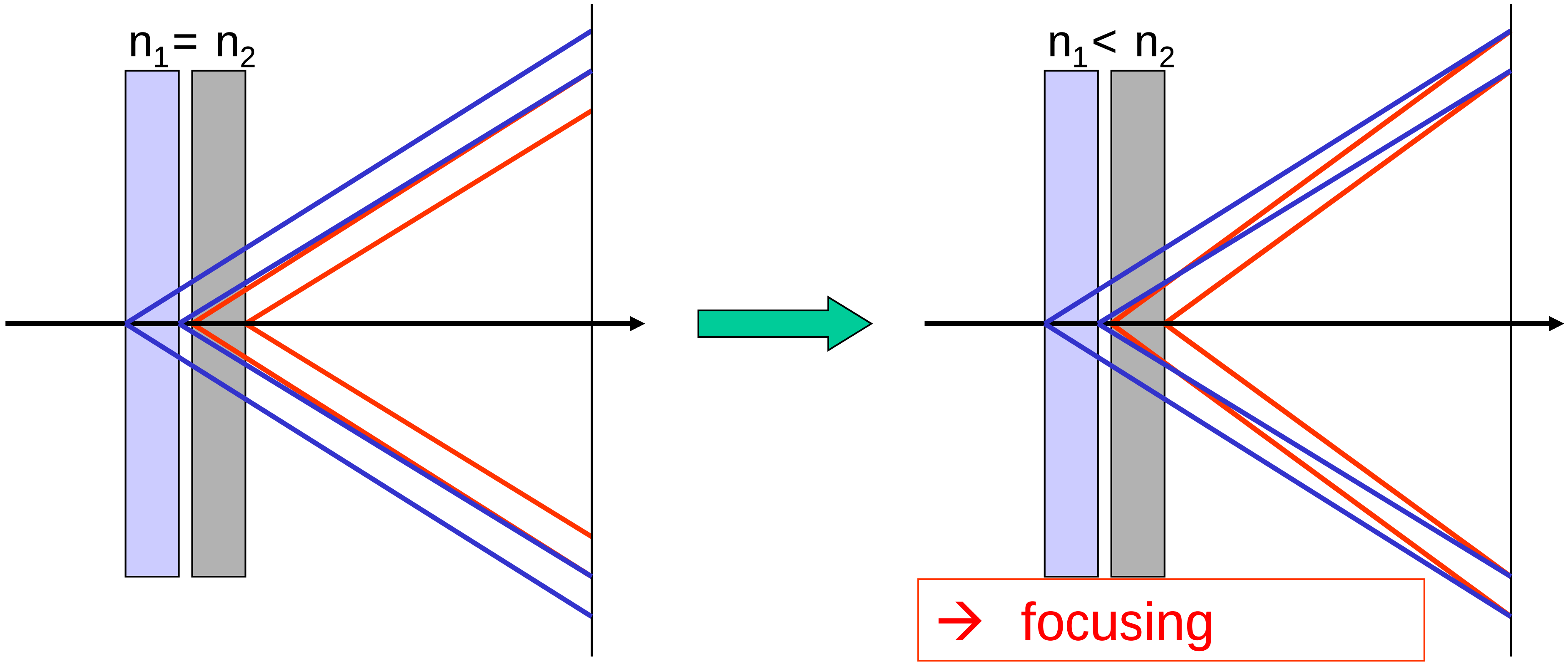
→ 5σ separation with N_{pe}~10

Radiator with multiple refractive indices

How to increase the number of photons without degrading the resolution?

→ stack two tiles with different refractive indices: "focusing" configuration

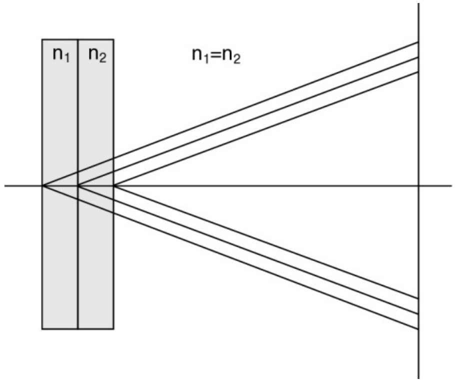
normal

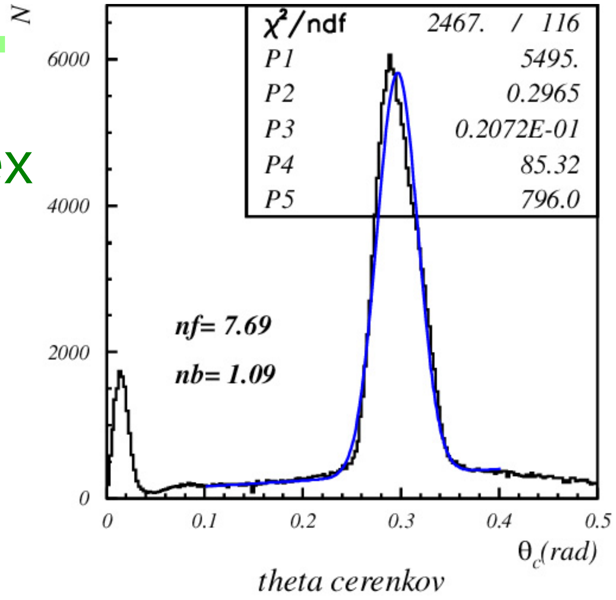


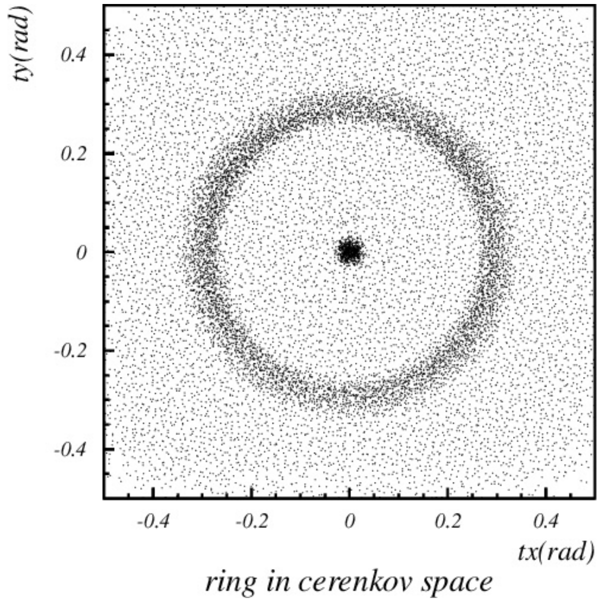
Such a configuration is only possible with aerogel (a form of Si_xO_y) – material with a tunable refractive index between 1.01 and 1.13.

Focusing configuration – data

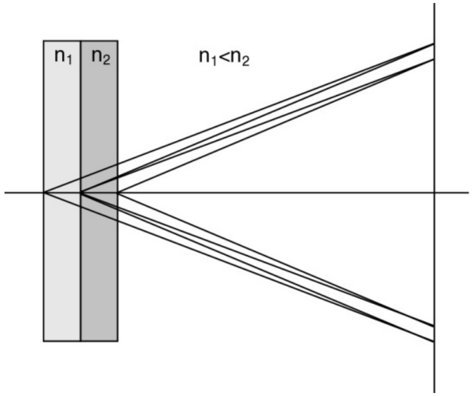
4cm aerogel single index

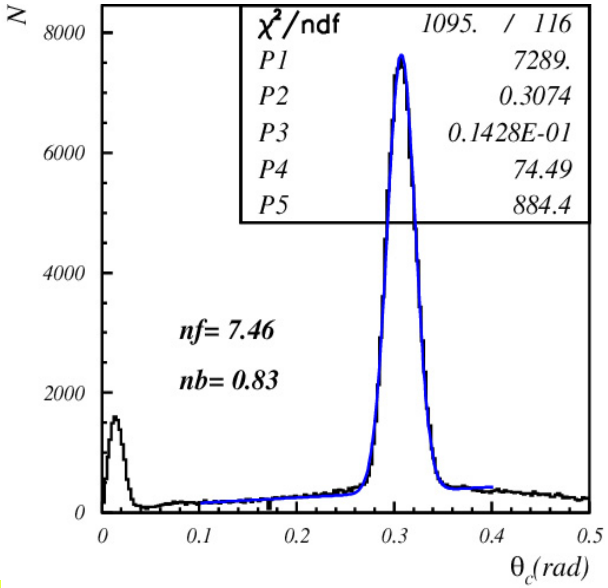


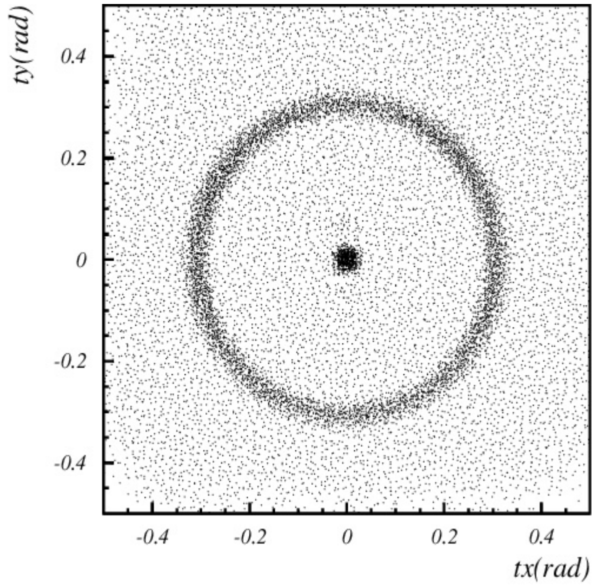




2+2cm aerogel





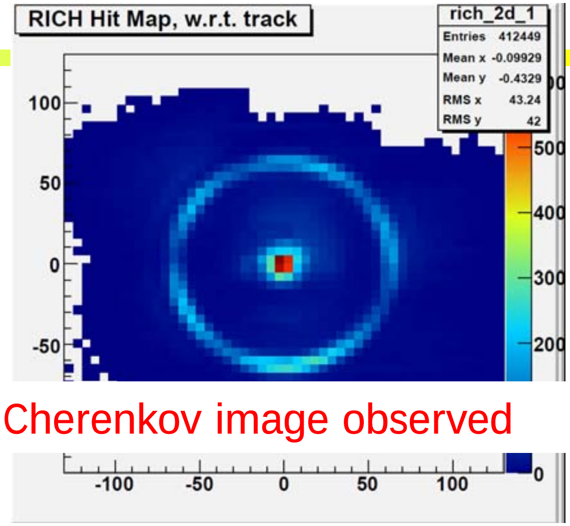


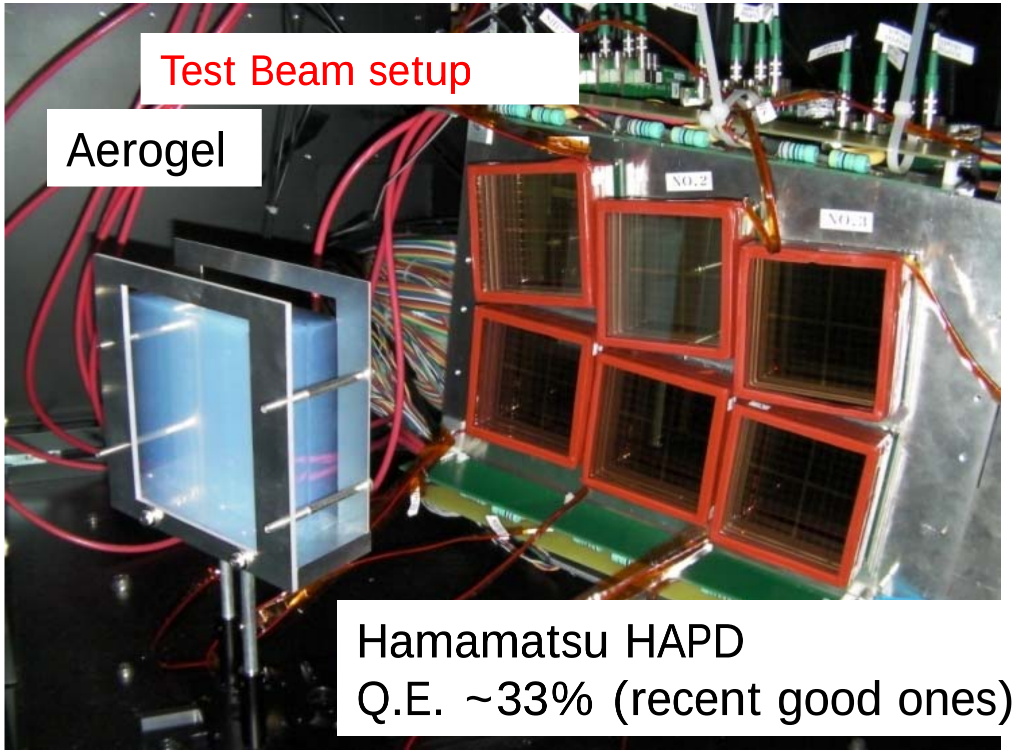
→NIM A548 (2005) 383, NIMA 565 (2006) 457

Aerogel RICH photon detectors

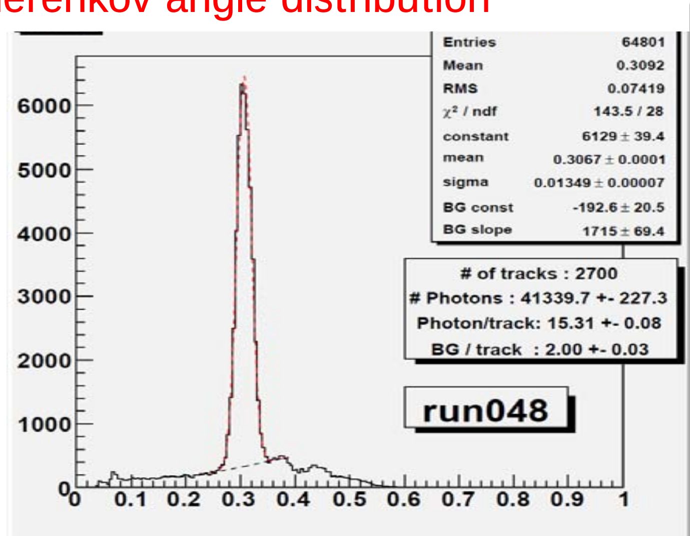
Need:
Operation in 1.5 T magnetic field
Pad size ~5-6mm

Baseline option: large active area HAPD
of the proximity focusing type





Cherenkov angle distribution



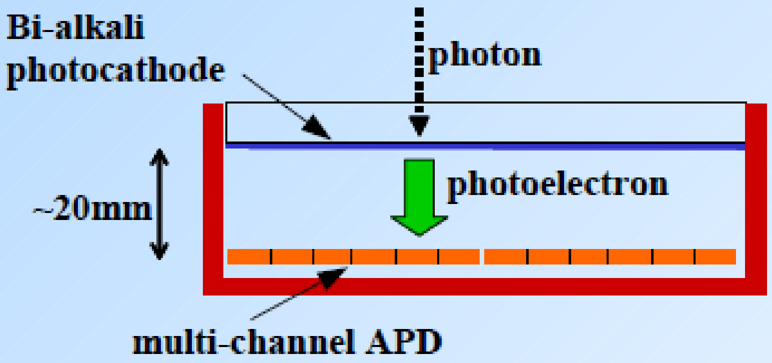
6.6 σ p/K at 4GeV/c !

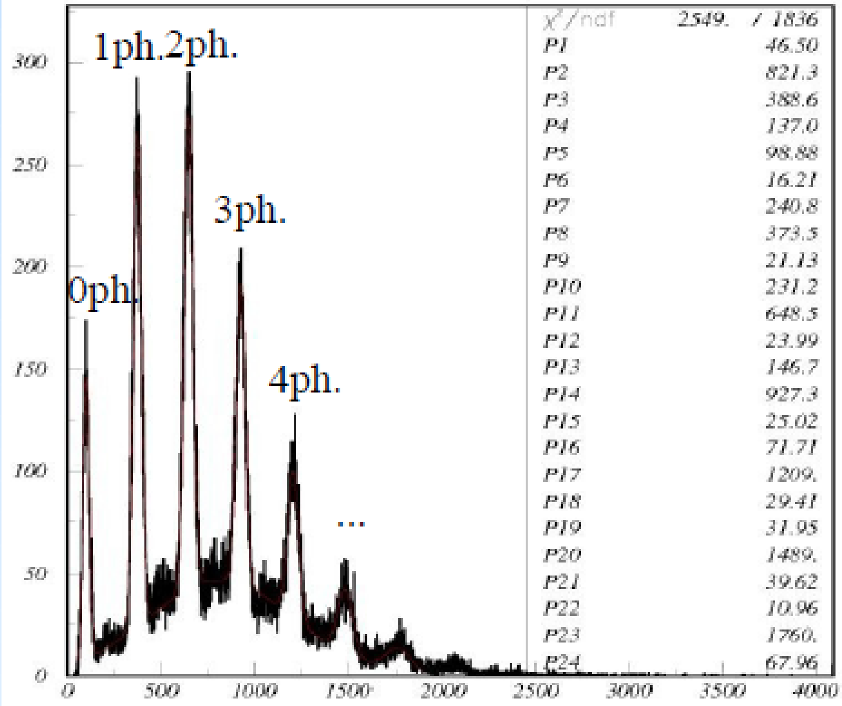
→ NIM A595 (2008) 180

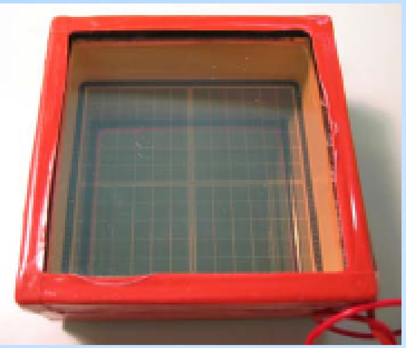
ARICH photon detector: HAPD

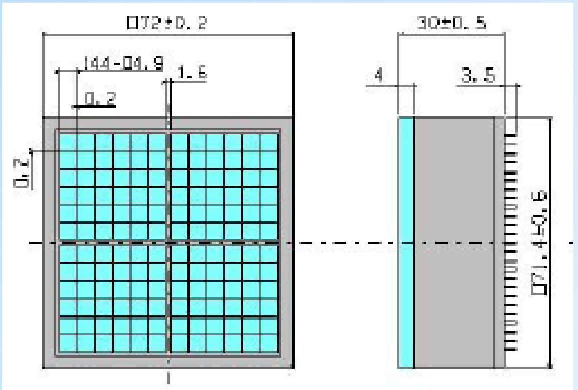
Hybrid avalanche photo-detector developed in cooperation with Hamamatsu (proximity focusing configuration):

- 12x12 channels (~5x5 mm^2)
- size ~ 72mm x 72mm
- ~ 65% effective area
- total gain ~ $10^4 - 10^5$
(bombardment ~1500, avalanche ~40)
- detector capacitance ~ 80pF/ch.
- typical peak QE ~ 30%
- works in mag. field (~perpendicular to the entrance window)





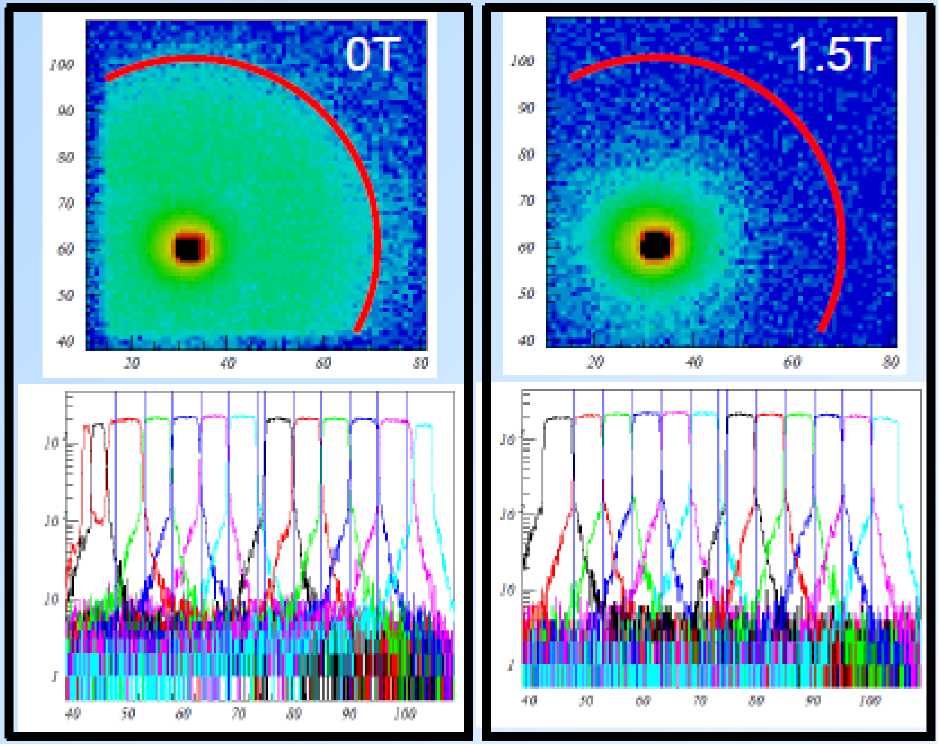




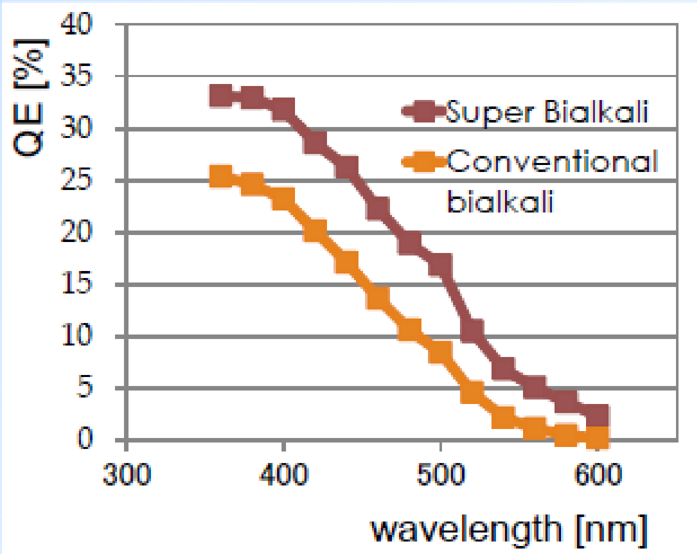
ARICH photon detector: HAPD

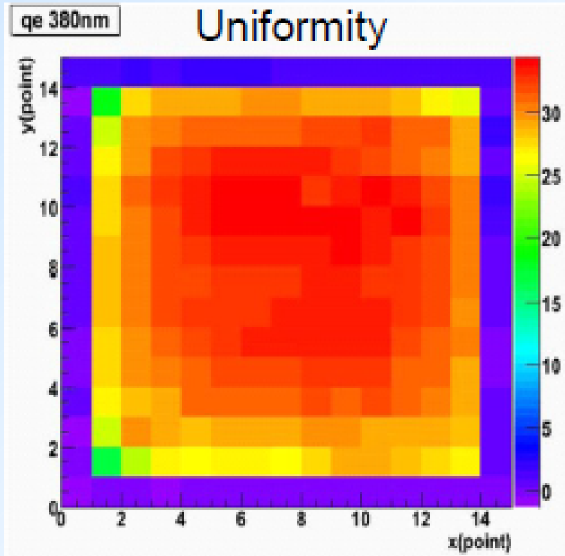
Tests in 1.5 T magnetic field show improved performance:

- no photoelectron back-scattering cross-talk
- Effect of non-uniformity of electric field disappears



QE improved by Hamamatsu with super bialkali photocathode: 25% → 32% peak

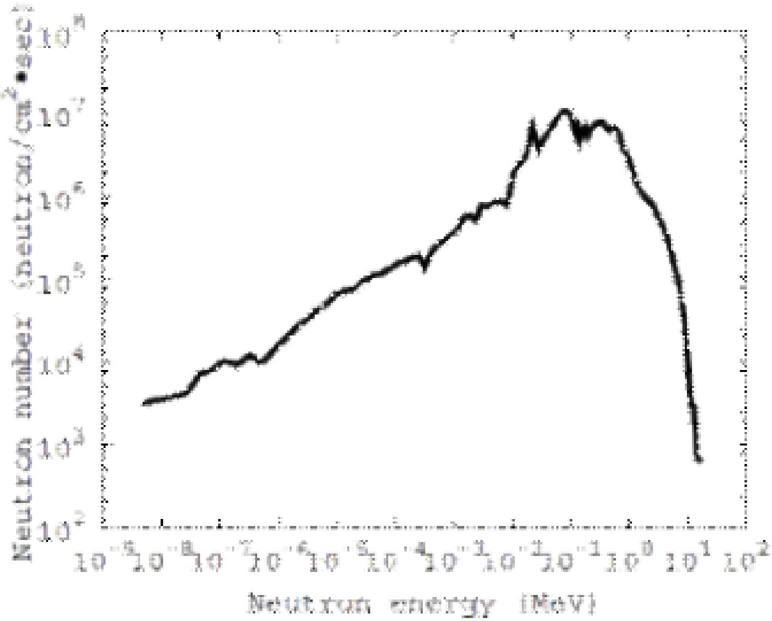


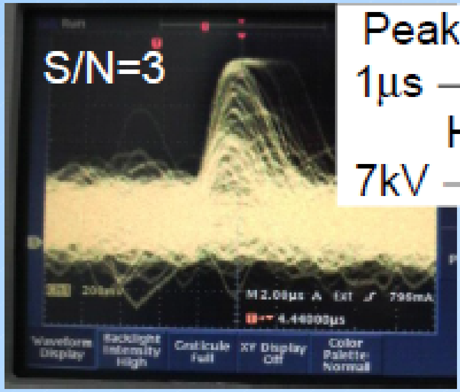


Neutron irradiation

Reactor "Yayoi" @ Tokyo U.

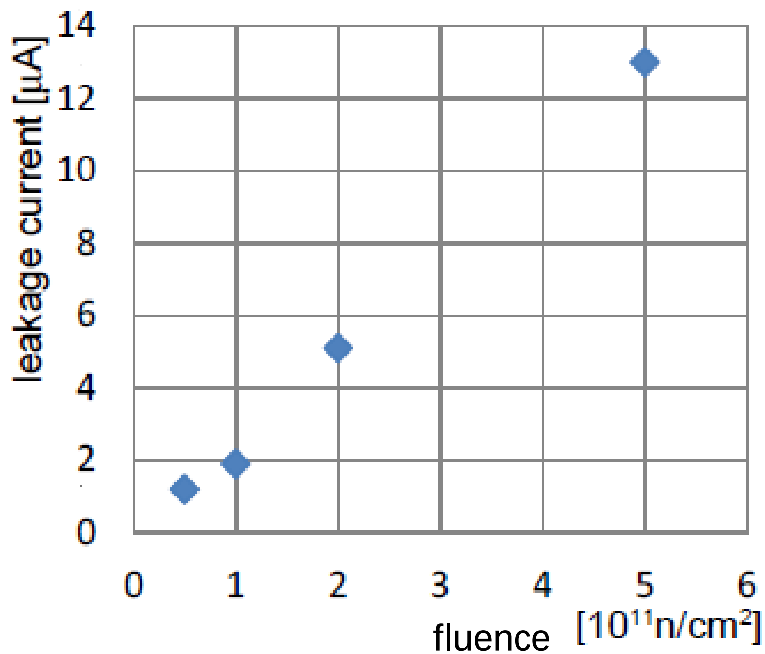
- Expected total fluence 10^{12} n/cm^2
- First test S/N drops to 7 @ 5×10^{11}n/cm^2





Peaking time:
1µs → 250ns
HV:
7kV → 8.5kV

→ Expected S/N~5 @ fluence 10^{12} n/cm^2, marginal operation



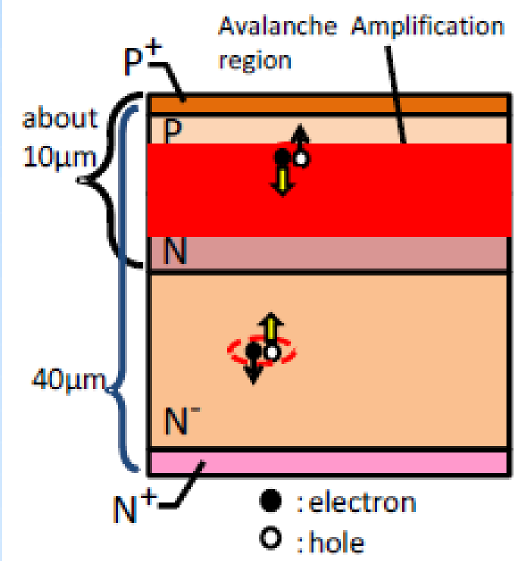
- Re-optimization of peaking time for larger leakage currents → shorter peaking time with next ASIC version
- Optimization of APD structure

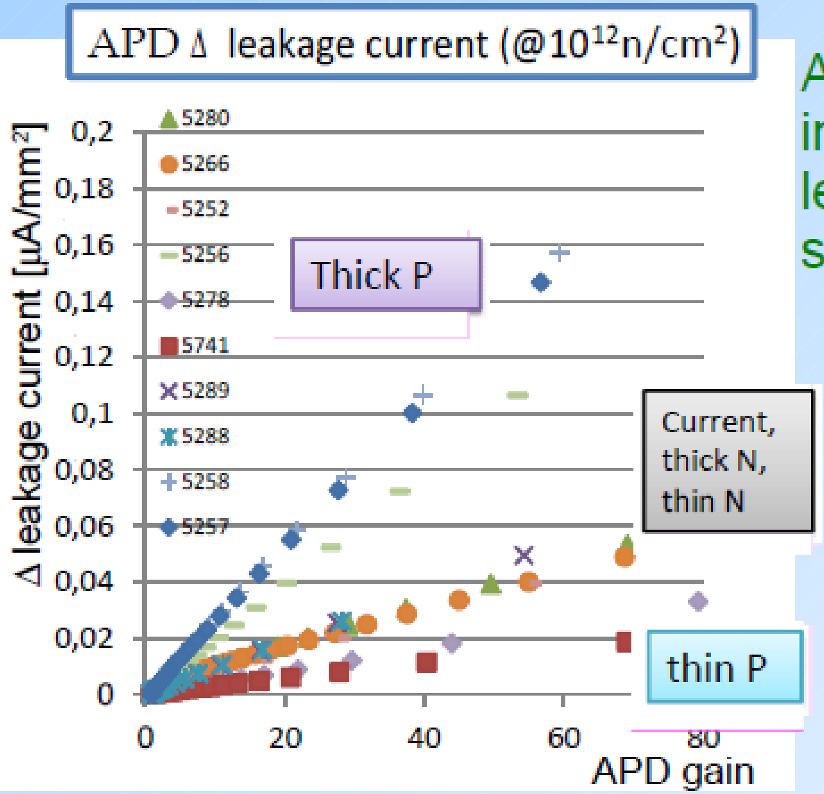
Samo Korpar, IEEE/NSS 2011

Neutron damage

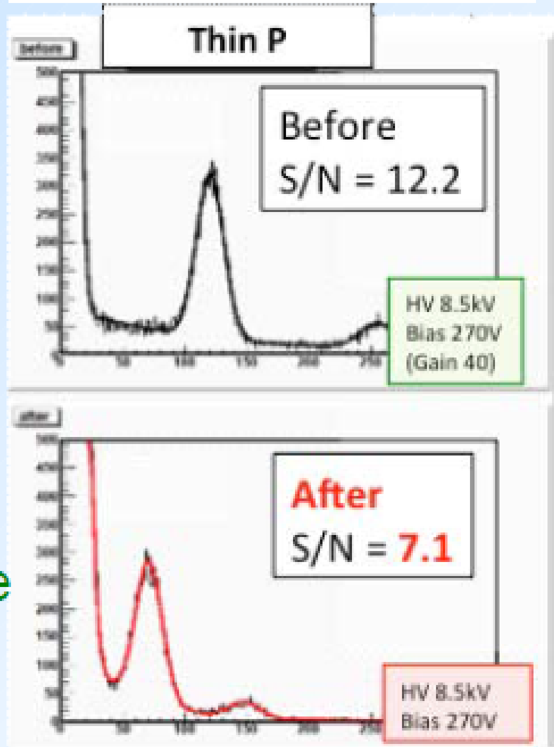
Modification of APD structure:

- Thinner p+ layer to increase bombardment gain
- Thinner p layer to reduce increase of the leakage current after irradiation – main source of leakage current are thermally generated electrons in p layer due to the lattice defects produced by neutrons





As expected the increase of the leakage current is smaller with thin p



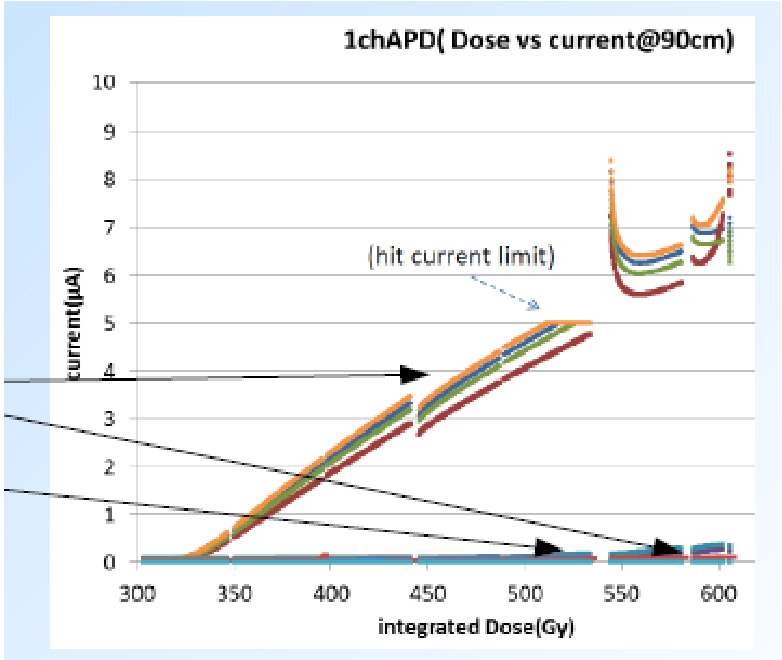
S/N for thin p sample is better than 7 after fluence 10^{12}n/cm^2

Samo Korpar, IEEE/NSS 2011

Gamma irradiation

- Expected total dose 100-1000 Gy
- Initial tests indicated a fast raise of leakage current - not previously observed with similar APDs.
- Source (found in irradiation tests of several sample types prepared by Hamamatsu): APD for HAPD has additional alkali protection layer to protect APD during photocathode activation process → charging up
- APD structure optimized

Standard alkali protection
No alkali protection
Optimized new alkali protection



Summary

- Belle II PID systems are challenging new devices, with very interesting novel features
- Most technical problems have been solved
- Finalize the design, get ready for the production with an agressive time schedule