High Energy Accelerator
Research Organization – KEK, Japan

Belle II

Behavior of HAPD for the Belle II Aerogel RICH in magnetic field

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On behalf of the Belle II ARICH group

Content:

- Belle II experiment
- Aerogel RICH
- HAPD
- Performance and issues in magnetic field
- Summary

THE 14TH VIENNA CONFERENCE ON INSTRUMENTATION
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The Belle II experiment & SuperKEKB

Belle II

New facility on the **intensity frontier:** **Virtual production of new particles** to probe energies beyond the energy frontier (prime examples: GIM, M_c, 3 gen., M_t)

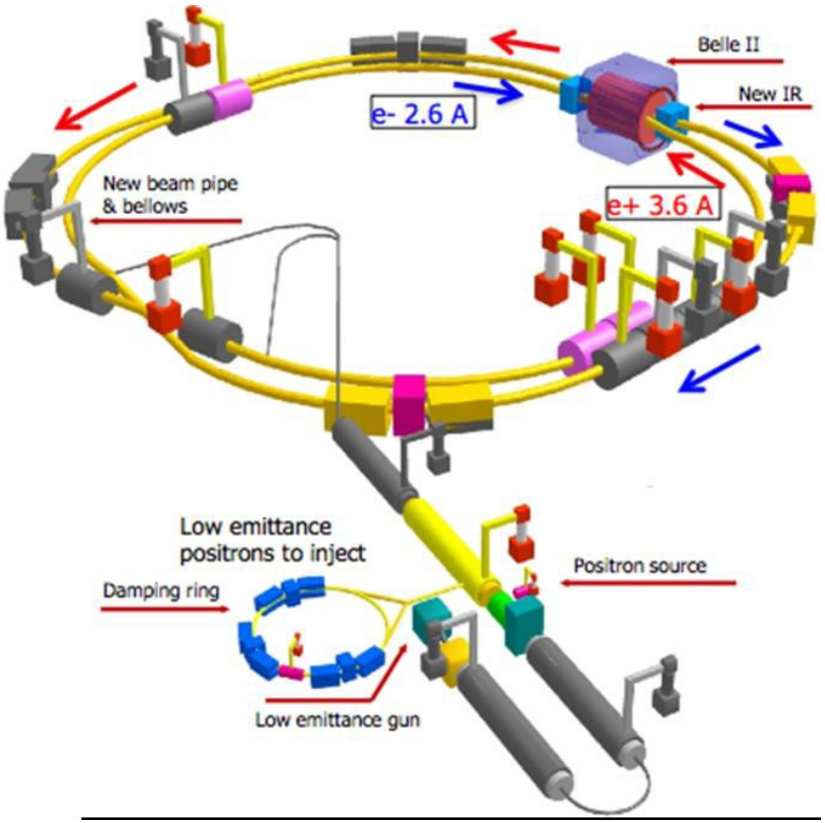
Successor of the very successful KEKB/Belle @ KEK, Tsukuba, Japan.

KEK / Belle
In operation: 1999-2010
Accumulated data: **1 ab^{-1}**
Peak luminosity: **2 x 10^{34} cm^{-2} s^{-1}**

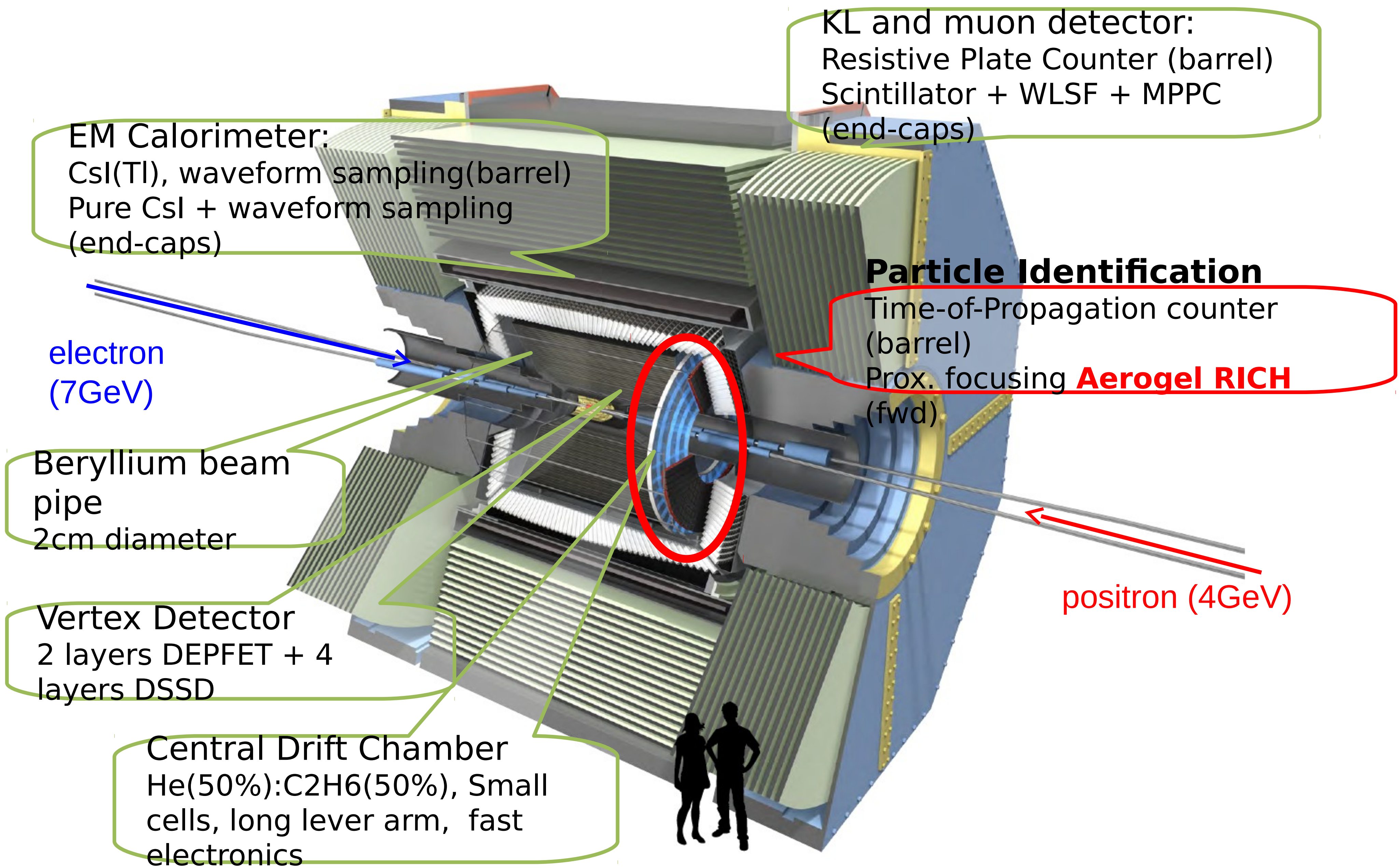
High precision confirmation of the SM flavor structure (KM mechanism is the main source of CPV,...).

KEKSuperB / Belle II
Physics runs start in 2018
Accumulated data: **50 ab^{-1}**
Luminosity: **8 x 10^{35} cm^{-2} s^{-1}** **(Belle x 40)**

Are there new CPV phases?
Are there right handed currents from NP?
Does nature have multiple Higgs bosons? ...



The Belle II detector

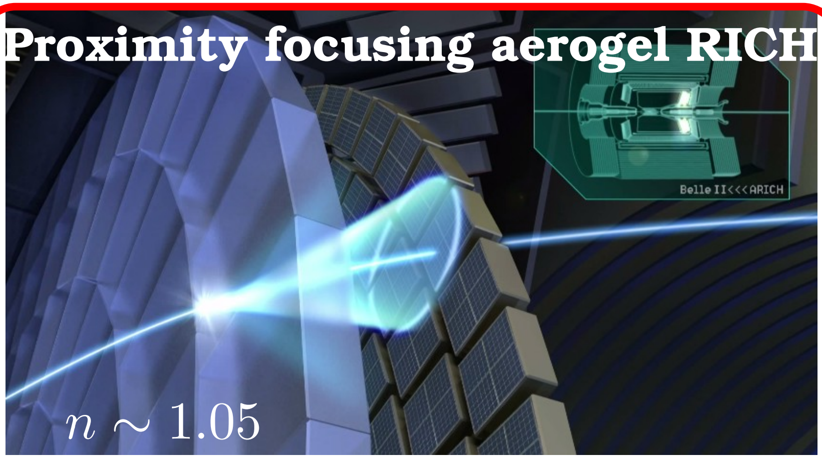


Aerogel RICH

Goal:
4σ π $/K$ separation, at 1.0 - 3.5 GeV
crucial not only for background reduction but also for B flavor tagging

Constraints:
- in 1.5 T magnetic field.
- limited available space ~28 cm.
- radiation hardness (n, γ).

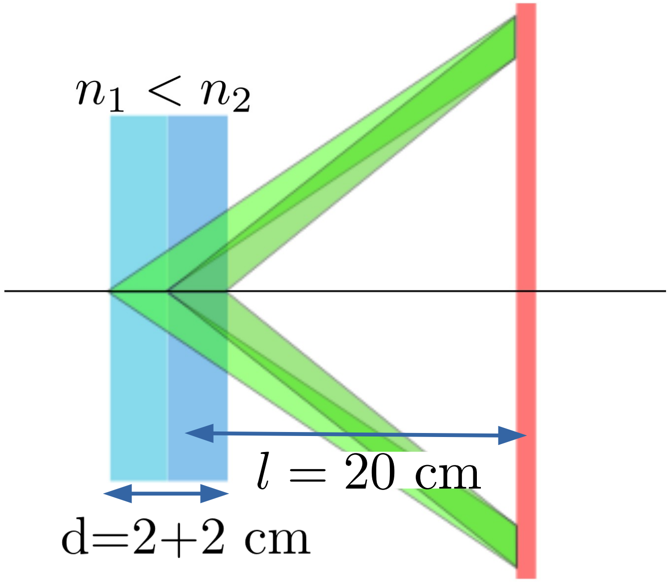
Proximity focusing aerogel RICH



$\theta_C(\pi) = 0.31$ rad @ 3.5 GeV

$\theta_C(\pi) - \theta_C(K) = 0.03$ rad @ 3.5 GeV

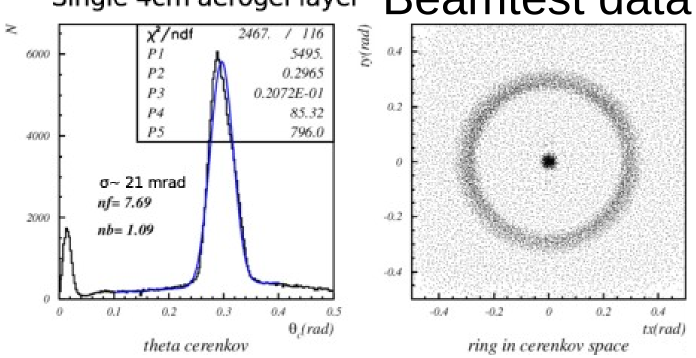
Novel technique of two aerogel layers in focusing configuration



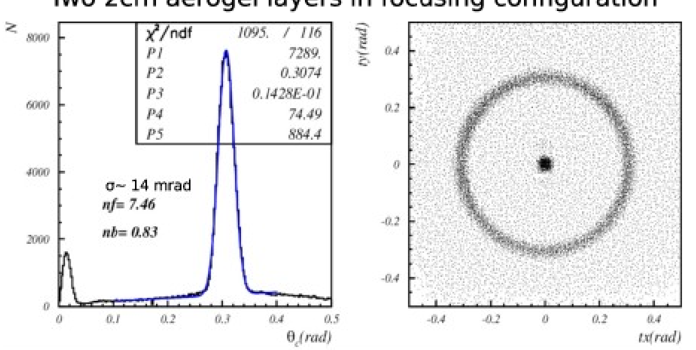
Almost doubling number of Cherenkov photons, without angle resolution degradation!

Beamtest data

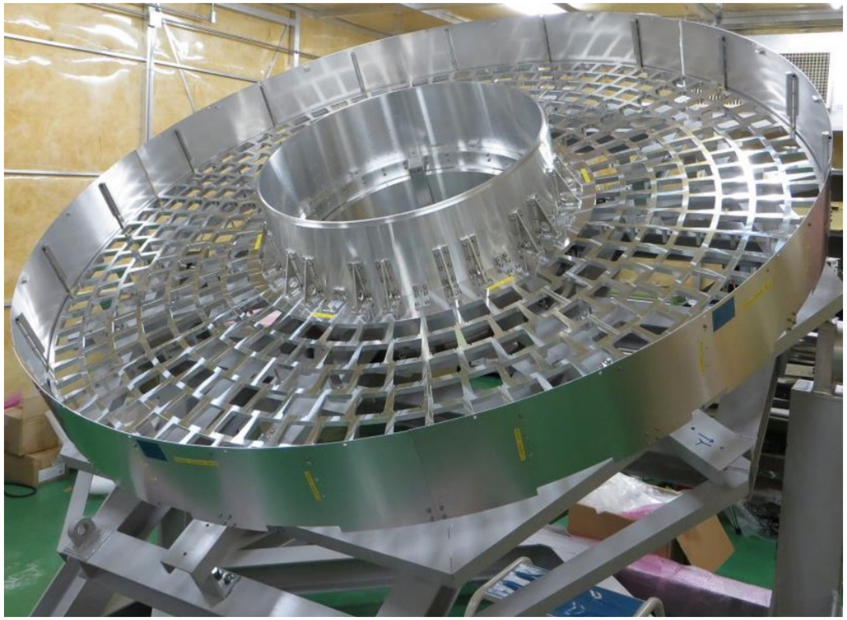
Single 4cm aerogel layer

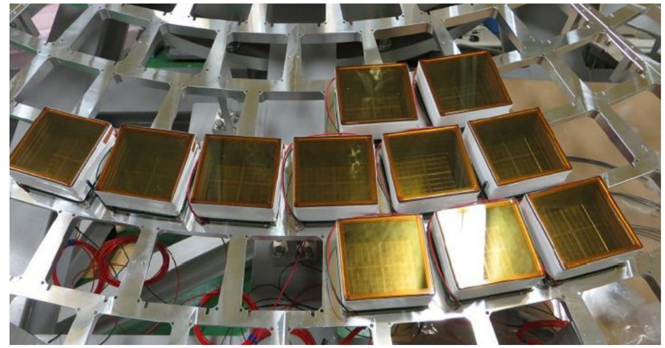


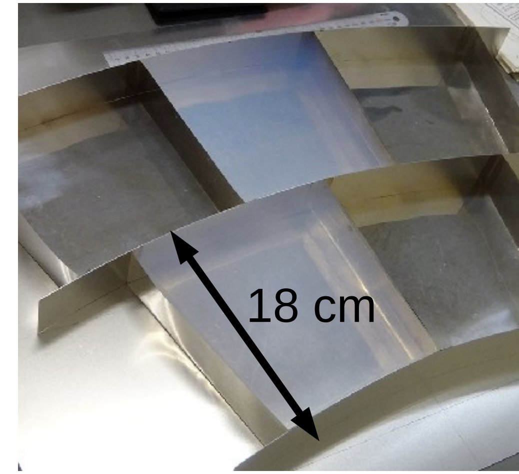
Two 2cm aerogel layers in focusing configuration



Aerogel RICH





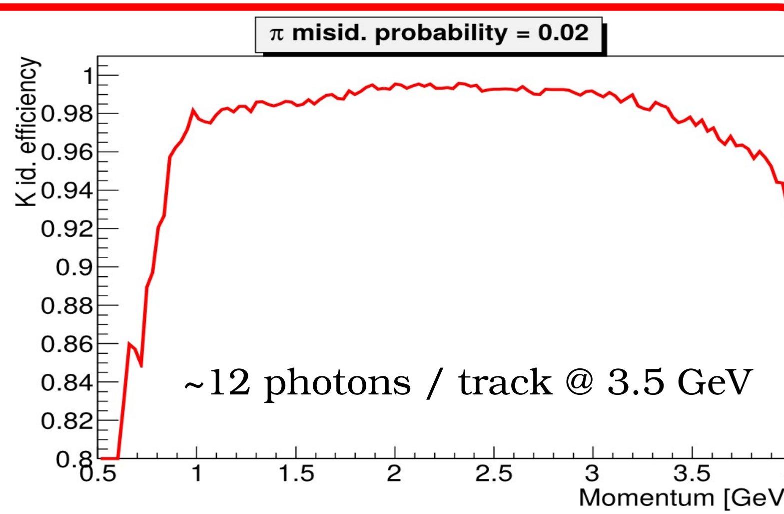


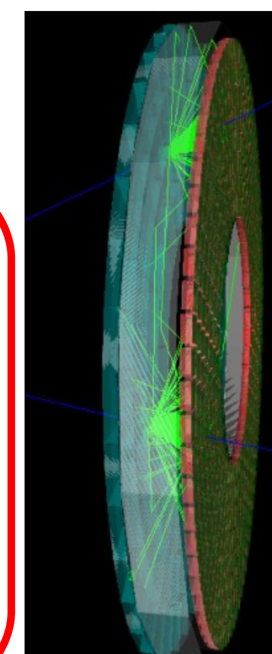
420 HAPDs are used to cover detector plane
2 x 124 aerogel tiles are used to cover radiator

Most of detector components are produced, assembling will start in March!

ARICH Perfomance from Belle2 Geant4 simulation

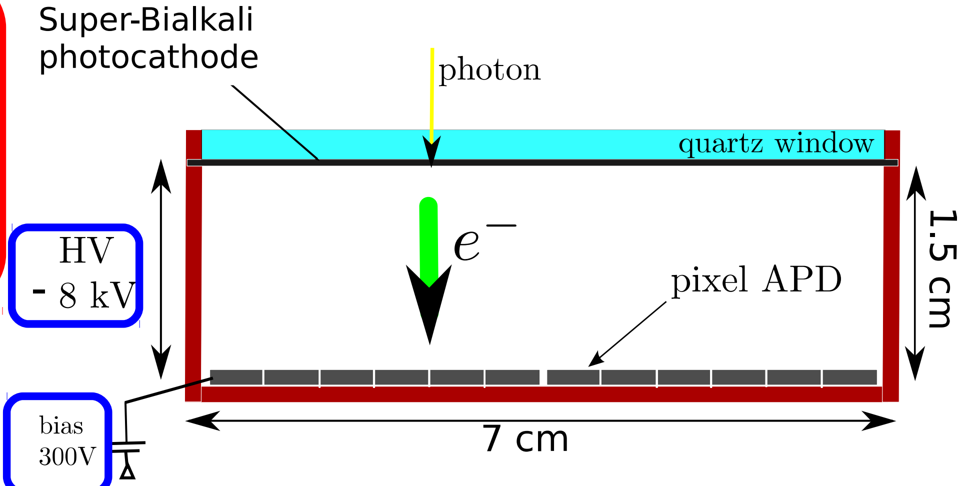
Desired 4σ π/K separation can be achieved





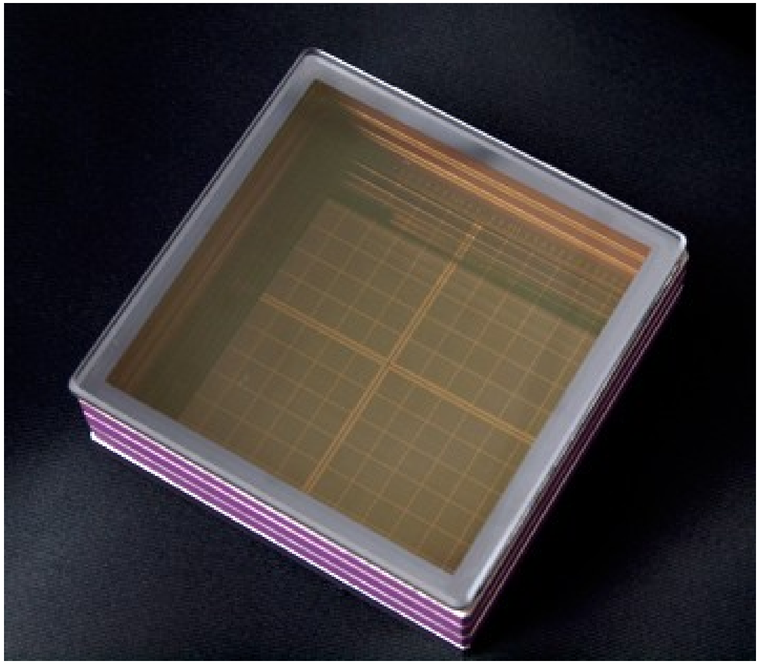
HAPD - Hybrid Avalanche Photo-Detector

Basic requirements for photon detector:
- high efficiency for single photon detection
- good position resolution
- operation in 1.5T magnetic field
- withstands neutron fluence of ~ 10^{12} n/cm^2



Selected candidate: HAPD

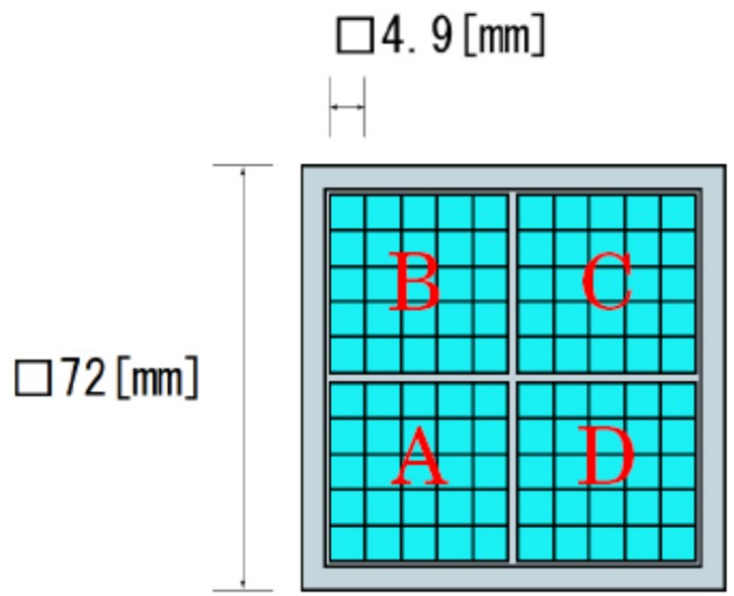
- Developed in collaboration with Hamamatsu Photonics K.K
- APD: 12 x 12 channels
- Package size: 72 x 72 mm
- Effective area: ~65%
- Total gain: ~4.8 x 10^4
  (~1500 bombardment gain * 40 avalanche gain)
- Detector capacitance: ~80 pF / ch

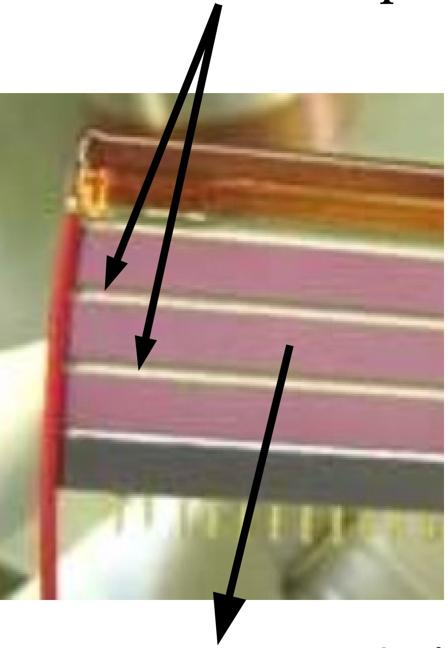


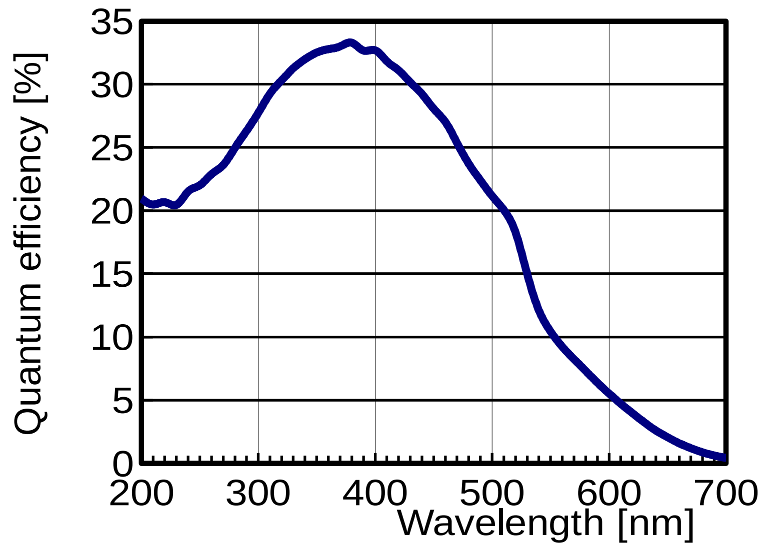
HAPD - Hybrid Avalanche Photo-Detector

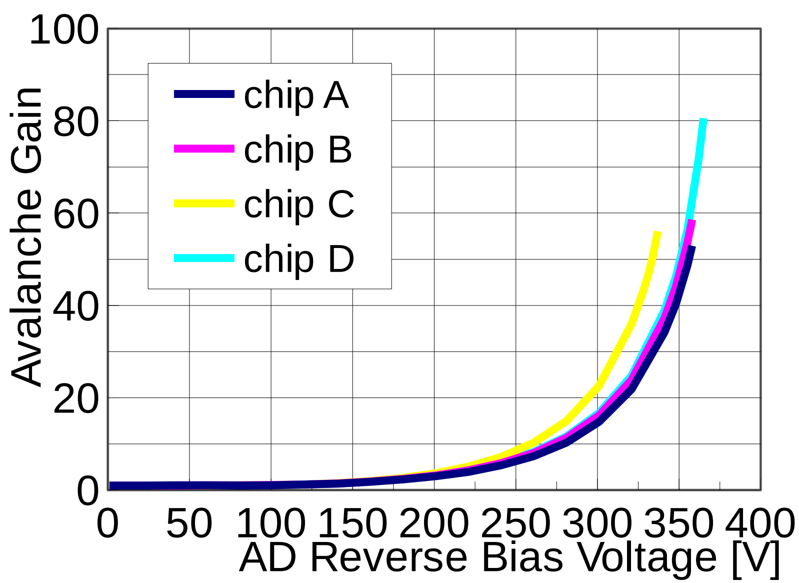
Belle II

- 4 APD chips, 36 ~5x5mm channels
- Nominal operation
  APD bias voltage: avalanche gain 40 (~320V)
  photocathode-anode (HV) voltage: 8 kV
- QE > 30% (@400nm)
- Two middle metal rings with floating potential between photocathode ring and anode



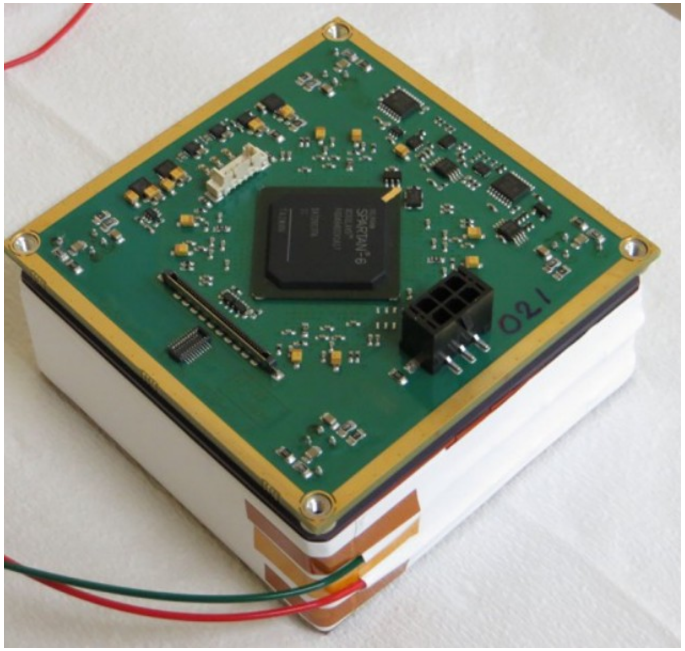

ceramic (alumina)

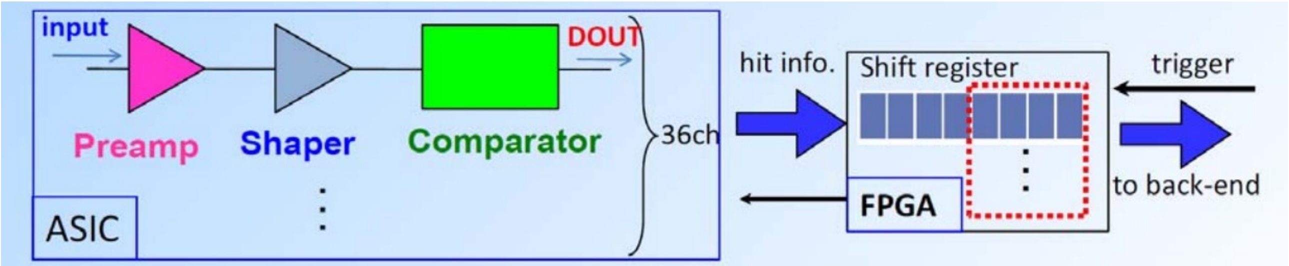


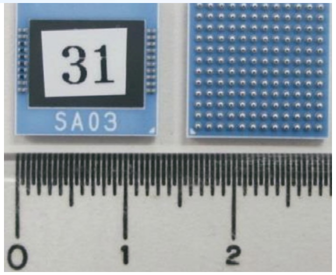


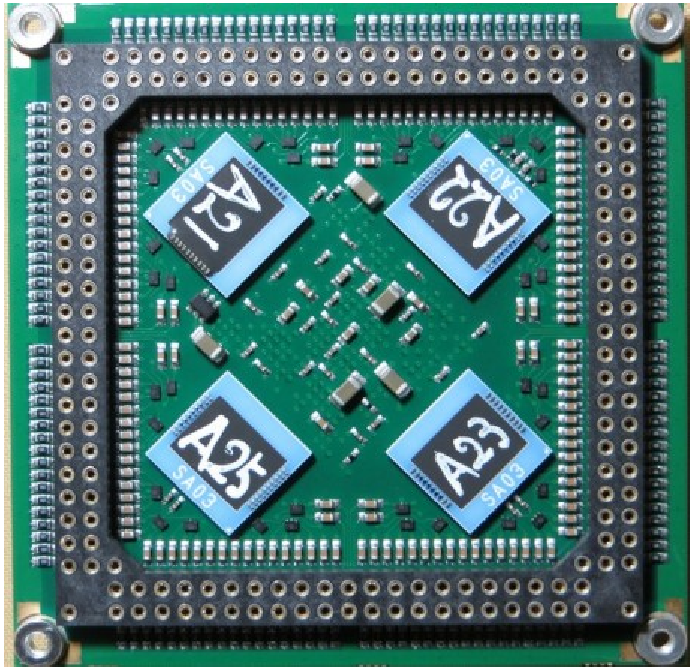
Read-out electronics

- Front-end board with 4 ASICs and Spartan6 FPGA
- 36 channel ASIC with preamp., shaper and comparator provides hit information (settings: 4 step gain, 4 step peaking time, offset level)
- FPGA (Xilinx Spartan6):
  - hit detection
  - DAQ
  - monitoring (supply voltages, temperature)



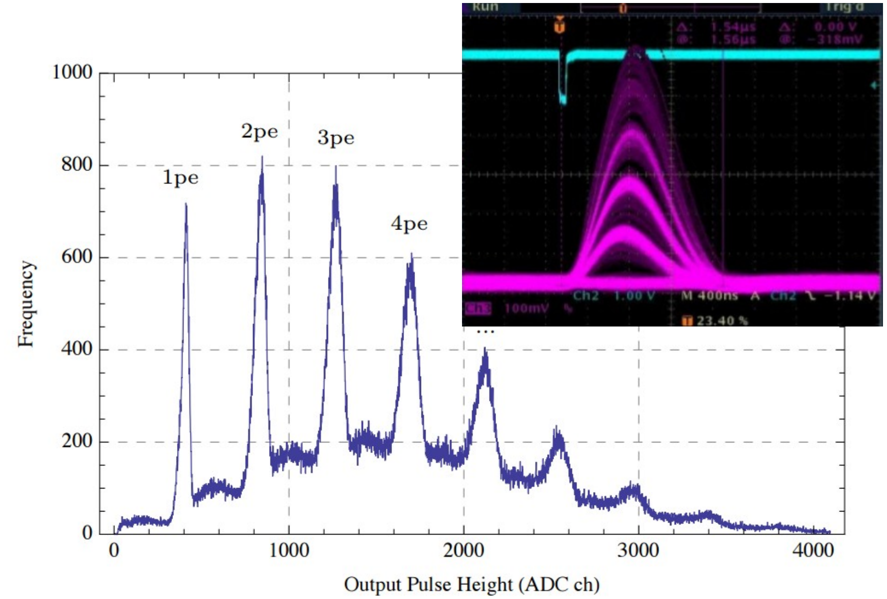


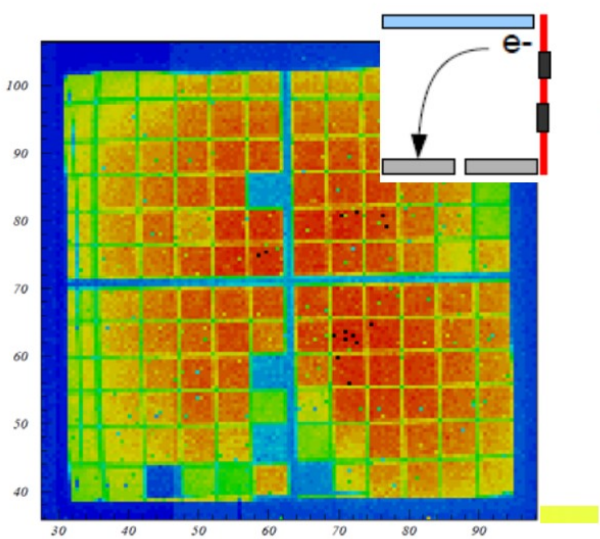


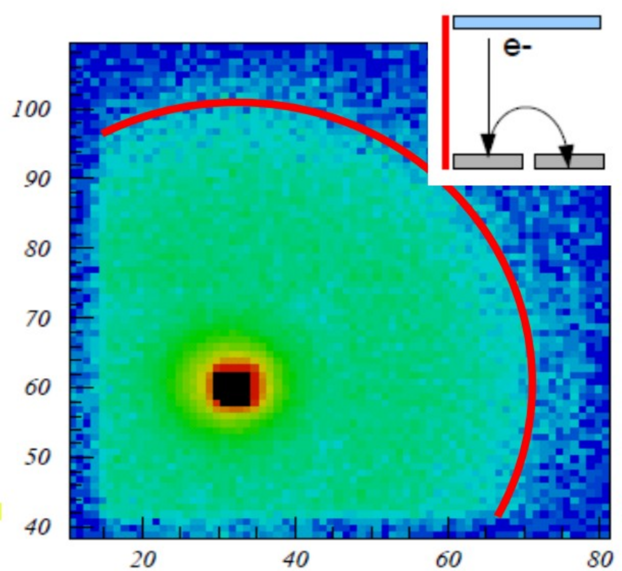


HAPD performance @ B = 0 T

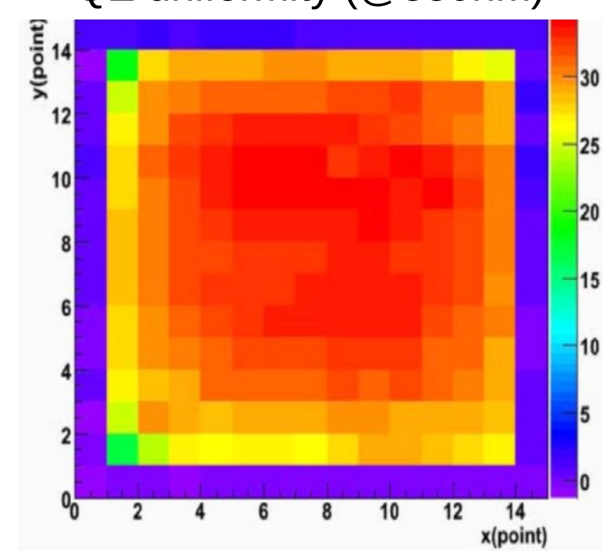
- Excellent photon counting ability
(high single photon detection efficiency)
- Counting ability affected by photo-electron back-scattering from APD surface
- Back-scattering induces crosstalk between adjacent channels
- Due to non-uniform electric field near the edges of tube surface image is distorted







QE uniformity (@380nm)

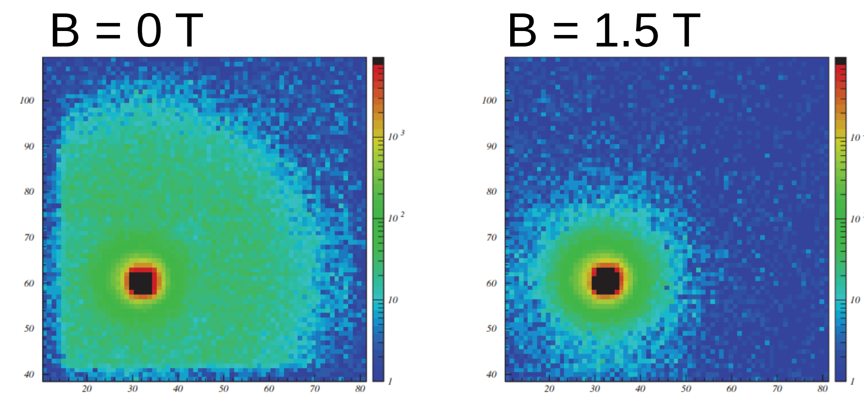


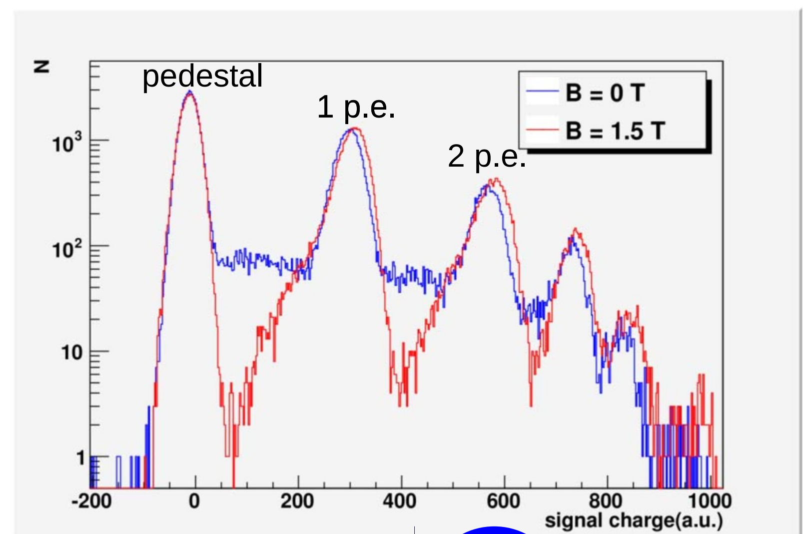
HAPD performance @ B = 1.5 T

- Before HAPD mass production started we tested few prototype samples in 1.5T magnetic field. Only beneficial effects were observed:

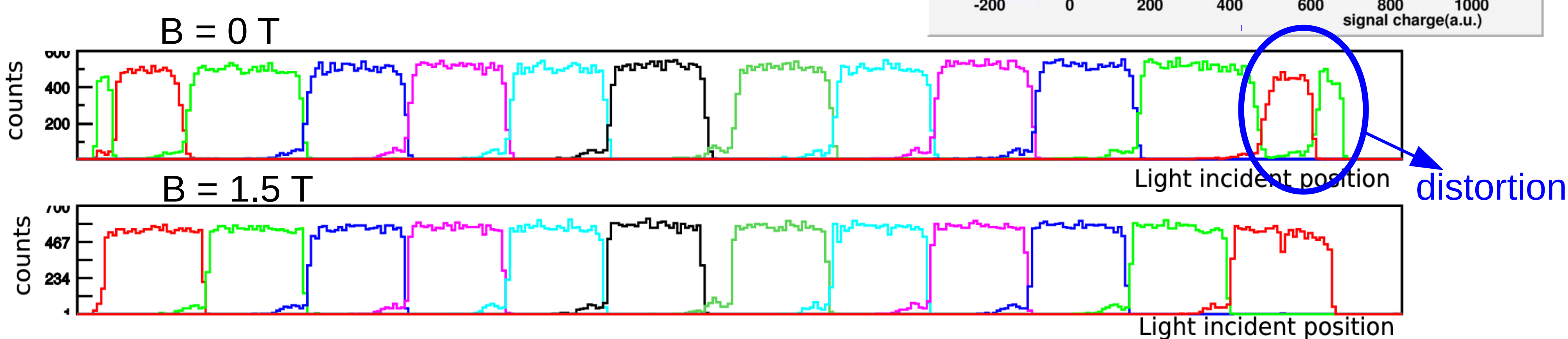
  - reduction of photo-electron back-scattering which reduces channel cross-talk + increases photon detection efficiency

  - image distortion due to electric field non-uniformity on the edges disappears. (photoelectrons circulate along magnetic field lines)





Laser scan over one line of channels:

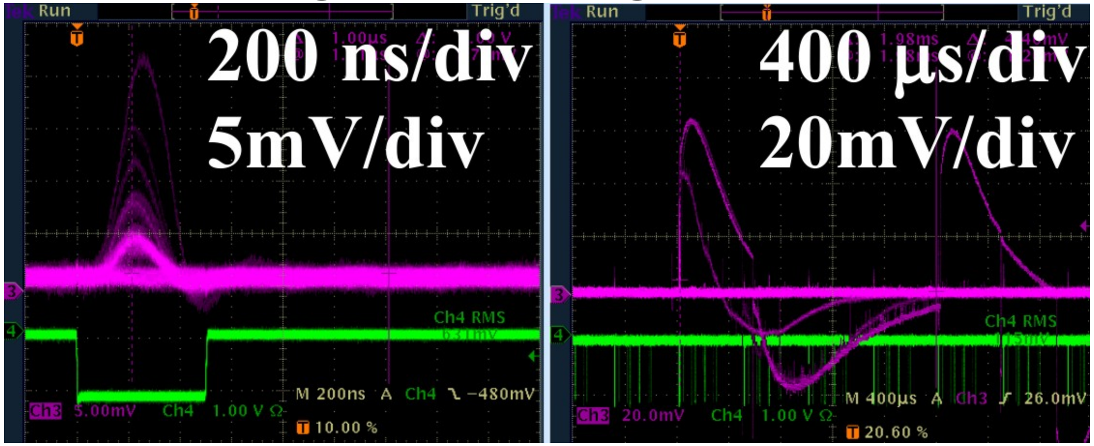


HAPD performance @ B = 1.5 T – Large pulses

- When more samples from the mass production were tested we observed that in some samples abnormally large signals (pulses) are generated when operating in magnetic field.

Analog output of one channel:

1,2 photon signal Large pulse



- Usually all HAPD channels (all 4 APD chips) are fired at the same time.

- The frequency of large pulses varies greatly from sample to sample:
  - for most HAPDs only individual pulses during HV/bias voltage ramp-up (in B)
  - but for some, pulses persist at ~constant rate even after long time.
  - frequency ranges from 0 to up to a few pulses per second.

- Frequency strongly depends on bias voltage (starting at ~150V, gain~1), ~lineary on HV (starting at ~1kV), and on magnetic field.

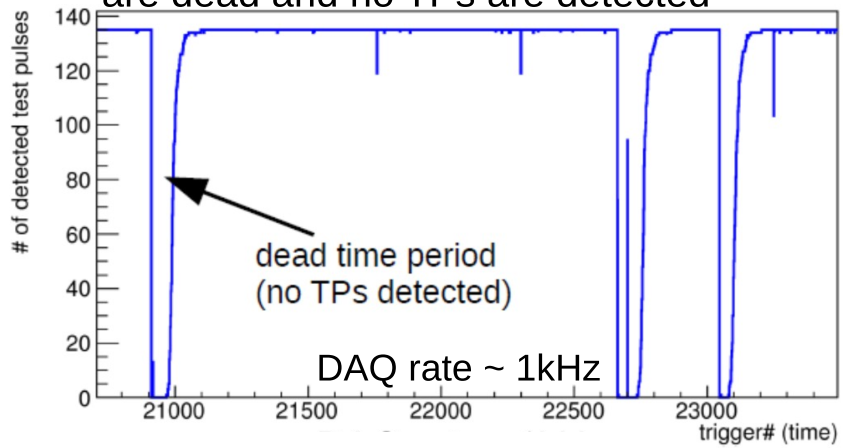
Effect of large pulses on HAPD performance

Belle II

Dead time

- After large pulse large part of HAPD area is dead (non-responsive) for ~0.1s
- For troublesome samples the induced fraction of dead time can reach >10%.

Internally generated test pulse is sent to all 144 channels. After large pulse inputs are dead and no TPs are detected

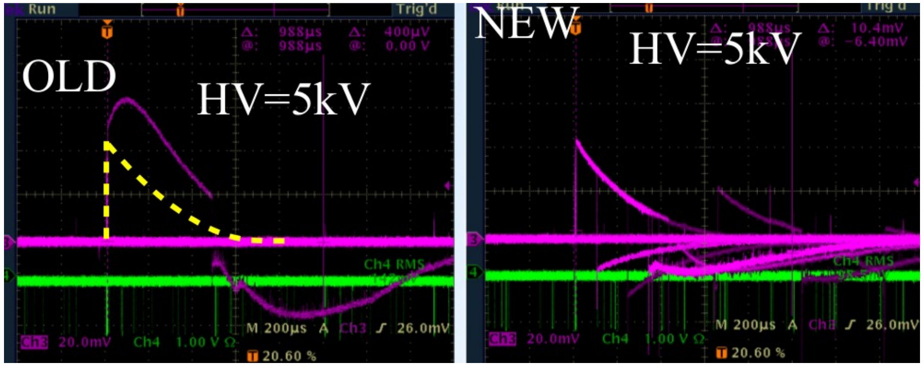


Readout electronics damage

- For some samples, under specific conditions, the frequency of large pulses suddenly starts to grow until the APD bias voltage trips due to over-current.
- Mainly while B → 0, with tube HV applied, or during APD bias voltage ramp-up.
- In few cases damage to read-out electronics was observed:

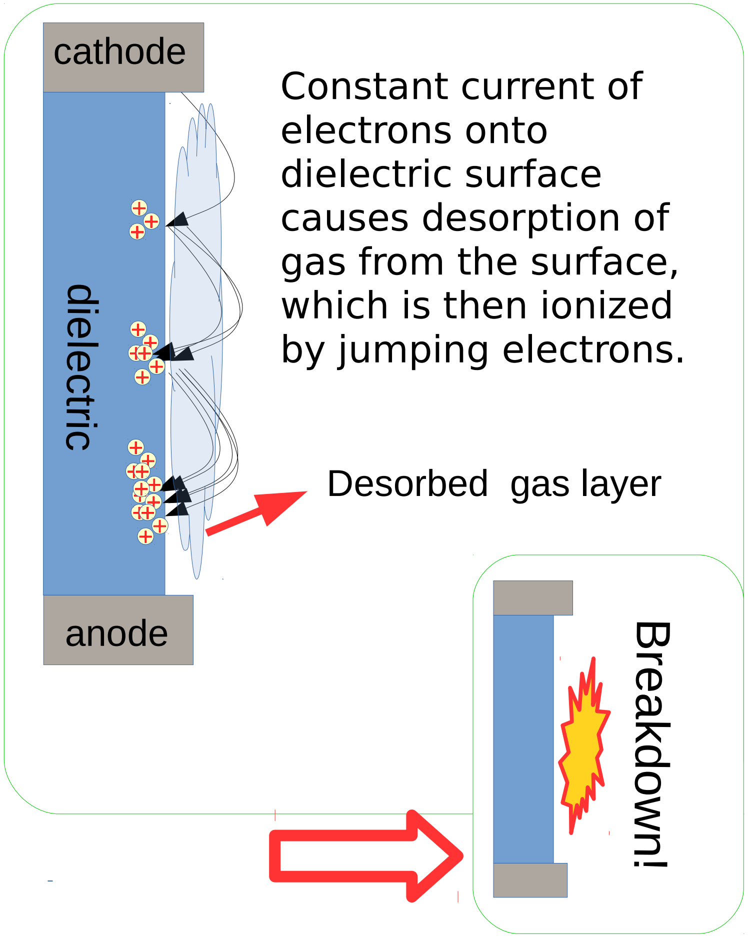
  - initially all channels of ASIC were damaged
  - later ESD protection diodes were added to front-end board → reduced large pulses → only individual channels damaged

With ESD protection



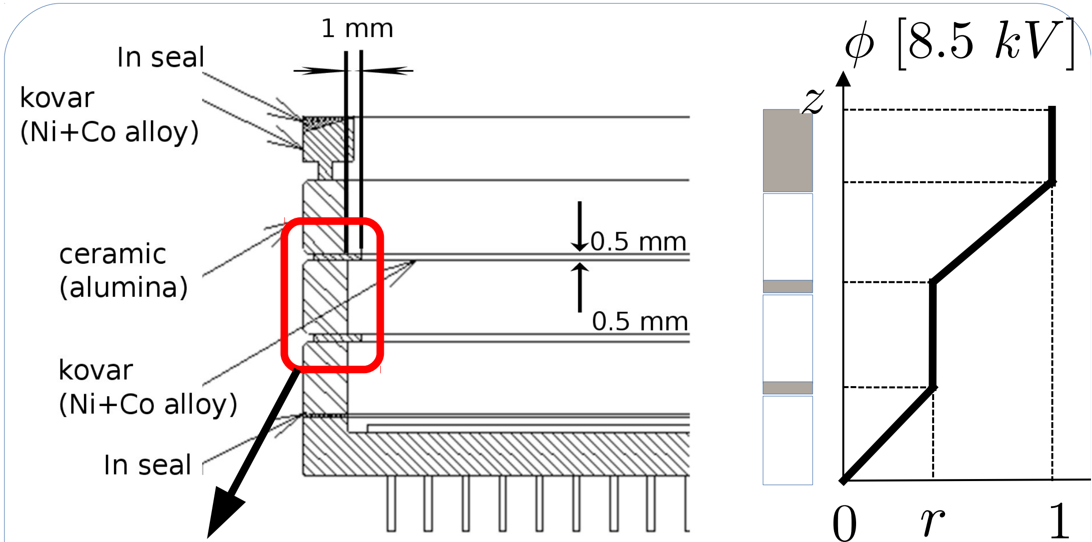
Surface flashover hypothesis

- As a possible origin of large pulses we consider surface flash-over effect on the ceramic sidewalls of HAPD.
- Initiated by field electrons emitted from cathode under certain conditions an electron avalanche can form, leading to desorption of gas and eventually to breakdown.
- Light emitted in the process spreads over photo-cathode → fires all HAPD channels.
- The breakdown voltage is known to depend on external magnetic field.
- CMS hadron calorimeter uses HPDs, and they observed similar anomalously large signals when operating in ~1T magnetic field.



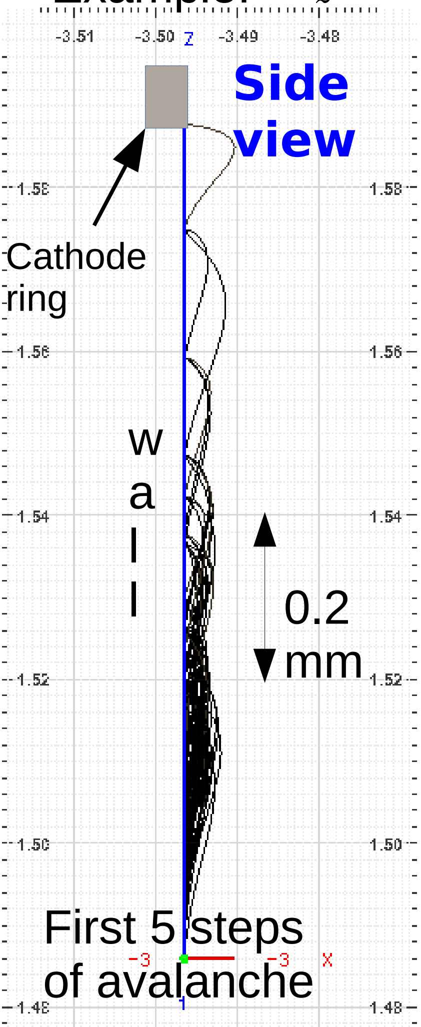
Surface flashover simulation

- We developed a simple simulation to see if electron avalanche can form on HAPD sidewalls.



Metal ring with floating potential

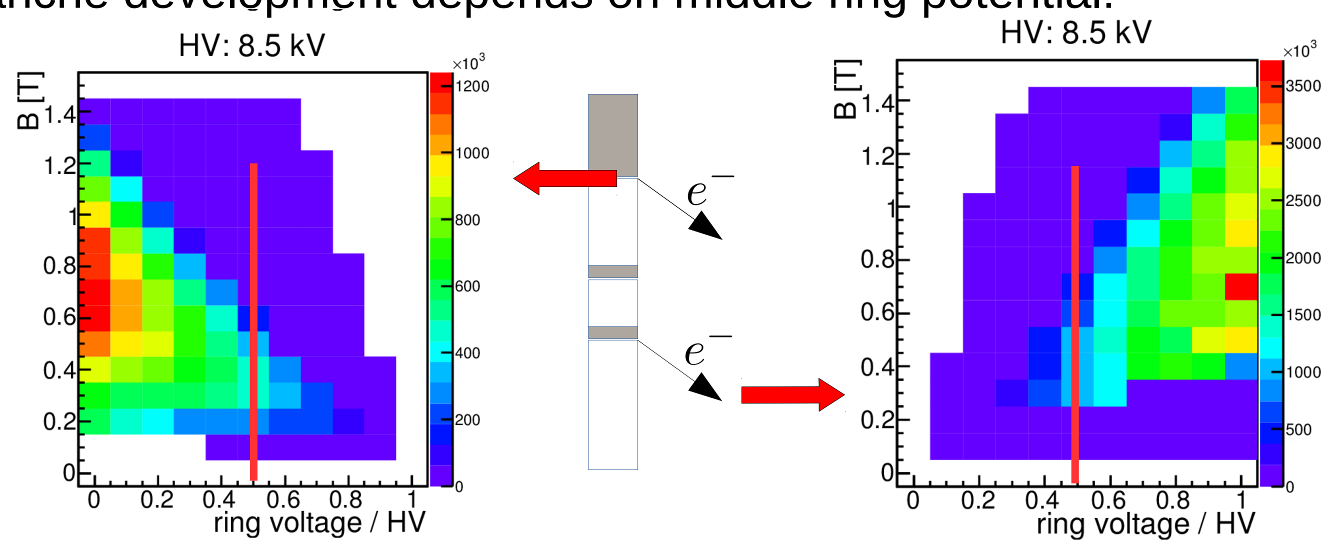
Example: $B_z = 0.5\ T,\ HV = 8.5\ kV,\ r = 0.5$



Avalanche can develop!

y

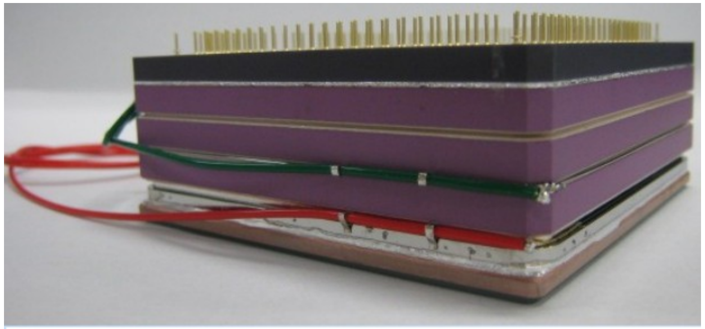
Avalanche development depends on middle ring potential:

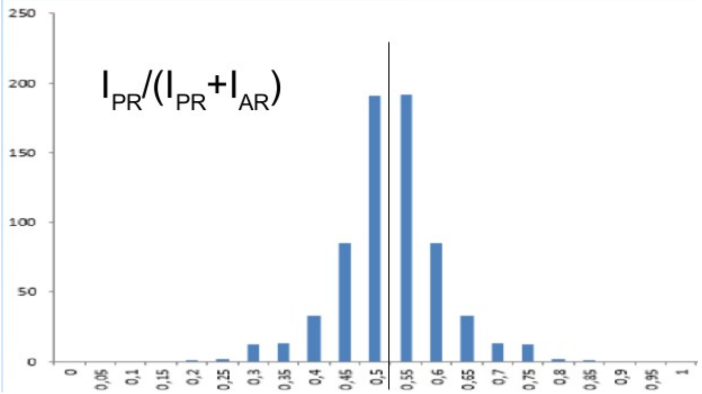


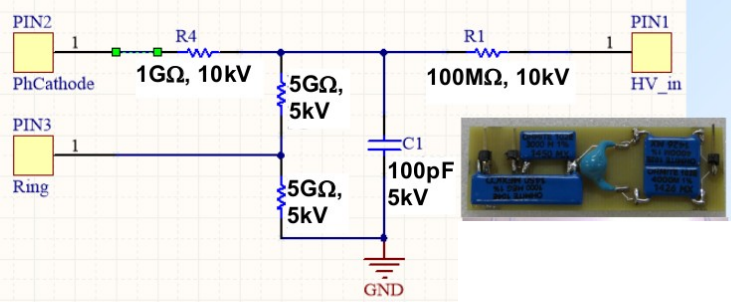
Color shows number of electrons in an avalanche

HAPD modification to fix middle ring voltage

- Measurements of tube leakage current show that in many samples middle ring voltage drifts from HV/2.
- In order to stabilize the performance we decided to modify all HAPDs by installing new cable to fix the middle ring voltage to HV/2.
- Small board with resistor divider is used.
- In experiment we demonstrated that if middle ring voltage is set too far from HV/2 indeed the rate of large pulses "explodes" → APD bias voltage trip
- Since modification, issues at low magnetic fields (~0.1T) with HV applied are reduced.
- However, in high magnetic fields the rate of large pulses mainly remained unchanged.

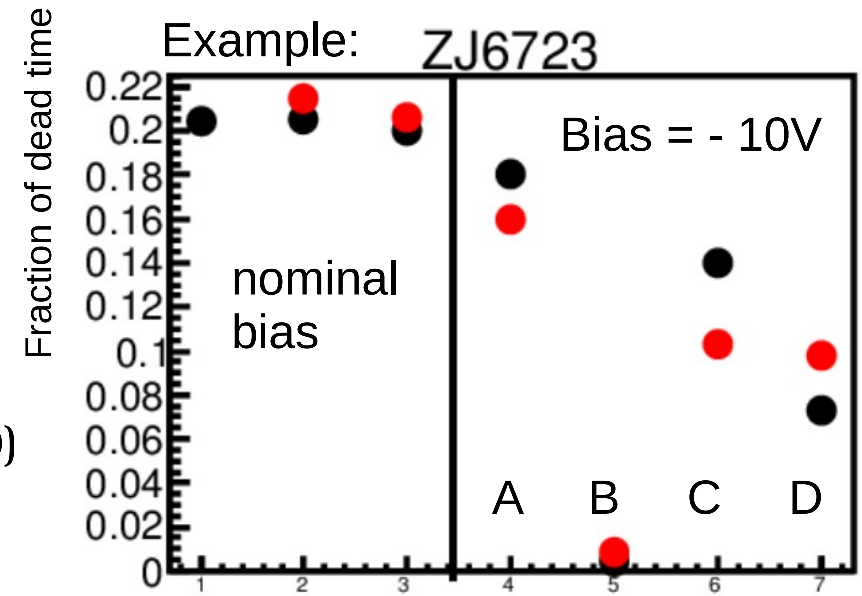


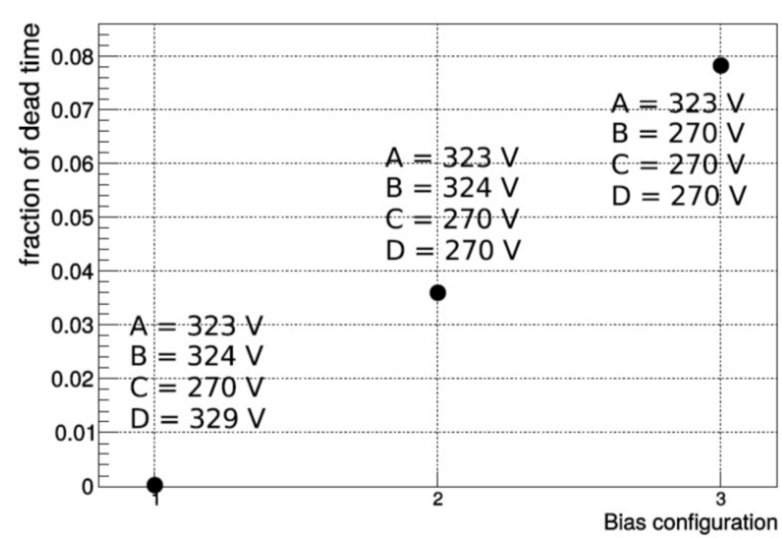




Puzzling dependency on APD bias voltage

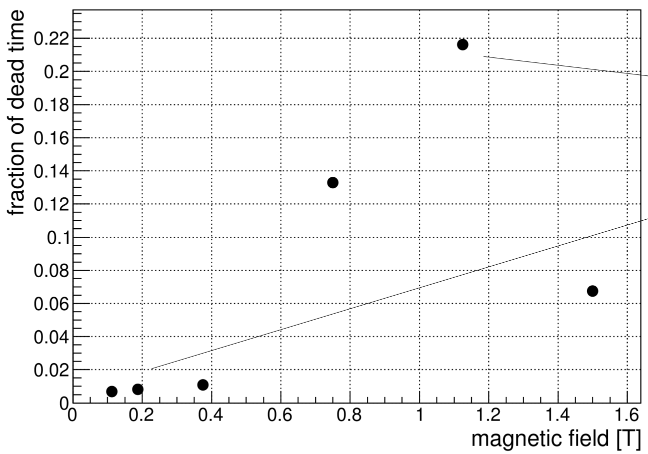
- For all HAPDs we observe complete disappearance of large pulses if any of 4 chip bias voltages is set < 200V.
- For many already a ~10V reduction of single APD chip bias (from its nominal value at gain 40) significantly reduces frequency of large pulses.
- Frequency of large pulses increases if all APD chips bias voltages are “similar”, even if set well below nominal values
- This observations are hard to explain and hardly compatible with the idea that light from flashover process is responsible for large pulses.

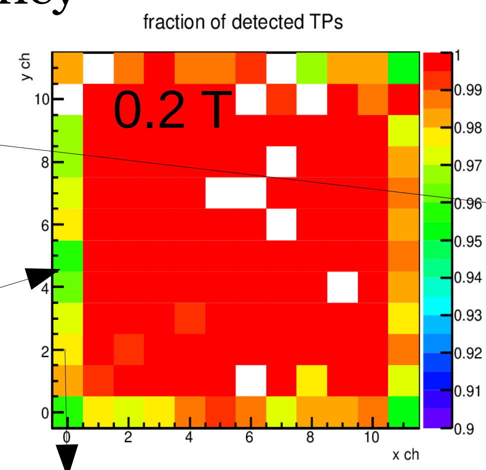




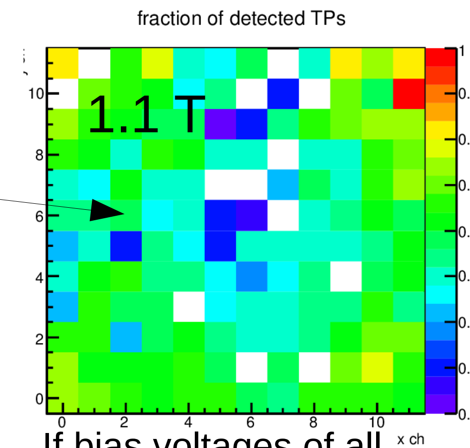
Few other observations

- By placing SiPM on top of HAPD we didn't observe any strong light emission (IR?)
- Magnetic field dependency

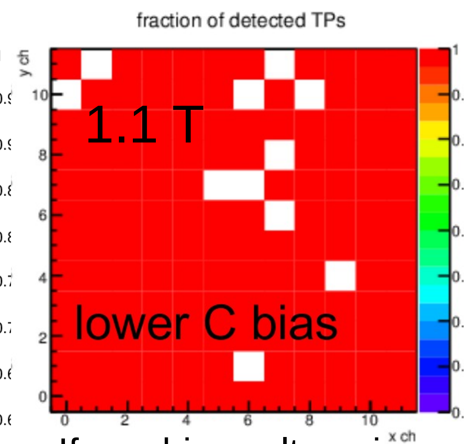




Individual large pulses on edge channels (flash-over?)



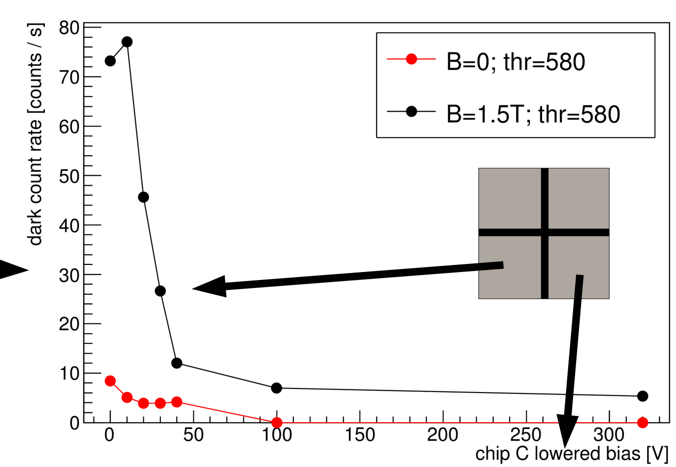
If bias voltages of all 4 APD chips are similar → simultaneous large pulses over full surface



If one bias voltage is lowered, no large pulses at all

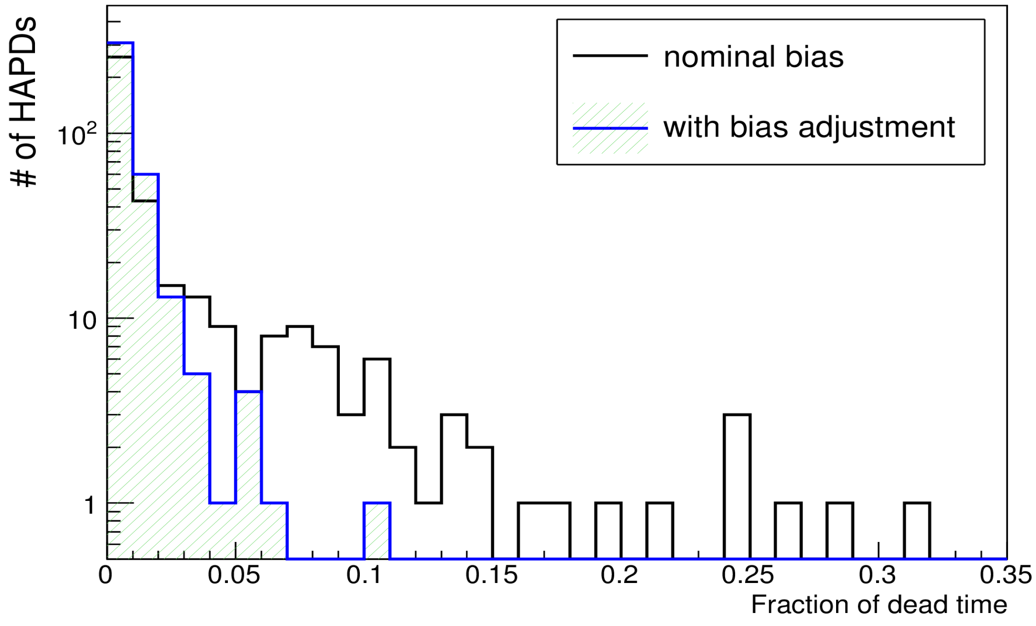
- Some light emission is involved in the process (maybe only side effect of the main mechanism)

  single photo-electron dark count rate on chip D vs. bias voltage of chip C



Magnetic test summary

- Because of the observed problems all HAPDs from mass production (~400) were tested in magnetic field.
- 22% of HAPDs have >2% dead time (5%, with 10V bias adjustment).
- Out of these 5 HAPDs are not functional in magnetic field → bias voltage trip.
- During test off all HAPDs in total 8 channels on front-end board died (minor issue)
- Highly problematic HAPDs will be replaced.



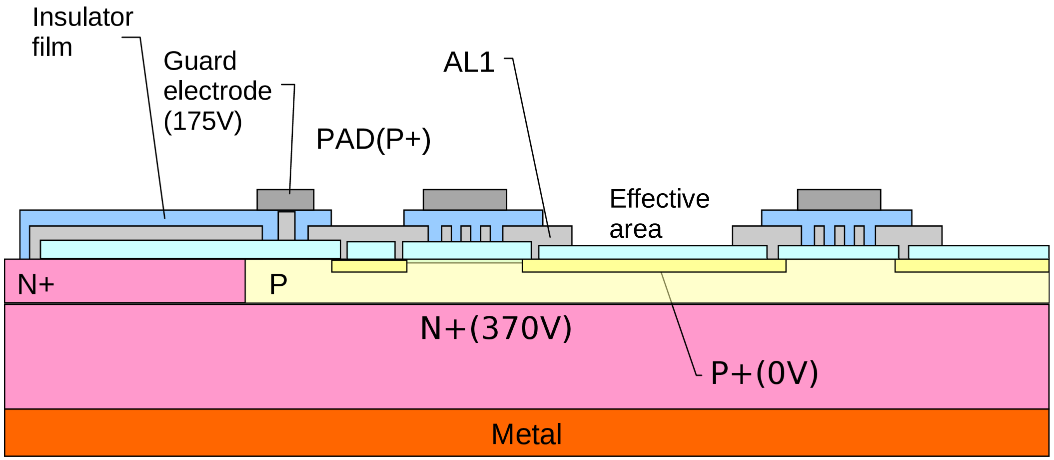
Summary

- For endcap PID of the Belle II experiment aerogel RICH, with HAPD as photon detector will be employed.
- HAPD shows good performance for single photon detection, with QE of >30%.
- Recently we found that in ~20% of HAPDs anomalously large signals are generated when operating in magnetic field.
- Large signal → ~0.1s period of dead time
→ for some samples significant overall fraction of dead time
- Initially we connected the problem with the surface flashover on the tube ceramic side-walls, but puzzling dependency of large signals frequency on APD bias voltage shows that flashover (if relevant at all) is not sufficient explanation.
- Test of all HAPDs in the magnetic field → replace highly problematic ones.
- Effect of large pulses on longer term HAPD operation is not known.
- In the following months more investigation on the origin of large pulses.

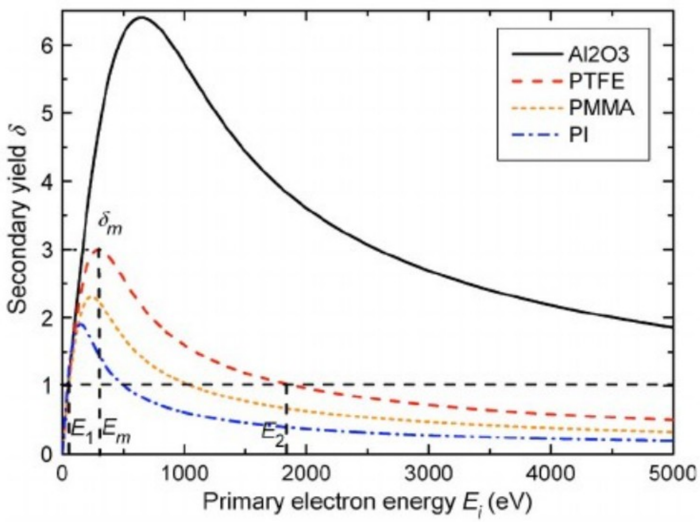
Thank you for your attention!

Backup plots

APD structure



Ceramics secondary electron emission



Circuit diagram