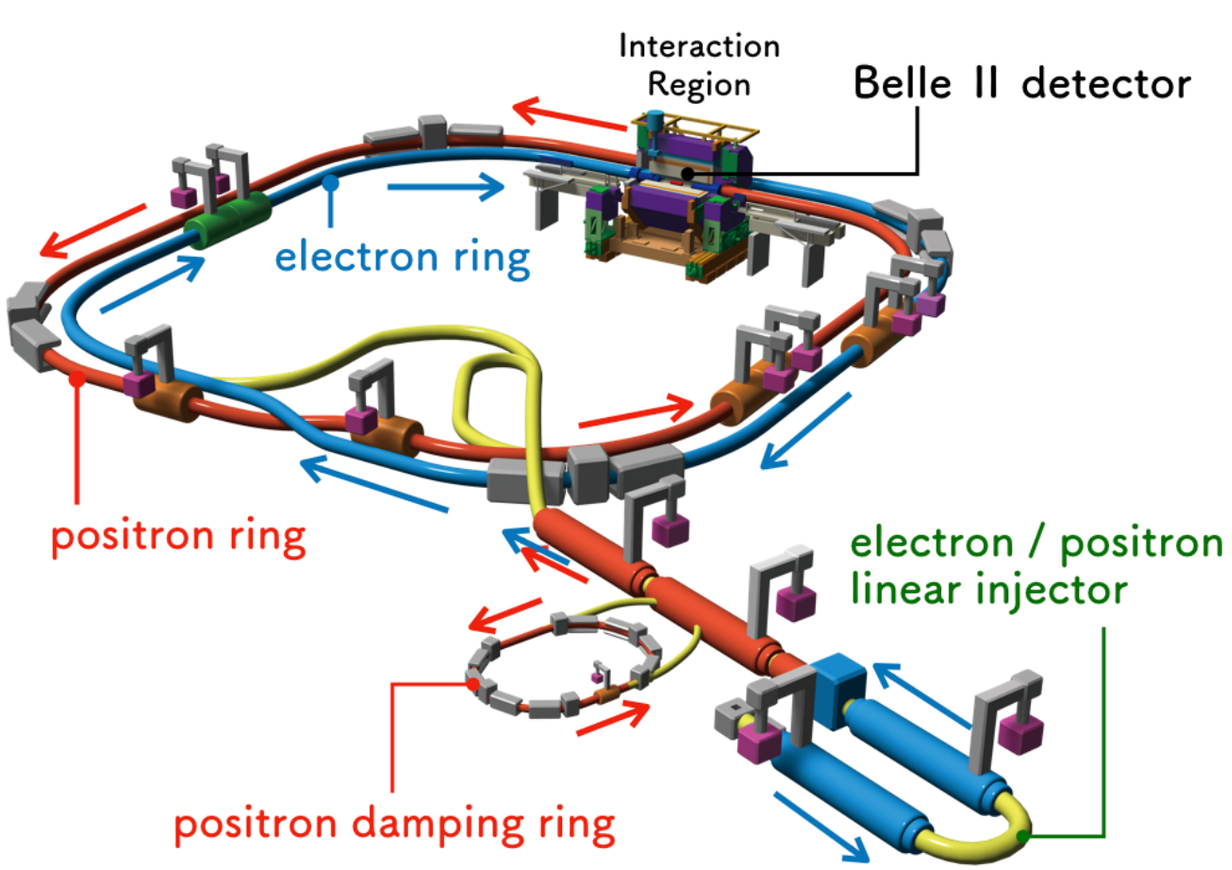
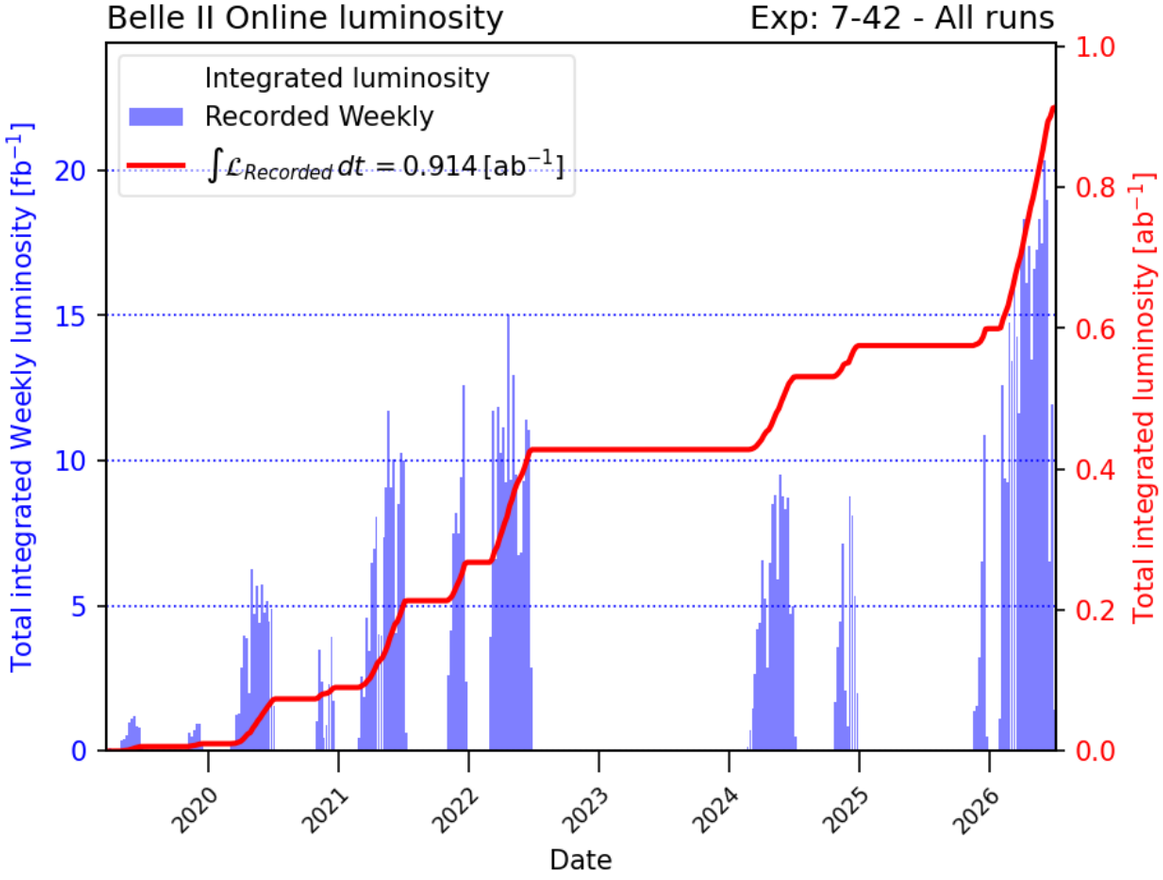
Study for the upgrade of Aerogel Ring Image Cherenkov detector of Belle II experiment

Yosuke Yusa
Niigata University

Belle II experiment

e^+e^- collider experiment with a high luminosity operated at $\Upsilon(4S)$ resonance energy (B-factory).
Search for new physics by comparing Standard Model prediction and precise measurement using high statistic sample.
Accessible to new physics in high energy scale through quantum effect in B meson decay (Luminosity frontier).

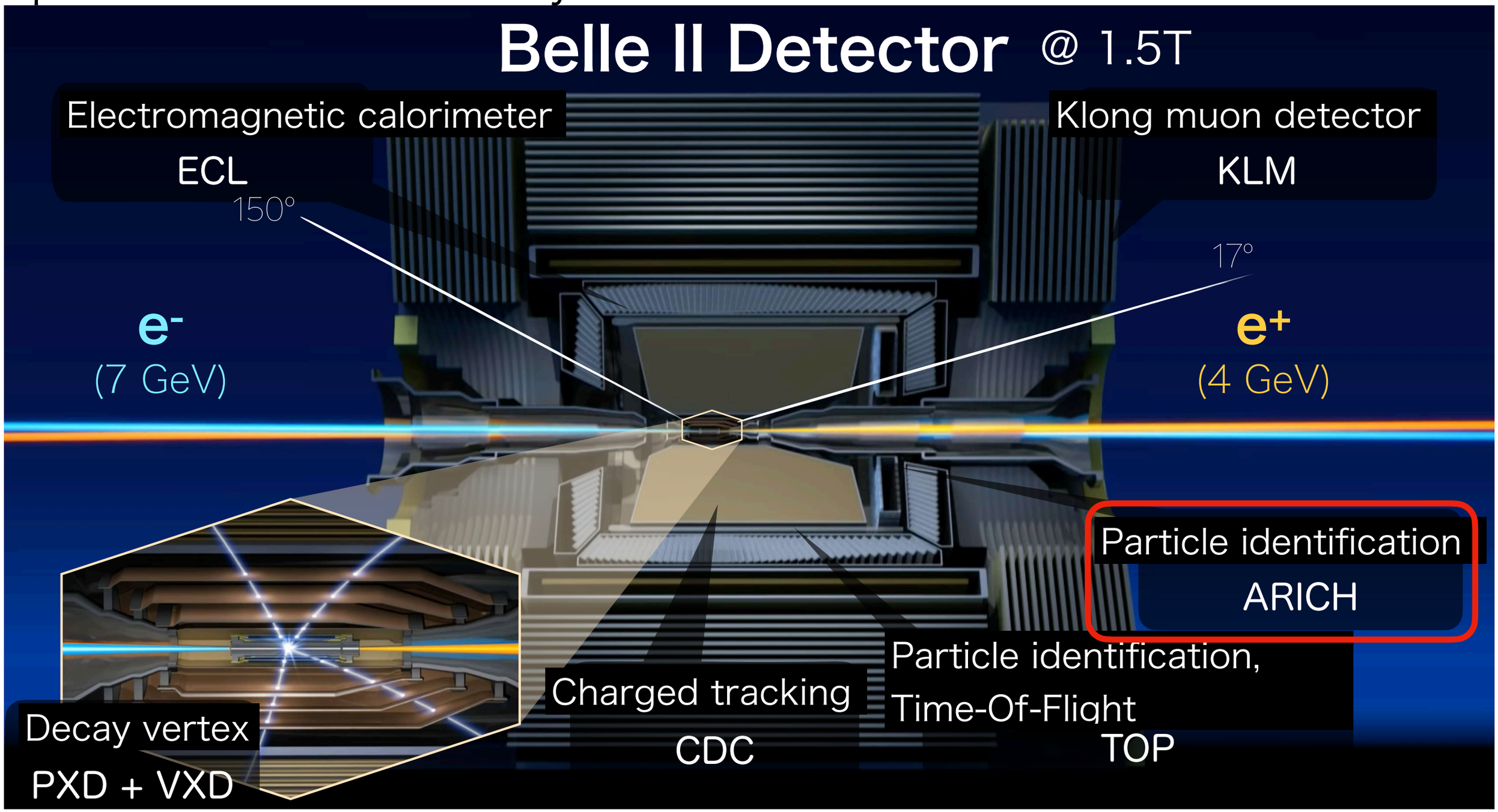




Belle II detector

B meson decays in various modes. → Many physics targets.

To obtain the specific decay mode, information of B meson decay products are recorded by several kinds of detector.



Aerogel Ring Imaging Cherenkov detector (ARICH)

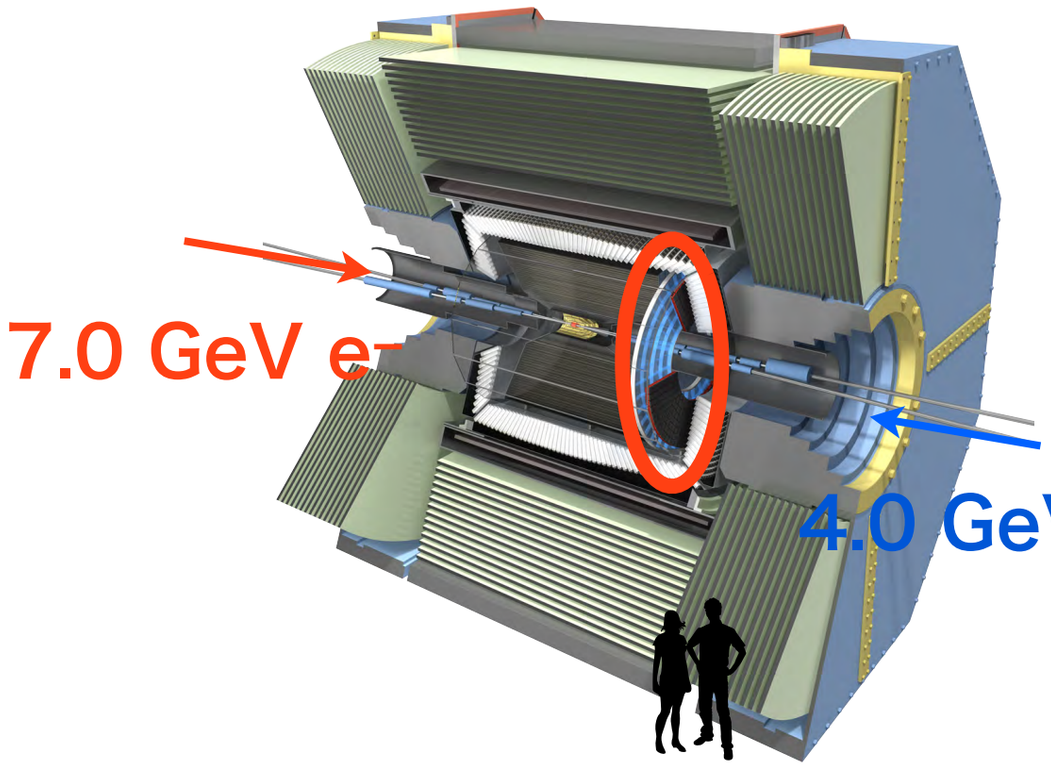
Identify particles in forward endcap (along e⁻ beam direction) region.

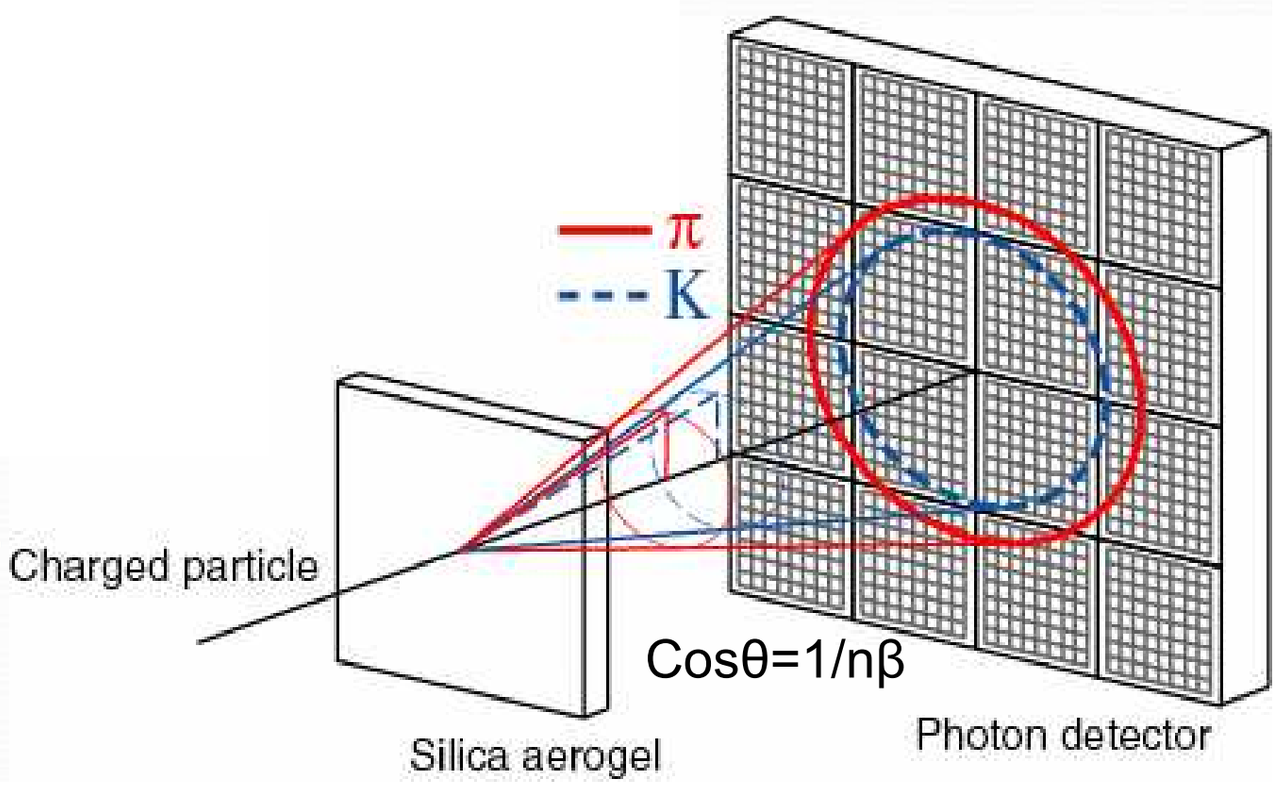
Emission direction of Cherenkov light depends on particle velocity.

→ Particle mass: $\dfrac{p\sqrt{n^2\cos^2\theta_{\mathrm{C}}-1}}{c}$

(p: momentum, n: refractive index, θ_{C}: Cherenkov angle)

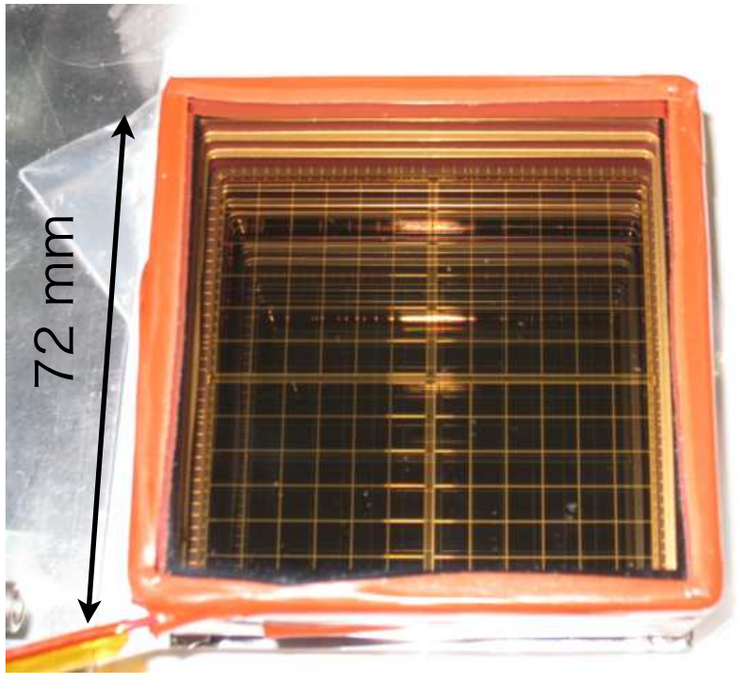
Observe ring image directly and measure θ_{C}.

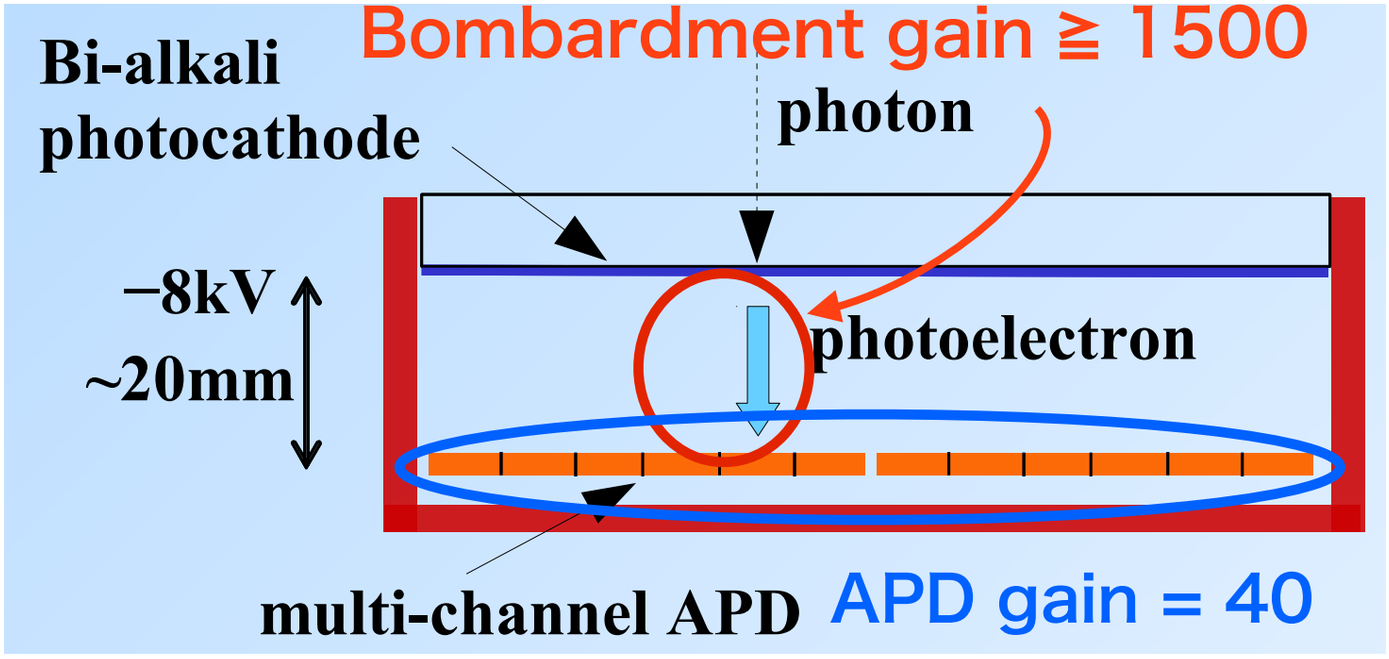




Aerogel Ring Imaging Cherenkov detector (ARICH)

To achieve single photon hit position information, Hybrid photon sensor was developed for ARICH (photomultiplier+avalanche photodiode).

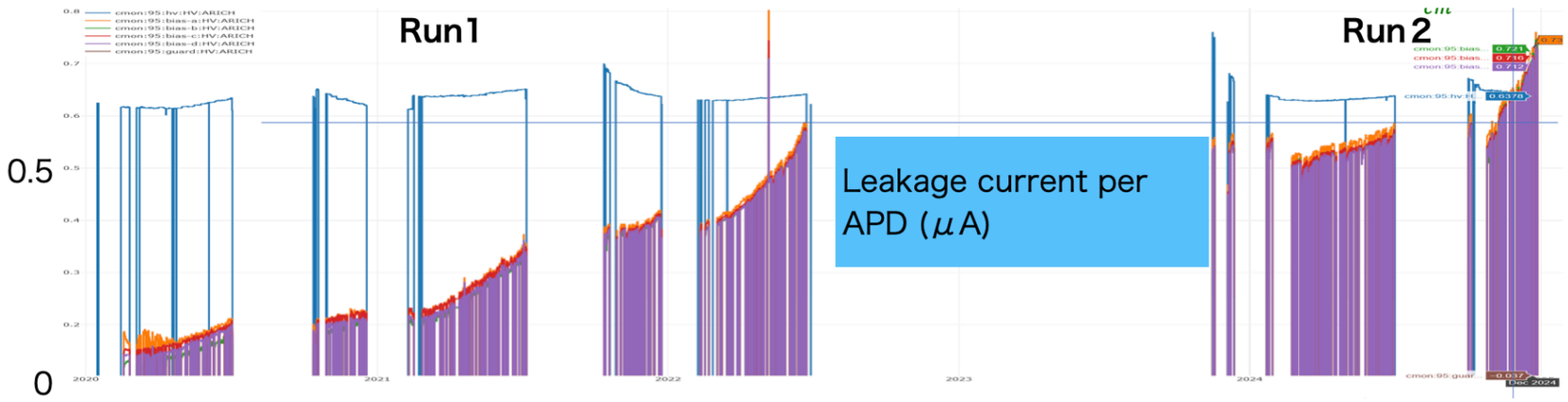




⇒ **Total gain ~6×10⁵.**

Degradation of APD due to neutron irradiation is seen.

→ still acceptable but need countermeasure for long-term operation.



Photon sensor upgrade

Disadvantage of hybrid photon sensor:

- Low yield due to complex structure.
- Need high voltage to achieve enough gain.

→ Consider to use different type sensor.

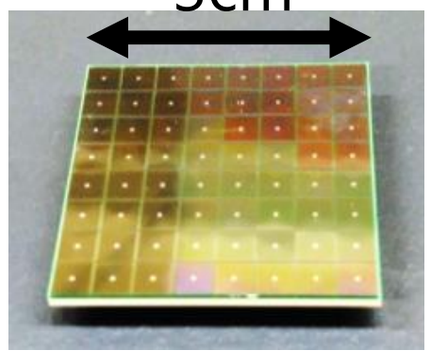
Multi-Pixel Photon Counter (MPPC, SiPM)

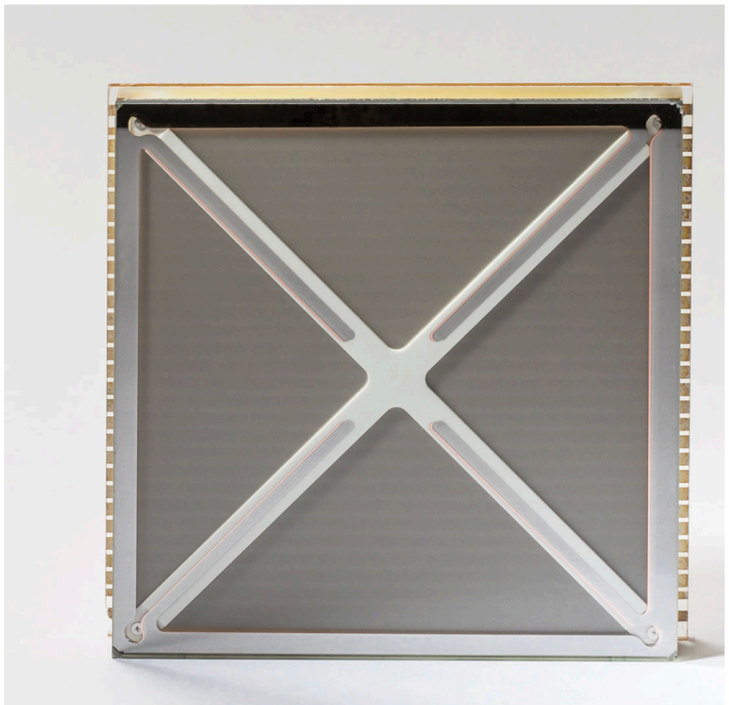
- Commercial product are widely used in many experiments.
- Operation in low voltage.
- Radiation hardness issue remains.

MCP-PMT

- High timing resolution.
- Shape flexibility of readout anode.
- Signal pulse might be diffused in magnetic field.

MPPC Sample
(HAMAMATSU S13361-3075AE-08)



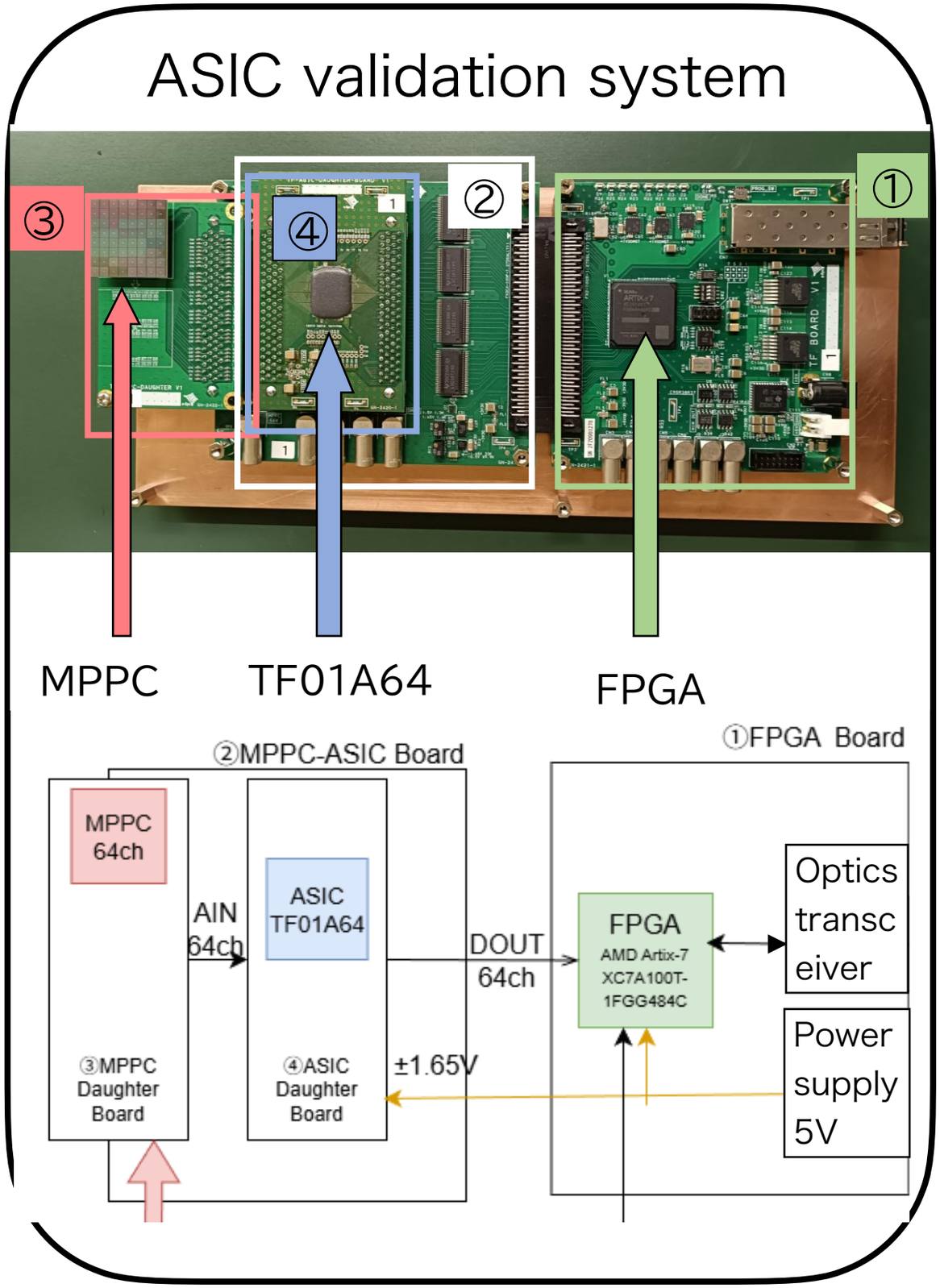


New readout for MPPC

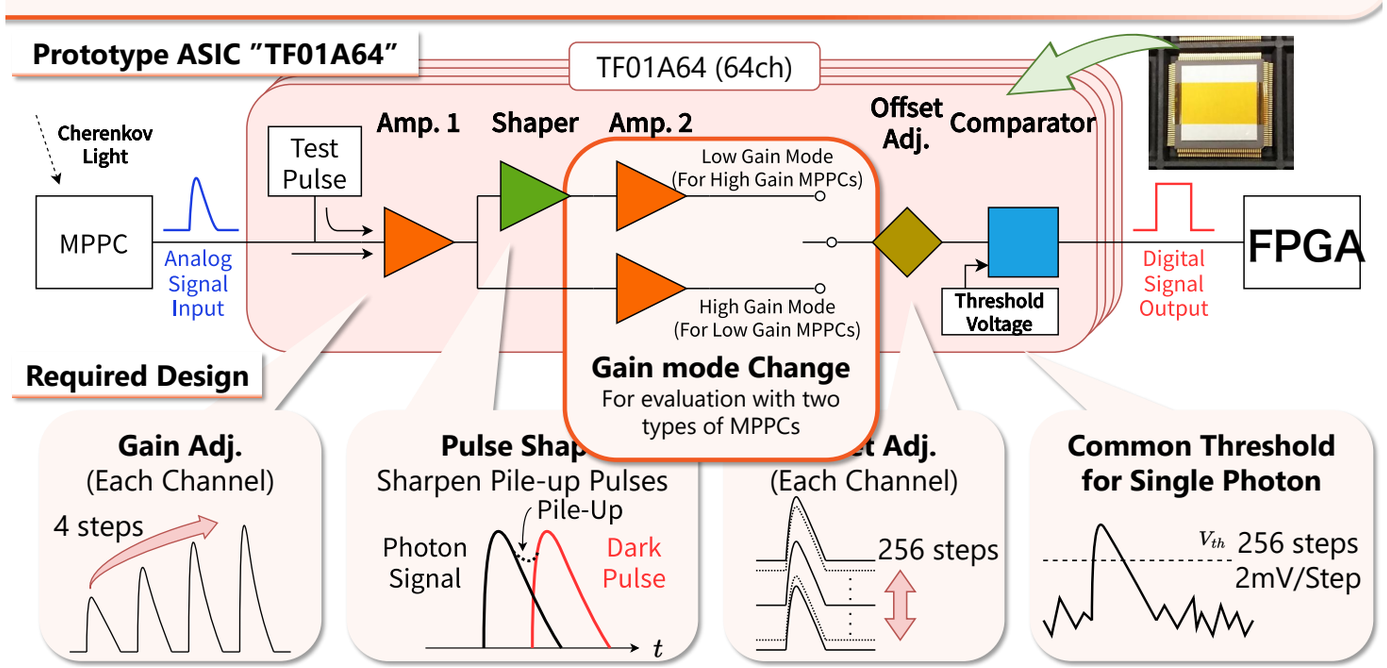
Performance requirements for ARICH:

- Hit information for single photon.
- High rate readout from a large number of channels.

→ Digitize signal with new ASIC and transfer to backend readout.



"TF01A64" ASIC for MPPCs



Validation test of new readout

Test bench setup:

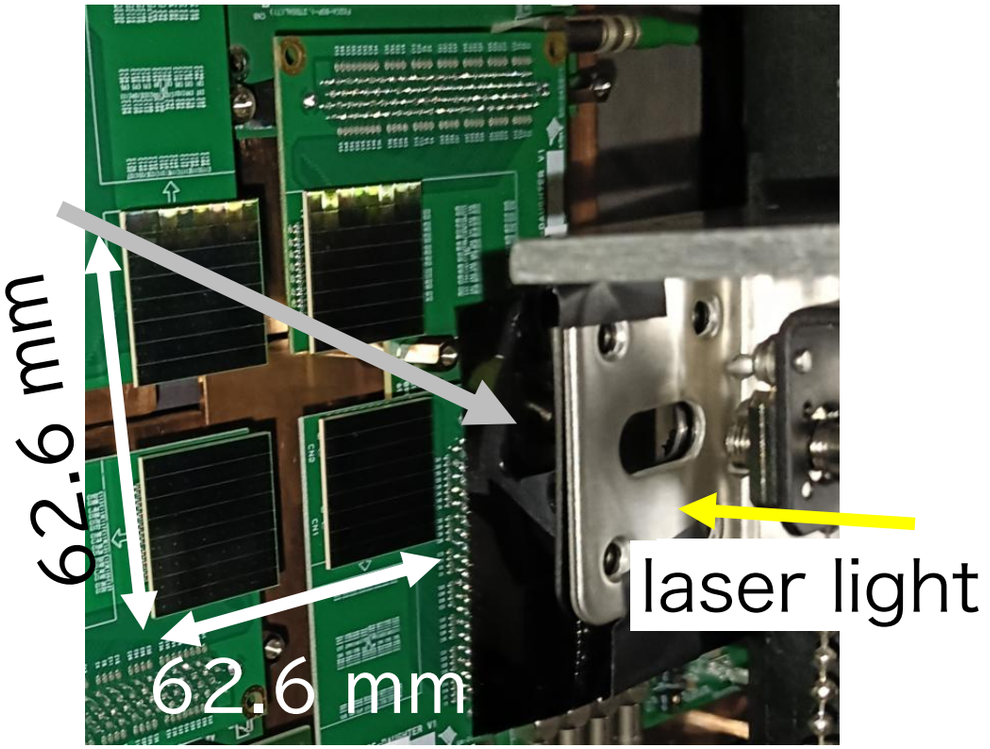
Light emission from pulsed laser.

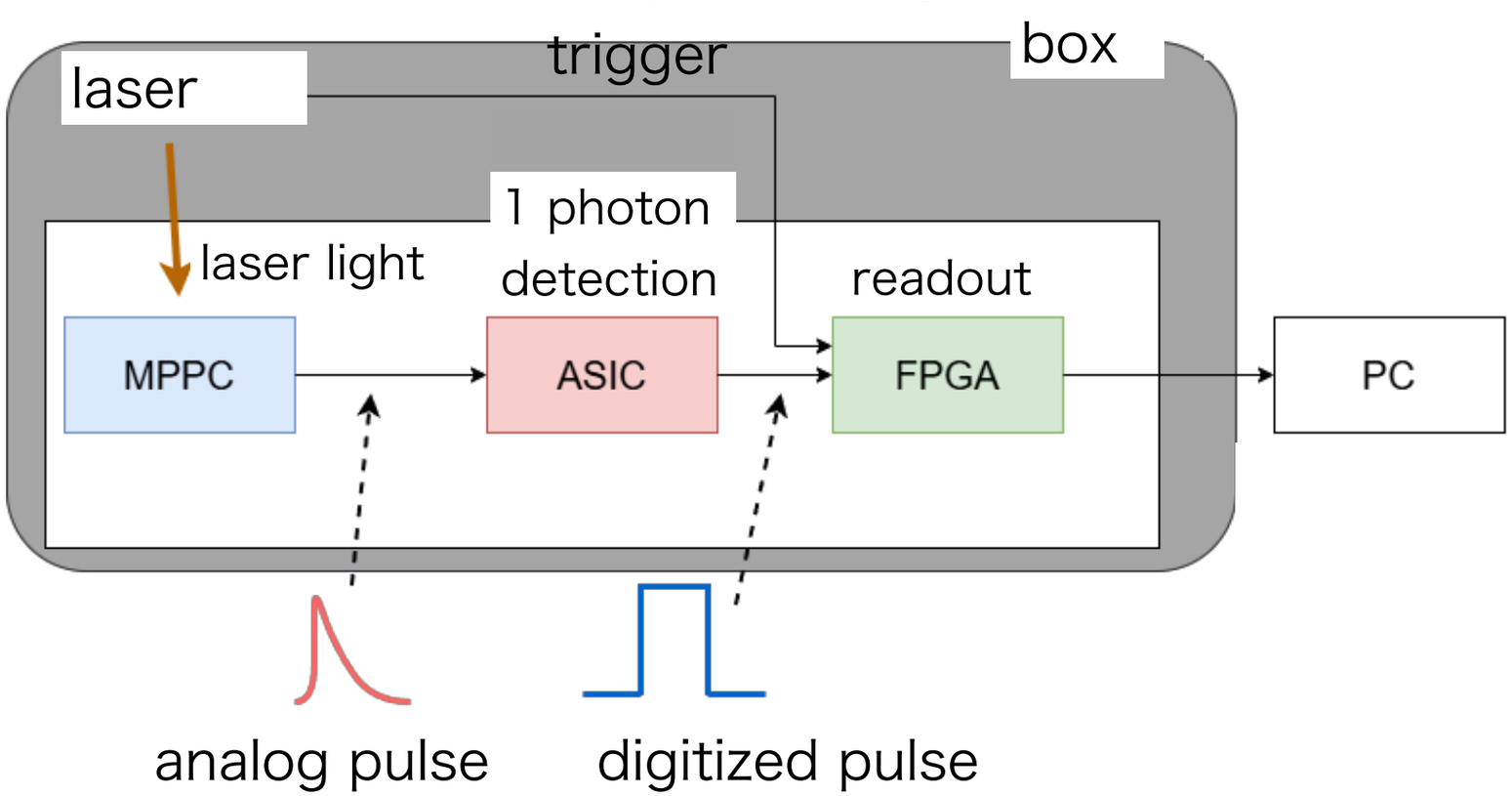
Reduce light intensity to 1 photon level using filter.

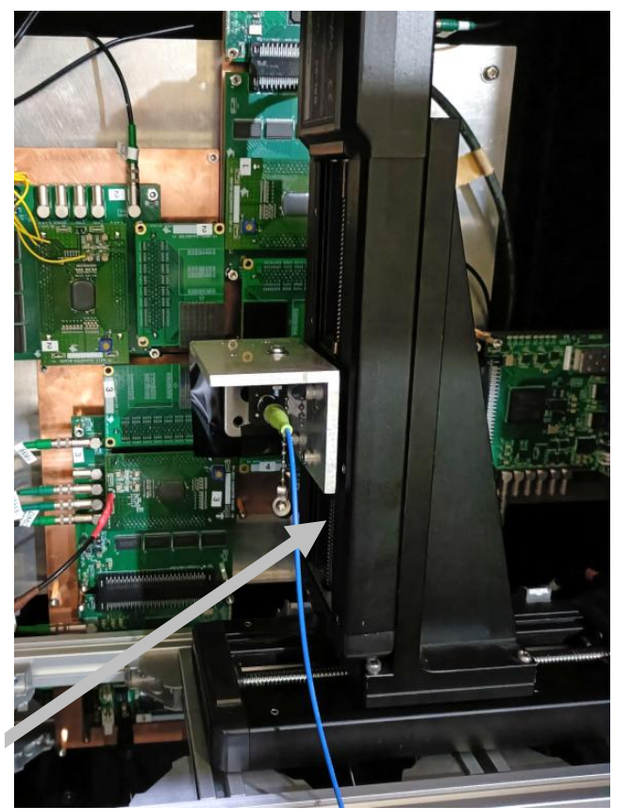
Signal from MPPC is processed by ASIC and measure hit rate.

(= recorded pulse/trigger pulse

Scan 4 sensors by moving laser.





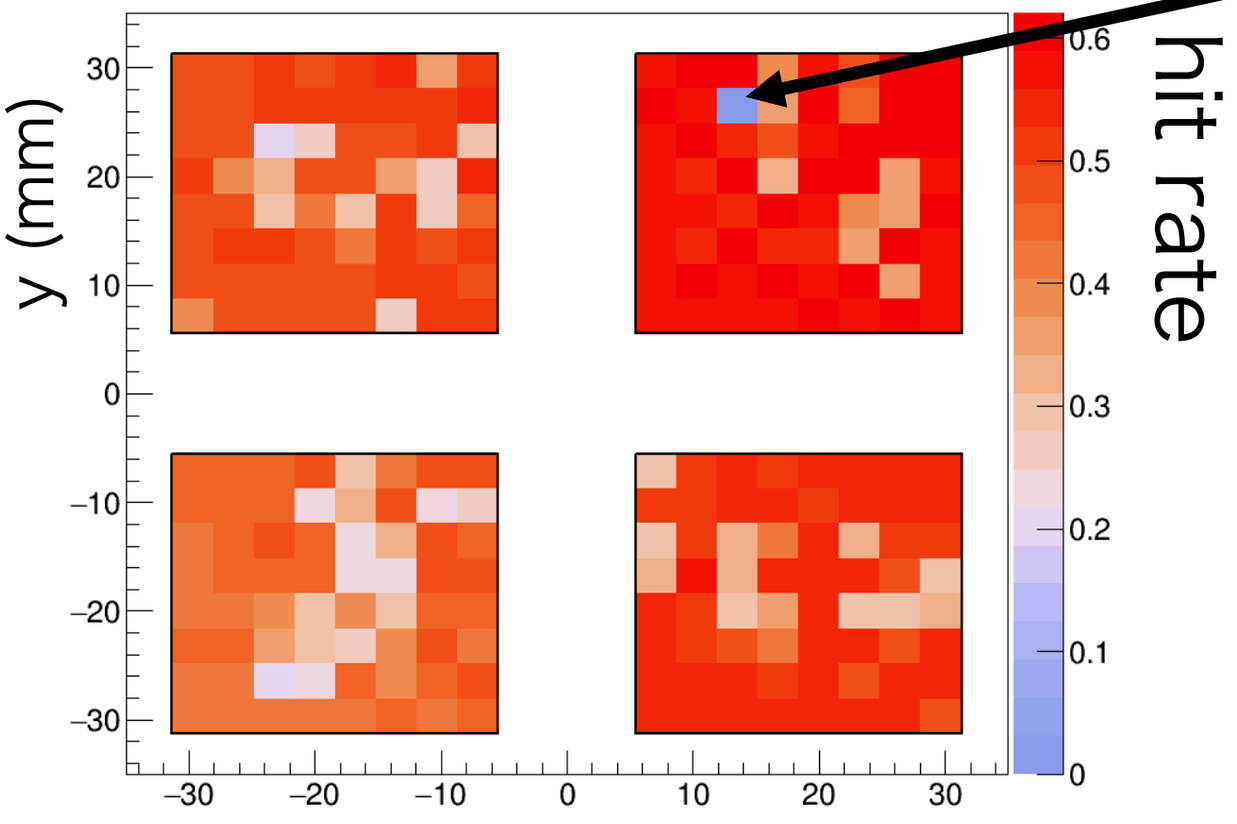


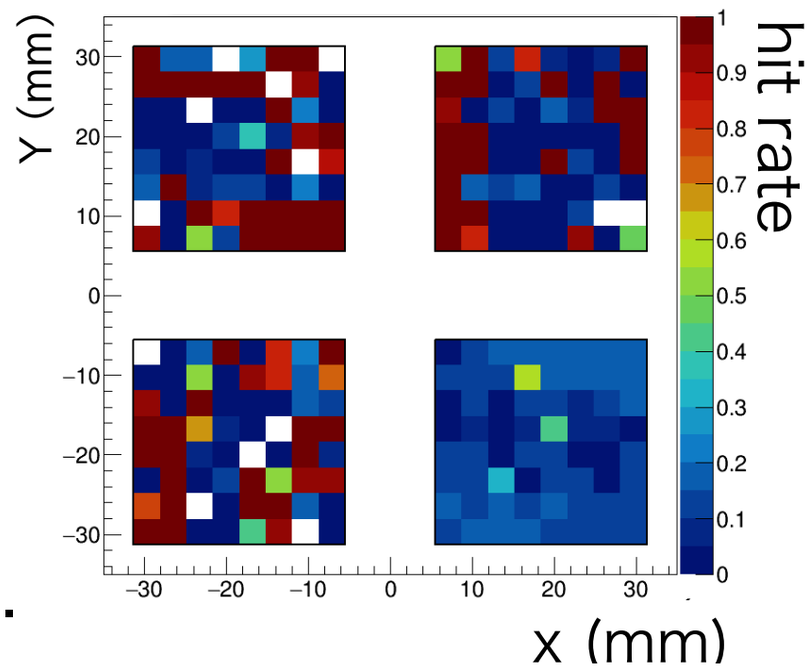
Validation test of new readout

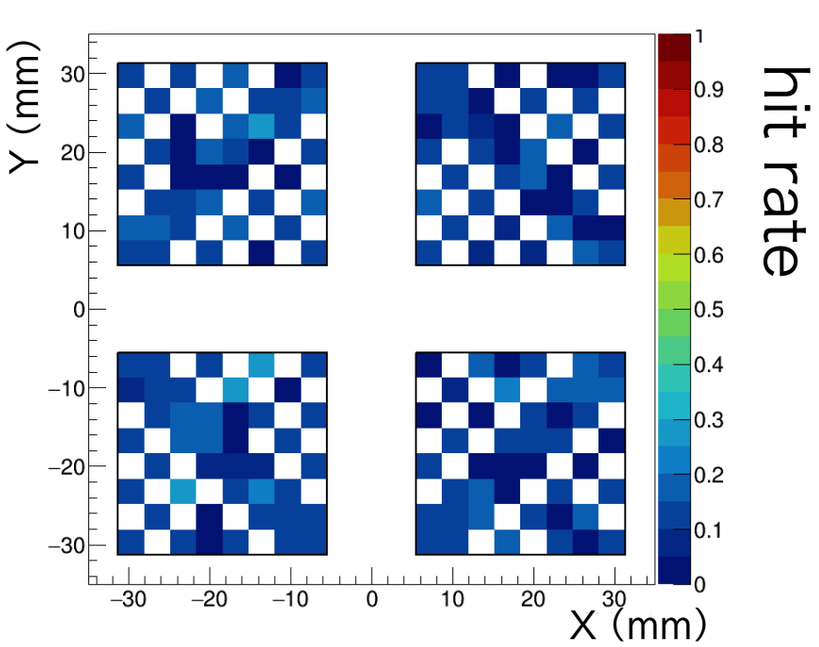
Channel by channel scan is performed.

We confirm most of the channels (255/256) correctly work from 2D hit rate for illuminated channel positions.

Noise hit happens when readout all channels at same time.
It is due to circuitry in ASIC and debug is needed.
We continue study by reducing active channels.







Limit on proximity focusing RICH

K-π separation power

$$= \frac{\Delta\theta_{K\text{-}\pi}}{\sigma_{\mathrm{Cherenkov}}}\sqrt{N_{\mathrm{photon}}}$$

$\Delta\theta_{K\text{-}\pi}$: K-π Cherenkov angle difference (~23 mrad @4 GeV/c)

Resolution of Cherenkov angle $\sigma_{\mathrm{Cherenkov}}$ becomes large due to radiator thickness.

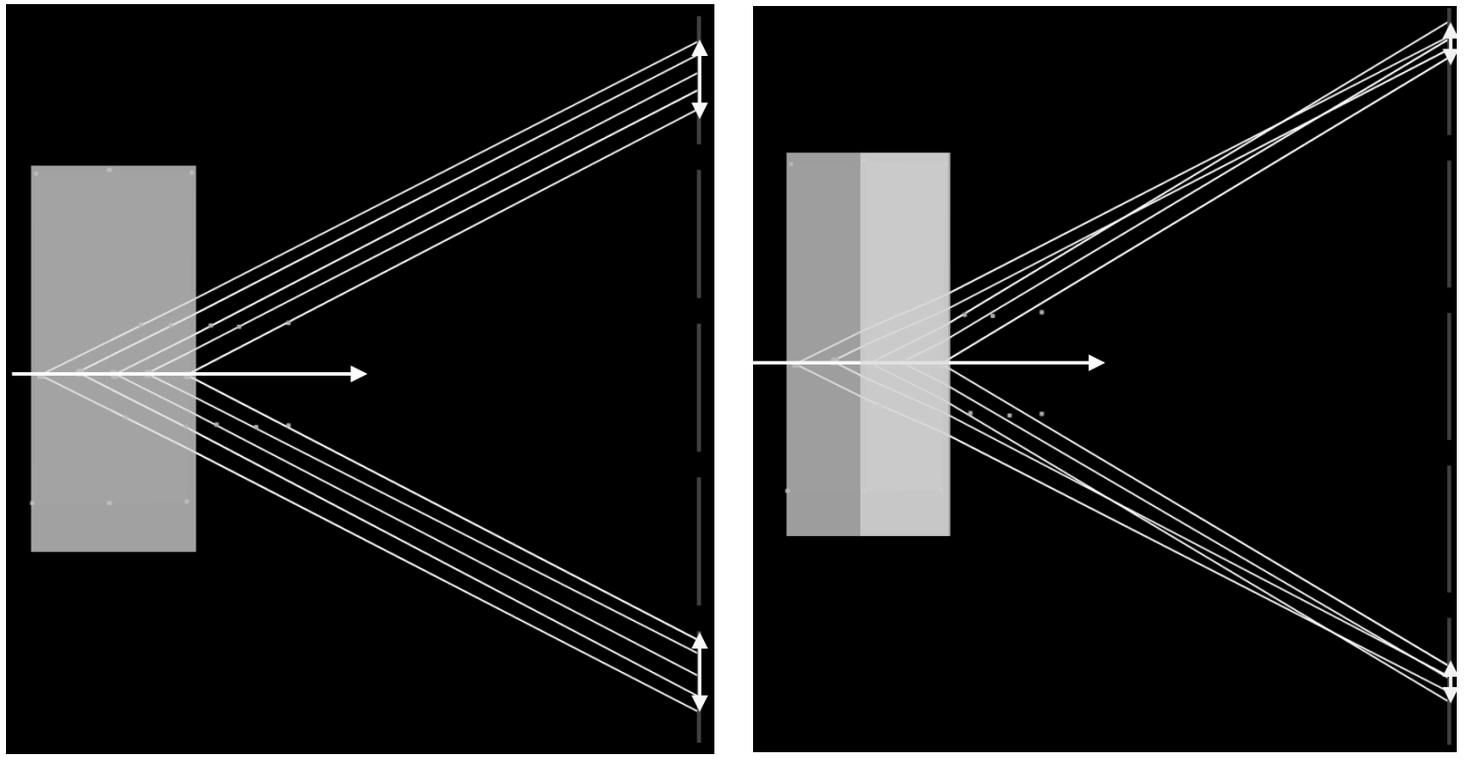
⇅

Number of photon N_{photon} becomes small when reducing radiator volume.

2 layer of aerogel of different refractive indices are used in Belle II ARICH (n~1.045, 1.055) .

For focusing of light from different aerogels, distance between radiator and sensor is needed.

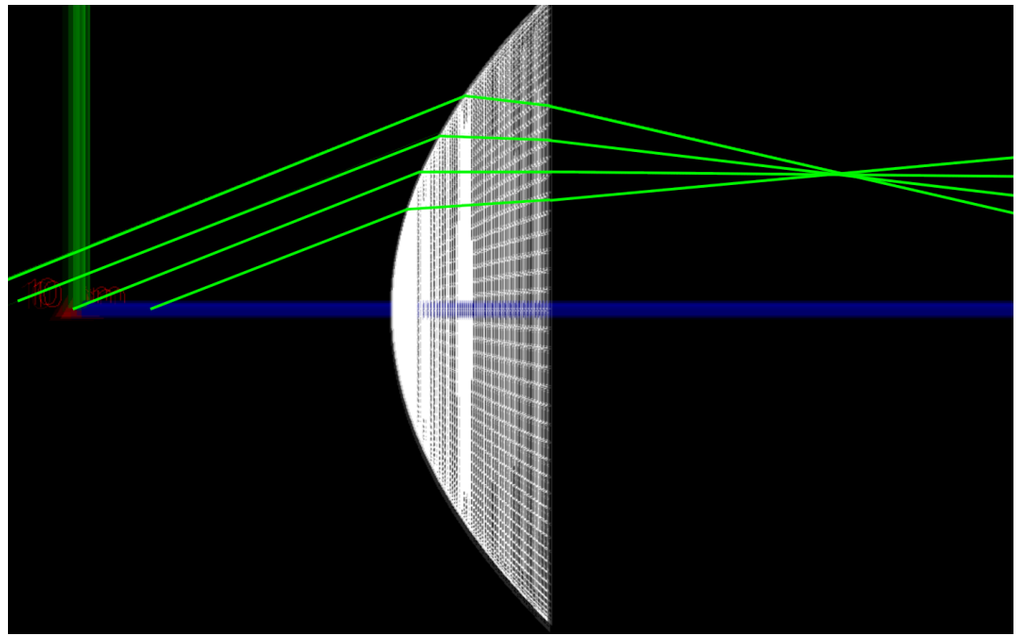
→ Empty space in detector.



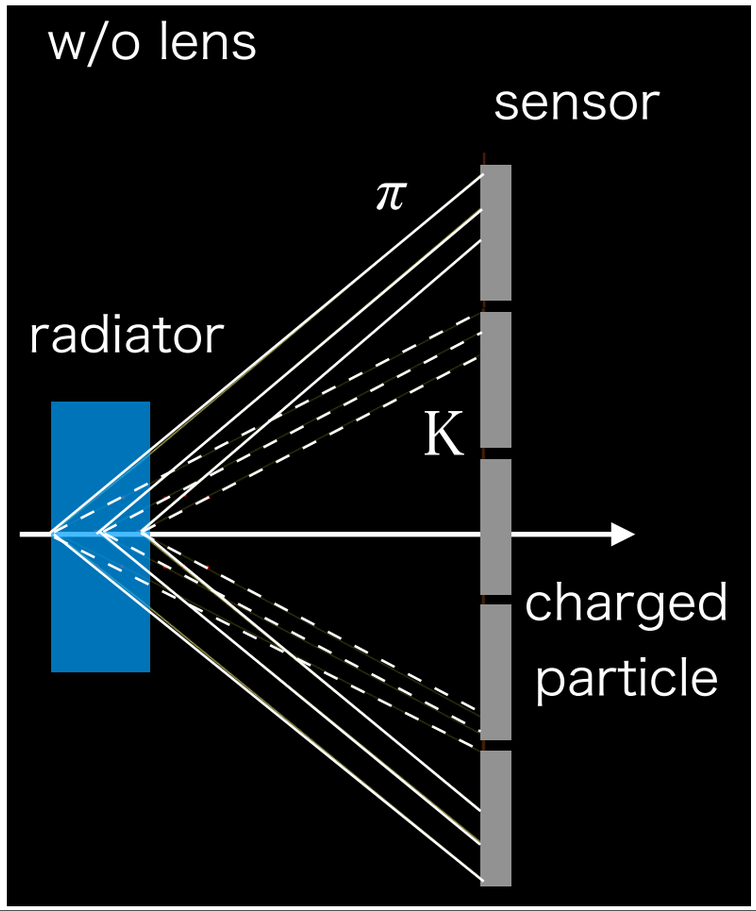
New concept RICH

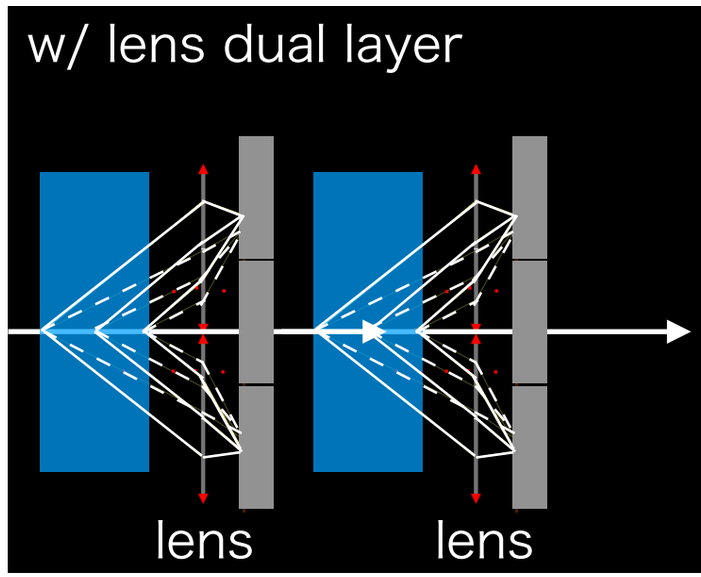
Introduction of focusing lens helps to solve trade-off between $\sigma_{\mathrm{Cherenkov}}$ and N_{photon}.

Parallel lights converge at focusing point.
→ Variation of Cherenkov photon emission points does not affect to resolution (mRICH in EIC https://doi.org/10.1016/j.nima.2023.168850).



Distance between radiator and sensor is shorten if we use lens of short focusing length.
→ Additional space is available for new configuration (dual layer, cooling, etc.).

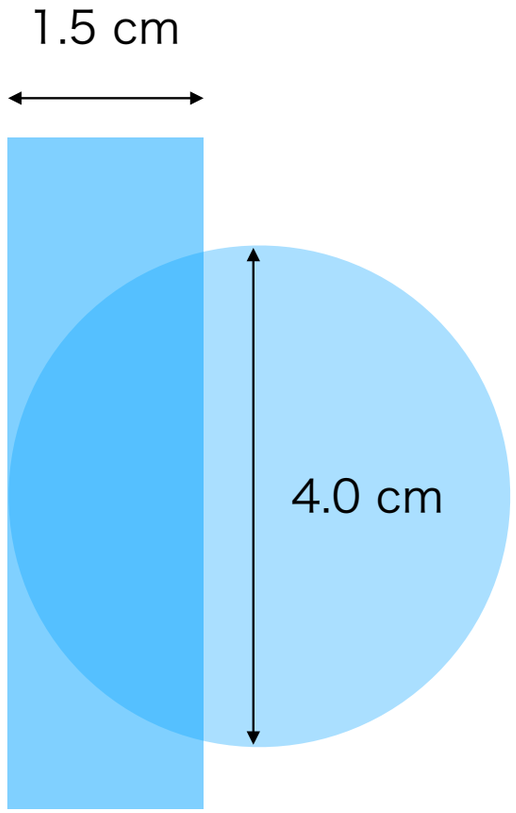


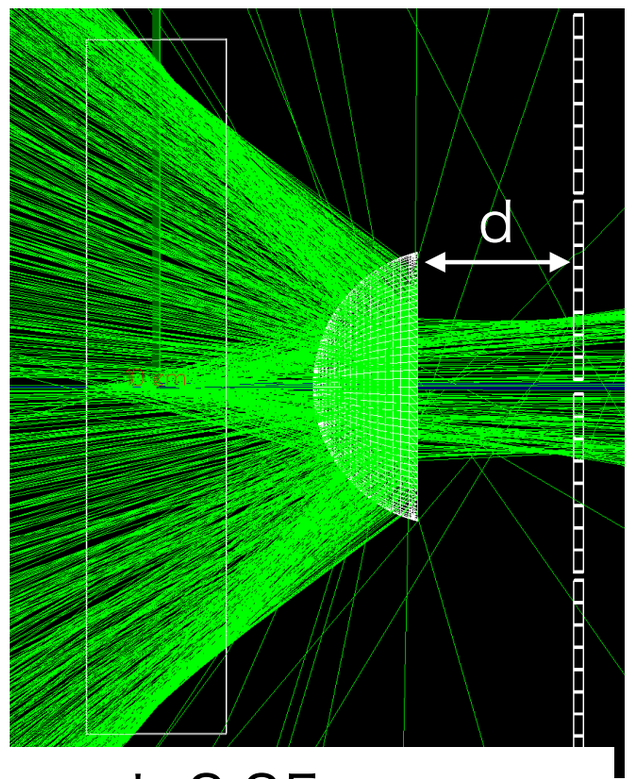


Simulation of RICH /w spherical lens

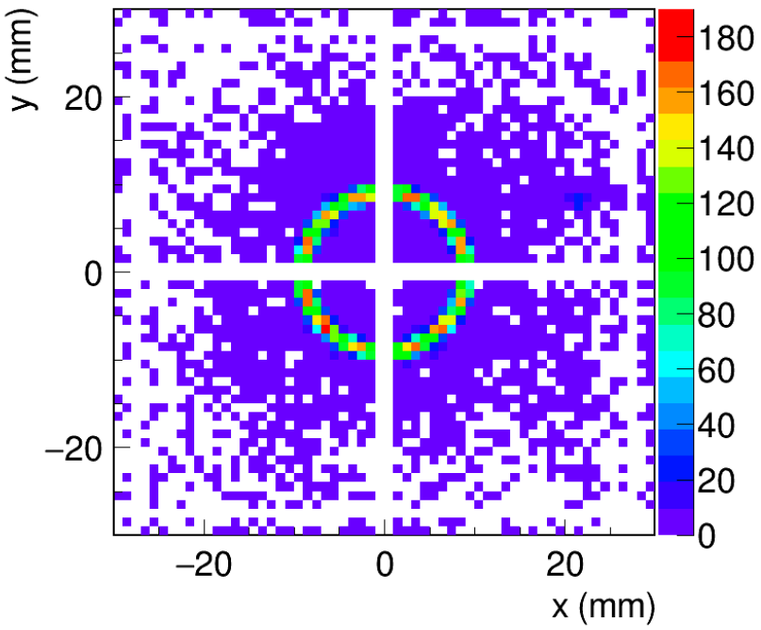
In GEANT4, lens made by glass by cutting sphere glass material.

Incident 2 GeV/c π and check Cherenkov photon hits distribution by changing a distance between lens and sensor.

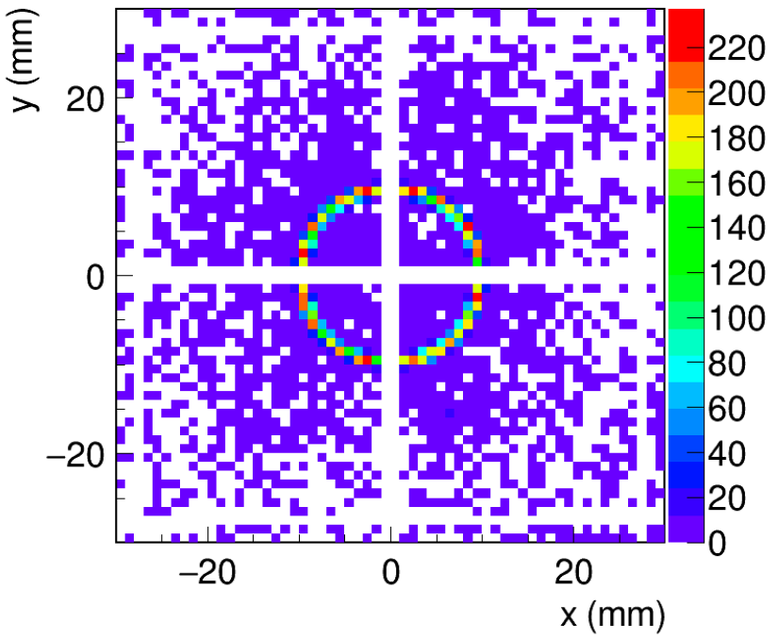




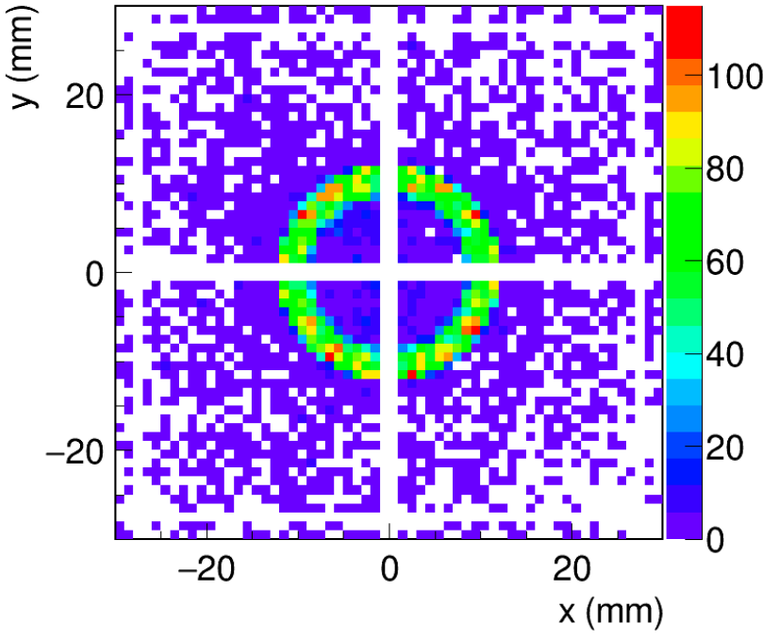
d=0.25 cm



d=1.25 cm



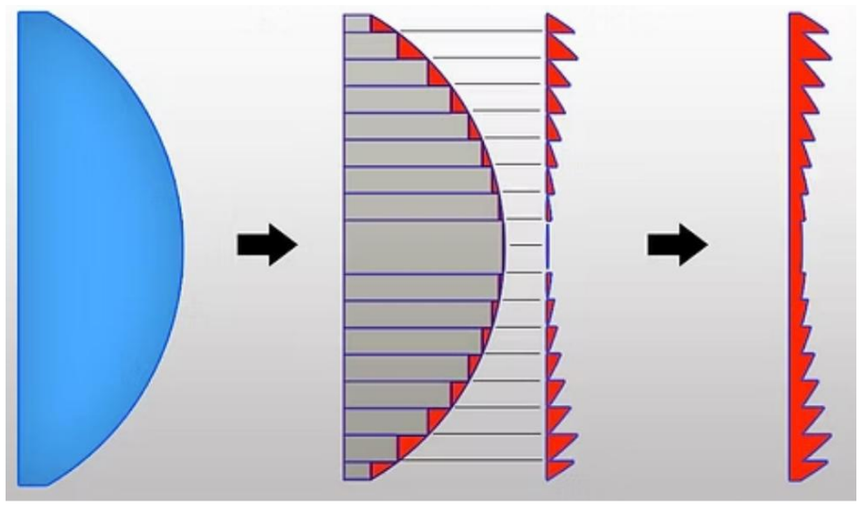
d=2.25 cm

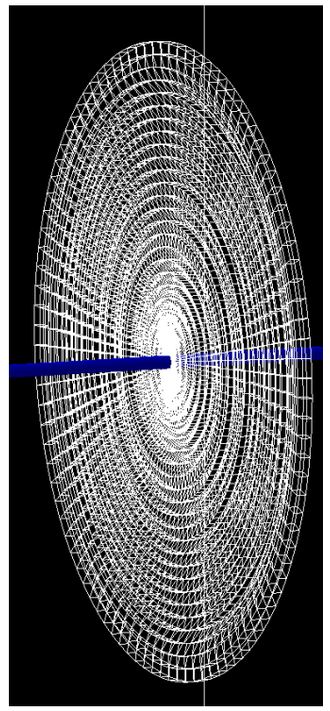


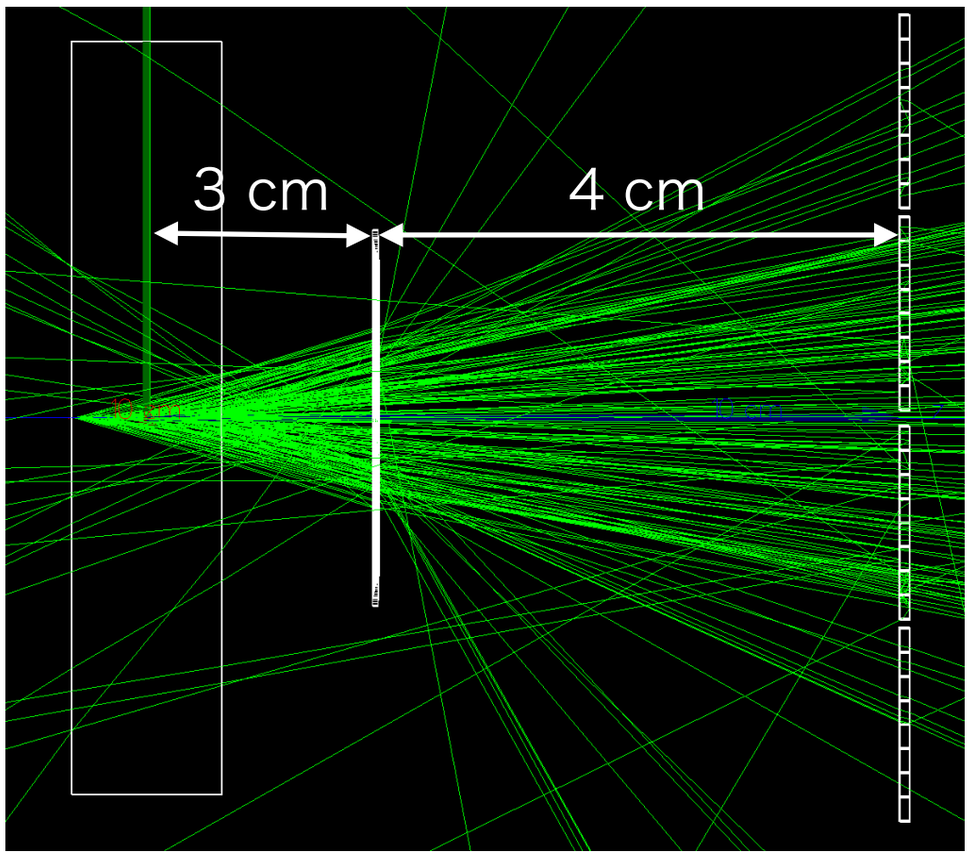
Focusing effect is clearly seen.

Simulation of RICH /w Fresnel lens

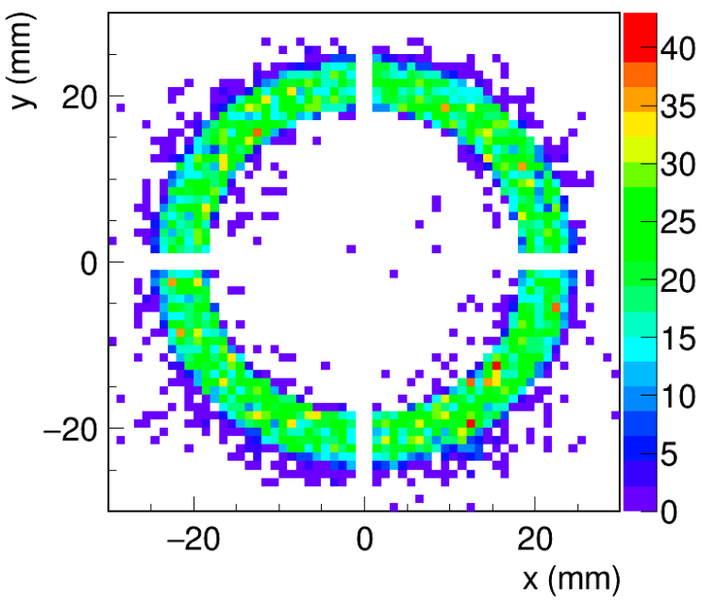
Many Cherenkov photons are emitted in thick glass material. Most of them go out to the opposite direction to sensor but it might affect in real setup.
→ Fresnel lens is simulated.



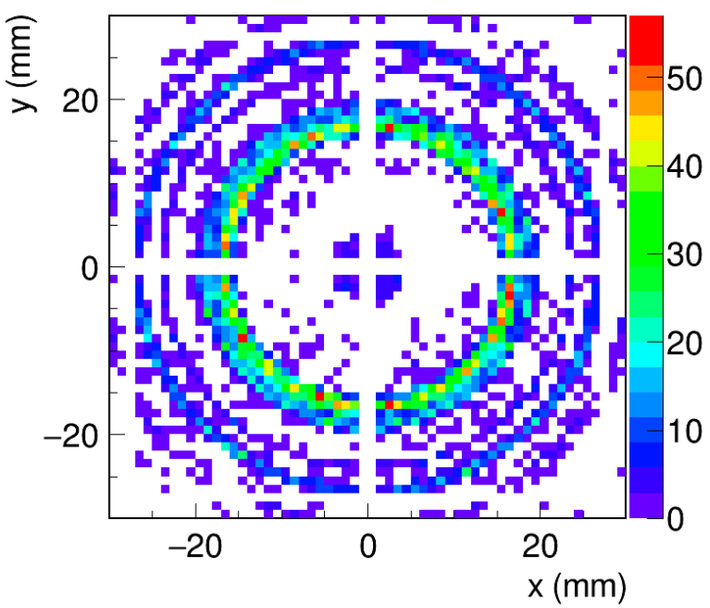




w/o lens



w/ lens

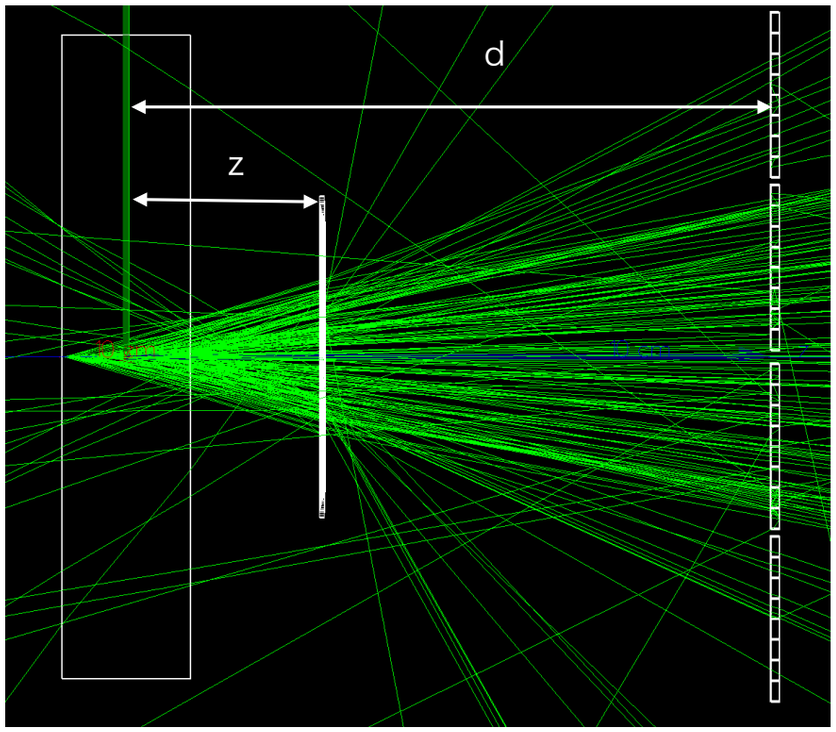


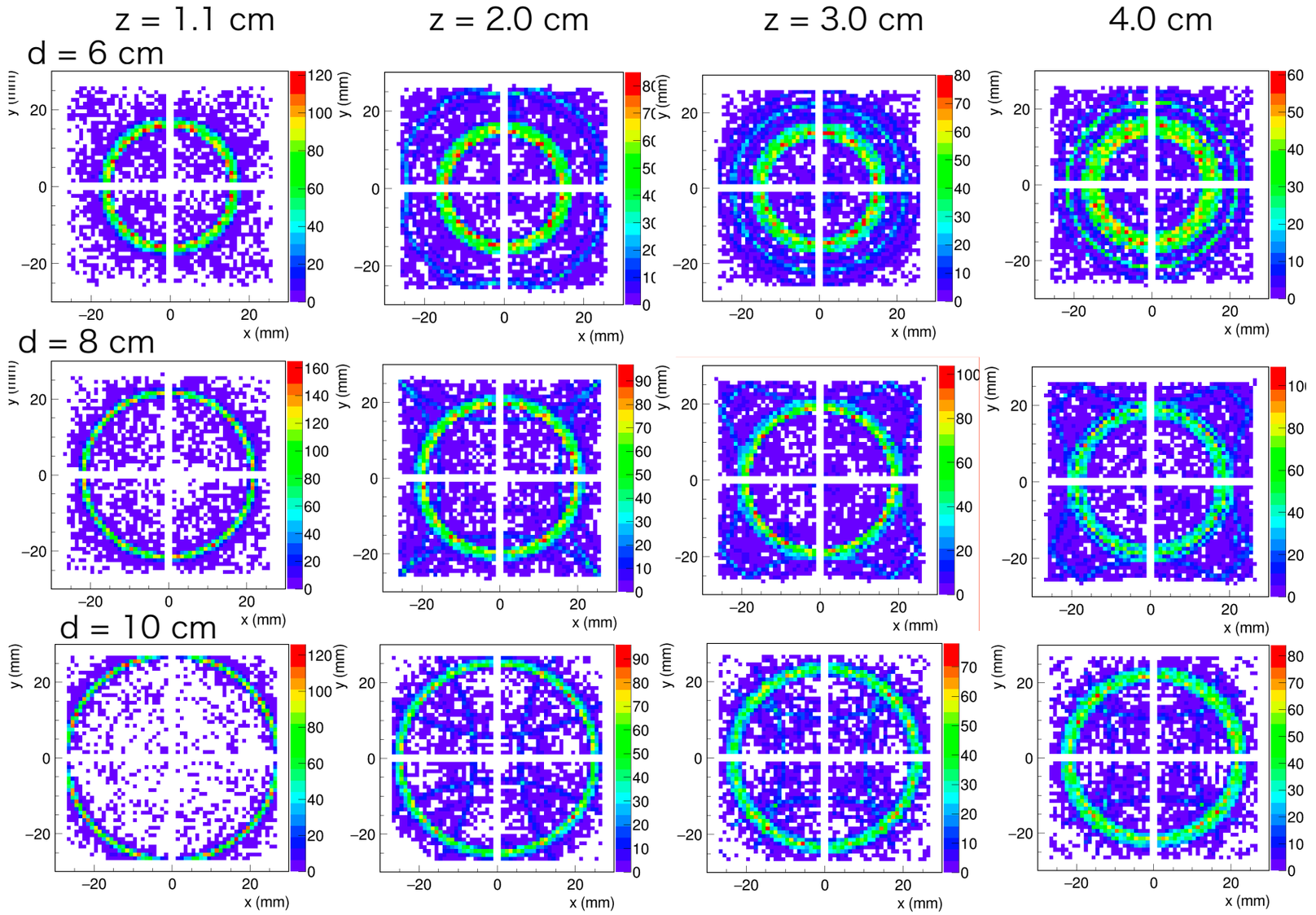
Reduction of Cherenkov light in lens and focusing effect are confirmed.

Design of prototype w/ Fresnel lens

To perform beam tests, prototype module is designed.

Check ring image by changing distances among aerogel, lens and sensors.



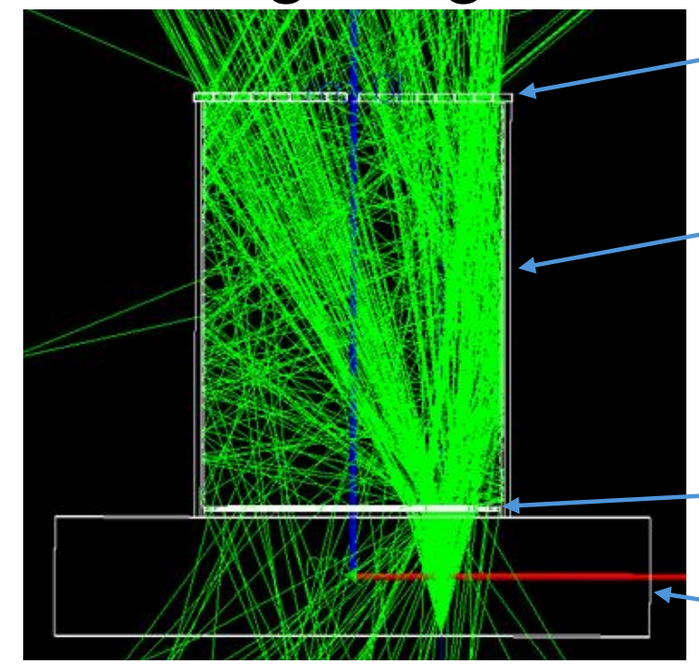


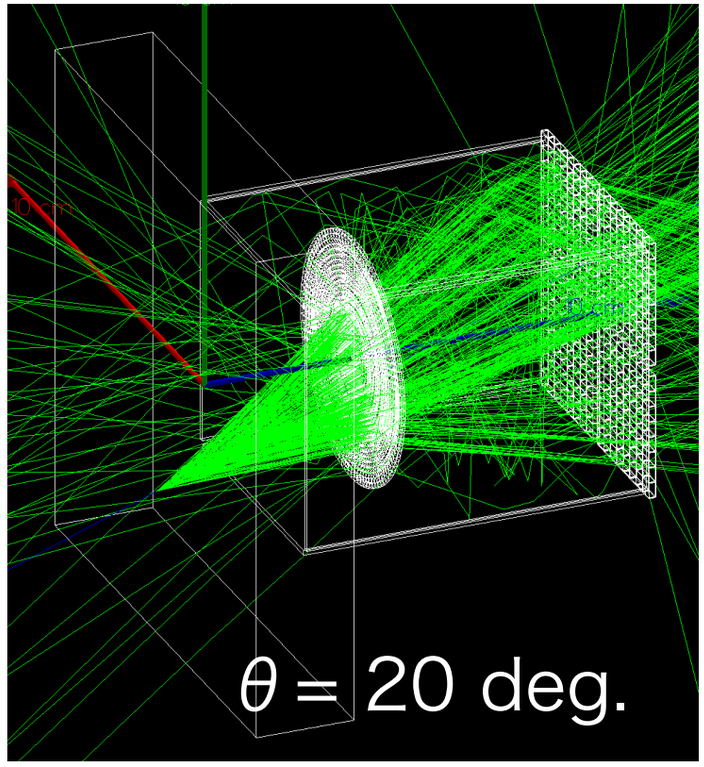
Best position: z=1.1 cm (lens is installed right behind areogel) and sensor is located 8 cm away from aerogel (was 20 cm in Belle II ARICH).

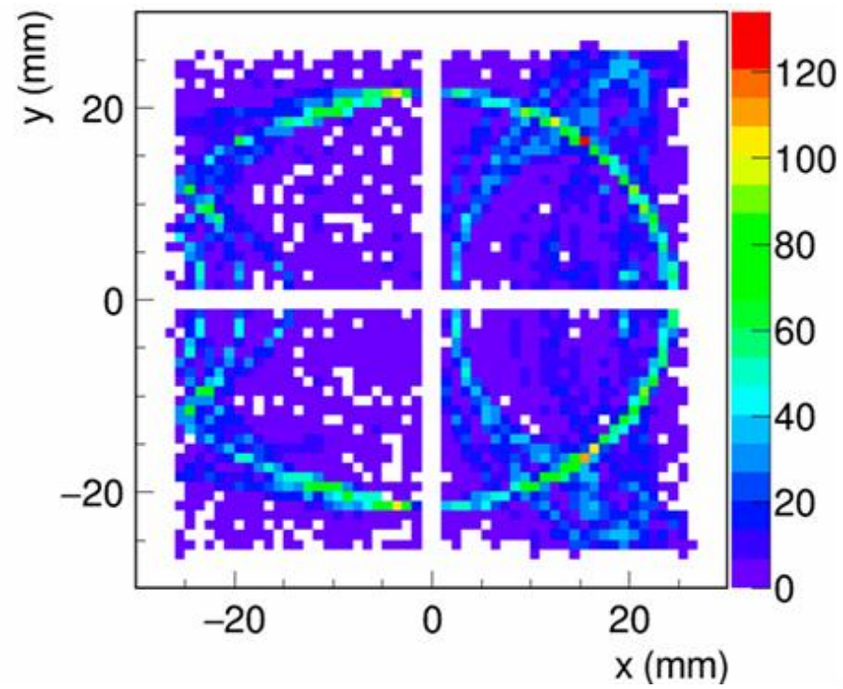
Ring image area can be covered using 4 MPPC arrays (256 channels).

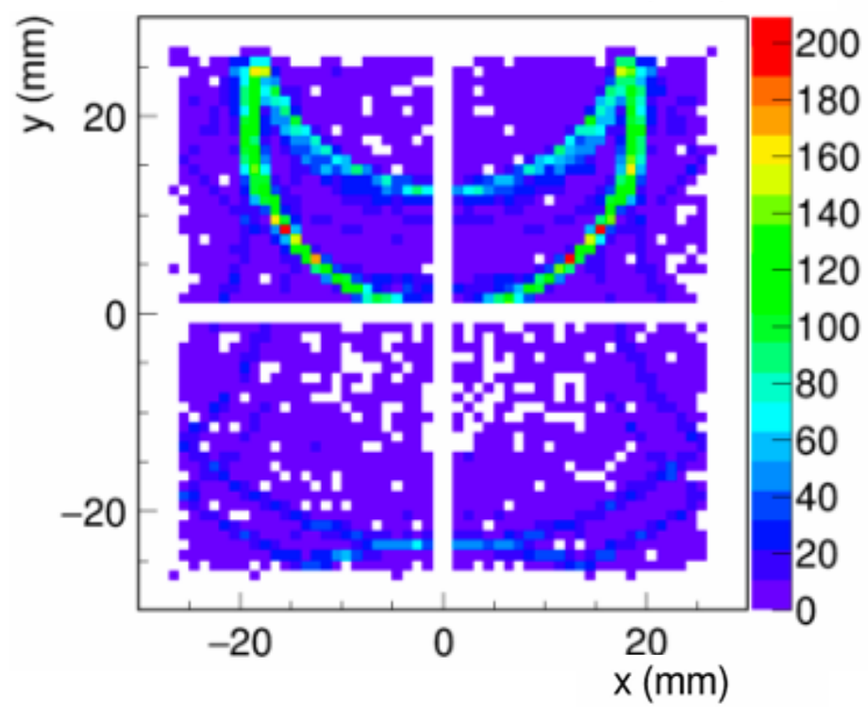
Design of prototype w/ Fresnel lens

In actual use, beam incident position is not center, incident angle is not 0. → Lights go outside can be recovered by mirror wall.









Concerns when using lens

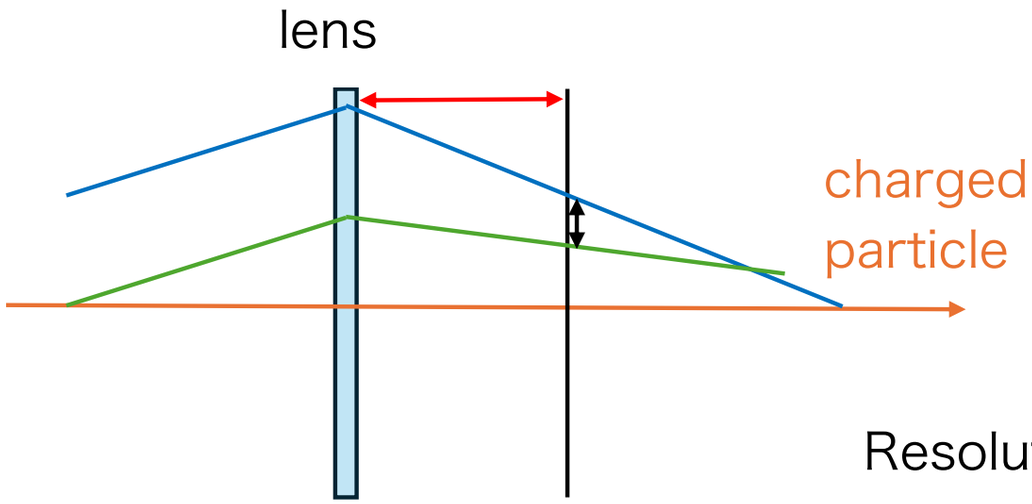
We need to control lens quality considering possible effect.

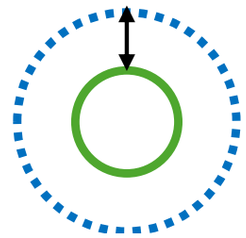
Aberration induces degradation of Cherenkov angle resolution.

A part of photons pass around edge structure of Fresnel lens without refraction.

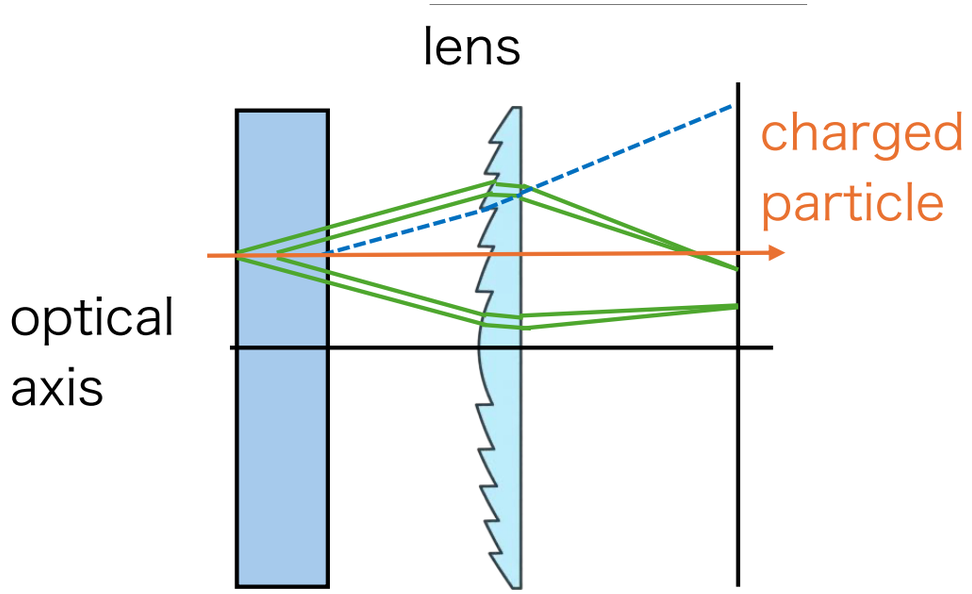
Transmittance of lens is not 100%.

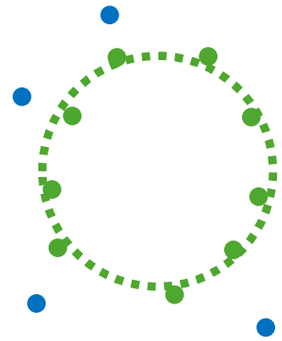
→ We first validate commercial plastic Fresnel lens (< 50 USD/pcs) is usable or not.



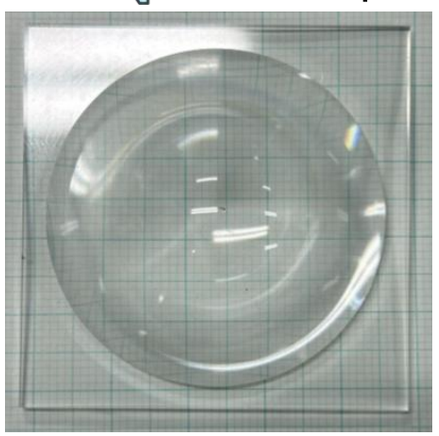


Resolution degrades





background hits



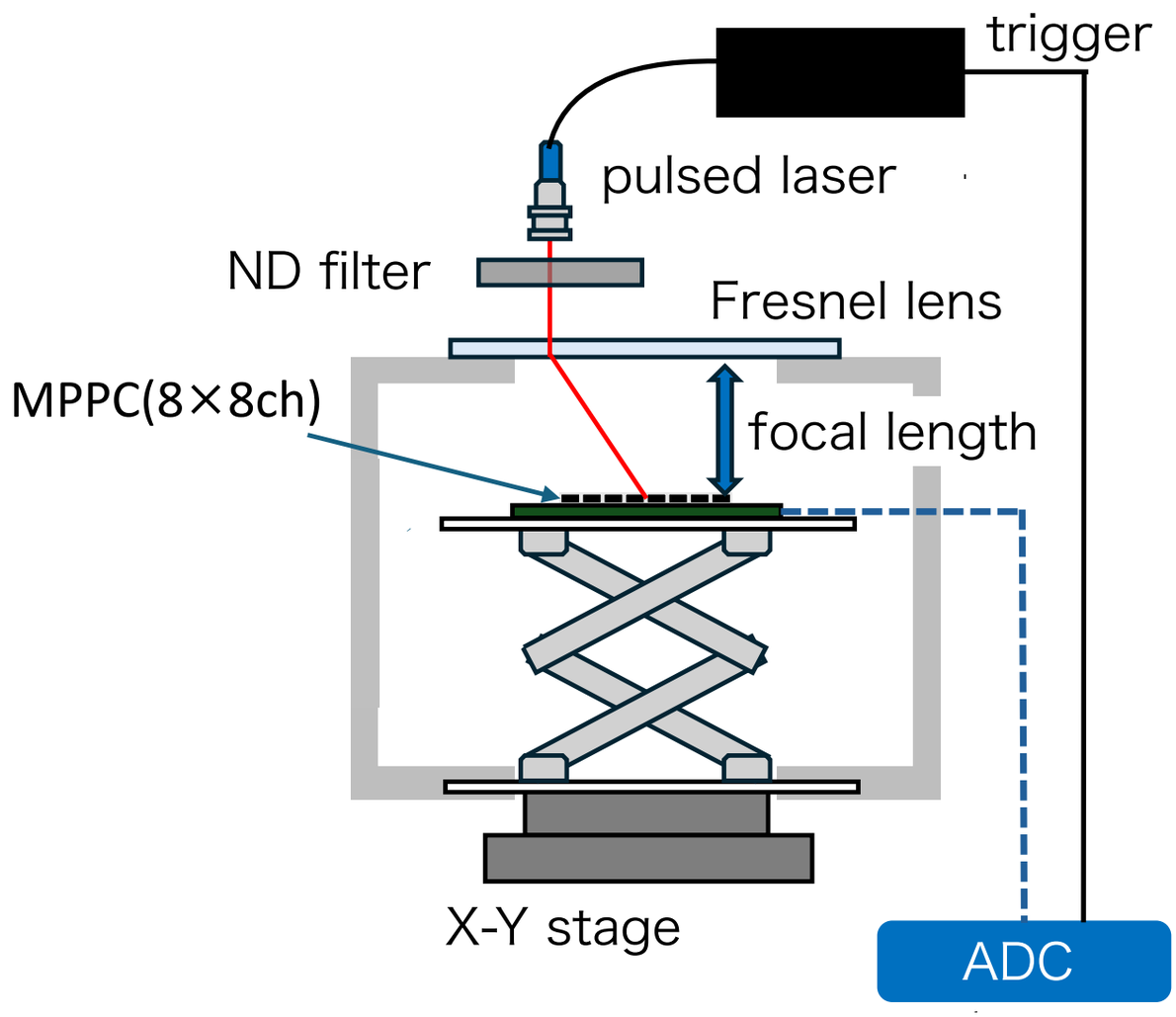
Yuki Kogaku f050
focal length 50 mm
lens radius 50 mm
thickness 2 mm

Test bench for lens validation

We set up scan system of lens with MPPC array.

Illuminate laser to lens and detect photon hits above pedestal of ADC distribution.

MPPC array is set at a distance of focal length.
→ photon hits position does not change when moving laser incident point.

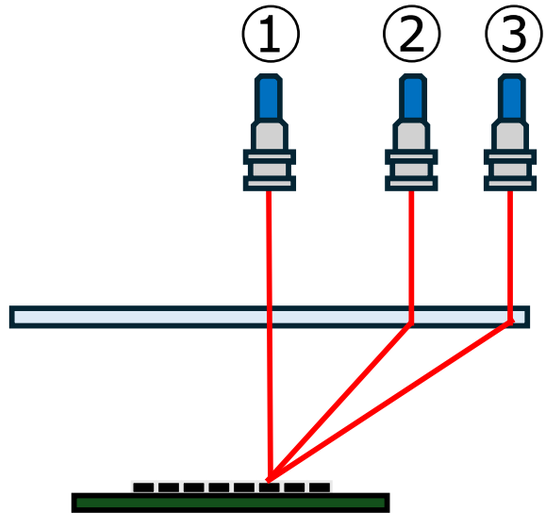


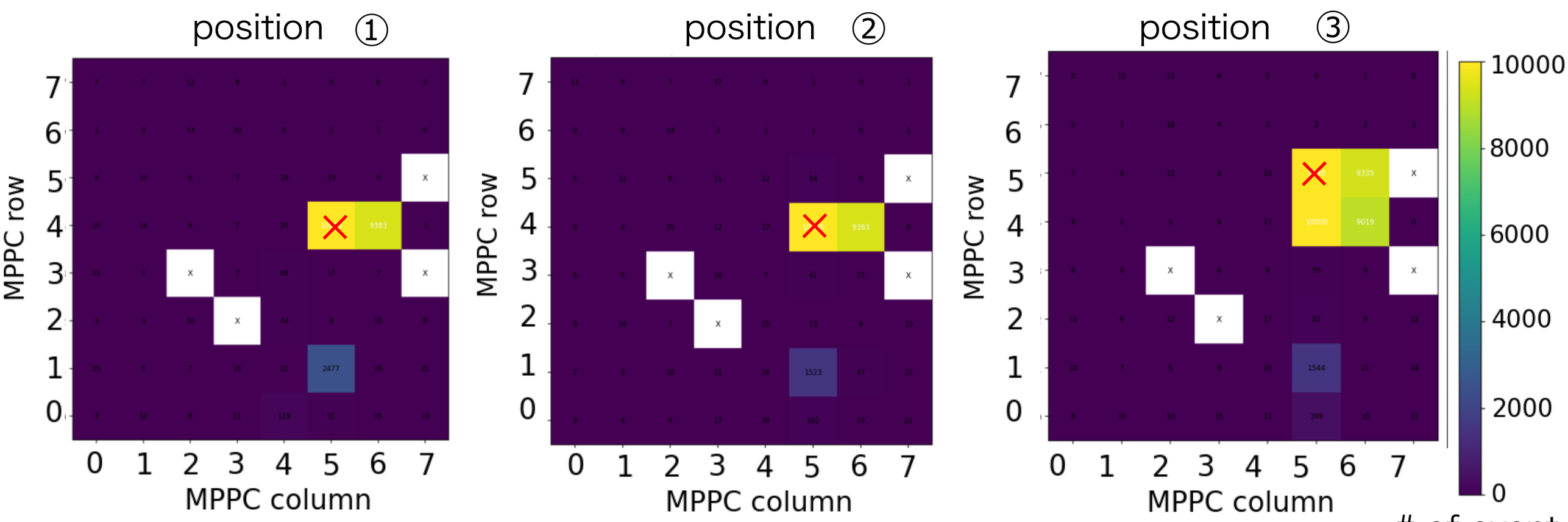
Lens surface is scanned and check effect of aberration as stability of hit point on sensor.
Target is detection of photon hits without significant shift within MPPC pixel size (3 mm).

2D hit map of refracted light

2D hit map is checked for the 10000 trigger of laser incident.

Pixel of the largest count is same when illuminating inner part of the lens but slight shift is seen in case of outside.





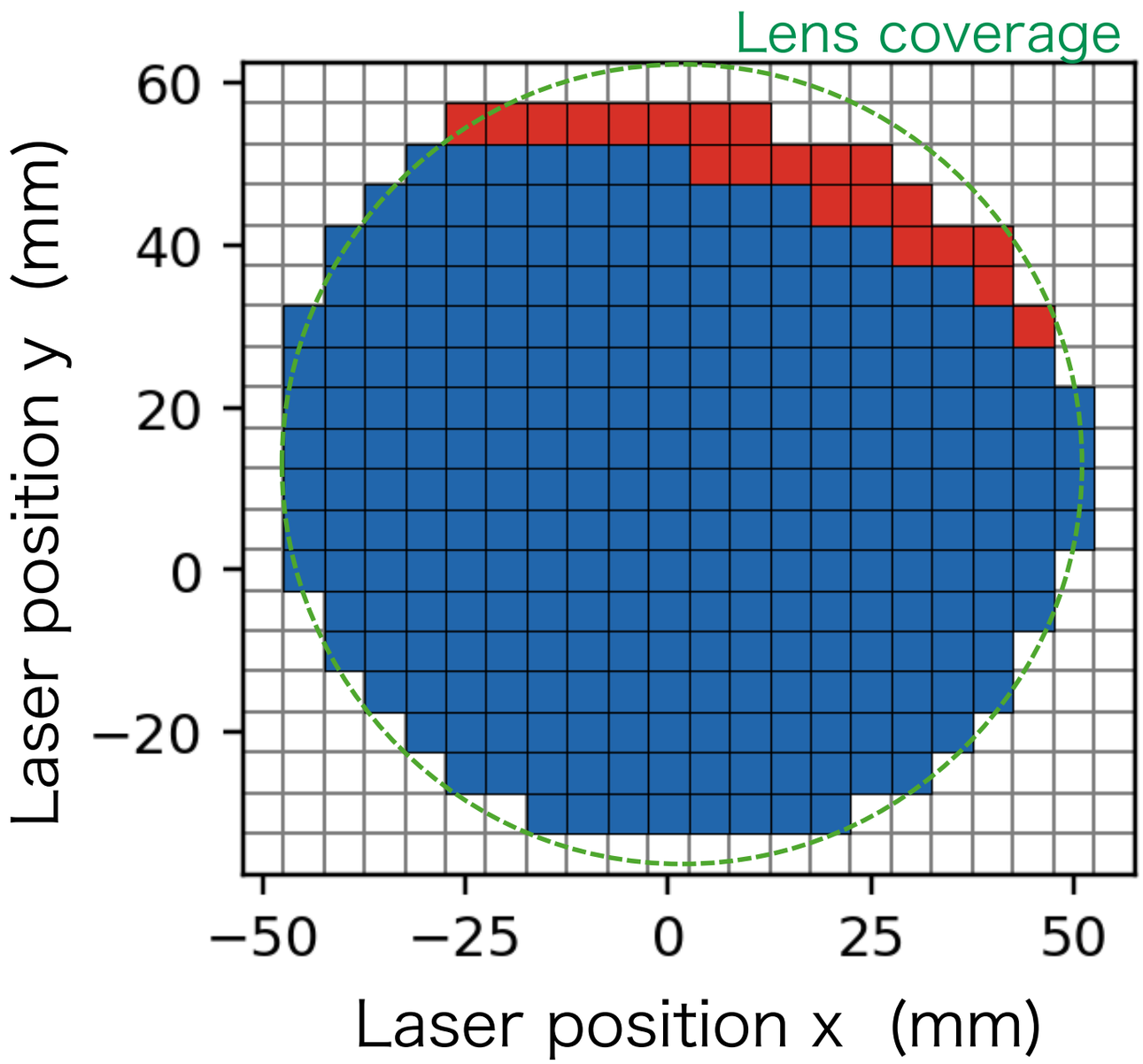
Check relation of shift between ideal pixel by considering refraction and pixel which has largest hit number (indicated as × in above).

Stableness of refracted light

Move laser incident position by 5 mm and check shift of observed pixel.

- Ideal position
- Shift to neighbor pixel

In most of the points, refracted light is seen in ideal position.
Shift to neighbor pixel is seen in edge of right top region.
Data is missing in same region due to some conflict of experimental setup.



→ Need to check source of the shift is related to lens performance.

Summary

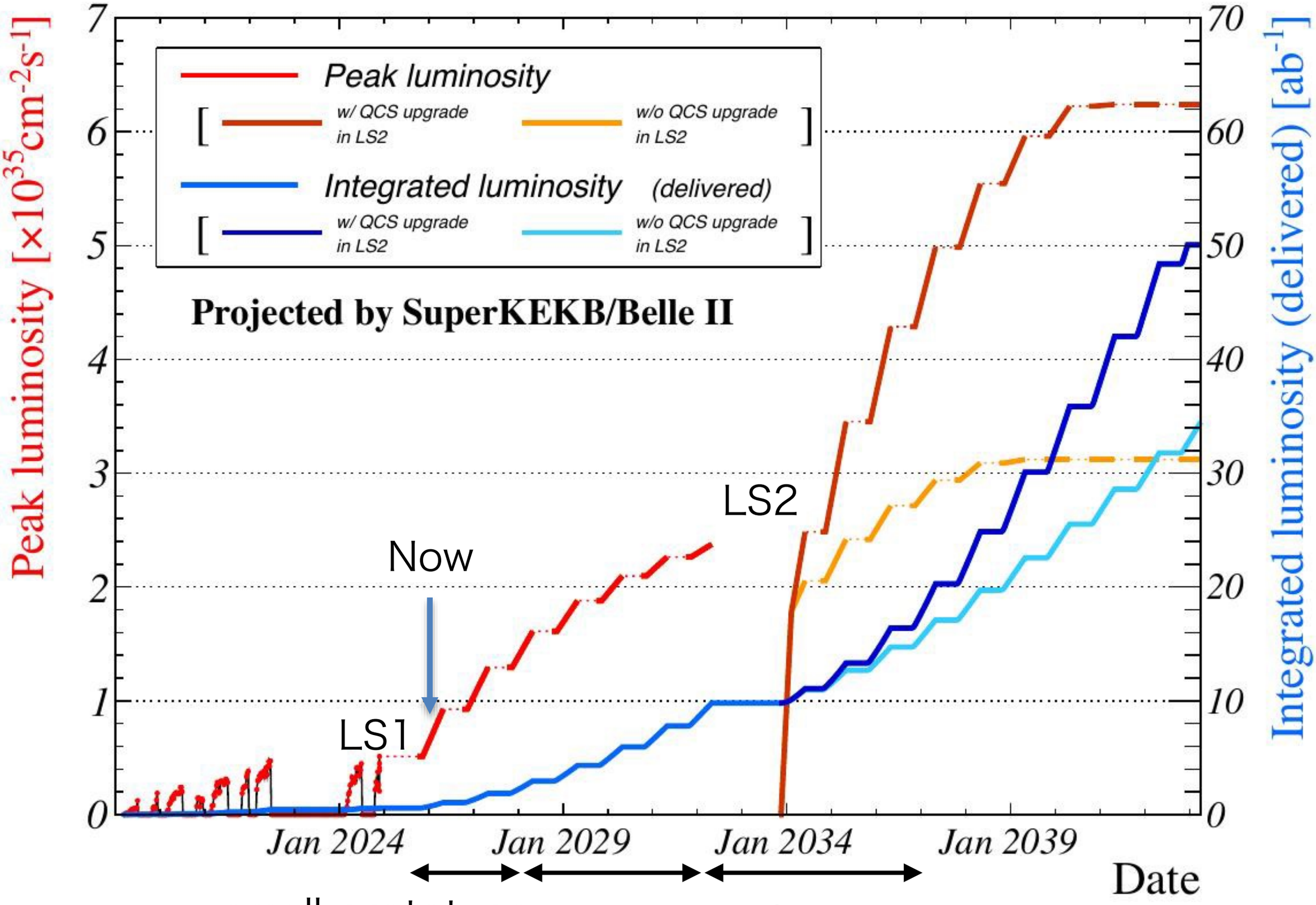
Proximity type of Aerogel RICH installed in Belle II forward endcap has been providing PID information.

For long-term operation we are considering upgrade plan by replacing photon sensor.

New readout ASIC has been developed and validated by laser emission.
Operation with 64 channels MPPC array works well but further debugging of circuit is needed.

To improve performance, study using lens focusing is ongoing.
Prototype design is decided by GEANT4 simulation.
Validation system of lens performance is constructed.
→ Select lens installed in prototype.

backup


Peak luminosity [×10^35 cm^-2 s^-1]
Integrated luminosity (delivered) [ab^-1]
Peak luminosity
w/ QCS upgrade in LS2
w/o QCS upgrade in LS2
Integrated luminosity (delivered)
w/ QCS upgrade in LS2
w/o QCS upgrade in LS2
Projected by SuperKEKB/Belle II
LS1
Now
LS2
Jan 2024
Jan 2029
Jan 2034
Jan 2039
Date
small prototype study
large prototype study / partial construction
full construction