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# Upgrade of the Belle II ARICH detector


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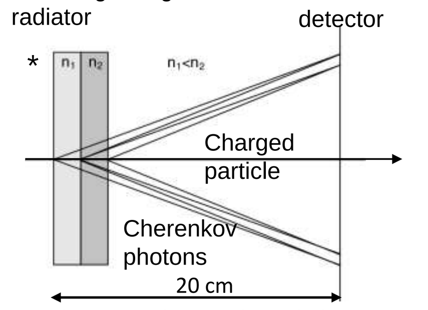
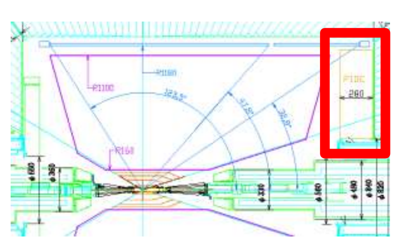
Aerogel RICH currently identifies charged particles in the Belle II spectrometer. Cherenkov photons, emitted in the aerogel radiator are detected by single-photon Hybrid Avalanche Photon sensors working in a 1.5 T magnetic field and occupying an area of 4.5 m². By 2030 the Belle II will reach its design goal of 50 ab⁻¹ and the HAPD performance will degrade. The upgrade of the spectrometer to extend its operation will thus require replacement of the ARICH photo-sensors. Silicon photomultipliers are one of the candidates. Due to its sizeable dark count rates and their sensitivity to neutrons – we expect fluences of up to $5x10^{12}$n/cm2 - such a device requires to read out the signals in a narrow time window of several ns, requiring optimized SiPM design and high integration with the read-out electronics. In the presentation, we will present a SiPM module design, a study of single-photon detection capabilities of irradiated SiPMs and read-out FastIC chip.

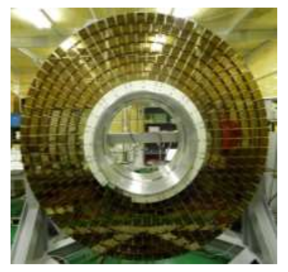

## Motivation: Proximity focusing Aerogel RICH at Belle II

In operation since 2018




* to increase the number of photons without degrading the resolution

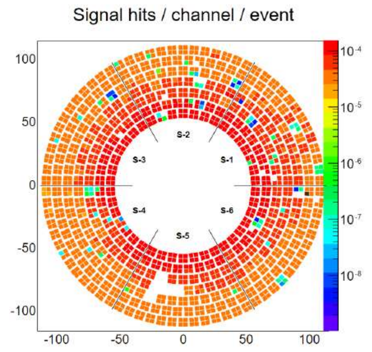




Goals and constraints:
- > 4 σ K/π separation @ 1-3.5 GeV/c
- **operation in magnetic field 1.5T**
- limited available space ~280 mm

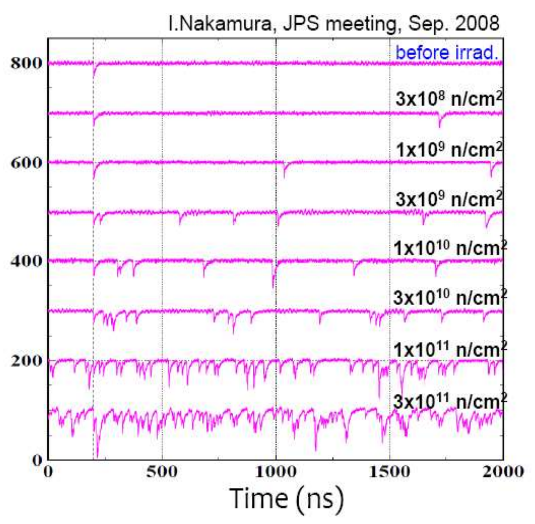
T.Iijima, S.Korpar et al. NIMA548 (2005) 383

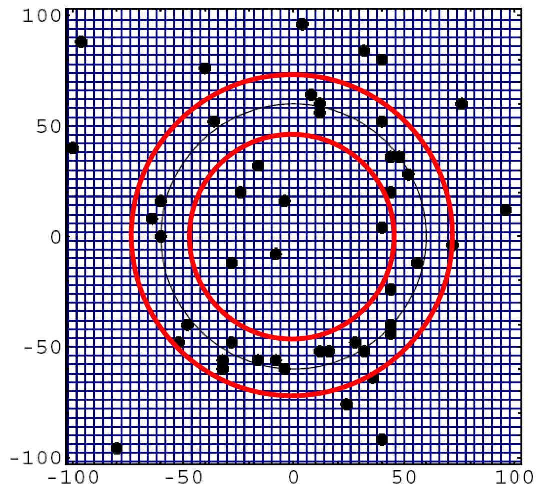
**Current detector:**
- ❑ aerogel radiator plane 124x2 pieces 20mm thick wedges
- ❑ photon detector plane with 420 Hybrid Avalanche Photo detectors (HAPD)
- ❑ front-end readout electronics – custom ASIC+ Spartan-6 FPGA




**Designed for** $L = 8x10^{35}$ $cm^{-2}s^{-1}$

- **fluence: up to ~$10^{12}$ n/cm2**
- radiation dose: up to ~1000 Gy

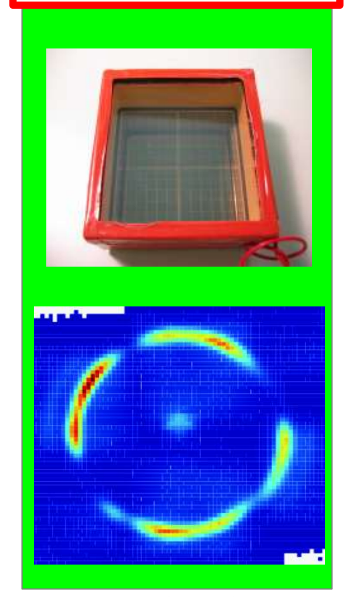


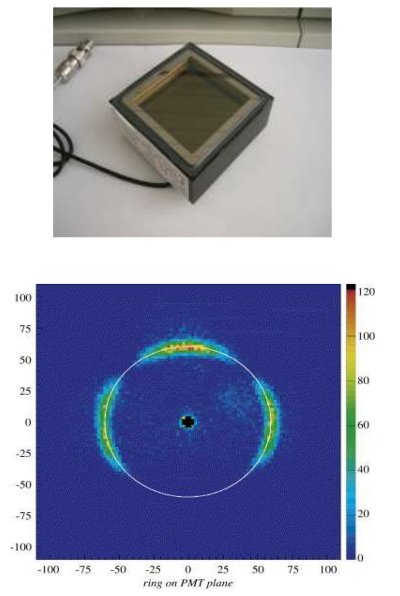



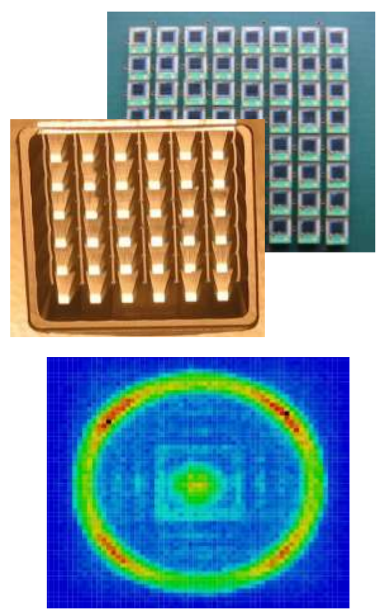
Belle II upgrade to high luminosity **5xL foreseen at 2030.**
- We expect the HAPD sensors will work until the original luminosity will be reached.
- The impact of slowly degrading performance is relatively small
- The biggest concern are disruptive events resulting in non working HAPDs
- 4% spare sensors are available for replacement, however Hamamatsu dismantled the production line.
- We are seeking for the replacement candidates able to detect single photons
  - with high efficiency and
  - would withstand the neutron fluence up to ~**$5x10^{12}$ n/cm2**

**During R&D of** Belle II ARICH, 3 candidates have been tested

| HAPD –chosen and installed | 64 ch. 10 µm MCP PMT | SiPM 1x1mm² + light guide |
|---|---|---|







AdvanSiD – ASD-NUV3S-P

S.Nishida et al. NIMA610(2009)65  S.Korpar et al. NIMA567 (2006) 124  S.Korpar et al. NIMA639 (2011) 162

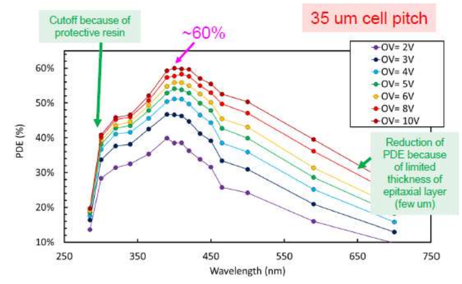
**This work focuses on the use of silicon photomultipliers as a photon detector.**

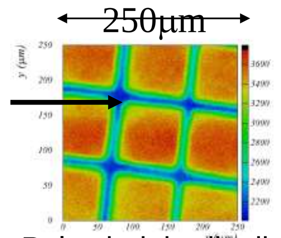
## Silicon photomultipliers

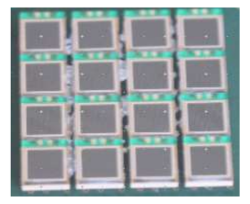
Advantages:

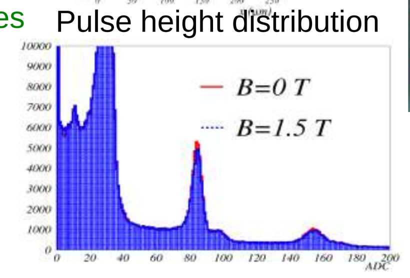
- low operation voltage~ 10-100 V
- gain ~ $10^6$
- peak PDE up to 65%(@400nm)
- PDE = QE x $\varepsilon_{geiger}$ x $\varepsilon_{geo}$
- $\varepsilon_{geo}$ – dead space between the cells
- $\varepsilon_{geiger}$ – Geiger discharge probability
- intrinsic timing resolution ~ 100ps
- can be combined in larger modules
- in contrary to PMT
- it works in the magnetic field

Disadvantages:
- dark counts ~ few 100kHz/mm²
- radiation damage (p,n)






SiPM very attractive sensor
Its use can be used to extend ARICH capabilities for low momentum region

Possible improvements in signal to noise ratio:

- ❑ operating the sensor at a lower temperature
- Cooling system might be a problem :
  - due to material budget (ARICH in front of electromagnetic calorimeter)
  - increased system complexity
- ❑ smaller ring image area
- ❑ narrower time window (fast timing electronics)
- ❑ use of light collection system (light guides) to increase effective area of the sensor

**Use of irradiated SiPMs at room temperature very challenging.**

In the context of EC Horizon 2020 AIDAinnova innovation pilot we are studying the SiPMs with improved radiation resistance.

❑ The impact of the radiation on the performance is much worse in the single photon detection regime.

Objectives we are addressing:

- ❑ SiPM design : Review the production process, change of the design and production
- Reduction of a cross-talk and after-pulses
- Use of smaller area SiPMs

❑ Integration of the readout electronics with the sensor:
- TSV interconnects with the ASIC
- Signal Processing in the front end

❑ Light collection:
- Focus light from e.g. 3x3mm2 to 1x1mm2

❑ Recovery of the operation at lower temperatures – annealing

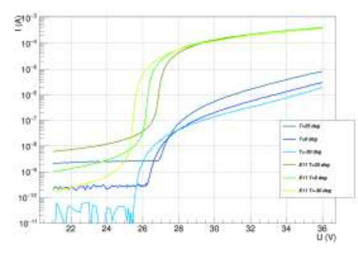
Goal : Improve robustness under neutron irradiation, while maintaining
- low cost
- high efficiency & good time resolution

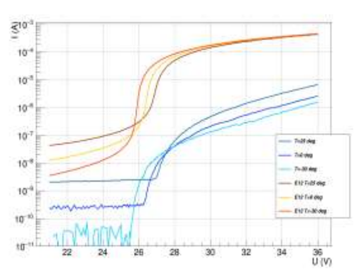
Systematic study of irradiated SiPMs at different temperatures
Study the dark-count noise performance at different temperatures.

Define working conditions for SiPMs to be used in the Belle II ARICH Upgrade

I-V at 25 ,0 and -30 °C

$10^{11}$n/cm²  Broadcom AFBR-S4N44C013  $10^{12}$n/cm²

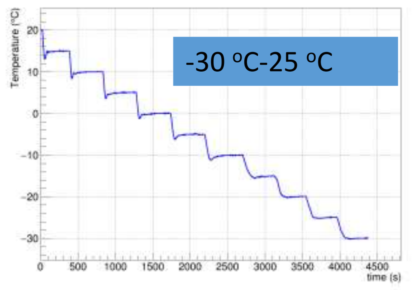


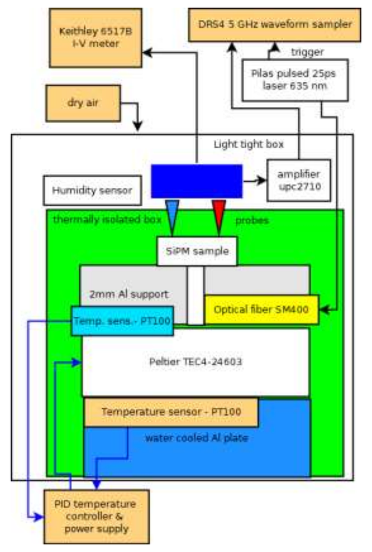


## Experimental setup

Probe station to measure:
- IV curves
- Waveform acquisition with DRS4
- DCR with NIM counter

Temperature controlled sample:
Peltier with water cooling



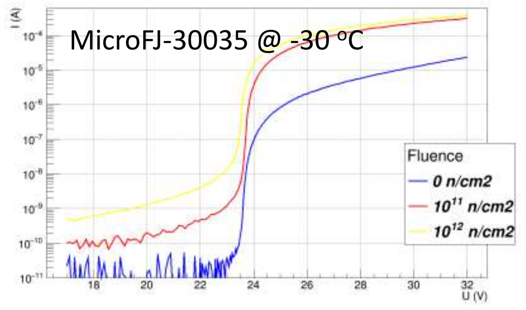



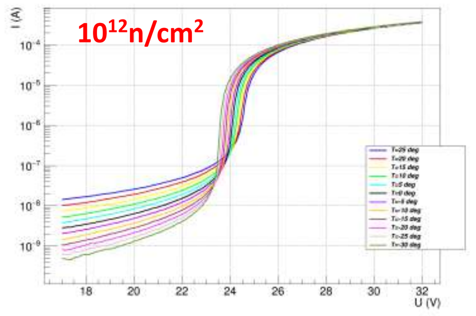
Irradiated samples

Irradiation @ TRIGA nuclear reactor at Jožef Stefan Institute, Ljubljana

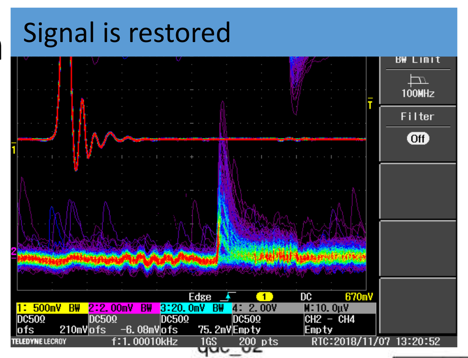
Fluence $10^{11}$n/cm² $10^{12}$n/cm²

No single photo-electron signals observed due to high DCR and baseline shift

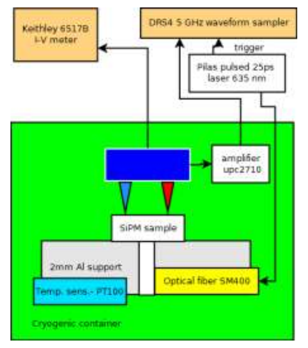


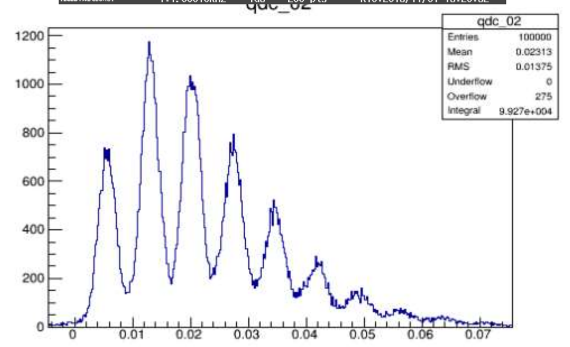




Tests at Liquid Nitrogen
T=-196 °C

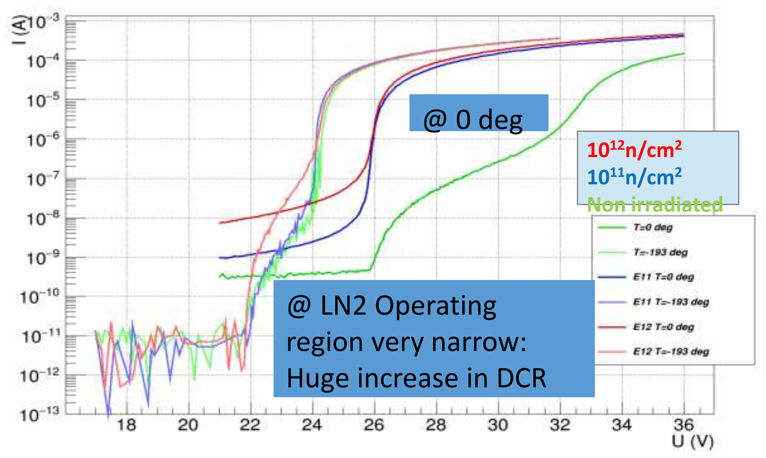



Dry Cryogenic container



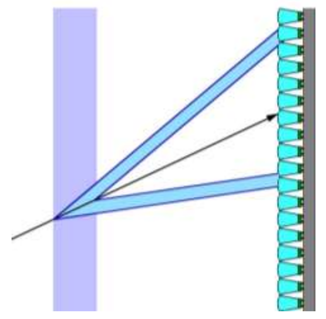


I-V curves @ low temperatures



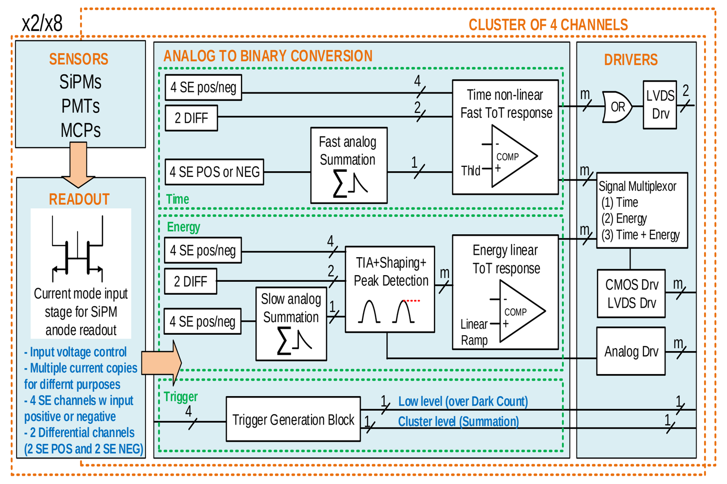

## Light collection

use of light collection system to increase effective area of the sensor.

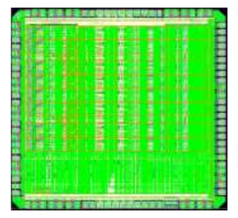


## Readout electronics

FASTIC current mode ASIC
- **8 Inputs:** 8 Single Ended (positive or negative) or 4 differential.
- **4/8 Outputs:** CMOS, LVDS and Analog.
- Summation in clusters of 4 channels.
- Energy: Linear Time over Threshold with high dynamic range.
- Different trigger levels and cluster trigger for monolithic crystals.



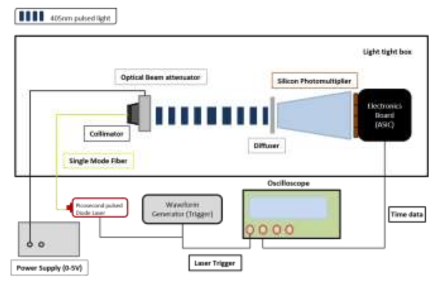
First prootype submitted May 20th 2020: 8 ch (6 to 12mW/ch depending on operational mode).
Final chip: Expected 32 channels.



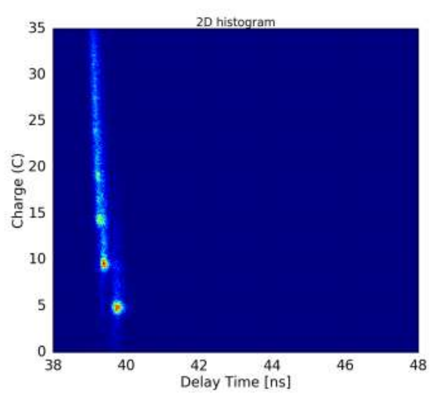
| Parameter | Value |
|---|---|
| Technology | 65 nm CMOS |
| Power consumption | ~ 9 mW/ch in SE mode ($V_{DD}$ = 1.2 V), depends on operation mode (~ 3 mW/Input Stage). *About 6 mW/ch for RICH/TORCH mode* |
| Number of channels | 8 SE / 4 DIFF |
| Connection Type | Configurable SE (Pos/Neg polarity), DIFF, Sum of 4 (Pos/Neg polarity) |
| Electronics Time Jitter | ~ 30 $ps_{rms}$ SPTR (330 pF 3x3 SiPM, LCT5 S13360 SiPM, Vov = 4.5 V, L = 1.2 nH) |
| Energy Resolution | Linear (~ 2.5 % Linearity error) |
| Dynamic Range | 5 uA - 20 mA |
| Maximum Rate | ~ 2 MHz (Linear ToT readout), > 50 MHz (Non-linear ToT. Pulse-shape-dependent) |
| Testing and Calibration | Yes |
| Interface | I2C (compatible with picoTDC) |
| Output | Configurable Digital (single-ended CMOS or differential SLVS) or Analog output (10 pF load). |

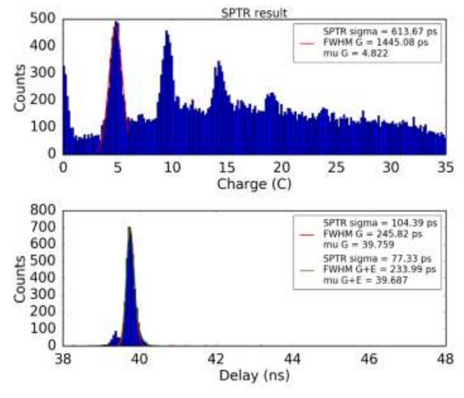
First prototzpe ASIC produced in 2020

- ❑ Initial tests of the ASIC showed that the ASIC is working.
- ❑ Main functionalities: Input modes (POS, NEG, DIFF, SUM) and output modes are working (SLVS, CMOS, Analog) are working.
- ❑ The ASIC response well for fast signals (of about 3 ns FWHM) using the non-linear ToT response.
- ❑ More electrical tests will be performed in the incoming months.



Shaper Charge Measurement
Sensor: S13360-3050CS (Hamamatsu)





SPTR - HV = 60.0V, Global Threshold = 2, T ≈ 23ºC