The experience of construction, production and exploiting of the Belle II muon system

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HSE

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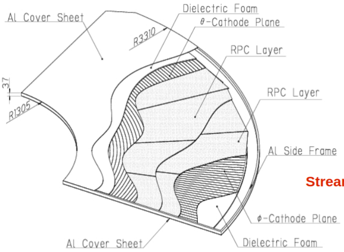
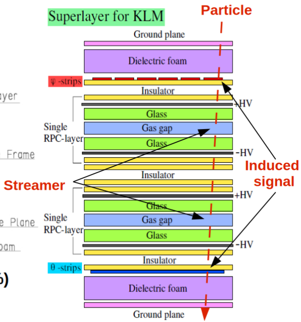
Belle endcap muon system

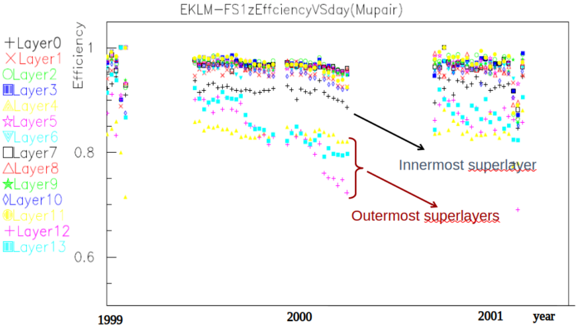




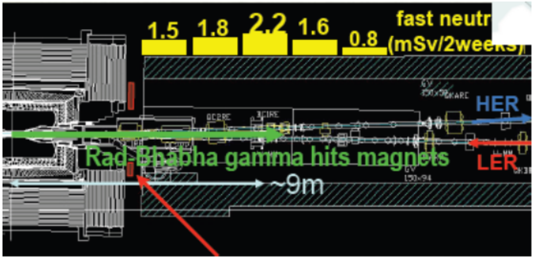
Gas: $Ar/C_4H_{10}/HFC\text{-}134a$ = 30/8/62 (%)
Voltage≈7kV

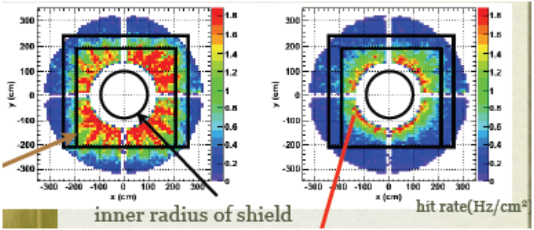
By the end of the first year of operation and efficiency degradation became evident. the effect was especially noticeable in the outermost layers. Main reason: RPC dead time due to neutron background.

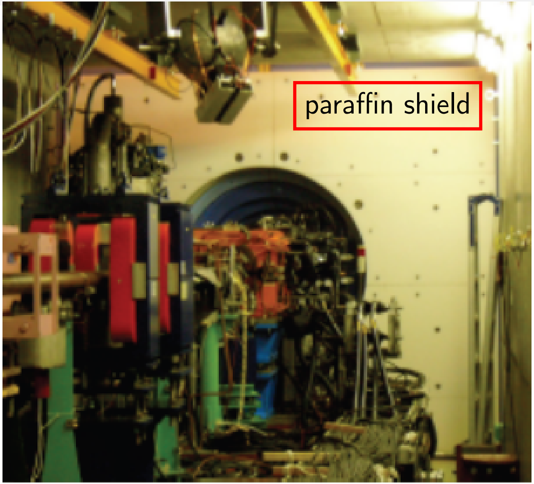
- RPC technology
- 14(BW) or 15(FW) layers btw. Fe plates
- RPC HV 7kV



Shielding

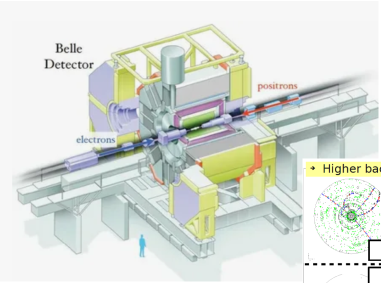


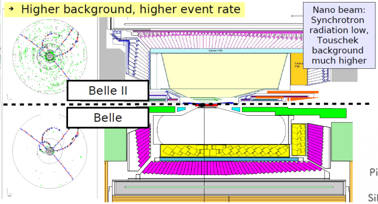


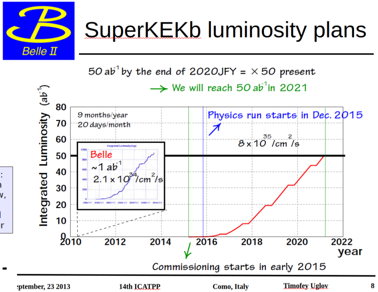


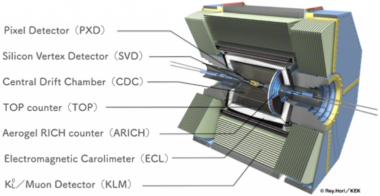
View from inside the accelerator tunnel

From Belle to Belle II









Luminosity increases

=

Background rises

Belle RPC efficiency in Belle II environment

Higher luminosity → Higher background → Larger dead time → Lower efficiency

Belle2 TDR

Moderate

Layer	Barrel		Endcap forward		Endcap backward	
	KEKB	SuperKEKB	KEKB	SuperKEKB	KEKB	SuperKEKB
0	0.91	0.70	0.91	0.0	0.90	0.0
1	0.94	0.81	0.93	0.0	0.90	0.0
2	0.96	0.87	0.94	0.0	0.90	0.0
3	0.98	0.91	0.94	0.0	0.90	0.0
4	0.98	0.94	0.94	0.0	0.89	0.0
5	0.99	0.95	0.92	0.0	0.88	0.0
6	0.99	0.95	0.93	0.0	0.89	0.0
7	0.99	0.96	0.92	0.0	0.87	0.0
8	0.99	0.94	0.92	0.0	0.86	0.0
9	0.99	0.96	0.90	0.0	0.85	0.0
10	0.99	0.98	0.87	0.0	0.82	0.0
11	0.99	0.97	0.82	0.0	0.80	0.0
12	0.99	0.96	0.78	0.0	0.81	0.0
13	0.99	0.97	0.77	0.0	0.76	0.0
14	0.99	0.96	N/A	N/A	N/A	N/A

Acceptable

Inacceptable

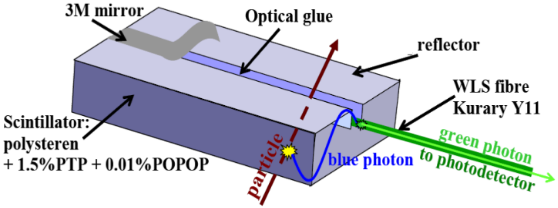
RPC efficiency measured in KEKB and extrapolated to SuperKEKB.

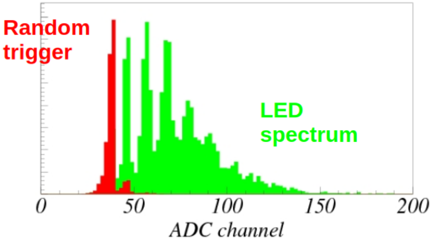
Requirements to the Belle II KLM system

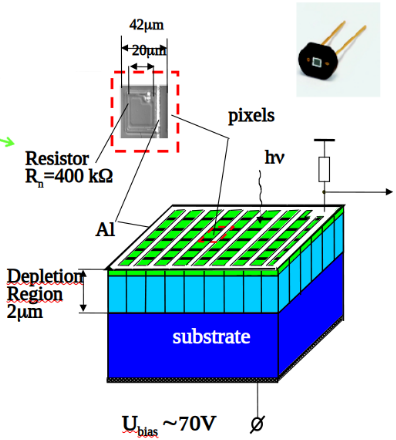
- High ($> 98\%$) MIP efficiency
- Large geometrical acceptance ($> 95\%$)
- Fast detector to diminish integration time (bg raise linear with integration time)
- Low efficiency to neutrons
- Geometrically compatible with existing frames (4 cm thick)
- As cheap as possible (largest detector in Belle II, $S \approx 1600$ m^2)

Solution: Scintillator-based detector with WLS light-collection with independent operation of X and Y layers, utilizing SiPM as a photodetector

Scintillator option for the Belle II KLM







Plastic scintillator+ WLS +SiPM scheme: pros and contras

Technology

The technology had never been tested in such large device

Neutron background

Contains a lot of hydrogen – effective neutron target

Adjustable threshold

In contrast to RPC, which produces hit at $\sim$ 100keV protons, scintillator sensitivity is justable and usually set at a half of MIP ($\sim$ 1MeV)

Birks's law

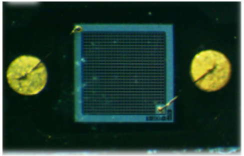
Protons from the neutron background are relatively slow and Birk's law reduces effective signal by factor of ~ 5

Two-layer scheme

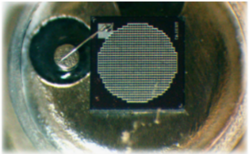
Independent operation of the two layers makes possible to use hit time information to from 2D hits and reduce neutron background which always produces 1D hits.

Choice of the photodetector

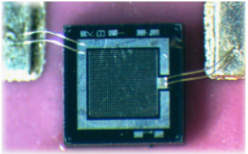
- A strong magnetic field inside the magnet yoke forbids the use of the PMT inside the module
- OPERA experiment used clear fibers to transport light from the WLS fiber to multi-channel PMT
- In the Belle II layout (reuse of RPC frames) the use of clear fibers seemed to be technically complex
- SiPM was chosen (Hamamatsu MPPC S10362-13-050)



MPPC S10362-13-050



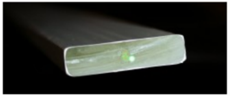
CPTA 143

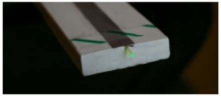


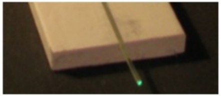
MEPhI/PULSAR

Choice of the scintillator producer

Fermilab (USA) (used in T2K ND ✗ | Kharkov (Ukraine) (used in OPERA) ✗ | Vladimir (Russia) (used in T2K ND) ✓

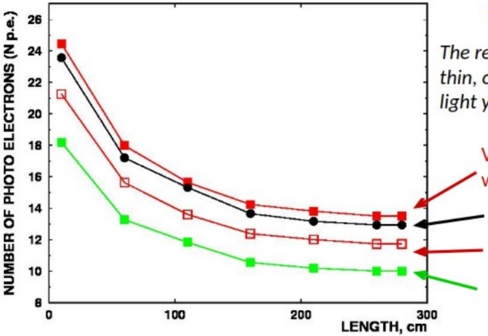






Kharkov & Fermilab thickness h = 10 mm
Vladimir thickness h = 7 mm

The reflective cover in case of Vladimir strips is thin, covering with mat white paper increases light yield by 15%



Vladimir, covered with white paper

Fermilab

Vladimir

Kharkov

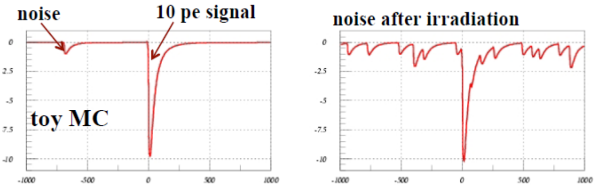
the figure is done using 1m strips, moved along the 3m WLS fiber

Chosen technology:

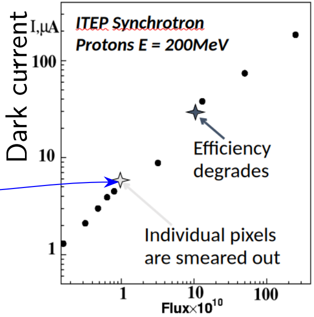
- Producer: Vladimir (UNIPLAST)
- Size: 7mm x 40 mm
- Reflective cover: diffusive, by chemical etching
- Groove for fiber: milled
- Fiber: Kuraray WLS Y-11(200)MSJ
- Optical contact: SUREL SL1 optical gel

Radiation hardness

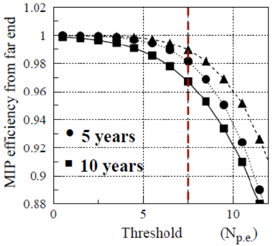
SiPM radiation damage

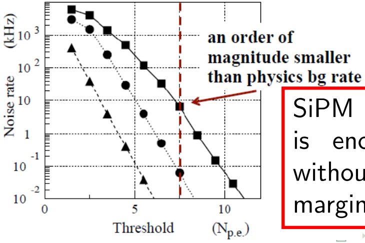


5 year Belle II dose estimation



Scintillation plastic and WLS fibers are known not to degrade at such doses



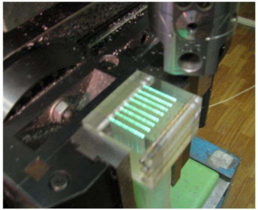


SiPM radiation hardness is enough for Belle II, without large safety margins, though

Improvement of the strip performance

Improving performance: WLS fiber

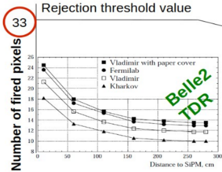
Milling with diamond cutter provides sufficient edge quality (both ends).

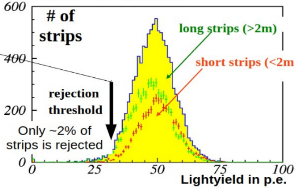


Mirroring far edge: study first T2K experience:

- use glueing of a mirroring foil as SMRD – effective but timeconsuming
- vacuum aluminization as FGD – low efficiency 70%.

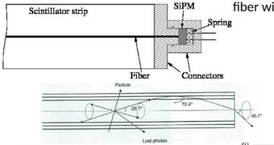
We tried many other options including spying of silver, until fast and efficient solution was found: just paint with silver shine paint (textile paint for fabrics) and get >90% efficiency for 1 sec operation.

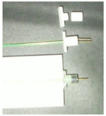




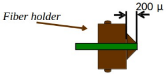
Improving performance: SiPM-fiber connector

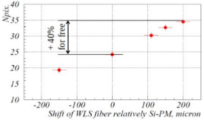
Connector is required to fix SiPM to fiber with 100 micron alignment





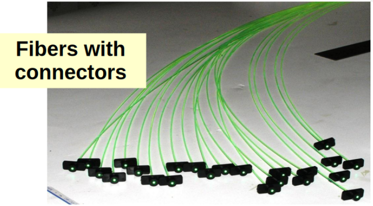
to reduce air gap between fiber end and SiPM modify the SiPM-fiber connector

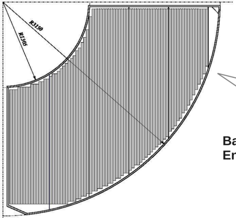




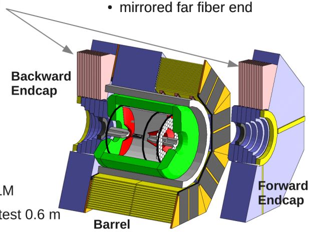
- Light yield is twice larger than at TDR
- For many strips the statistics is nice: good Gaussian distribution with a small RMS

Strip mass production





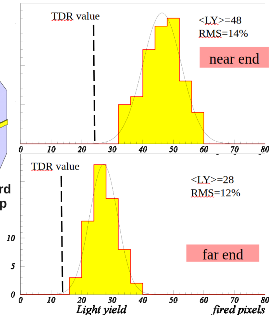
- WLS fiber in each strip
- SiPM at one fiber end
- mirrored far fiber end

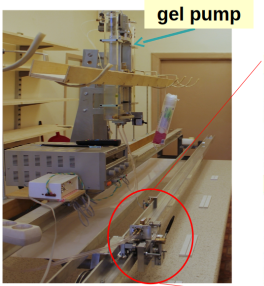


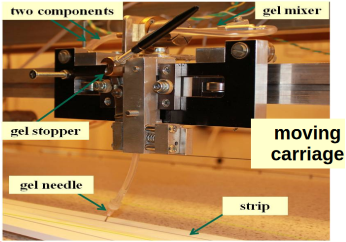
75 strips (4 cm width)/sector

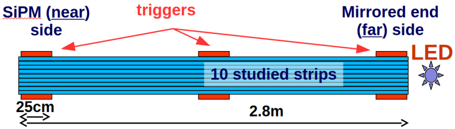
16800 strips for F&B Endcap KLM

the longest strip 2.8 m; the shortest 0.6 m

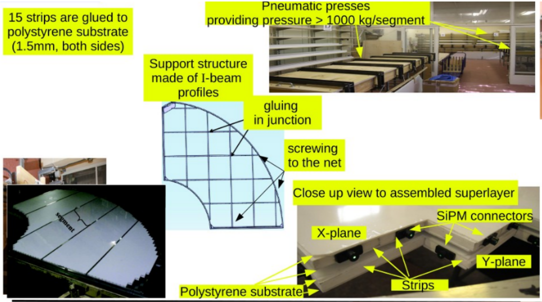


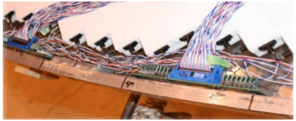


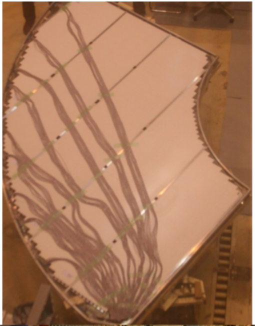


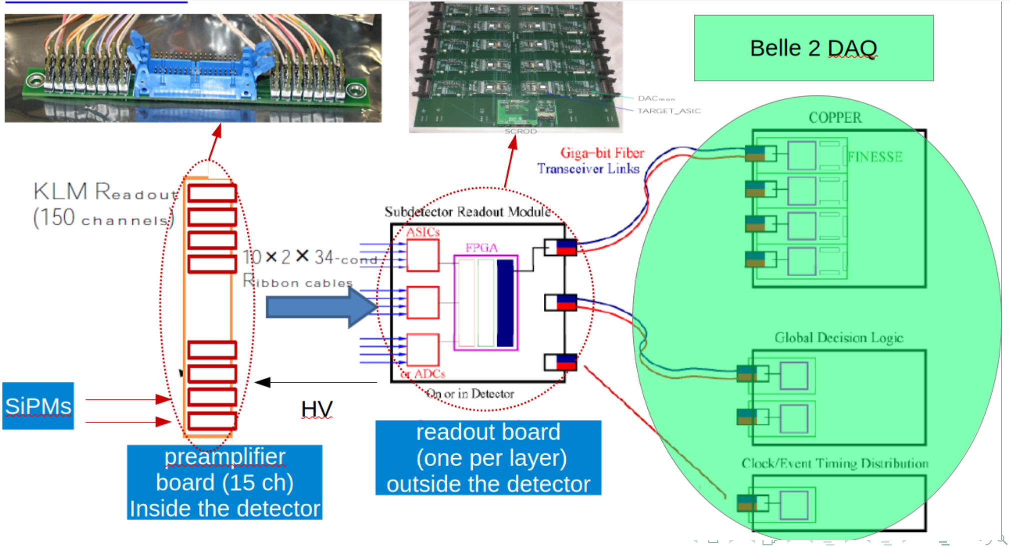


Assembly and installation







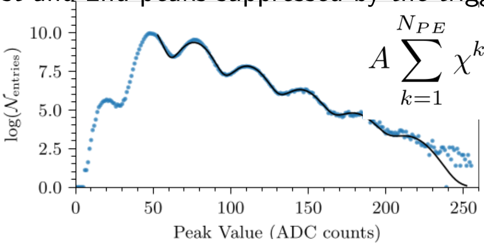

Belle 2 DAQ
DACmon
TARGET_ASIC
SCROD
COPPER
FINESSE
Giga-bit Fiber
Transceiver Links
KLM Readout
(150 channels)
10 × 2 × 34-cond
Ribbon cables
Subdetector Readout Module
ASICs
FPGA
or ADCs
On or in Detector
Global Decision Logic
Clock/Event Timing Distribution
SiPMs
HV
preamplifier
board (15 ch)
Inside the detector
readout board
(one per layer)
outside the detector

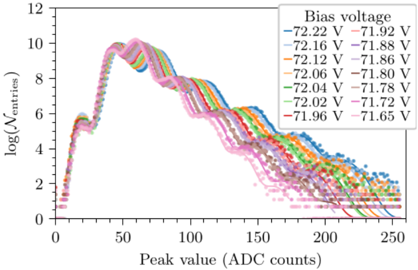
Calibration

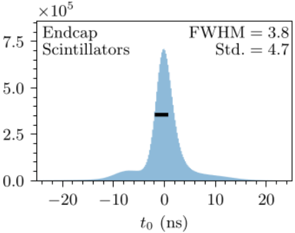
Single photon spectrum

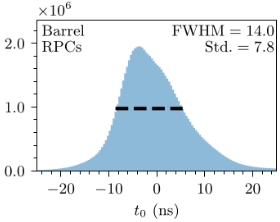
1st and 2nd peaks suppressed by the trigger

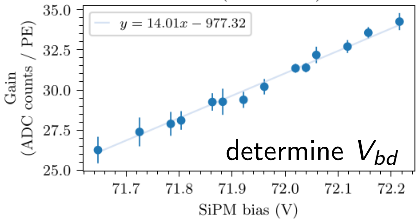
$$A \sum_{k=1}^{N_{PE}} \chi^k e^{\frac{-(x-(x_0+ka_0))^2}{2(\sigma_0+k\sigma_1)^2}}$$











determine V_{bd}

Current RnD activities

Long-term stability

The last Belle II muon system component was installed $\sim$ 10 years ago.
Now is the very time to test it long-term stability.

- Disassemble spare segments
- Re-test strips to compare parameters with data collected during mass production

Neutron background measurement

- The neutron background is poorly known and highly depends on the focusing magnets/masks etc.
- Polystyrene scintillator strip is sensitive to the neutrons

$\rightarrow$ turn Belle 2 muon system to the neutron detector by strip response calibration with known source.

- Waveform-based analysis can distinguish btw. neutron and MIP hits

Conclusion

- First used for the muon detector at the large-scale accelerator experiment in Belle II, **organic scintillator – WLS – SiPM** technology is now matured and well-established
- Good time resolution, tiny dead time and ability to measure signal amplitudes allows to cope with higher background and be efficient at flavor superfactories, including STCF.
- Huge expertise in developing, producing and assembling has been collected during Belle II KLM production
- R'n'D works aimed to better understanding long-term stability of the technology and its future developments are ongoing