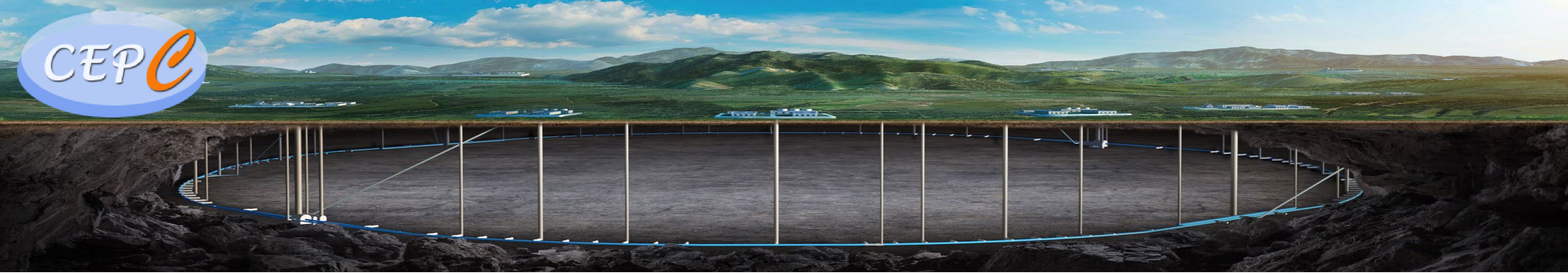

CEPC Muon Detector

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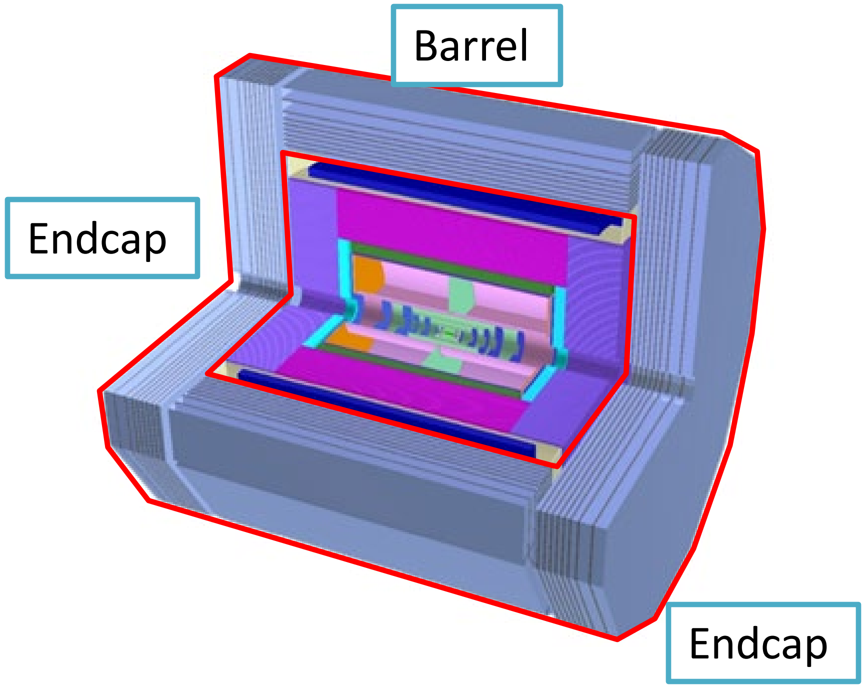
Content

- Introduction
- Requirements
- Technology survey and our choices
- Technical challenges
- R&D efforts and results
- Detailed design
- Readout electronics
- Performance from simulation
- RPC related and testing
- Research team and working plan
- Summary

Introduction

Muon detector, the outermost detector with the largest volume.

- Production of Higgs: $e^+e^- \to ZH$, Higgs could be determined in the recoil of $Z \to \mu^+\mu^-$.
  - Special determination of muon with $p \approx 40\ \mathrm{GeV}/c$.
- Muons provide in many theoretical models a characteristic signature for new physics.
- Muon detector is designed for muon identification, but not limited to this.
  - Could be used to detect the leakage of HCAL.
  - Can be used for trigger, like in ATLAS.
  - Could be useful for T0 determination. $\sigma(T0) = \sigma(T_{hit})/\sqrt{n_{hits}}$
  - Can be used to search for Long-lived particles, with its large volume, and relatively clean environment outside HCAL.
- Furthermore, it must be robust and low cost.



We seek excellent performance from the muon detector!

Requirement

- Solid angle coverage: $0.98 \times 4\pi$
- Detection efficiency ($p_\mu^T > 2.0\ \mathrm{GeV}/c$): $> 95\%$
- Fake ($\pi \rightarrow \mu$) @ $30\ \mathrm{GeV}/c$: $< 1\%$
- Position resolution: $1.5\ cm$
- Time resolution: $1 - 2\ ns$
- Rate capability: $\sim 60\ \mathrm{Hz}/cm^2$

Solid angle coverage and detection efficiency → High efficiency

Fake rate → Low fake rate

Position resolution → Resolution due to the multiple scattering of muon

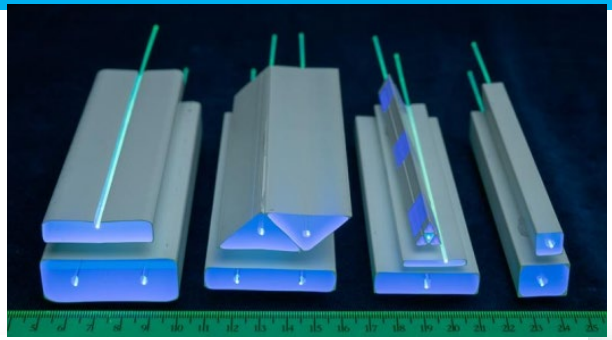
Time resolution → A typical time resolution of modern muon detector, and useful for trigger, T0 and background suppression.

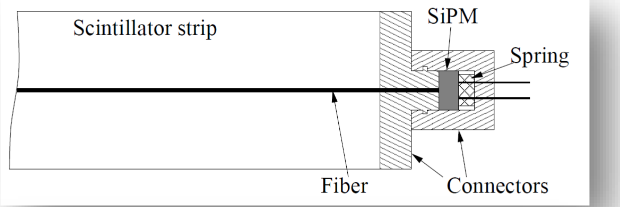
Rate capability → Compatible with the high luminosity operation

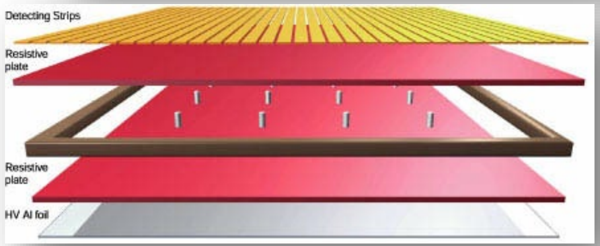
Technology survey and our choices

- Extruded plastic scintillator (PS) technology
  - Belle II, JUNO-TAO, MATHUSLA, LHAASO, sPHENIX, etc.
- RPC technology:
  - Belle, BESIII, Dayabay, ATLAS, CMS
- μ-RWELL (MGPD) technology
  - IDEA
- Experiments @ LHC
  - ATLAS: Thin Gap Chamber, RPC, Monitored Drift Tube, Small-Strip Thin-Gap Chamber, and Micromegas
  - LHCb: MWPC, RPC
  - CMS: Drift tube, Cathode Strip Chamber, RPC

Simple structure: PS bar, fiber, SiPM





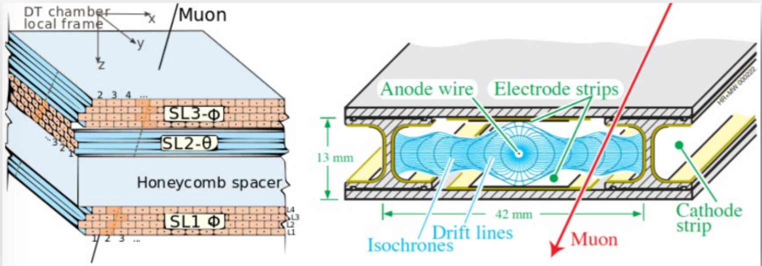


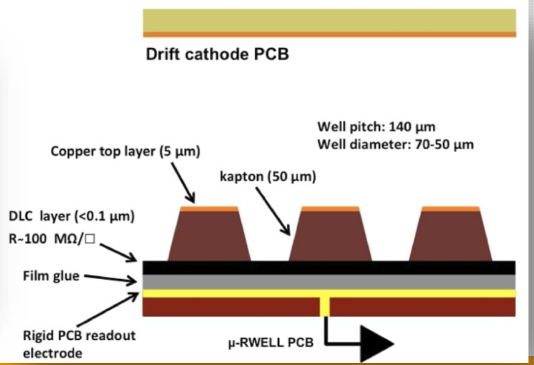
Summary of performance and technical requirements for different gaseous μ detectors

	MDT/DT	CSC	TGC	MRPC	RPC
Spatial resolution [μm]	150	100	5mm	15mm	15mm
Time resolution [ns]	40	7	4.3	0.075	2
Averaged efficiency [%]	98	98	99	95	95
Hit rate [Hz/cm^2]	200	500	1000	500	100
Eletronic dependence	A	A	B	A	C
Software dependence	B	A	B	C	C
Technology requirement	A	A	B	B	C
Cost per channel	H	H	M	M	L

A-C are in descending order of the requirements,H-High,M-Middling,L-low.

+PS





Comparisons

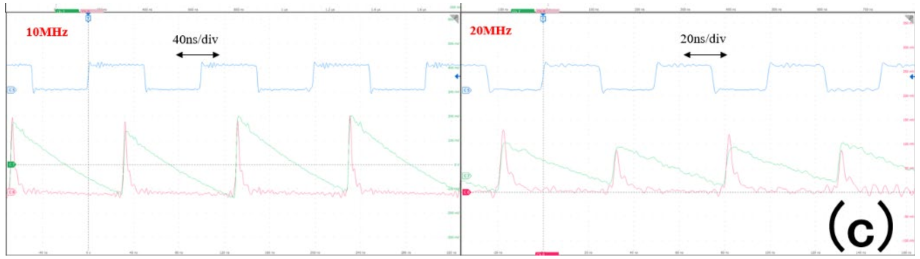
	Advantages	Disadvantage
PS(+SiPM)	Solid detector, structure simple, high rate capability, low operation voltage, use SiPM similar to HCAL, time resolution	DCR of SiPM
RPC	Cost, mature tech., time resolution	Fill gas, HV system
μ-RWELL	Spatial resolution, high rate capability	Structure, number of readout channels, time resolution, cost.

Consideration of rate capability:

- Decay time: ns level
- SiPM+FE: $< 100\ ns \rightarrow 10$ MHz
- Typical area of a bar: $1600\ cm^2$
- Pulse shape: width ~ 10-20 ns
- Rate capability: $5{\sim}10 kHz/cm^2$

Table 5.3. *Characteristic parameters of some organic scintillators [87, 93, 94, 102, 103]*

Scintillator	base	density ϱ [g/cm^3]	τ_D [ns]	L_{ph}, N_{ph} [per MeV]	λ_{em} [nm]	$n(\lambda_{em})$
Anthracene		1.25	30	16 000	440	1.62
BC-408 (BICRON)	PVT	1.032	2.1	10 000	425	1.58
BC-418 (BICRON)	PVT	1.032	1.5	11 000	391	1.58
UPS-89 (AMCRYS-H)	PS	1.06	2.4	10 000	418	1.60
UPS-91F (AMCRYS-H)	PS	1.06	0.6	6 500	390	1.60



EPS and RPC have similar cost.

Our choice: PS as the baseline option, RPC for comparison in R&D.

20MHz tested for SiPM+FEE with laser.

Main Technical Challenges

- Long detector module: could be ~5m
- How to achieve the efficiency and the time resolution required from a long PS bar?
  - 2.8 m bar has been used at Belle II;
  - 1.5 m bar has been tested in lab;
  - It's possible since Kuraray fiber has an attenuation length of 6.8 m.

R&D efforts and results

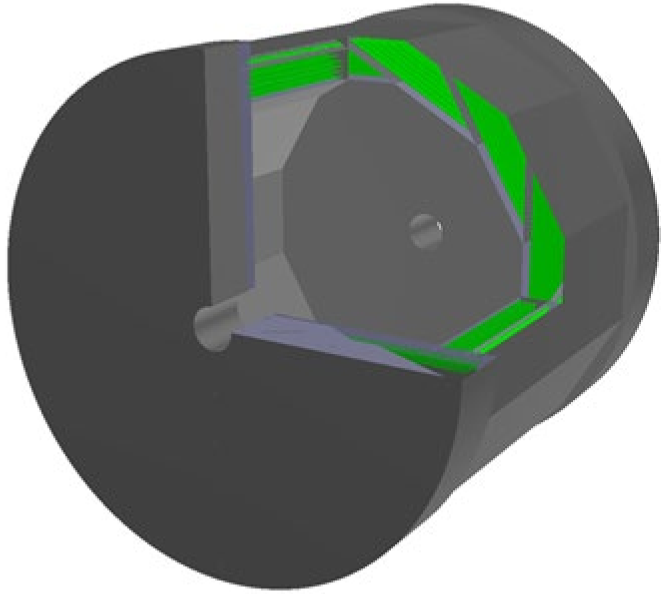
- Simulation and software
- Performance of PS bars
- Front-end electronics
- Prototype and CR testing

Published papers:

1. Design and performance of a high-speed and low-noise preamplifier for SiPM, Nucl. Sci. Tech. 34, 169(2023)
2. Design and test for the CEPC muon subdetector based on extruded scintillator and SiPM, JINST 19 P06020(2024)

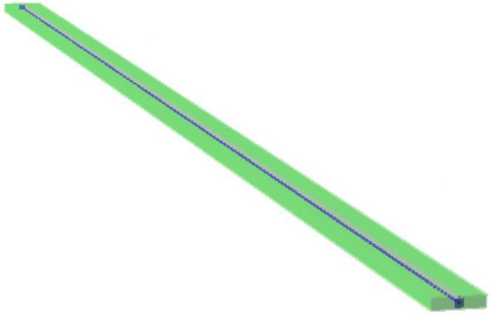
Simulation and software

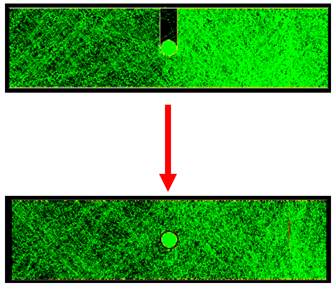
- Simulation based on Geant4
  - Standalone
  - Implemented in CEPCSW
- Simulation for single channel
  - Light collection and compared to lab test
  - Fiber embedding: Groove → hole, $N_{pe} \times 1.4$
  - Diameter: $1.2mm$ → $2.0mm$, $N_{pe} \times (2 - 2.8)$

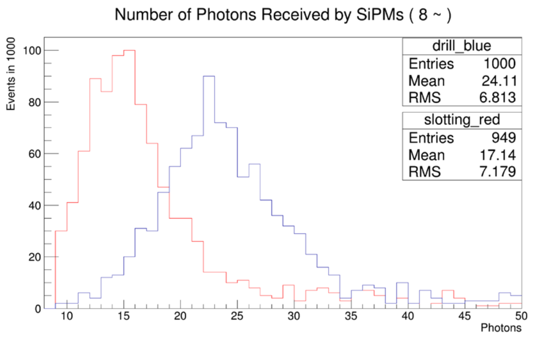


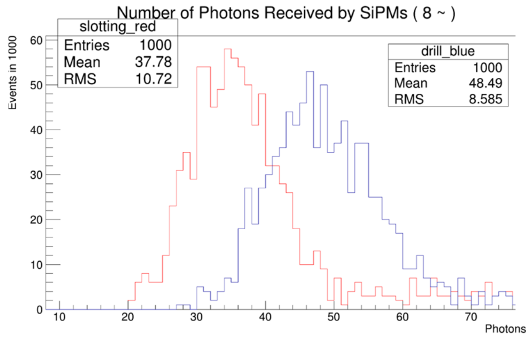
Geometry of endcaps is being modified.

Simulation shows potential to increase the light yield by a factor of $(2.8 - 3.9)$, which is helpful for building long detector module.

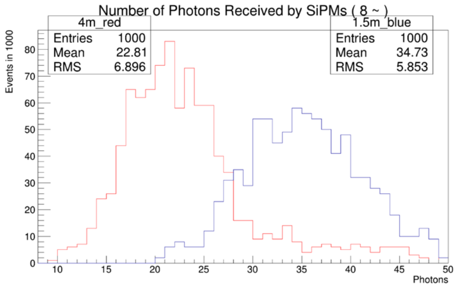








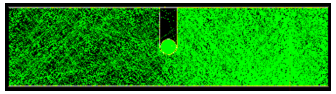
PS bar length

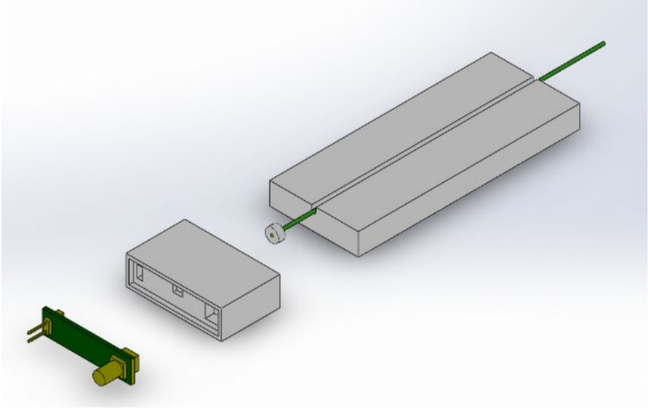


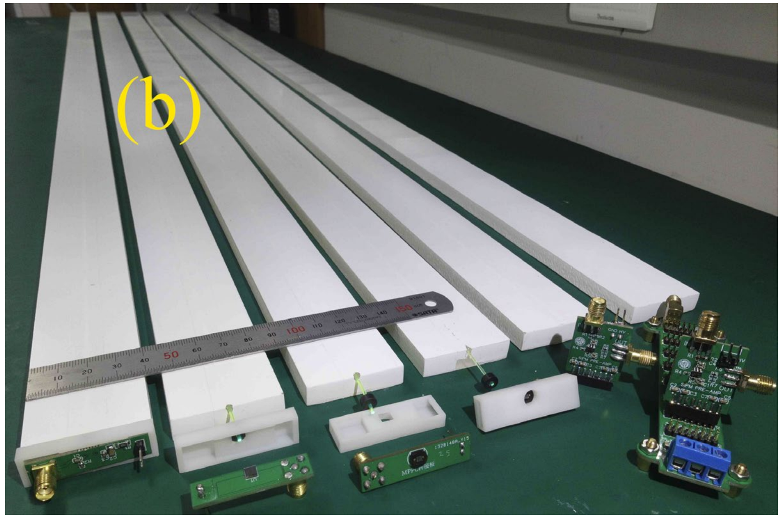
Performance of PS bars

- PS bars made by GNKD company
  - Increase the light yield;
  - Develop/improve the reflection layer with Teflon;
  - Strip production.
- The quality of $1.5m$ bars has achieved the required performance, which will be described later.

All samples with U groove



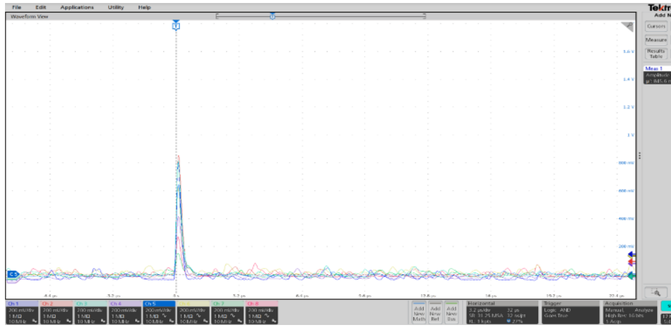


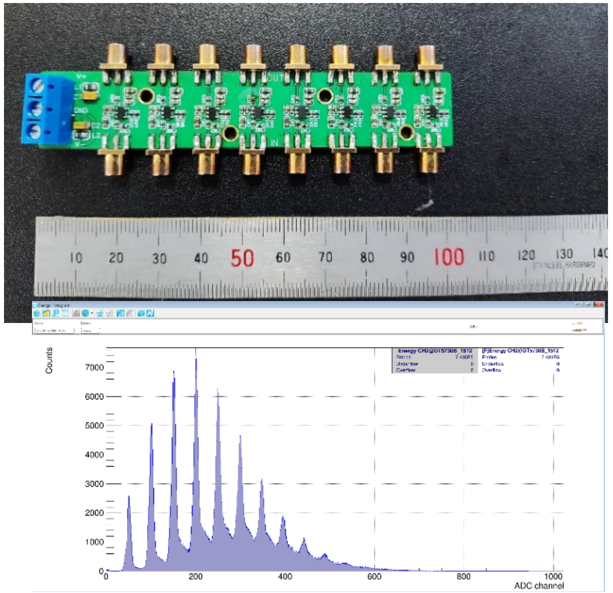


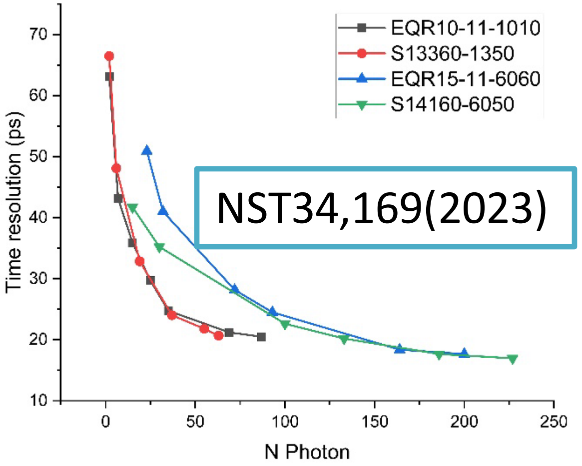
R&D for front-end electronics

- Many different kinds of preamps for SiPM have been designed and tested, such as:
  - Design high-speed and low-noise preamp for SiPM.
    - Baseline noise of 0.6 mV, bandwidth of 426 MHz, and time resolution of 20 ps.
    - Test with laser input at 20MHz.
    - Clear N_{pe} spectrum.
  - Design FEE to test with 16 ch ADC
    - Develop the FPGA for ADC.
    - Works well, but time resolution is several ns due to the DCR.

ADC output signals of scintillators

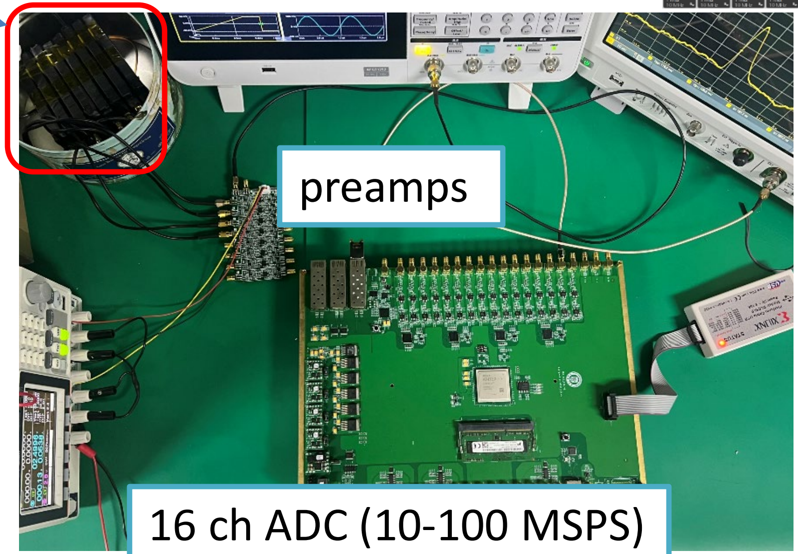






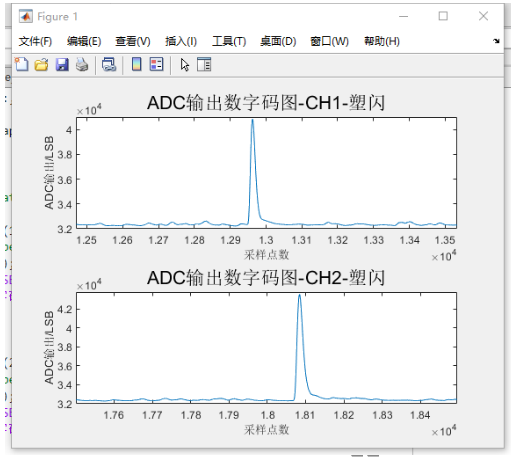
NST34,169(2023)

8ch PS short bars



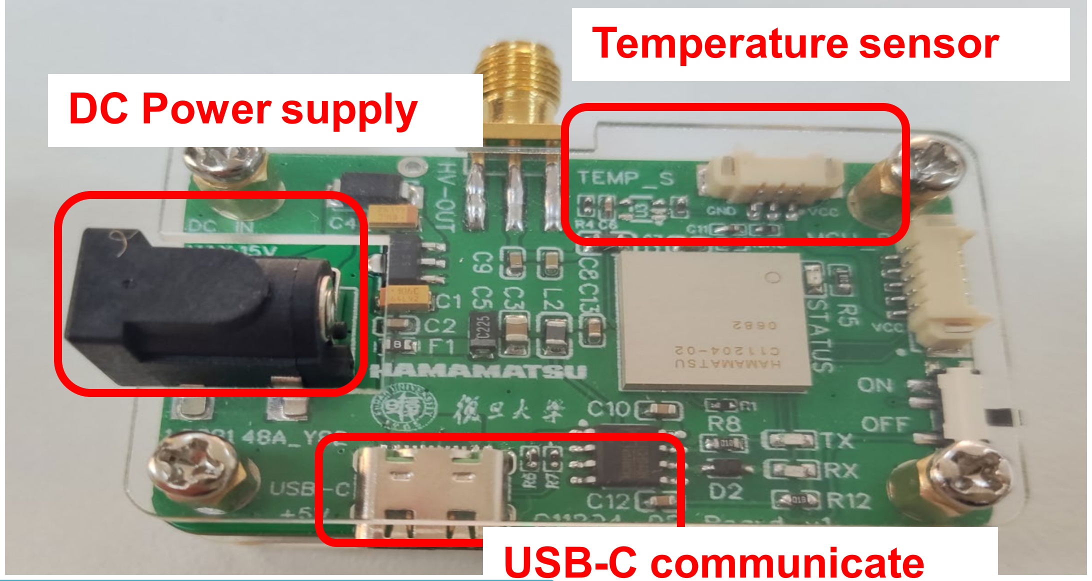
preamps

16 ch ADC (10-100 MSPS)



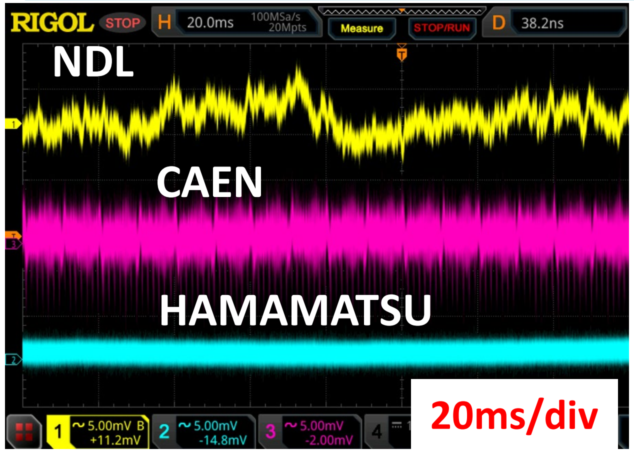
SiPM_Mini Power

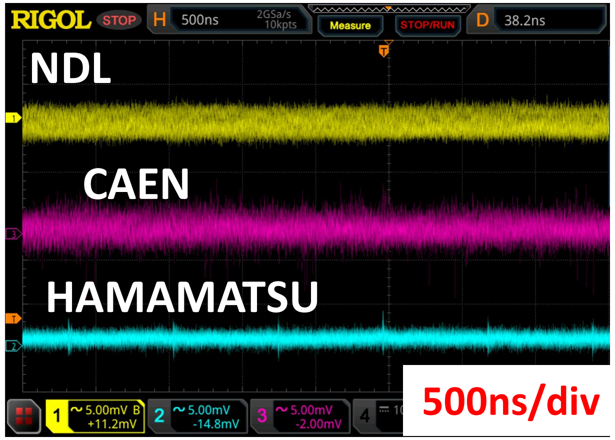
- Study on mini power to be integrated into the FEE.

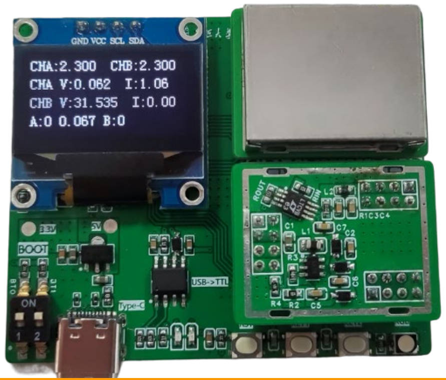


SiPM POWER	BIAS-2-14/70 @NDL	C14156 @Hamamatsu	MAX5026 @Fudan
Voltage (V) Output Range	14~70	0~80	0~71
Current (mA) Output Range	0.5mA	2mA	2mA
Number of SiPMs driven	100	400	400
Power consumption（mW）	250	100	200
Ripple noise(mV)	5.2 mVp-p	0.1 mVp-p	2mVp-p
Price (¥)	~2000	500	30

Ripple noise @ OUTPUT:45V

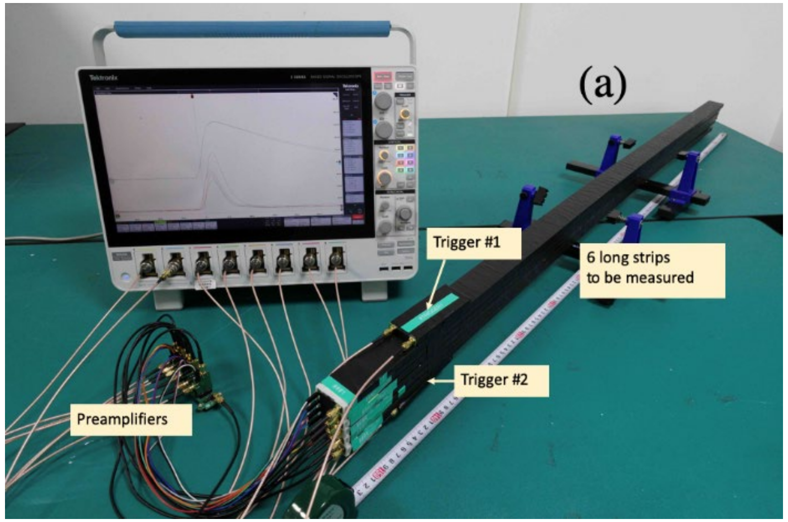






Prototype and CR test

- Study of SiPMs, WLS fibers
- Prototype:
  - $1.5m$ PS bar + Kuraray WLS fiber + NDL SiPM/MPPC
- Performance:
  - $\epsilon > 98\%$
  - Time resolution better than $1.5ns$



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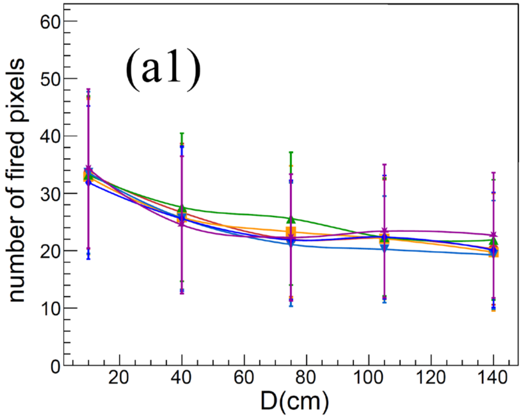
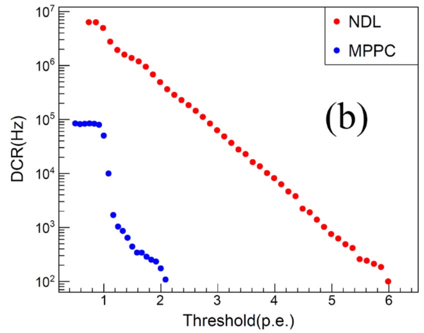
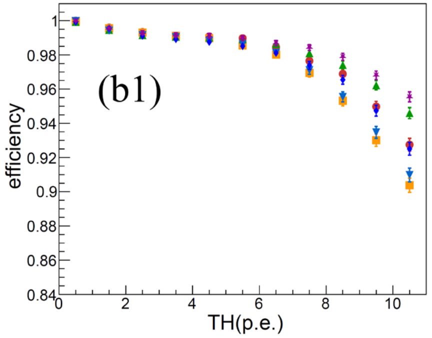
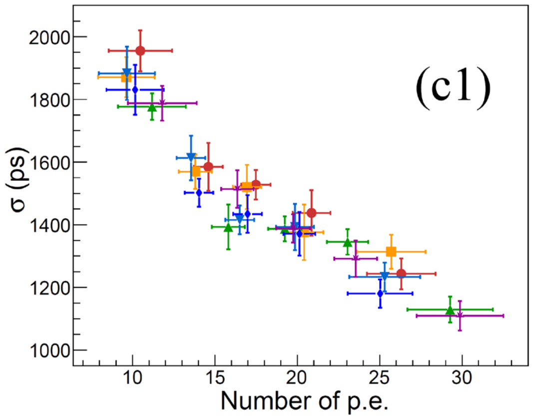
Effective attenuation length of fiber $L_{Att} = 2.63 \pm 0.37\ m$

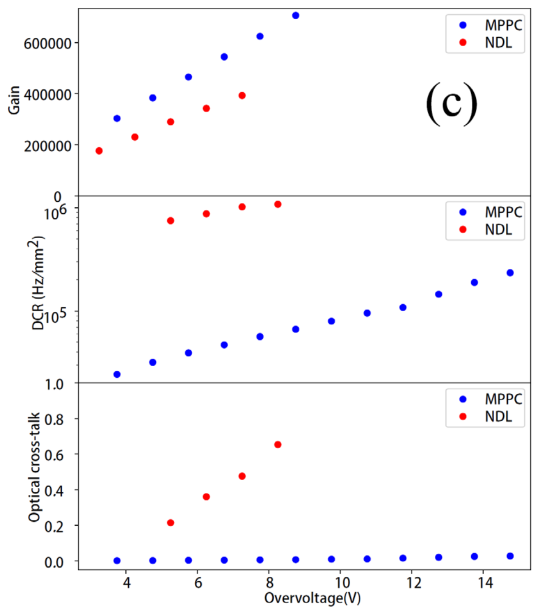


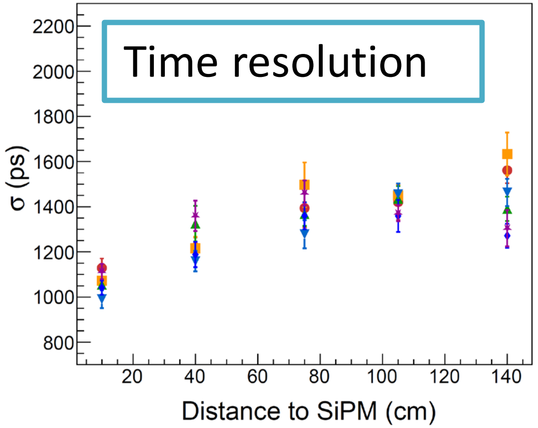






Properties of SiPMs





Detailed design

- Geometry: barrel and endcaps
- Detector channel elements and module
- Consideration on readout electronics (preliminary)

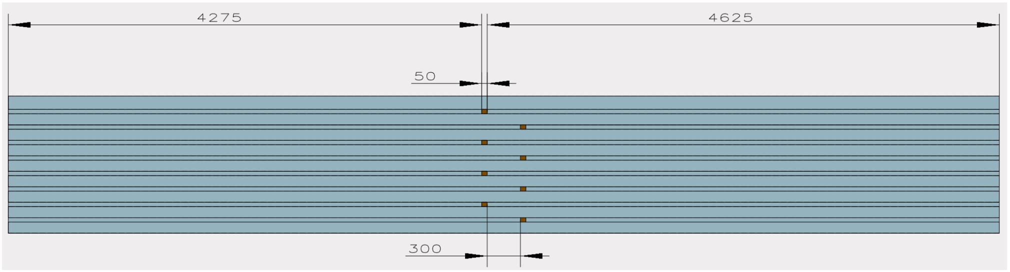
Detailed design - geometry

Geometry:

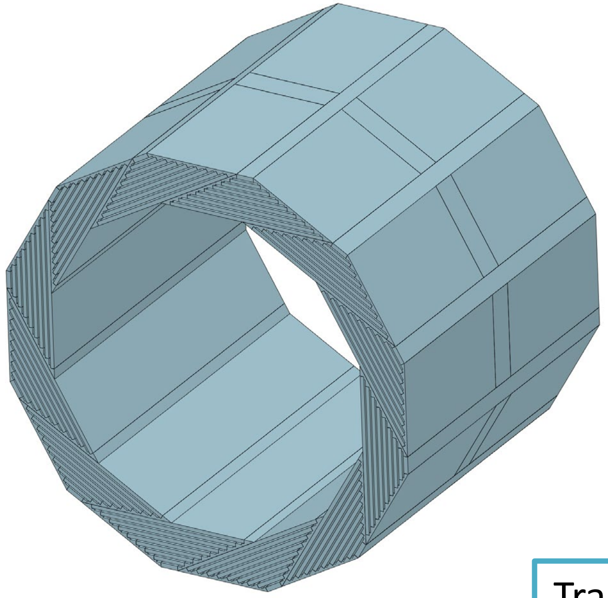
- Barrel: Helix dodecagon sectors.
- Rectangle modules inserted in the gaps between iron plates.
- Cable: towards the gaps between barrel and endcaps.

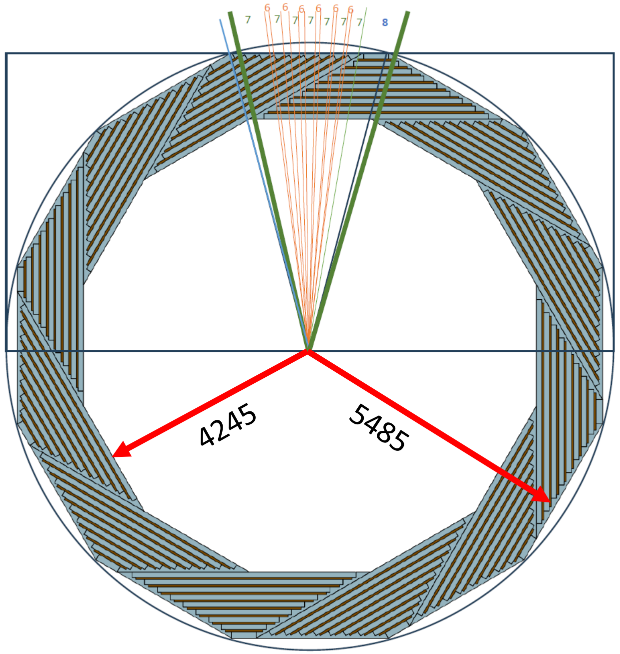
$L = 4.275m$ or $4.625m$

cables

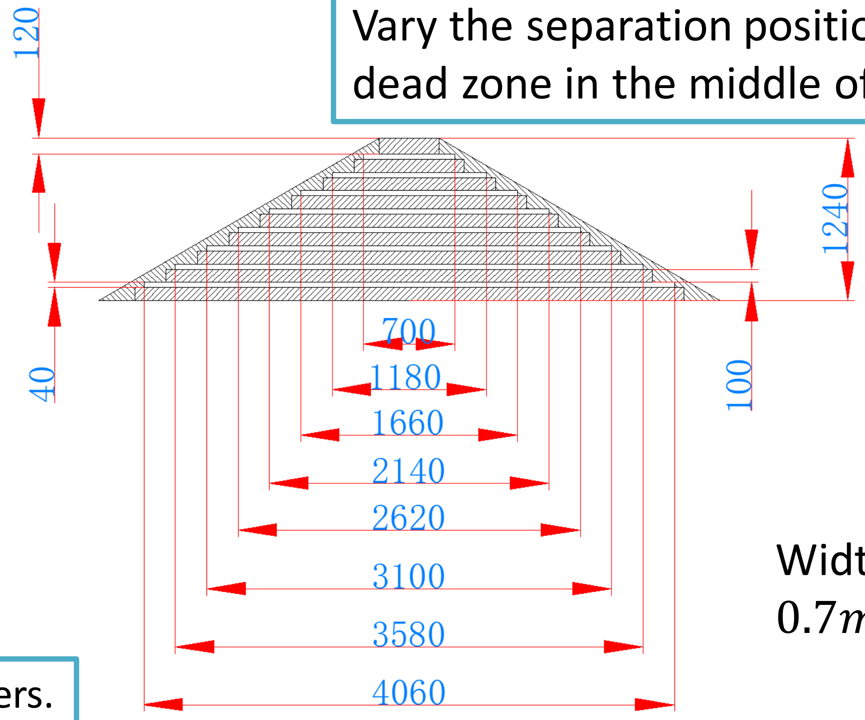


cables





Vary the separation position to avoid dead zone in the middle of barrel.

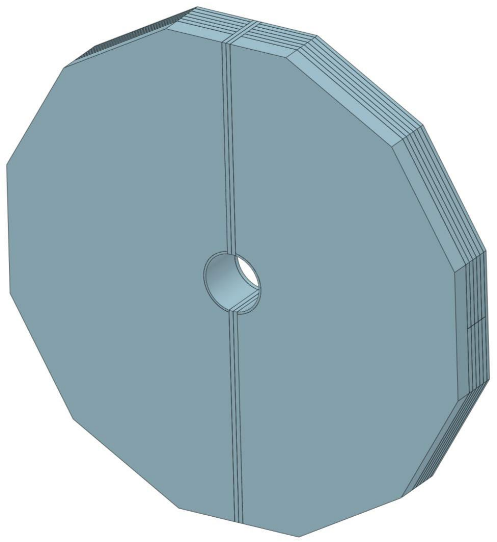


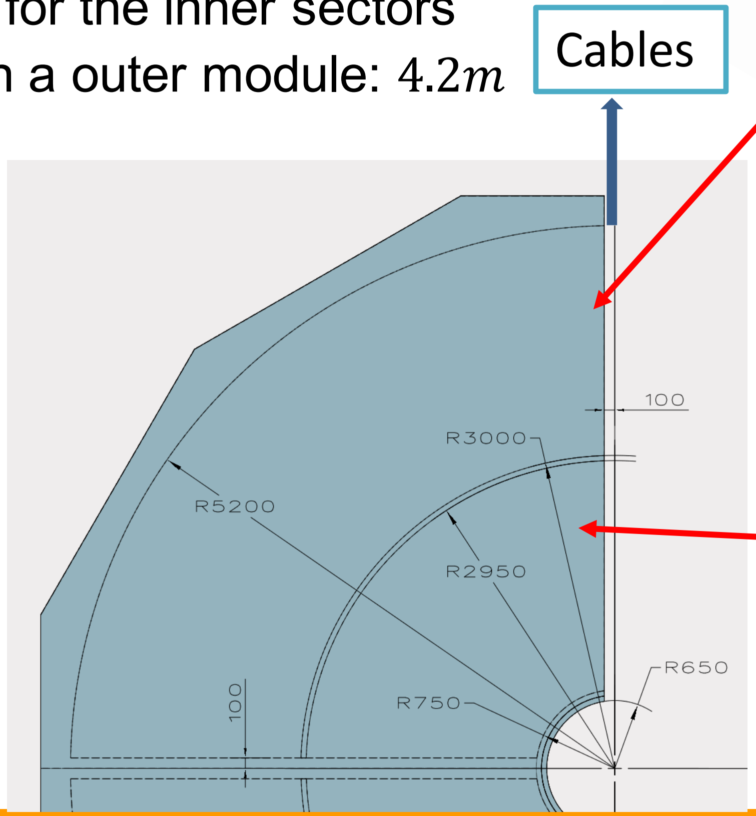
Tracks with high momentum passing 6, 7, or 8 layers.
6-layers: ~25%, 7-layers: ~50%, 8-layers: ~25%

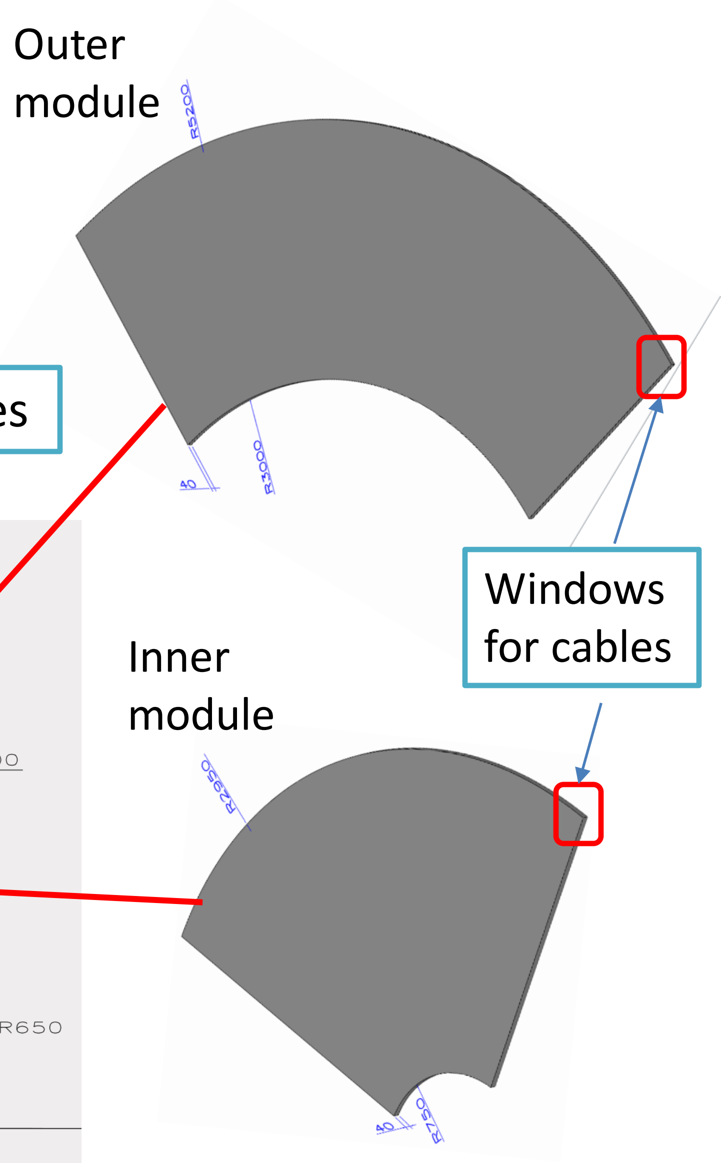
Width from $0.7m$ to $4.06m$

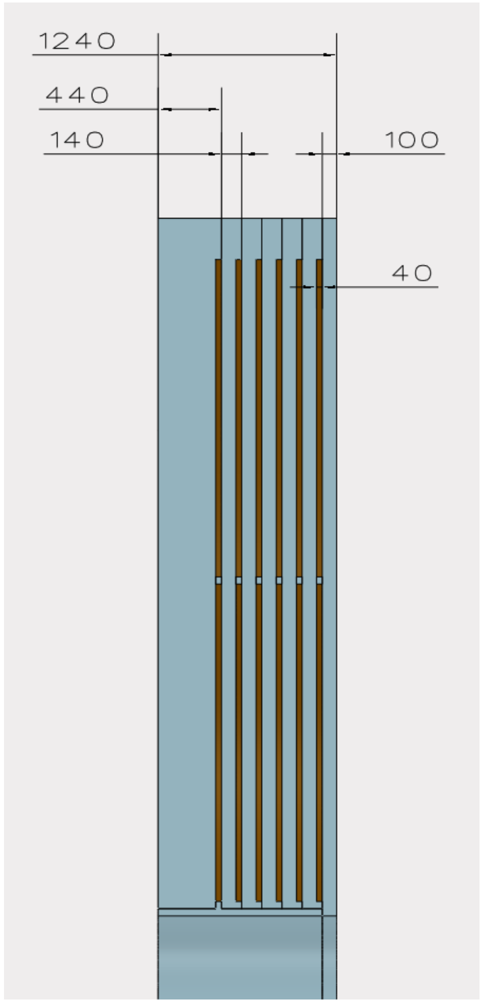
Detailed design - geometry

- Geometry:
  - Endcaps: inner and outer sectors
    - Inner: $R = 0.75 - 2.95m$
    - Outer: $R = 3.00 - 5.20m$
  - High hit rates for the inner sectors
  - Longest bar in a outer module: $4.2m$



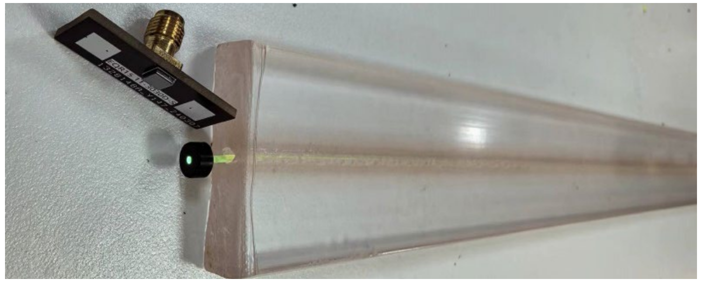






Detailed design – channel and module

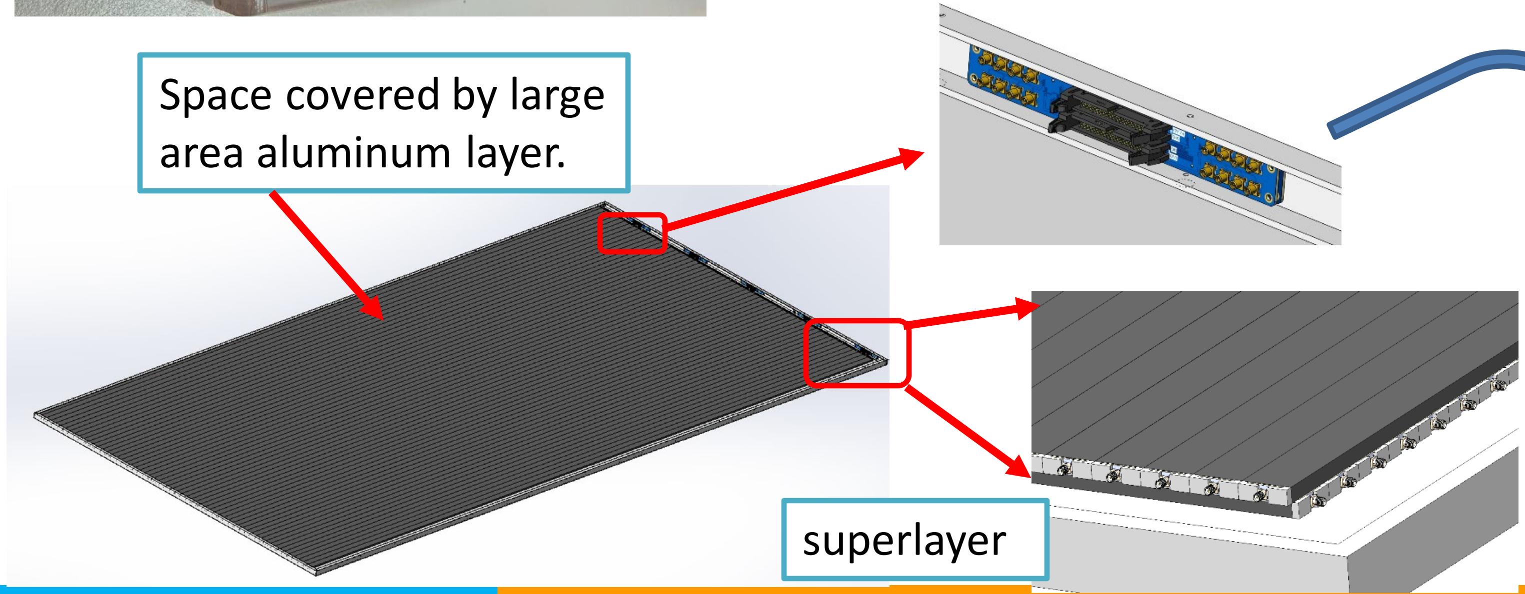
- Detector channel
  - PS bar: $4cm \times 1cm$ cross section
  - WLS fiber: $\phi = 2.0mm$
  - SiPM: $3mm \times 3mm$



R&D on the new production is ongoing

- Detector module
  - Superlayer with perpendicular channels
  - Carriers for preamps held at the frame
  - Space between PS bars and aluminum layer is allowed for long cables.
- Mechanics
  - Aluminum frame, PS bars

Space covered by large area aluminum layer.



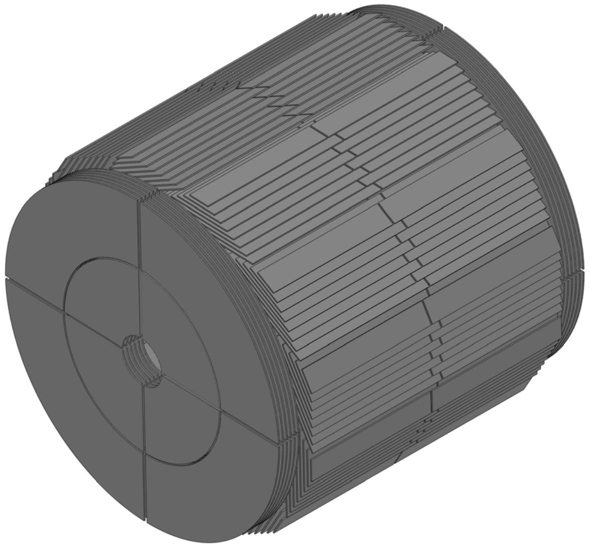
superlayer

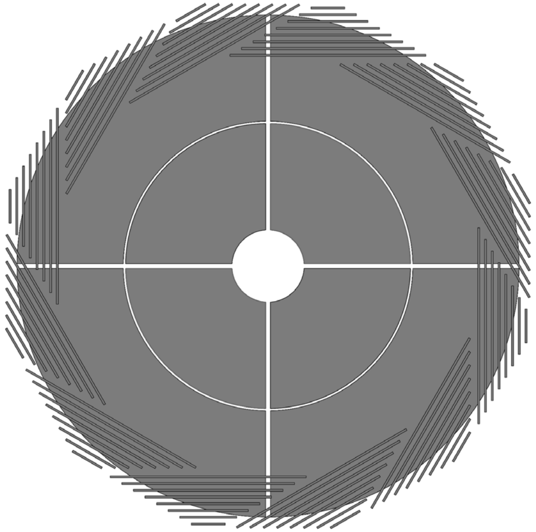
Carrier for the FEE, inside the module

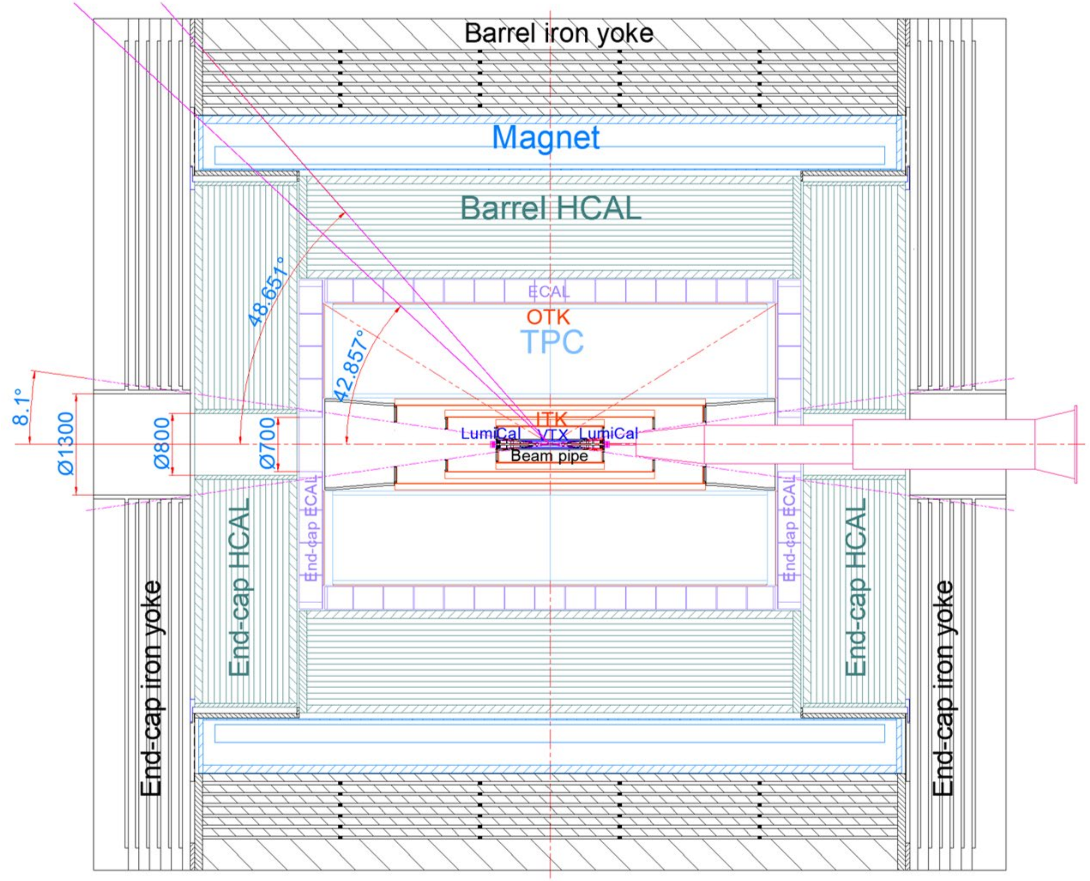
To BEE with ribbon cables

Detailed design - overall

- Number of channels: (288 modules) 51,744
  - Barrel: 192 modules, 32,544 ch
  - Inner endcaps: 48 modules, 6,912 ch
  - Outer endcaps: 48 modules, 12,288 ch
- Sensitive length: $148{,}416m$
  - Length for PS bar and WLS fibre
- Sensitive area: $5936m^2$



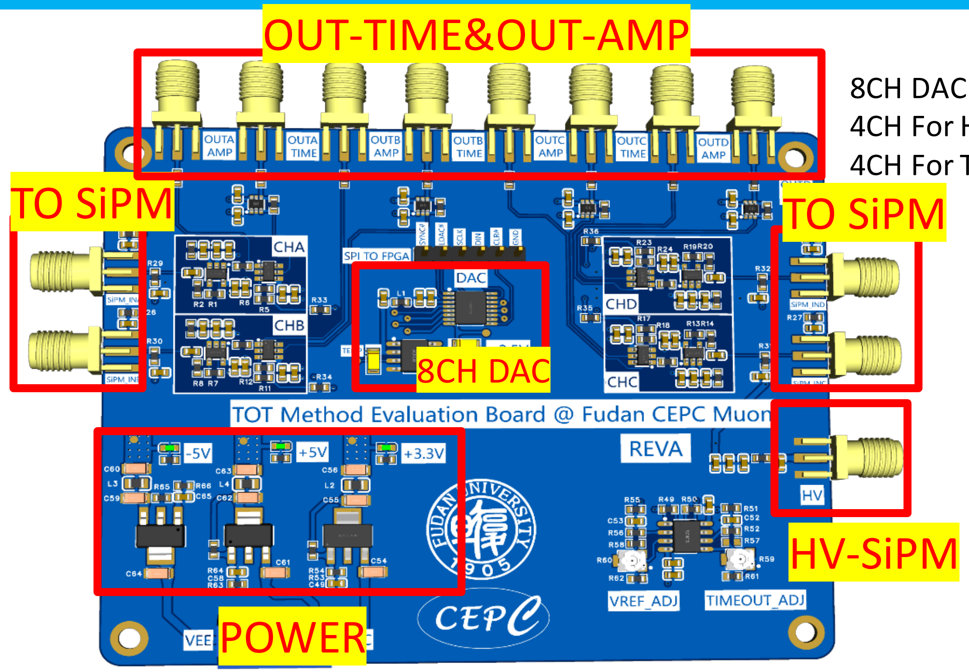




Detection dead area: ~1.5%
No dead zone in the barrel, 0.07% from the cross in endcaps, and 1.4% due to the beampipe

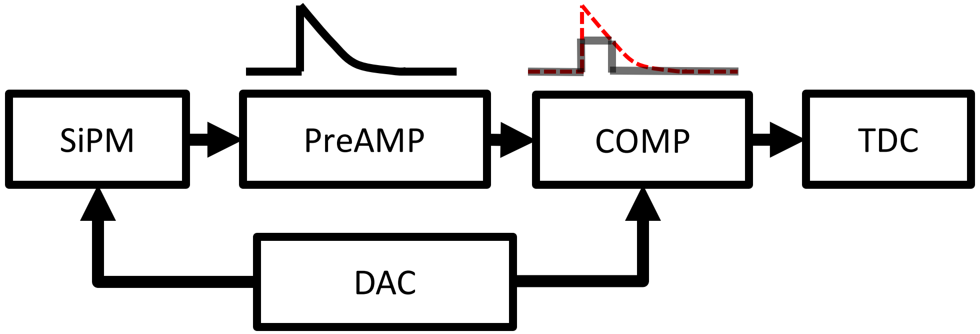
Readout electronics: Time-over-threshold (TOT) scheme

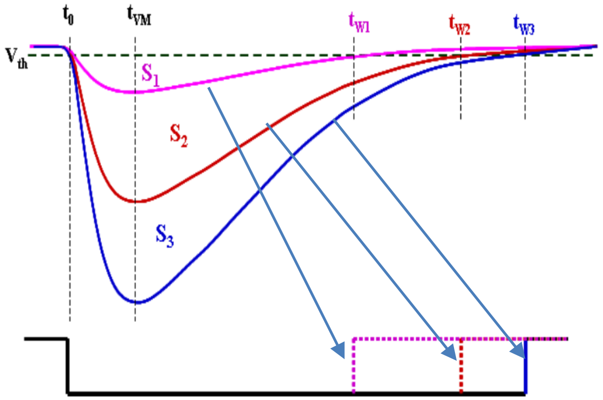
- Front-end electronics
  - High time resolution preamp: $\sigma_T \approx 20\ ps$
  - High-speed discriminator shows $\sigma_T \approx 0.2\ ns$
- Implementation of TOT: operational amplifier + high-speed discriminator + TDC.
- FEE integrated DAC to adjust threshold and SiPM bias voltage.
- It's possible to get N_{pe} according to TOT.
- Investigating the possibility of integrating the BEE into the detector module: only power cable and signal fiber.

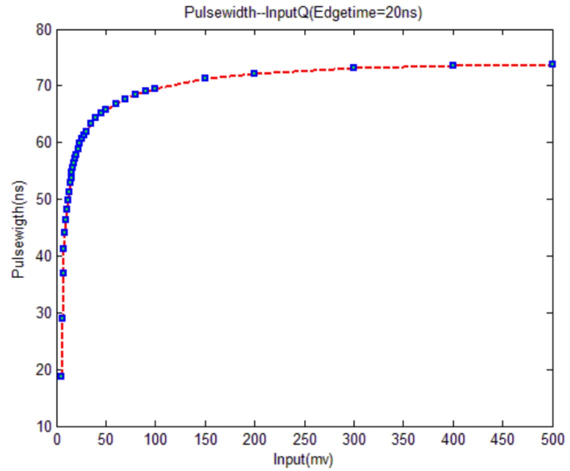


8CH DAC AD562
4CH For HV_ADJ
4CH For TH_ADJ

Temperature sensor will be included.

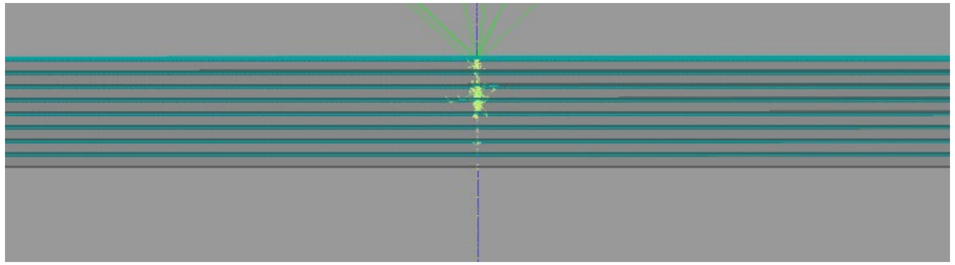






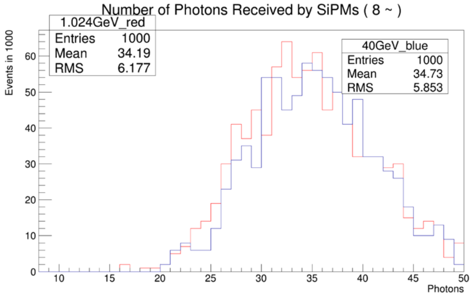
Geant4 simulation for performance

- Geometry and Geant4 simulation is implemented in CEPCSW, reconstruction and performance studies are onging.
- Still have a lot of work to do:
  - Study of the Molière radius of muons originating at the interaction point and traversing the ECL and HCAL.
  - Algorithm for muon ID based on multiple hits in the detector, using PFA, Kalman filter, etc.
  - Tracking reconstruction.
  - Fake rate of $\pi \rightarrow \mu$.
  - Simulation of final states including muon track(s). → Physics performance.
  - Background and hit rate!



Preliminary simulation on hits of muon track with 40 GeV/c momentum

1 GeV/c vs. 40 GeV/c



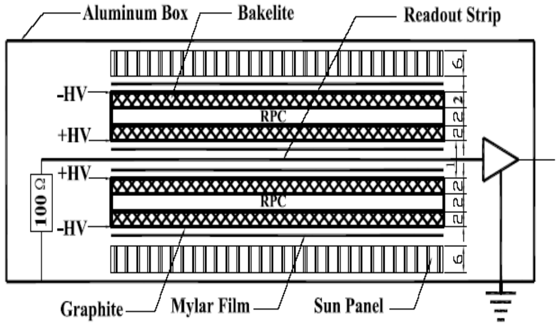
RPC technology – BESIII MUC

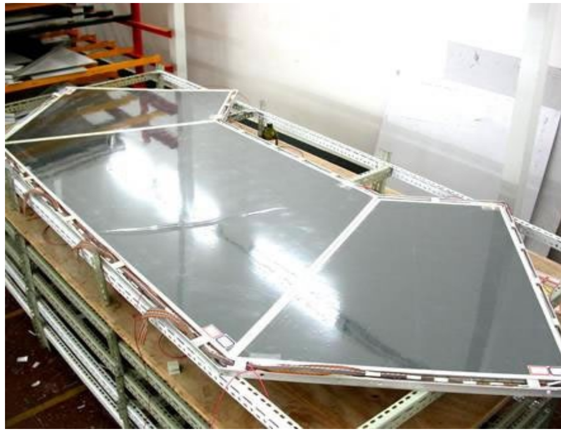
- Homemade Oil-free Bakelite RPC;
- Gas mixture: Ar:R134a:ISO-B=50:42:8
- First time successful mass production in China, bare chamber pass rate $> 90\%$;
- Good performance and keep running even now (>15years)!

Bare RPCs	$1{,}272\ m^2$
Box	136
Readout strip & insulation materials	$636\ m^2$
Electronics	9,152ch

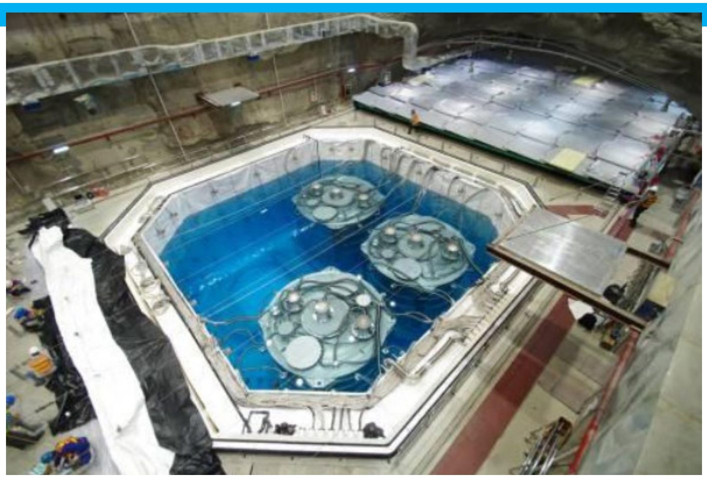
Table 2-4 BESIII Detector Performance

Parameters		Design Target	Real Performance			
			Cosmic Ray	Double μ	$\pi\pi J/\psi(\mu\mu)$	Total
Average Efficiency		95	94.7	95.11	95.17	93.6
Counting Rate		$< 0.1Hz/cm^2$	0.04 (Random Trigger)			
Spatial Resolution	$\sigma_{R\Phi}$	$< 20mm$	19	18	19	17.6
	σ_Z	$< 30mm$	23	21	22	22.5
$P(\pi \to \mu)@1GeV/c$		$< 5\%$	5.5% (MC)			



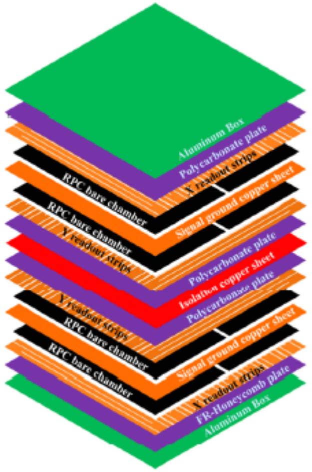


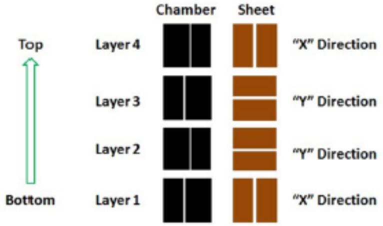
RPC technology – Dayabay



- Super module:
  - Two layers of 2-D readout
  - 4-layer RPCs
- Module size: $2.17m \times 2.20m \times 0.08m$
- Module number: 194
- Bare RPC sizes: $1.0m \times 2.10m$, $1.1m \times 2.1m$
- Bakelite plate size limitation: $2.4m \times 1.2m$!

Bare RPCs	$3{,}200\ m^2$
Box	195
Readout strip & insulation materials	$3{,}200\ m^2$
Electronics	6,000 ch





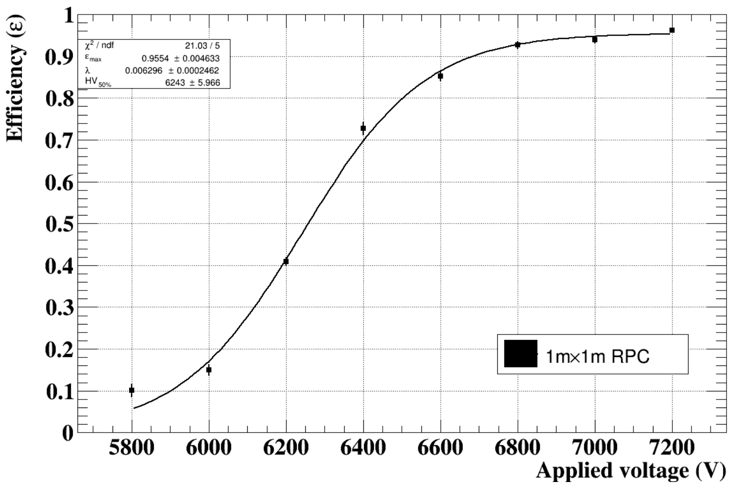
We have the tech. based on bakelite ready.

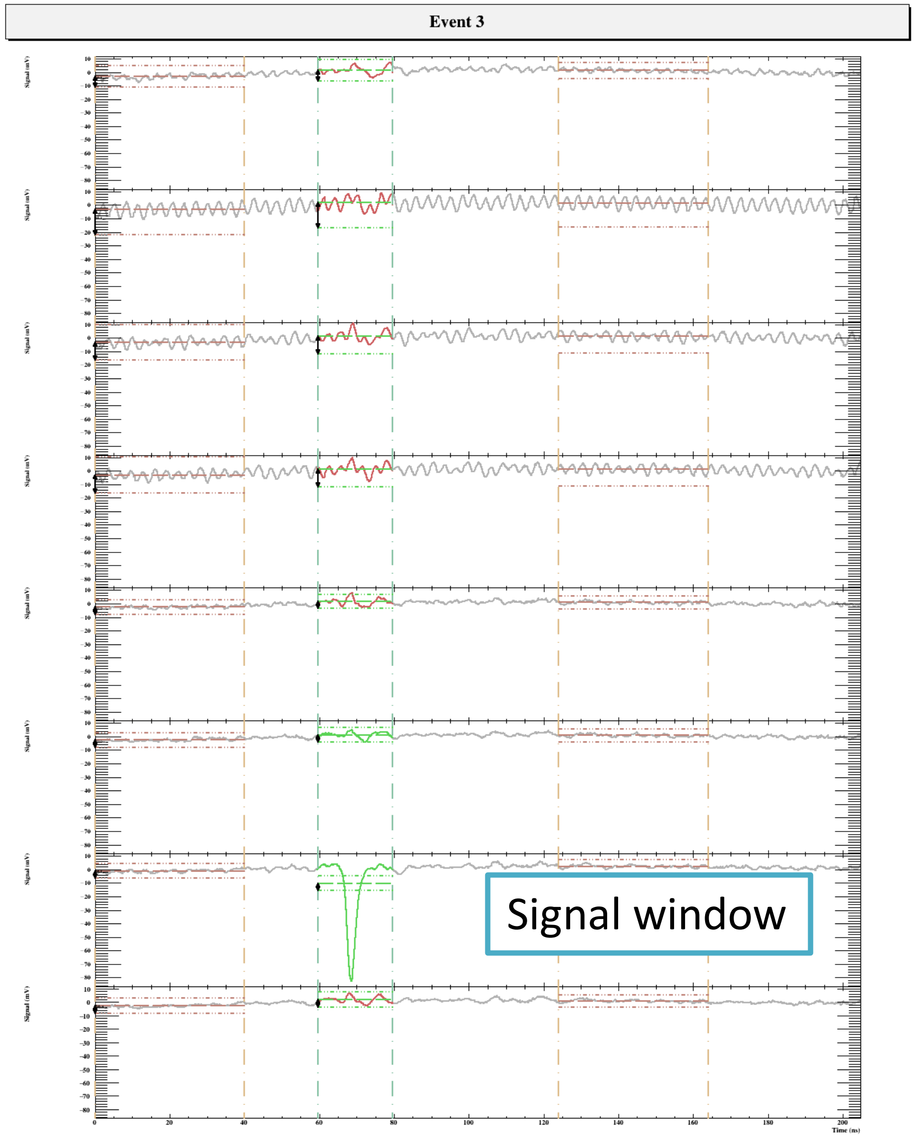
Ongoing test at SJTU

- A prototype from ATLAS (upgrade).
- Use R134a gas.
- Efficiency curve of large RPC determined.

Fit to $\boldsymbol{\varepsilon} = \frac{\varepsilon_{max}}{1+e^{\lambda\times(HV_{50\%}-\boldsymbol{U})}}$

CR test





We will perform the R&D focusing on glass with low resistance of $10^{10}\Omega m$, which is available in China.

Research Team

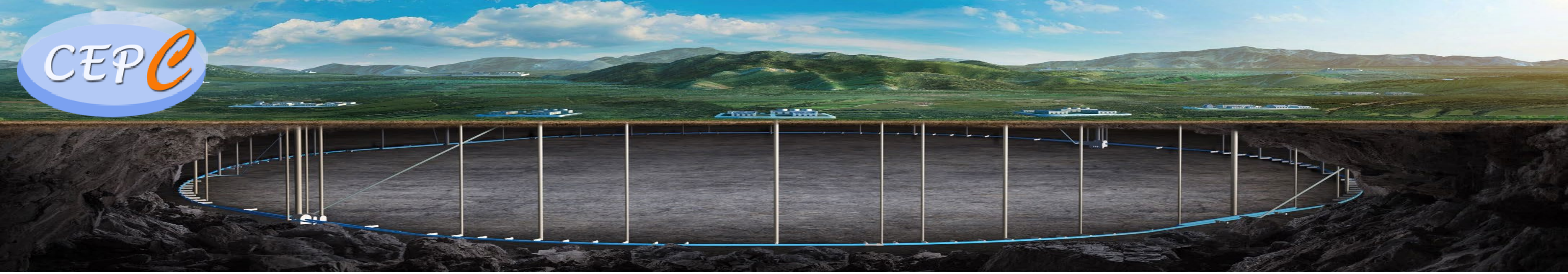
- Institutions and faculties/staff: 11
  - Fudan University (FDU): Xiaolong Wang, Wanbing He, Weihu Ma
  - Shanghai Jiaotong University (SJTU): Jun Guo, Liang Li
  - IHEP: Zhi Wu, Yuguang Xie
  - South China Normal University (SCNU): Hengne Li
  - Nankai University: Minggang Zhao, Junhao Yin
  - USST: Qibin Zheng
- Task board:
  - Overall: X.L. Wang
  - Software and simulation: H.N. Li, L. Li, J.H. Yin, M.G. Zhao
  - R&D on PS scheme: X.L. Wang, Z. Wu, W.B. He, W.H. Ma
  - R&D on PRC scheme: J. Guo, Y.G. Xie
  - Production and testing: Z. Wu, Y.G. Xie
  - Electronics: X.L. Wang, Q.B. Zheng
- Graduate students: ~15
- We are inviting BINP (Russia) to join.

Working plan

- Improvement and optimization of PS bars
  - Increase the light yield to reduce the weight of a long module
- Electronic readout
  - Study on the TOT scheme
  - Implementation of the CEPC electronics frame
  - An open question: how about integrating the BEE into the module, and try wireless like 5G/6G to avoid the troubles from long cables?
- Build a prototype module and testing
  - The performance of a module with a length of $5m$: efficiency, time resolution
- Optimization of structure design
- Software and simulation
  - Algorithm for muon ID
  - More physics performance study

Summary

- Muon detector will be designed for muon ID, but not limited to this.
- Many R&D efforts have been performed: FEE, prototype, simulation, etc.
  - Performance of a $1.5m$ prototype: $\epsilon > 98\%$, $\sigma_T < 1.5\ ns$
- Detailed design:
  - Barrel: 8 layers, 2 long modules per layer, helix dodecagon
  - Endcaps: 6 layers, 4 sectors per layer, two modules (inner and outer) per sector
  - Large area modules with long PS bars.
  - $51{,}744$ channels, $5{,}936\ m^2$ area, and $148{,}416\ m$ long fibre, in total.
- Work plan will focus on electronics, software and simulation for performance, prototype modules with long bars.

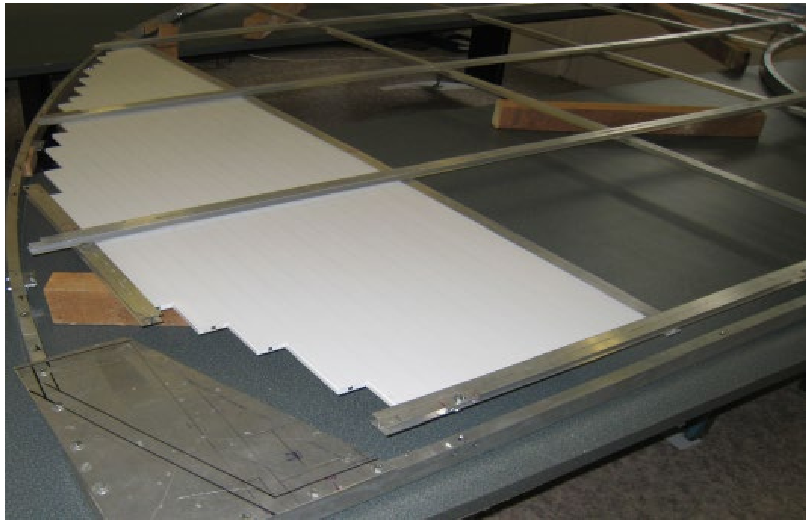


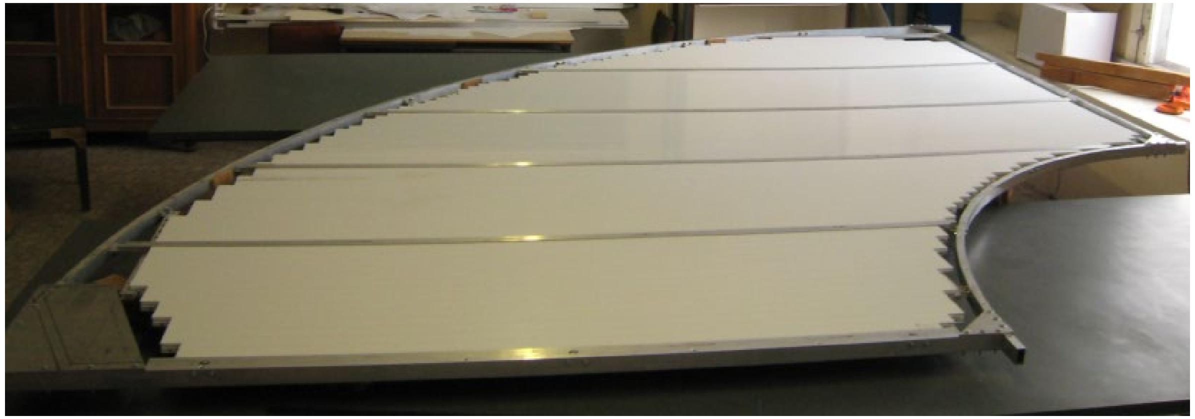
Thank you for your attention!

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

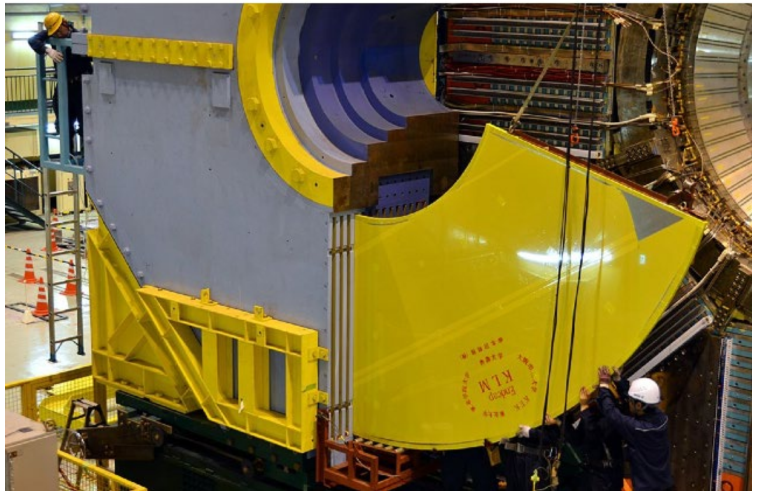
Reference for endcaps

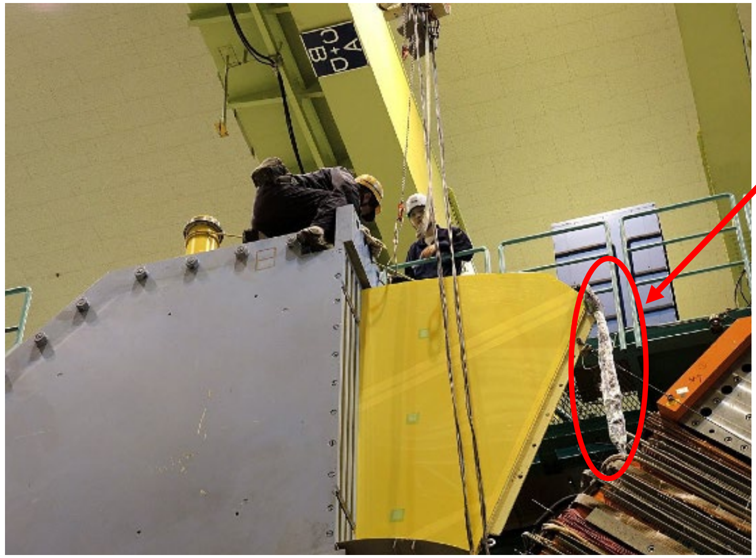
- Structure of a module





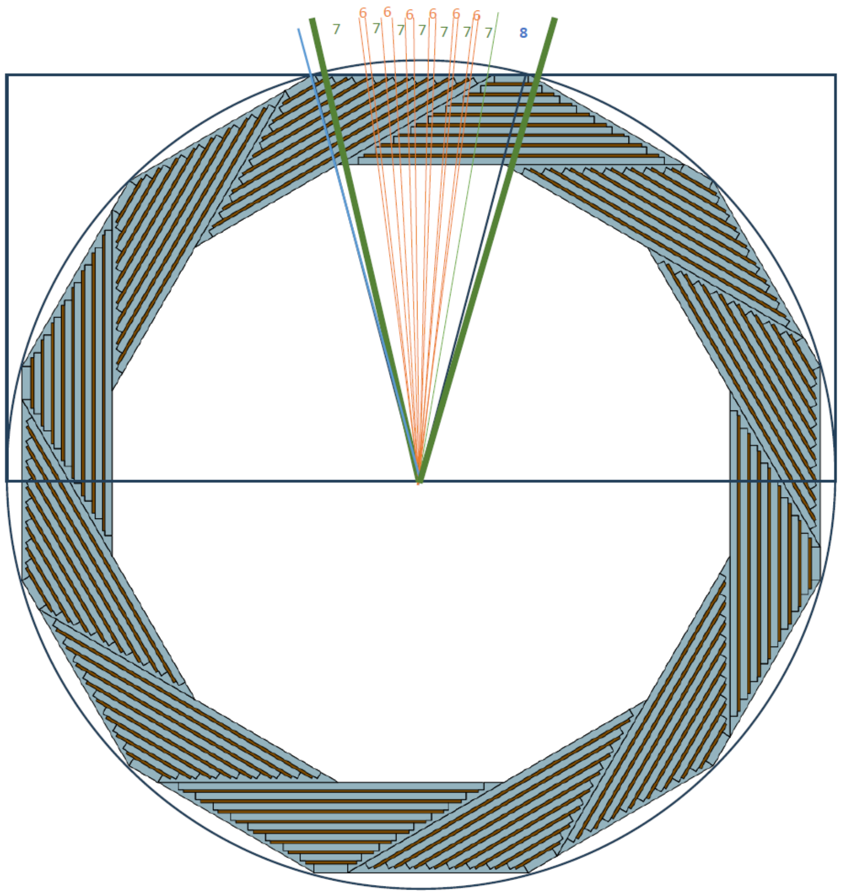
- Installation



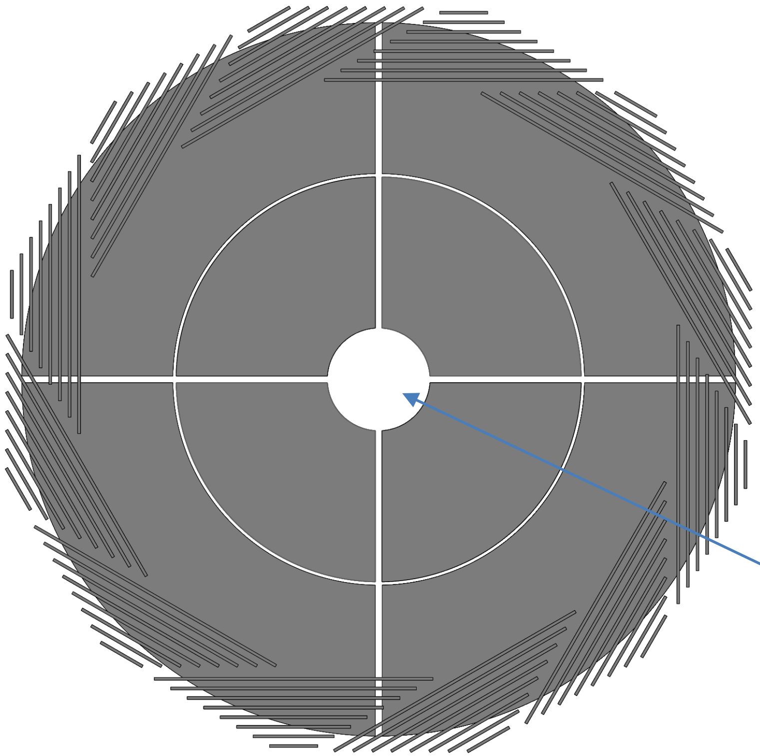


Cables

Estimation of dead zone



Tracks passing 6, 7, or 8 layers.
6-layers: ~25%, 7-layers: ~50%, 8-layers: ~25%



- Cross (+) = dead zone
- Width of the cross: $10\ cm$

For beam pipe,
$R = 75cm$

Conclusion:

There is no dead zone in the barrel.

Due to the cross: $0.00214 * 2.09829 * 2/4\pi$=0.07%

Due to the beam pipes: $2 * \Omega_1 = 0.173$; $2 * \frac{\Omega_1}{4\pi} = 1.4\%$

Cost estimation – PS scheme

Unit: CNY

SiPM+FEE:

- Number of detector channels: 51,744
  - Endcaps:
    - Inner modules: $72 \times 2 \times 4 \times 6 \times 2 = 6{,}912$
    - Outer modules: $128 \times 2 \times 4 \times 6 \times 2 = 12{,}288$
  - Barrel: $1356 \times 2 \times 12 = 32{,}544$
- Cost: $51{,}744ch \times 80/ch = 4.14\ M$

SiPM: ￥50/ch

Preamp: ￥30/ch (could be ￥10)

PS + fiber

- Sensitive length: 148,416 m
  - Endcaps: $(154.83 + 343.73) \times 2 \times 4 \times 6 \times 2 = 47861.76\ m$
  - Barrel: $4189.76 \times 2 \times 12 = 100{,}554.24\ m$
- Sensitive area: $5936.64\ m^2$
- Scintillator volume: $59.3664\ m^3$

Cost for fiber: $148{,}416m \times 45/m = 6.68\ M$

Cost for scintillator: $59.3664m^3 \times 200/L = 11.87\ M$

Total cost: $4.14 + 6.68 + 11.87 = 22.69\ M$

Consider 20% is for additional costs, like the module structure, wastage, etc.

$$22.69 \times 1.2 = 27.228\ M$$

CEPC RPC Muon cost

A previous estimation

Bare RPCs (Bakelite)	5080 m^2	2200/m^2	11.18 +0.6 = 11.78M	From GNKD
Bare RPCs(glass)	5080 m^2	1000/m^2	5.08+0.6=5.68M	Estimated
Box	280	3500/module	0.98 M	Estimated
Readout strip & insulation materials	5080 m^2	1000/m^2	5.08 M	Ref to DYB
Subtotal			17.84(Bakelite)/11.74(glass)	
Electronics (discrete)	31100 ch	~200/ch	6.22 M	From USTC
Electronics (ASIC)	31100 ch	~146.5/ch	4.55M	From USTC
HV system			1.5M	Estimated
Gas system			1.0M	Estimated
Total	Bakelite RPC: 26.56M(discrete)/2.489(ASIC); Glass RPC: 20.46M(discrete)/18.79(ASIC)			

RPC mass production condition

Vendor: GaoNengKeDi co.ltd only, currently; glass RPC no problem. A new clean room is needed. Raw materials are not an issue. (Bakelite, graphite, glass, glue, strips of insulation film, etc.)

➢ Bakelite or glass?

Major factors for choosing glass:

1. Module size is too big, Bakelite bare chamber size limited in 2.3*1.1m (Bakelite plate 2.4*1.2m). Glass can be larger, 2.44*2.0m (2mm glass plate 2.44*2.0m) . Two workers can handle.
2. Much cheaper, float glass plate -2mm, 10.6/m^2, 21.2(double layer)/m^2 for glass RPC. So bare chamber cost should be much lower than the Bakelite one. (e.g, half or 1/3).
3. Strength and performance improved for glass, not fragile, bulk resistivity could be controlled to 0.1~1*10^12 Ωm*cm

Parameters		Bakelite	Glass
Bulk resistivity [Ω· cm]	Normal	$10^{10} \sim 10^{12}$	$> 10^{12}$
	Developing	$10^{8} \sim 10^{9}$	
Max unit size (2 mm thick) [m]		1.2×2.4	1.0×1.2
Surface flatness [nm]		< 500	< 100
Density [g/cm^3]		1.36	2.4~2.8
Min board thickness [mm]		1.0	0.2
Mechanical performance		Tough	Fragile
Rate capability [Hz/cm^2]	Streamer	100@92%	
	Avalanche	10K	100@95%
Noise rate [Hz/cm^2]	Streamer	< 0.8	0.05

Table 7.2: Comparison of the main parameters of Bakelite and glass RPCs. Both technologies would satisfy the CEPC detector requirements.

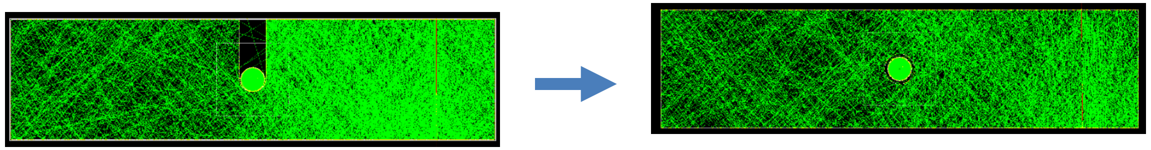
Old data

For CEPC RPC, glass should be a better choice according to current survey in China.

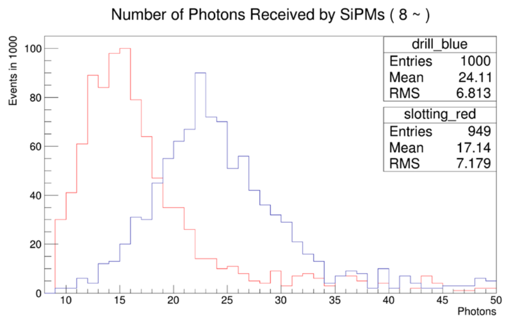
But glass RPC option needs some R&Ds, rate capability and aging are the main issues.

Geant4 simulation for performance

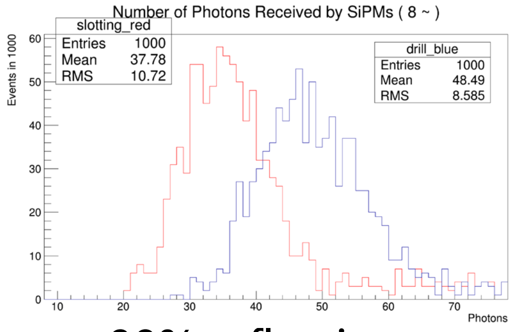
- Reflection layer: 90% → 98%
- Scintillator for fiber: groove → hole
- WLS fiber diameter: $1.2mm \rightarrow 2.0\ mm$
- PS bar length: $1.5m$ vs. $4.0m$



Comparison of groove & hole (40 GeV mu-) (1.5m)

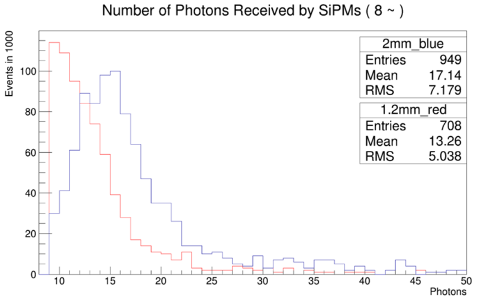


90% reflection

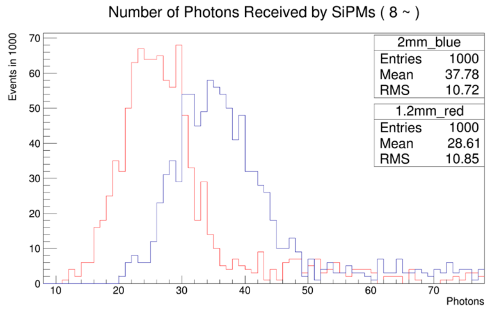


98% reflection

Comparison of 2mm & 1.2mm fiber (hole) (40 GeV/c) (1.5m)

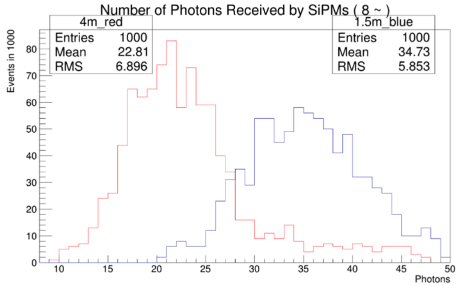


PS bar length



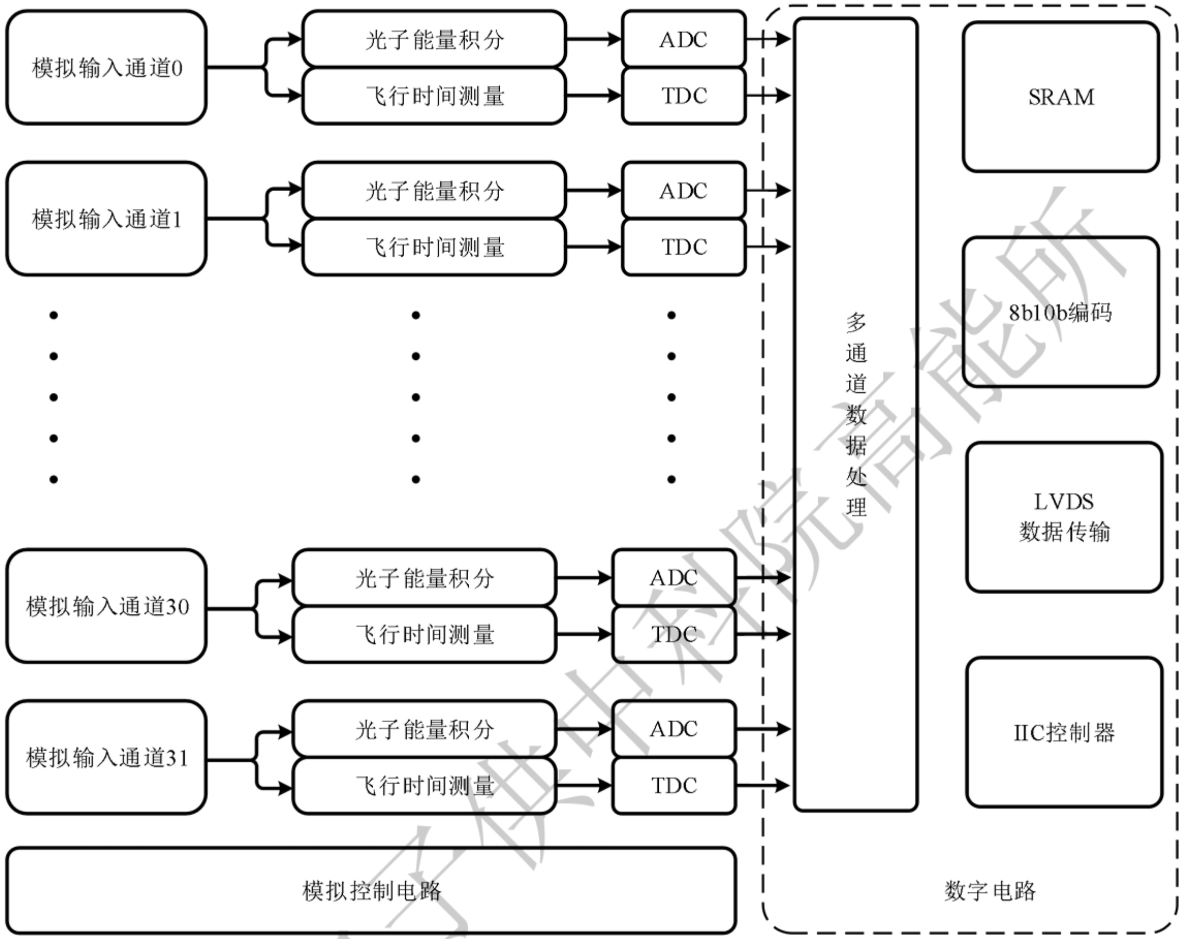
Muon momentum

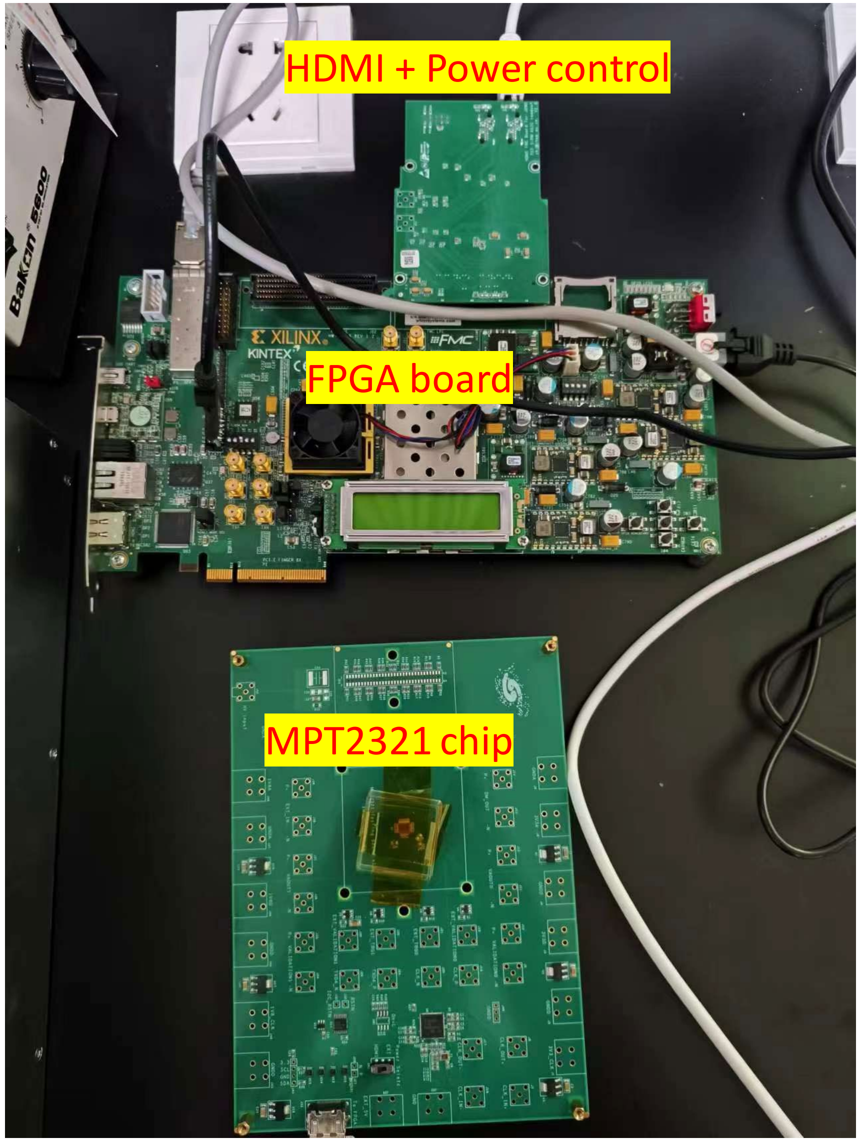
- Reflection layer: 90% → 98%
- Scintillator for fiber: groove → hole
- WLS fiber diameter: $1.2mm \rightarrow 2.0\ mm$
- PS bar length: $1.5m$ vs. $4.0m$



The sub-group for software and simulation was founded less than one year ago.
We still have a lot of work to do for the performance based on simulation.
Hits of muon tracks with different momentum.
Muon ID efficiency

SiPM – ASIC MPT2321





MPT2321, made in China

32CH ADC (12bit) + TDC(50ps)