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

The Chinese Academy of Sciences

The 20 inch MCP-PMT for Neutrino Detector

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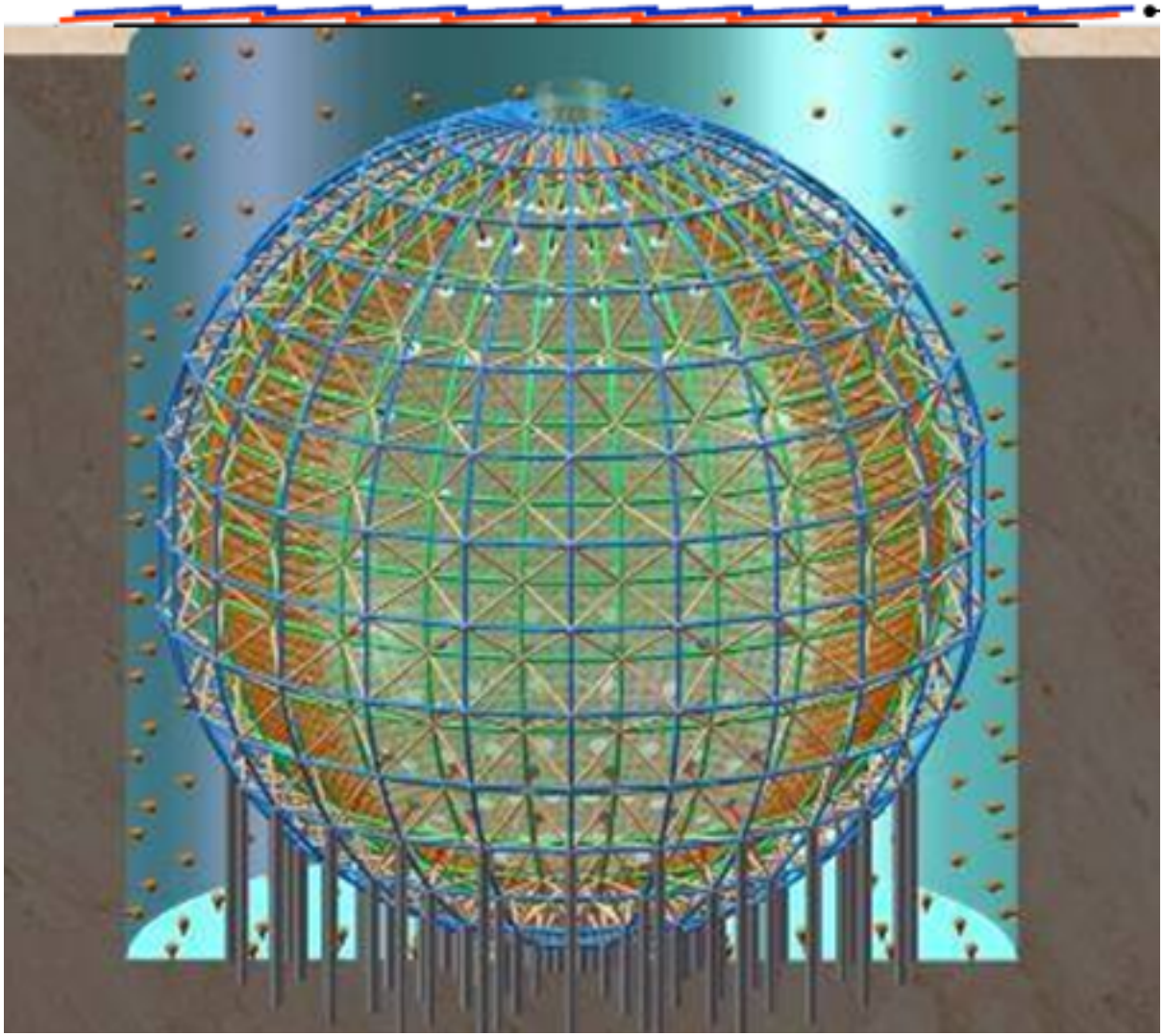
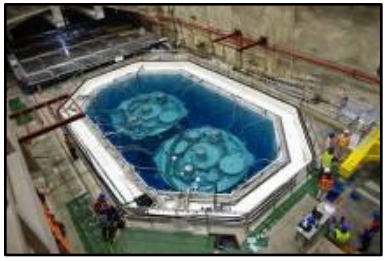
➢ 0. The Neutrino Experiment in China

➢ JUNO Experiment



➢ Daya Bay Experiment



Generation 1: DayaBay: ~3,000 8-inch Dynode-PMTs from Hamamatsu

Generation 2: JUNO: ~20,000 20-inch PMTs from Where?

Outline

- **1. The R&D of the MCP-PMT for JUNO;（2009-2015）**

  the 8 inch， the 20 inch ， the high PDE prototypes；

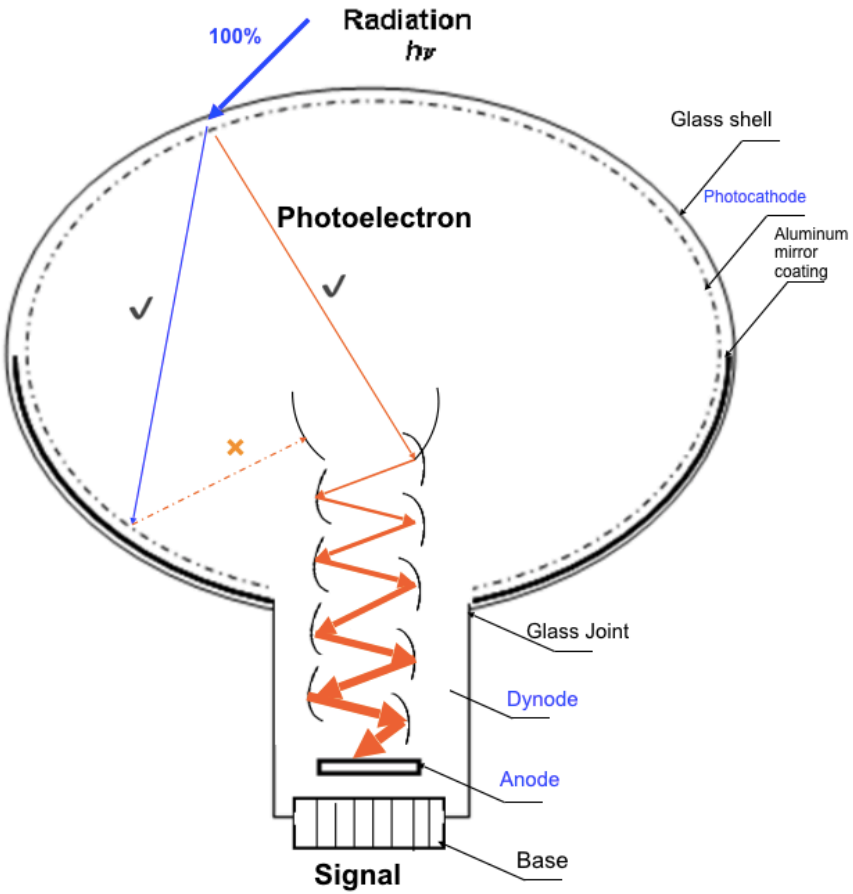
- **2. The Mass production and Batch test;（2016-2019）**

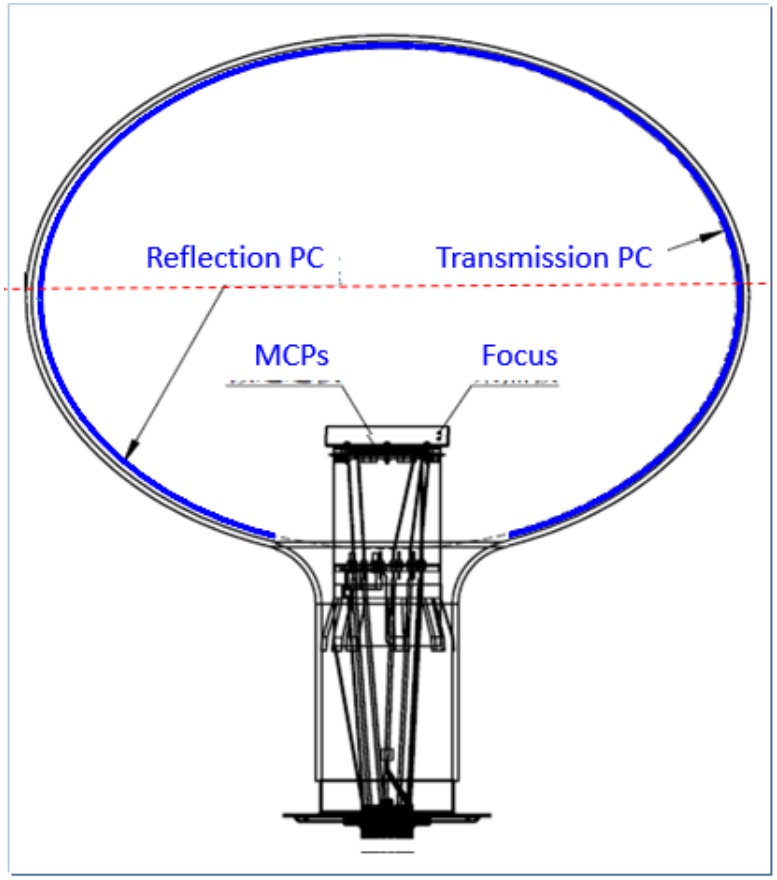
- **3. The improvement of the MCP-PMTs;（2016-2018）**

  the High QE prototypes, the fast prototypes;

1.0 The design of the MCP-PMT in 2009

Photon Detection Efficiency : PDE = $QE_{Trans+Ref}$ * CE





Dynode:(PDE)= QE_{Trans} * CE

= 20% * 70% = 14% (2009)

= 30% * 90% = 27% (2015)

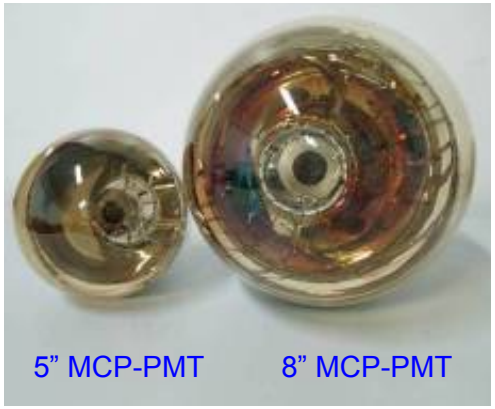
MCP :(PDE)= QE_{Trans} * CE

= 27% * 100% = 27% (2016)

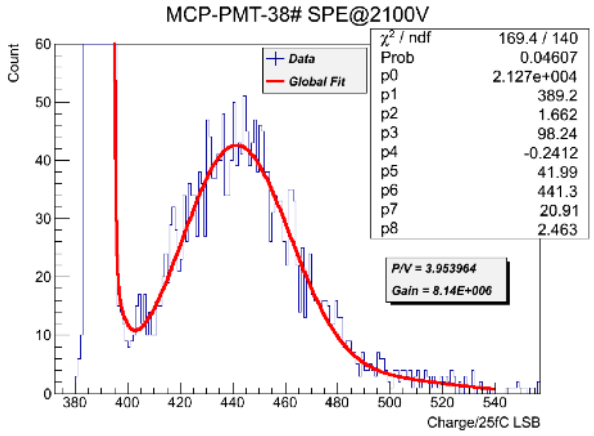
➢ 1.1 The prototypes at the beginning

➢ The First **5 inch MCP-PMT** was produced in 2011, which was the first large MCP-PMT for the single photon detection, but this prototype can not **"see"** the SPE.

➢ The **8 inch MCP-PMT** was produced in 2012, which could get the best signal of the MCP modules, but still **without the SPE** anyway.



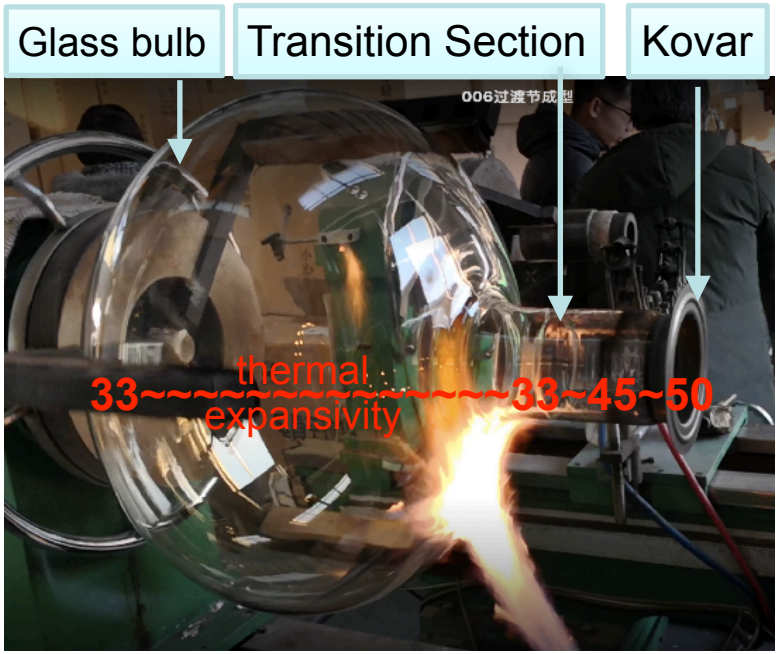
The 8 inch MCP-PMT prototype



The SPE of the 8 inch prototype

➢ **IN 2013,** the 8 inch MCP-PMT was produced with two shapes, vertical and horizontal ones, both of these two types of MCP-PMTs has the best MCP modules for the single photon detection, and the P/V of the SPE （>4）is better than the Dynode-PMTs, but the CE was only 70%, QE was 25%.

How to produce the 20 inch Glass bulb

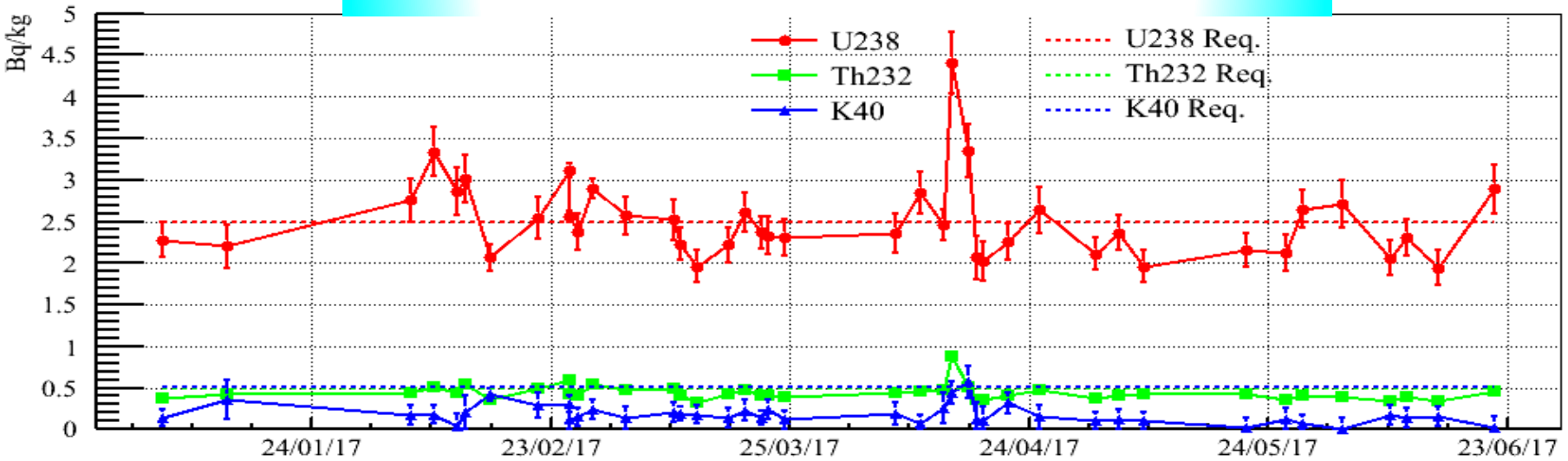


--> 20 inch Glass bulb was **manual blowing** by the skilled workers in China;

-->For better water compatible, using the hardness glass, **transition Section**(the thermal expansivity from 33 to 50) , welding with Kovar;

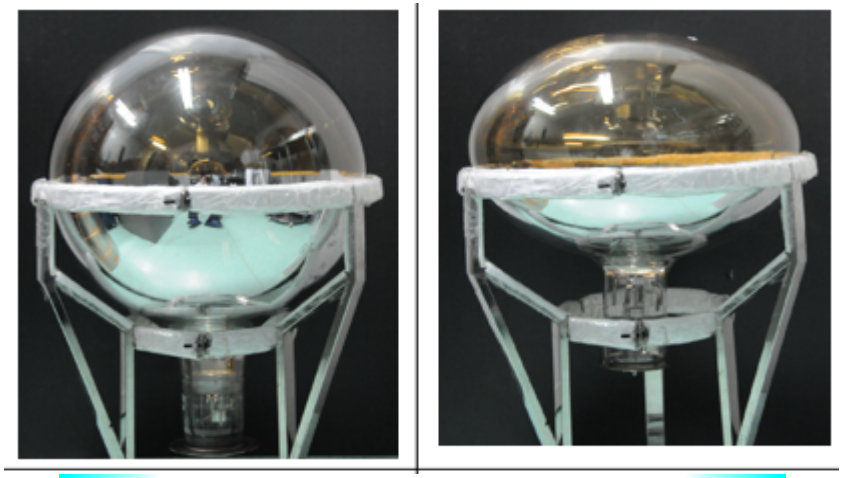
--> By controlling material, producing process and environment, the **radioactive background** of the glass was really low;

the radioactive test during the glass producing process

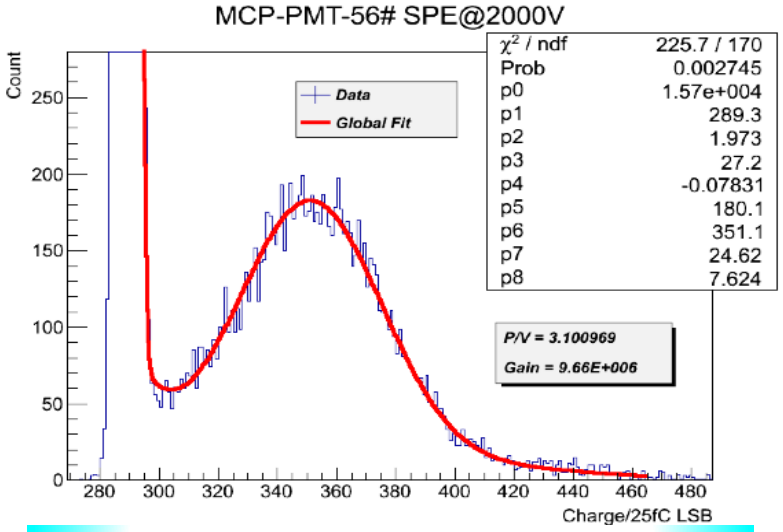


1.2 the 20 inch prototypes with normal performance

IN 2014, the 20inch glass was produced, and also the 20 inch MCP-PMT was produced with two shapes, vertical and horizontal ones, and both of them were good at the SPE test.



The 20 inch MCP-PMT prototype

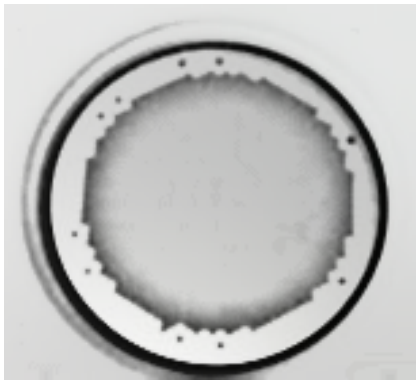


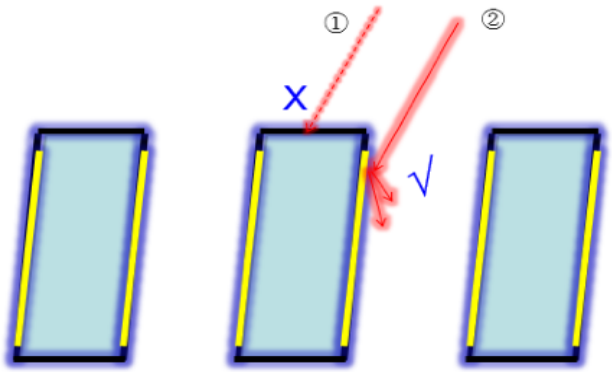
The SPE of the MCP-PMT prototype

- The performances of these types of 20 inch MCP-PMT were as good as the 8 inch ones.
- And we did lots of work to improve the QE and CE, but the CE was still only 70%.

HV	Gain	P/V	Rise Time	Fall Time	Dark rate @1E7 Gain(0.25PE)	QE@400nm	CE
2000V	~1E7	~3	~1.2ns	~15ns	~50kHz	25%	70%

How to improve the Collection Efficiency of the MCP modules



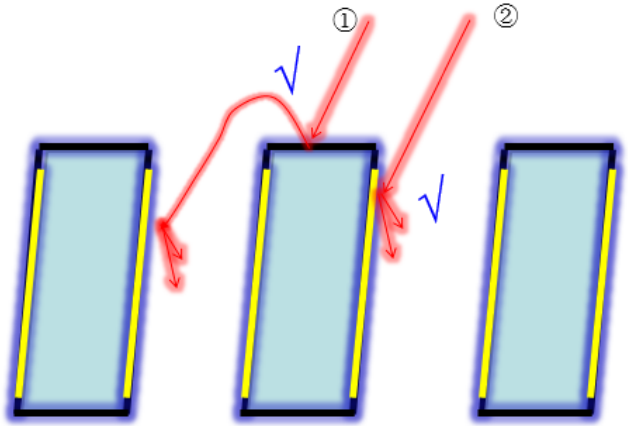


CE = 70%

The p.e. into the channel directly ~70%

change

The Diameter of the MCP: **33mm; 50mm;**
The Diameter of the Hole: **6um; 8um; 10um; 12um**;
The Inclined Angle: **0°**; **8°**; **12°**;
The Open Area Ratio: **60%**; **77%**;
The Depth of output electrode:……



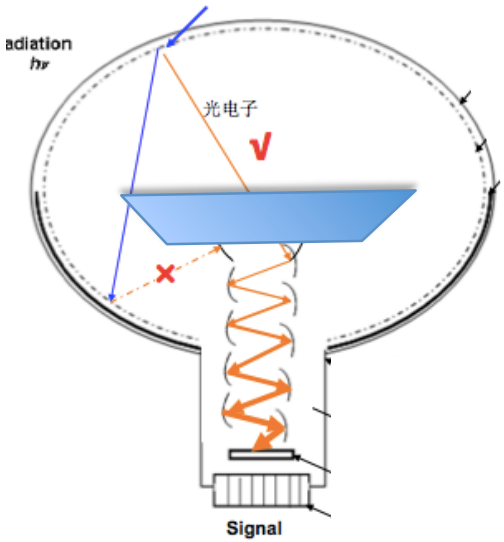
CE = 100%

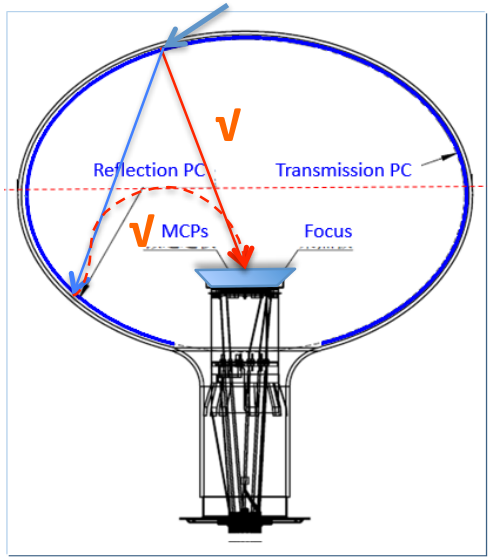
The p.e. into the channel directly ~70%
The p.e. from the electrod indirectly ~ 30%

How to improve the CE of the MCP, please see the poster by Shulin

1.3 the 20 inch prototypes with HDE performance

- In 2015, the MCP-PMT work group did the best to improve the CE of the MCP modules, and finally, the CE of the MCP-PMTs was improved from 70% to 100%.

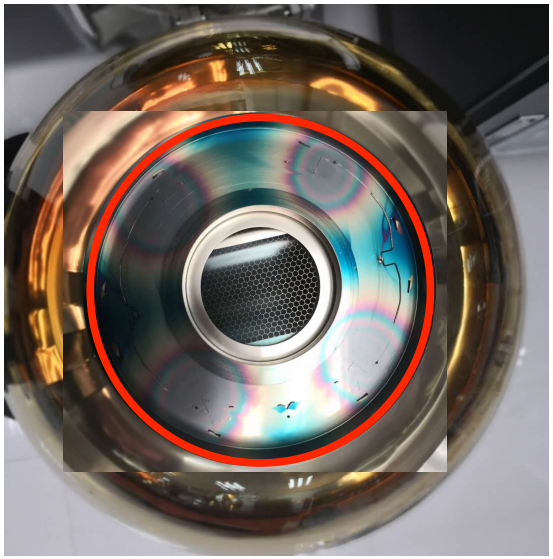


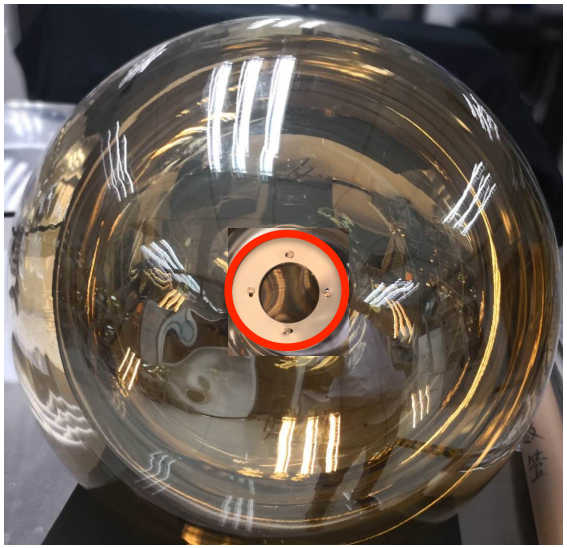


QE=20% → QE=30%

CE=70% → CE=100%

DE=14% → DE=30%





1.4 PMT Purchasing of JUNO

Characteristics	MCP-PMT	Dynode-PMT
Electron Multiplier	MCP	Dynode
QuantumEfficiency (400nm)	26 (T), 30 (T+R)	30%
Detection Efficiency	~ 100%	90%
P/V of SPE	~5.6	> 3
TTS on the top point	~12ns	3ns
Glass	Low-Potassium	normal glass

- With the QE Trans.+Ref. photocathode together:

  QE could be **30% @400nm**;

  CE of the MCP increased to **100%**,

  DE of the MCP-PMT could be **30%@400nm**;

- The Glass is the **low potassium glass** to decrease the radioactivity of the PMT materials.
- The TTS of this type of MCP-PMT was not good.

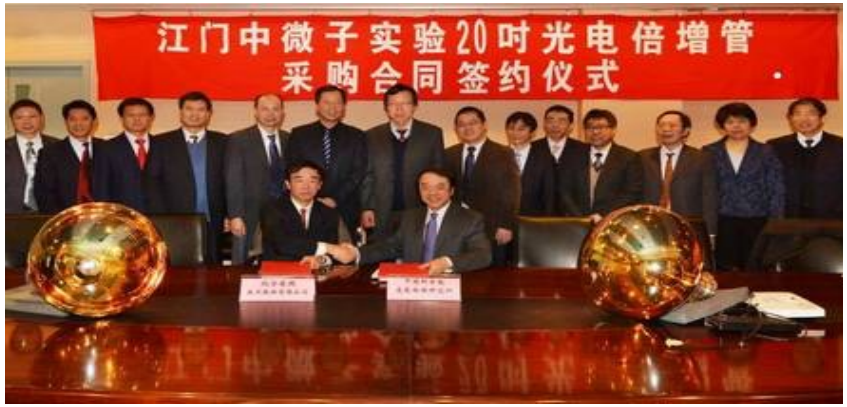
Decision based on

risk, price,

performance merit for physics

15k MCP-PMT (75%) from NNVT

5k Dynode (25%) from Hamamatzu



How to make the decision, please see the presentation by Liangjian

Outline

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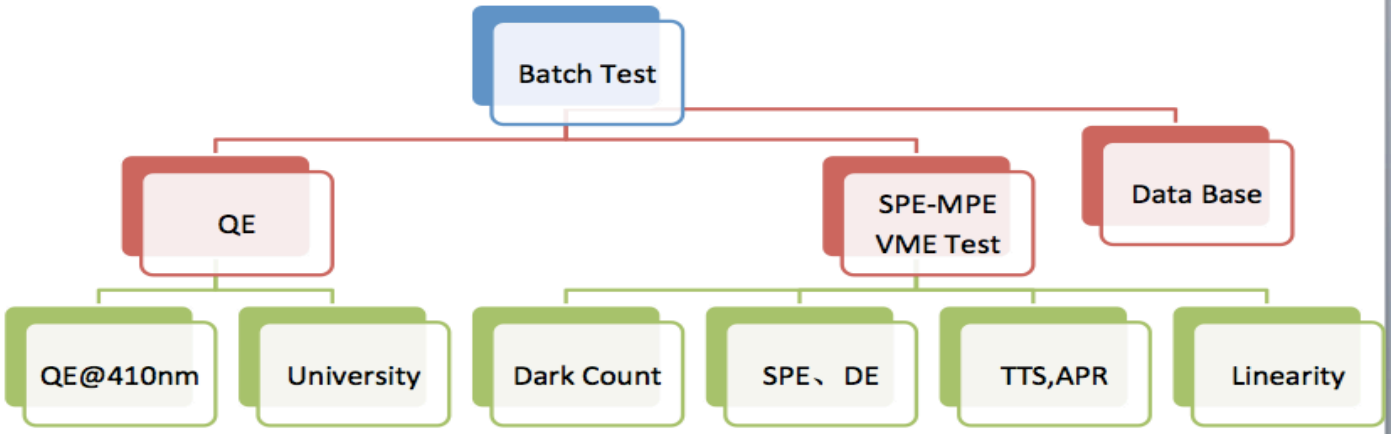
  the High QE prototypes, the fast prototypes;

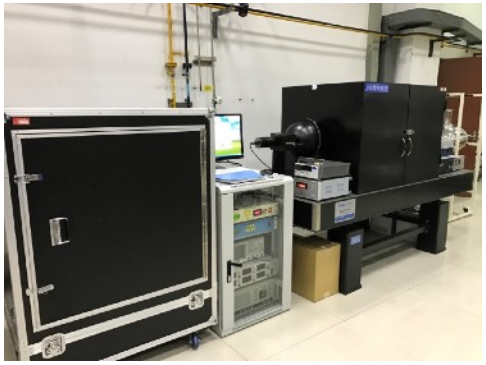
➢ 2.0 The Batch test platform in the NNVT Company

PMT	JUNO Contract	NNVT test
QE@ 410nm	—	A
QE-Un	B	A
QE-λ	B	B
SPE	A	A
Gain	A	A
DE	B	A
TTS	B	A
APR	B	A
Linearity	B	A
RT/FT	A	A
DR	A	A

A: will be test 100% one by one;
B: will be test 10%~20%, part of them.



➢ QE sub-system



➢Equipment: 2 pic;
➢Time: 0.5h / PMT;

➢ SPE Batch Test sub-system

➢with soft iron to shielding EM
➢Equipment: 2+1 Dark Room;
—> 1 dark room = 32 PMTs

➢ One Day: Test 30 pics PMTs; Test Ratio: 100%;

➢ 2.1 The Batch Result —Quantum Efficiency (QE)

—The QE of the photocathode is really improved during the mass production process.

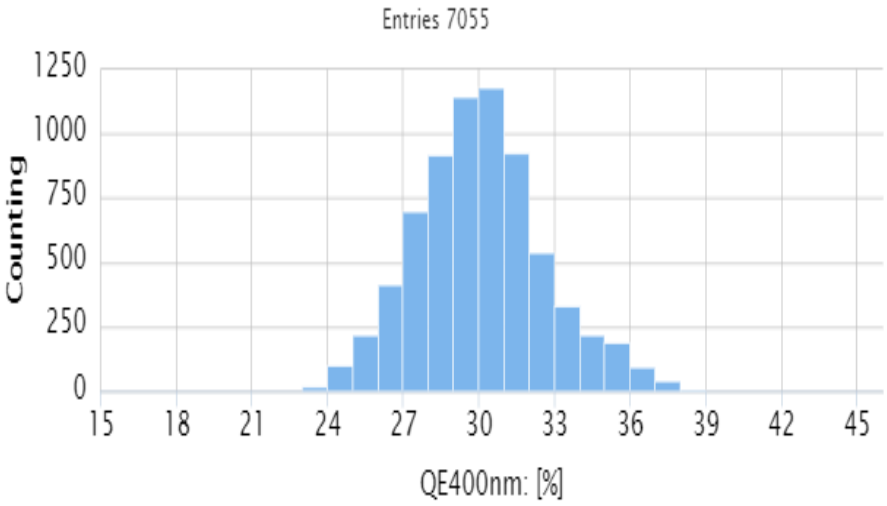
The QE of the **transmission photocathode** is achieving 30%@ 400nm.

20 inch PMTs	Typical Dynode-PMTs	~7055 MCP-PMTs
QE.Trans @ 400nm	30%	30.1%
Uni-QE @ 400nm	< 10%	7.3%

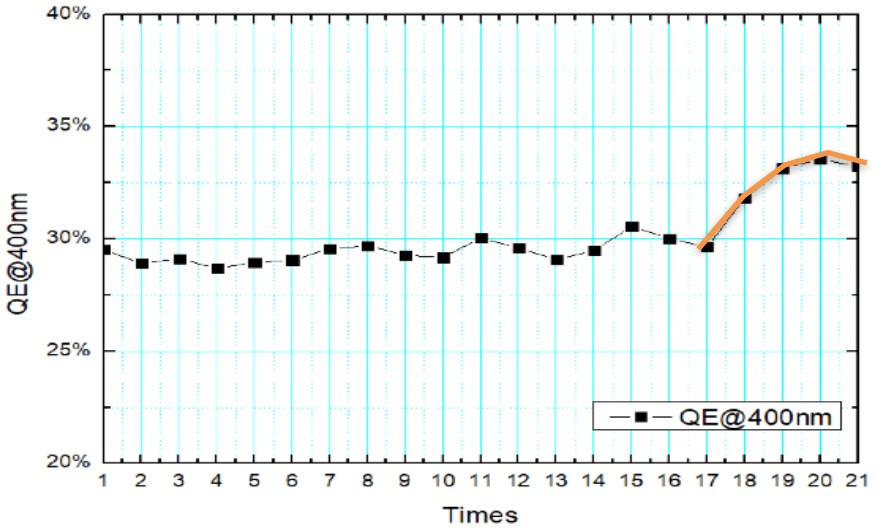
—The DE Uniformity of the PMT is affected by the QE Uniformity of the Photocathode;

We need to control the Uniformity of the QE less in 10%,

The average data of 6K pics is about 7.2%, which is better than the Dynode-PMT.



QE.Trans @ 400nm

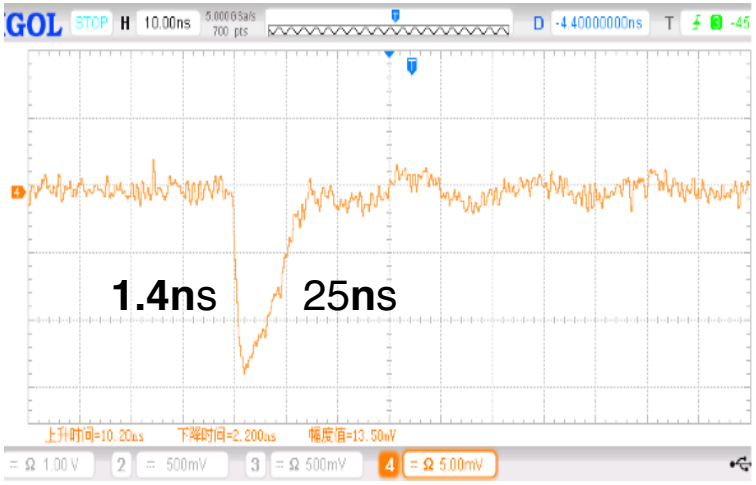


Average QE for different batch from NNVT to JUNO

➢ 2.2 The Batch Result — The time characteristics of the PMTs

—The Rise time of the MCP-PMTs is really fast within **1.4ns** for the average of 7K pics.

—For better shape of the waveform, the Fall time is enlarged from 10ns to **25ns** in production.



Waveform of the MCP-PMT

--> the large area photocathode for better QE,

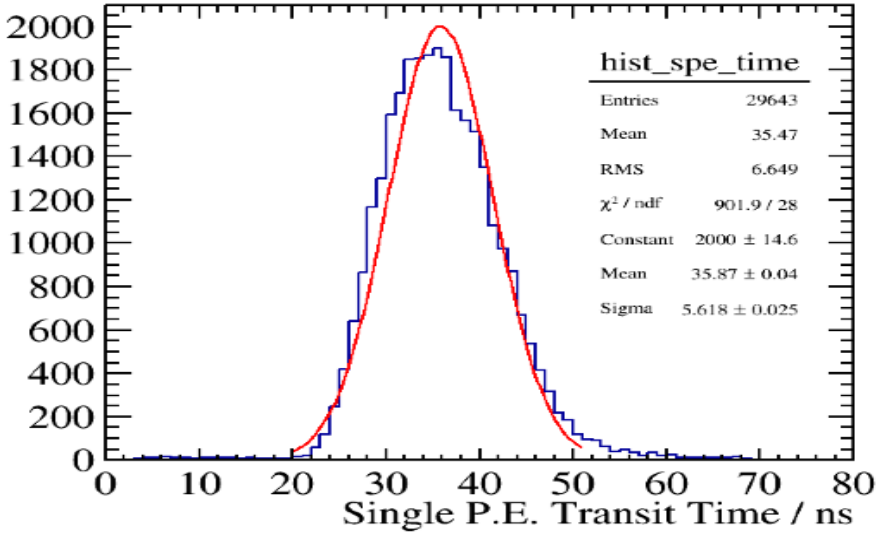
--> the special MCPs for better CE,

--> the special HV distribution for better SPE,

The TTS of the MCP-PMTs is also enlarged:

from the prototype data 13ns to

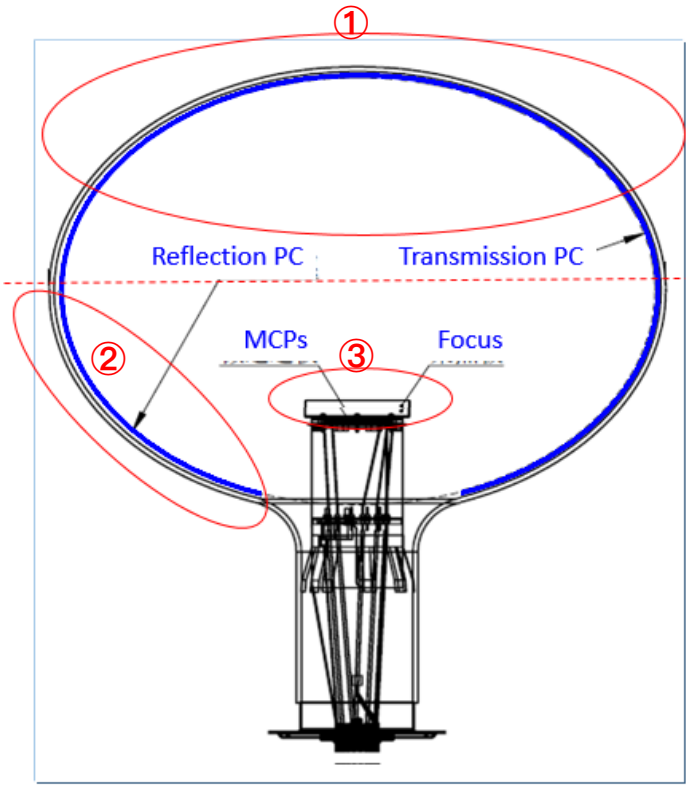
20ns in mass production process



TTS of the MCP-PMT

➢ Why the TTS of MCP-PMT was not good?

Why is the TTS so Large!

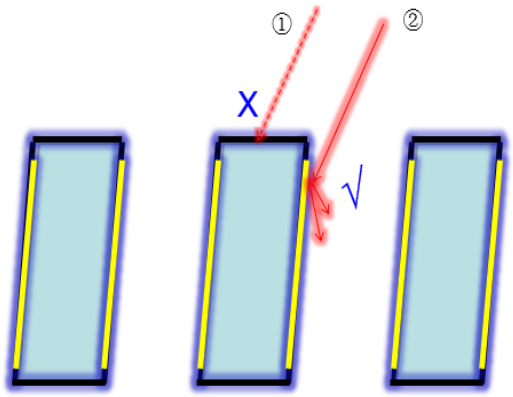


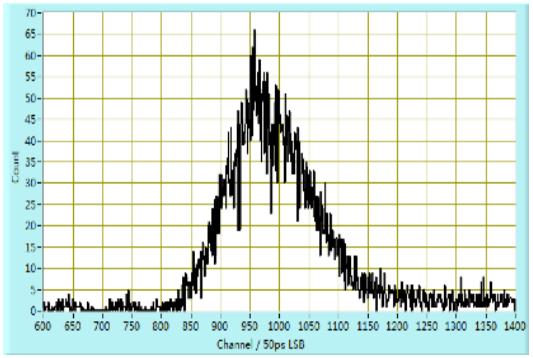
The prototype

--> with Trans.+Ref.PC for better QE;

--> with special MCP for better DE;

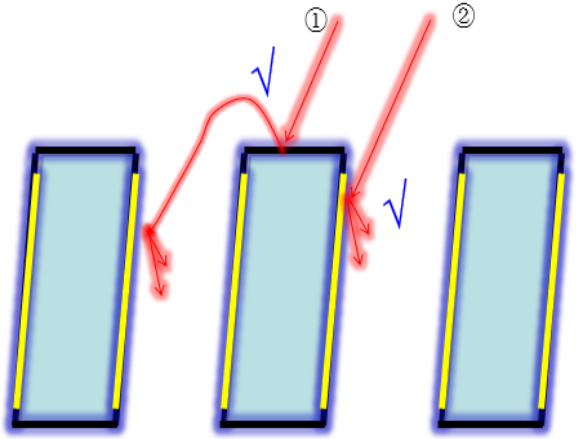
But the TTS will be worse!

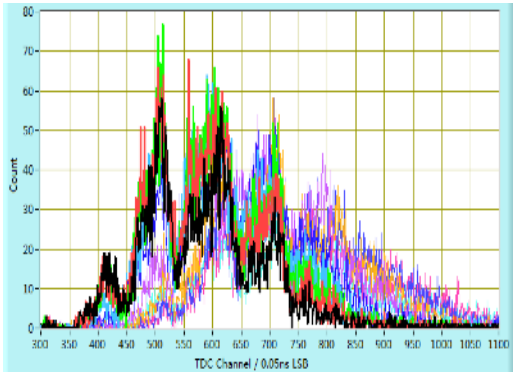




➢With the contribution of the second electron from the electrode (30%),

the spectrum of the TTS present several peaks, which made it's TTS worse.





➢ 2.3 The Batch Result — The P/V, DE of the SPE

—With the special MCP modules, the special HV distribution of the PMT,

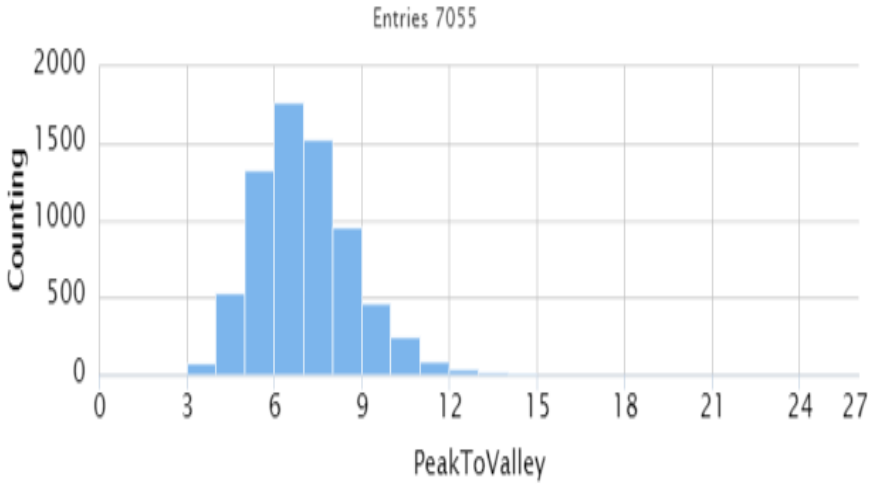
the P/V of the SPE is improved from 5 to 7 in the mass production process, better than Dynode one.

—With the special MCP modules, the CE of the MCP modules is about 100%;

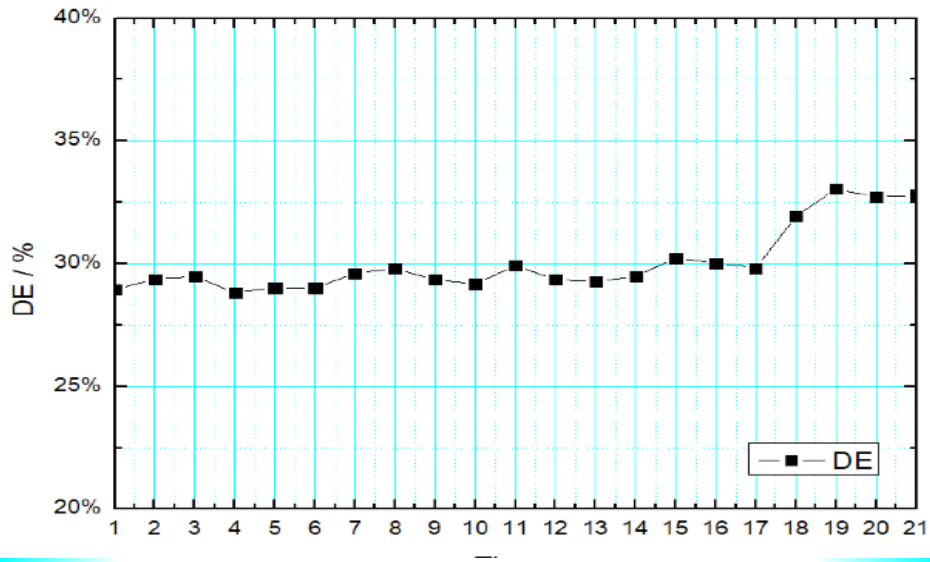
—With the improved technology of photocathode, the QE is increasing to 30%;

the DE of the MCP-PMTs is improved from 26% to nearly 30% (the average data of the 7K pics)

—the improving of the Photocathode Quantum Efficiency is continuing for better ……



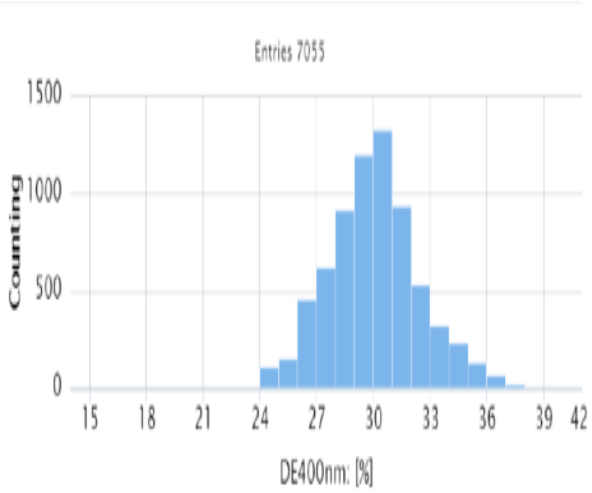
P/V of the SPE



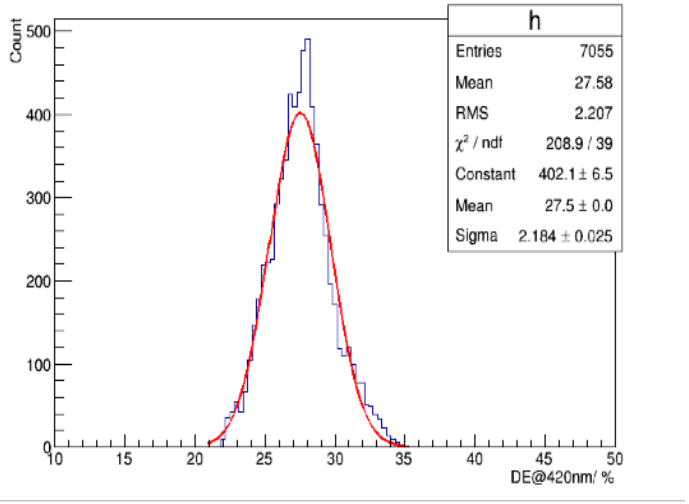
Average DE for different batch from NNVT to JUNO

—The DE of the MCP-PMTs from the NNVT bath test is about 30.1% @ 400nm;

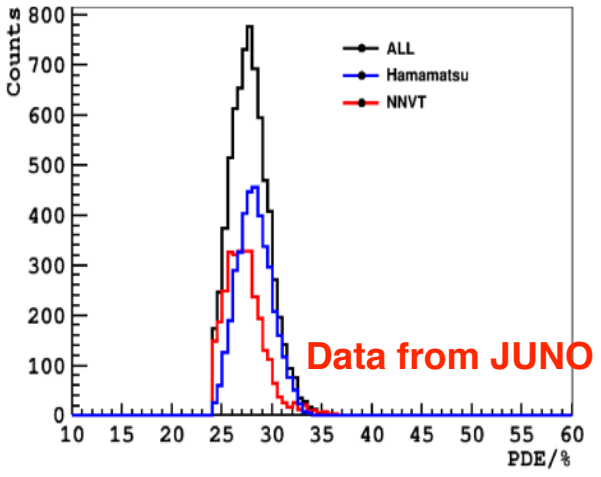
But the JUNO ordered the DE@420nm.



DE=30.06% @400nm @NNVT



DE=27.5% @420nm @NNVT



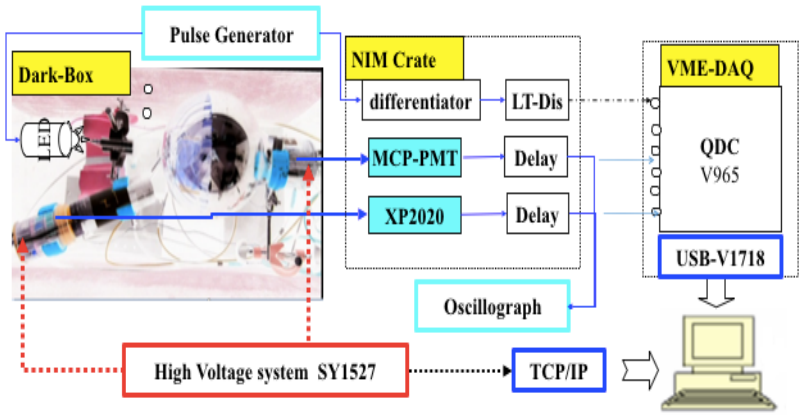
DE=27.2% @420nm @JUNO

—The QE in different wavelength with different DE. The peak wavelength of the PC is about 390nm~400nm, so the data of the DE@420nm is smaller than the DE@400nm;

—The average DE@420nm of **7K** MCP-PMTs is about **27.5%** in the NNVT batch test.

—The average DE@420nm of **3K** MCP-PMTs is about **27.2%** in the JUNO batch test;

2.4 The Aging behaviors of the MCP-PMT

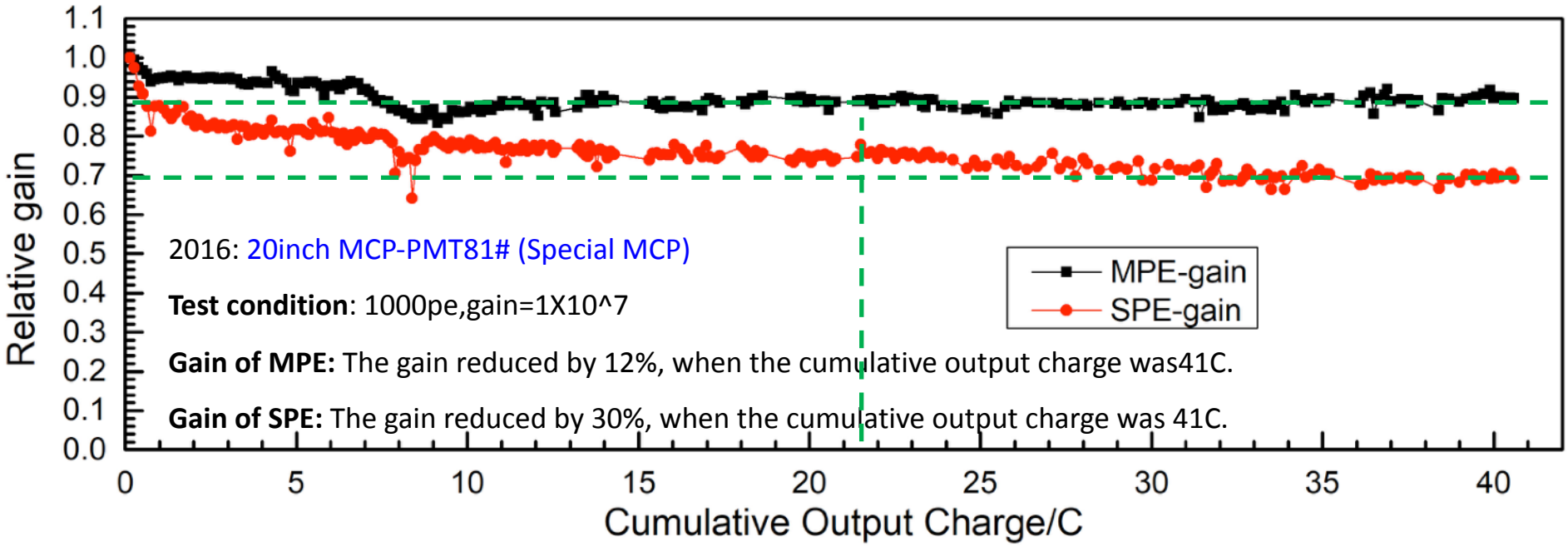


--> One 20 inch PMT was monitored within 1000 MPE for 1.5 year without stoping;

--> The Aging behaviors could be accept by JUNO for 20 years operation;

--> The lost gain could be enhanced by increasing the HV less than 100V;

The performance of new type MCP-PMT was largely improved（420 days @ with operation 1000 pe）



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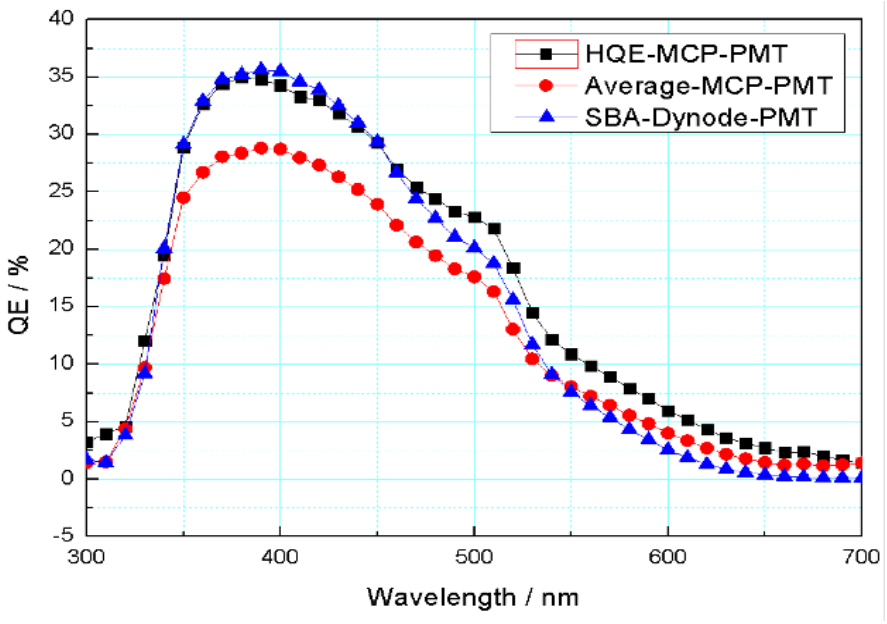
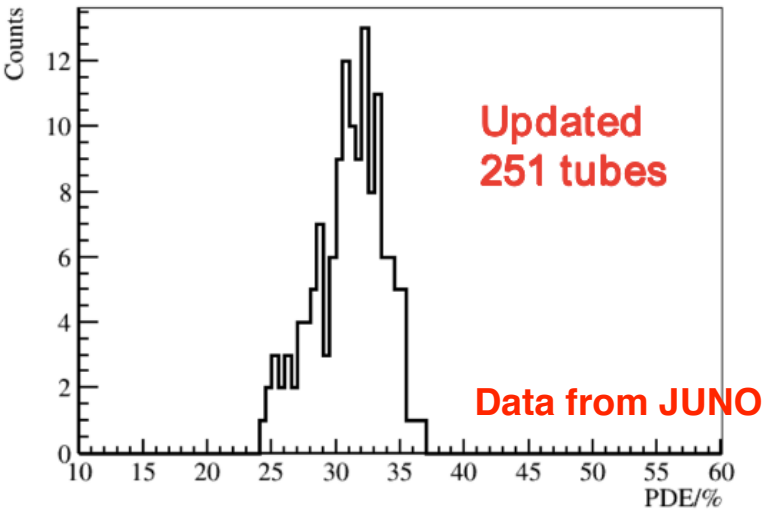
  the High QE prototypes, the fast prototypes;

3.1 the improvement of the QE & DE for JUNO





High_QE tube PDE	Preliminary updated Mean(%)
NNVT	31.0 （peak ~32%）

—The QE of the PC is improved from 30% to 35%@peak wavelength for the HQE-MCP-PMT.

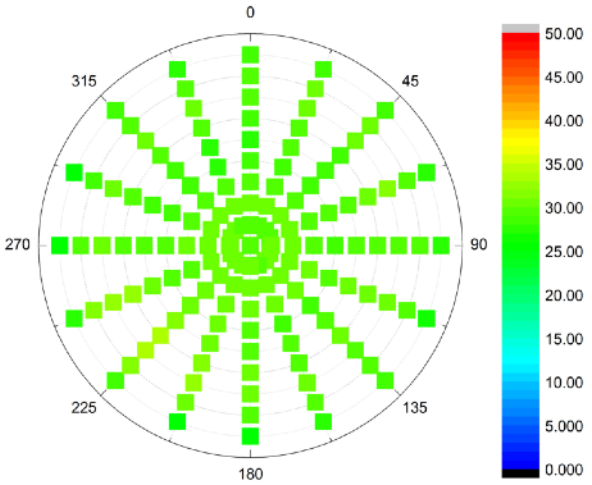
— The DE of the PMT is also improved by the increasing QE；

The average DE=**27.5%**@420nm of **7K** pics normal MCP-PMTs

The average DE=**31.0%**@420nm of 140 pics HQE-MCP-PMTs

PMTs	Hamamatsu	~7000 Normal MCP-PMTs	~250 HQE-MCP-PMT
QE @ 400nm	30%	30.1%	32.3%
DE @ 420nm	28%	27.5%	**31.0%**

- The **Uniformity of DE** in the 20 inch PMTs depend on the **QE Uniformity** of the PMT;
- The Uniformity of detection efficiency has also been obviously improved through the improvement of photocathode technology.



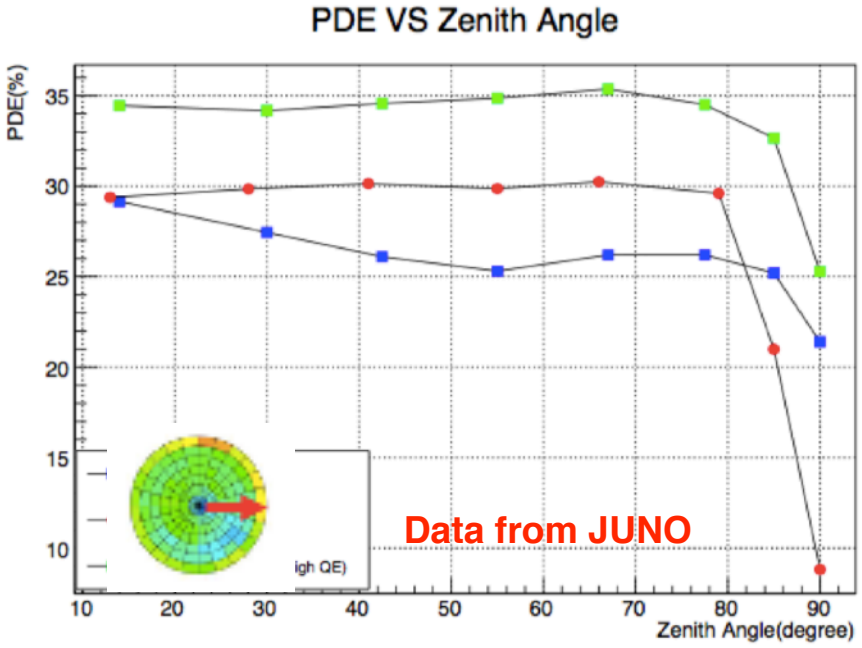
The average data of the QE uniformity of 3000 piece PMTs

DE angular response

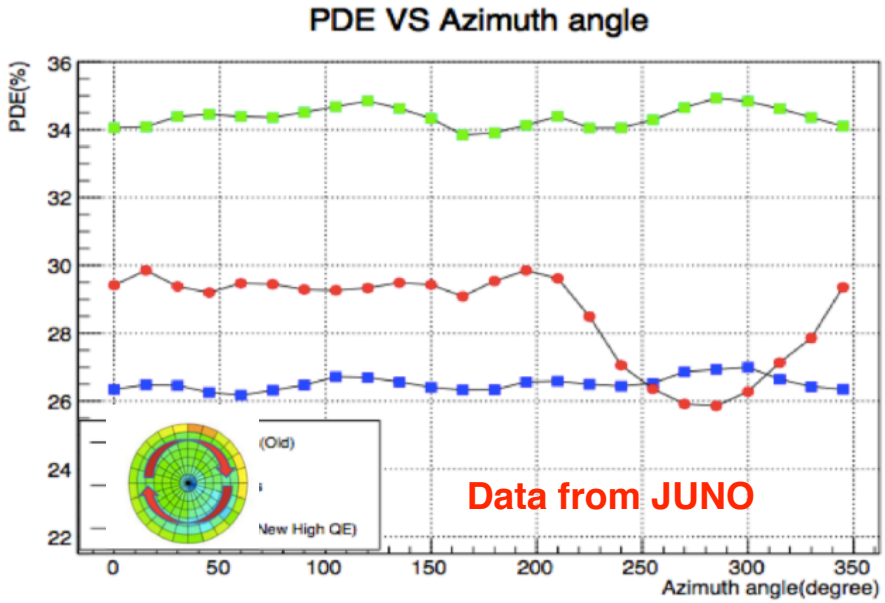
—**Green line**：shows the HQE MCP-PMT tube;

—**Blue Line**：shows the typical MCP-PMT tube；

—**Red Line**：shows the typical Dynode-PMT tube；



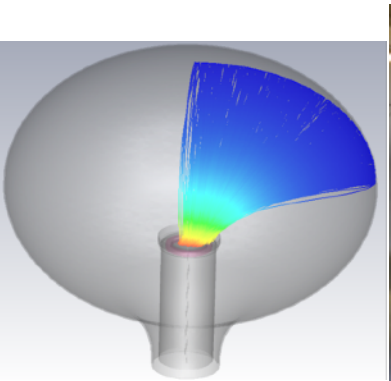
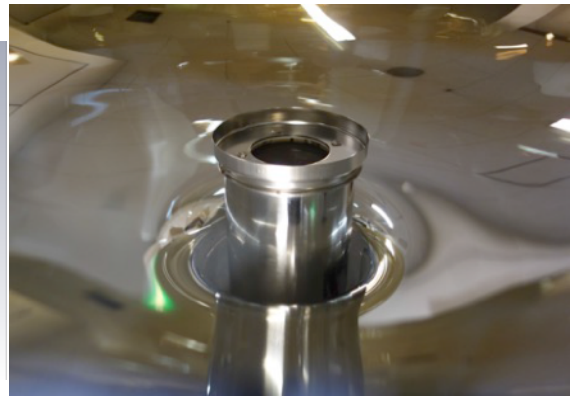
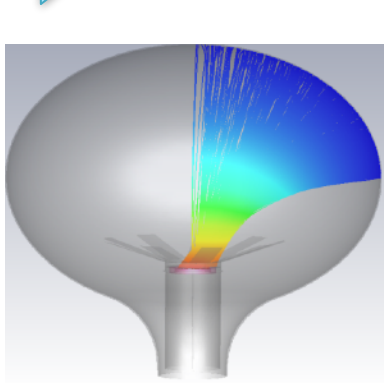
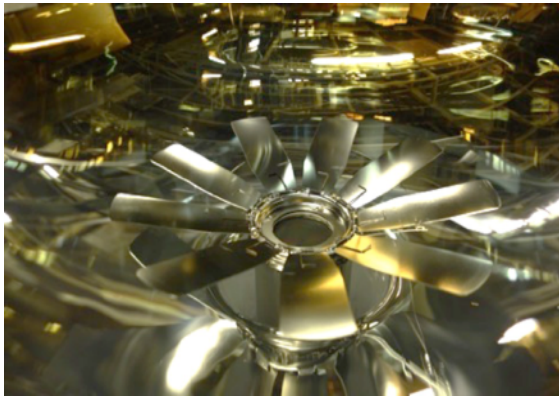
DE uniformity with Longitude



DE uniformity with Latitude

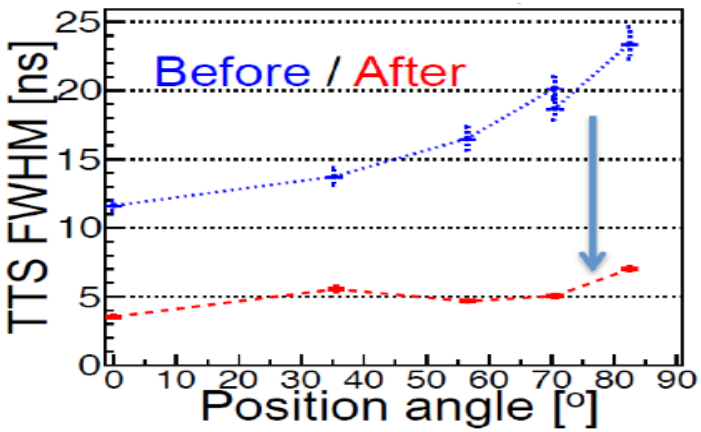
3.2 the improvement of the TTS for HyperK

Normal focusing electrode → Flower-like focusing electrode

—By changing the constructer of the focusing electrode, using the flower-like one, the TTS of the PMTs is improving from 20ns to 5ns, but the CE of the prototype is decreasing to 85%,

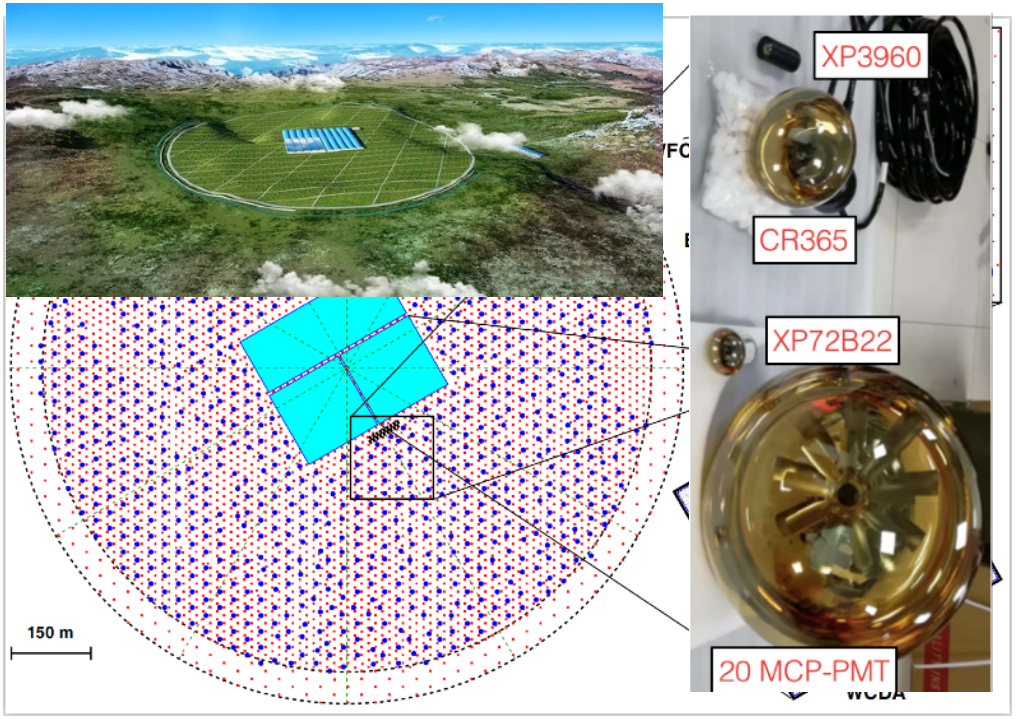
—By decrease the area of the photocathode for better TTS, the dark rate of the PMT also much better than the normal one, from 40KHz to 20KHz.



Characteristics	Normal focusing electrode		Flower-like focusing electrode
QuantumEfficiency（400nm）	~30%		~30%
Relativity Detection Efficiency	~ 100%	↓	85%
P/V of SPE	~ 7	↓	~ 5
TTS on the top point	~20ns	↑	5 ns
Anode Dark Count	~40KHz	↑	~20KHz

3.3 The Flower-like-PMT for LHAASO

Application of the Flower-like-PMTs



—LHAASO（Large High Altitude Air Shower Observatory), has already ordered 2270 pics 20" Flower-like-MCP-PMT.

—The 20 inch Prototype with potting has already post to the HyperK PMT Group in Tokyo University for the testing.

—The performance are different from the tubes for JUNO.

Parameters	Average 7K for JUNO	Average 10 for LHAASO
Gain	1X10^7	0.5X10^7
HV	~ 1745V	~ 1880V
SPE-P/V	**~ 7.0**	~ 2.7
QE@400nm	30.1%	29.9%
DE@400nm	**30%**	26.8%
Dark Rate	~ 37KHz	**~ 15KHz**
TTS	~20ns	**~6.5ns**
Rise Time	~ 1.4ns	~ 1.5ns
Fall Time	~25ns	~23ns
APR	≤ 1%	≤ 1%
Linearity <10%	~ 1300pe	**~ 3000pe**

➢ The summary of the R&D of the MCP-PMT

2009 Design

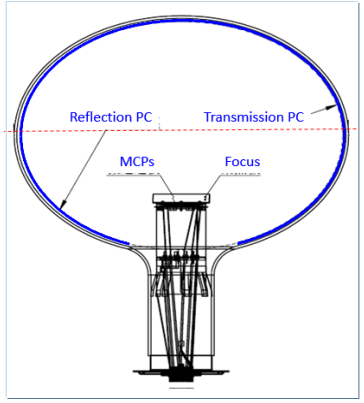
2010-2013 5”(8”) prototype Transmission +reflection

2014-2015 20” prototype Transmission +reflection

2016 Production line batch test sys

Mass production Batch test

2017-2019 **HQE PMT;** New type?



—① The MCP-PMT group has already produced **6K** pics normal MCP-PMTs （**DE=27%@420nm**） for JUNO；

—② The HQE-MCP-PMT with the **DE=30%@420nm** is researched and produced for the last PMTs for JUNO;

—③ The new type of **Flower-liked MCP-PMT** with TTS = 5ns is ready for the **HyperK**;

Many Thanks!

谢　谢！

➢ 2.4 the MCP-PMT parameters Test in NNVT for JUNO

PMT Parameters	data in Contract	Prototype	7055pic PMTs
Quantum Efficiency - QE@400nm	≥ 26.5%	~ 26%	30.1%
QE Uniformity	≤ 15%	≤ 10%	≤ 7.3%
SPE-P/V	≥ 2.8	~ 5.6	~ 7.0
HV@1X10^7	~ 2800V	~ 1930V	~ 1745V
Detection Efficiency @400nm	?	~ 26%@400nm	~ 30.1%@400nm
Detection Efficiency @420nm	≥ 24%@420nm	?	~ 27.5%@420nm
Dark Rate	≤ 50KHz	~ 30KHz	~ 37KHz
TTS	≤ 15ns	~12ns	~20ns
APR	≤ 5%	~ 2.5%	≤ 1%
Linearity <10%	≥ 1000pe	~ 1000pe	~ 1300pe
Rise Time	≤ 2ns	~ 1.2ns	~ 1.4ns
Fall Time	≤ 12ns	~10.2ns	~25ns