中国科学院高能物理研究所
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The Chinese Academy of Sciences

The R&D and Mass Production of the 20 inch MCP-PMT in China

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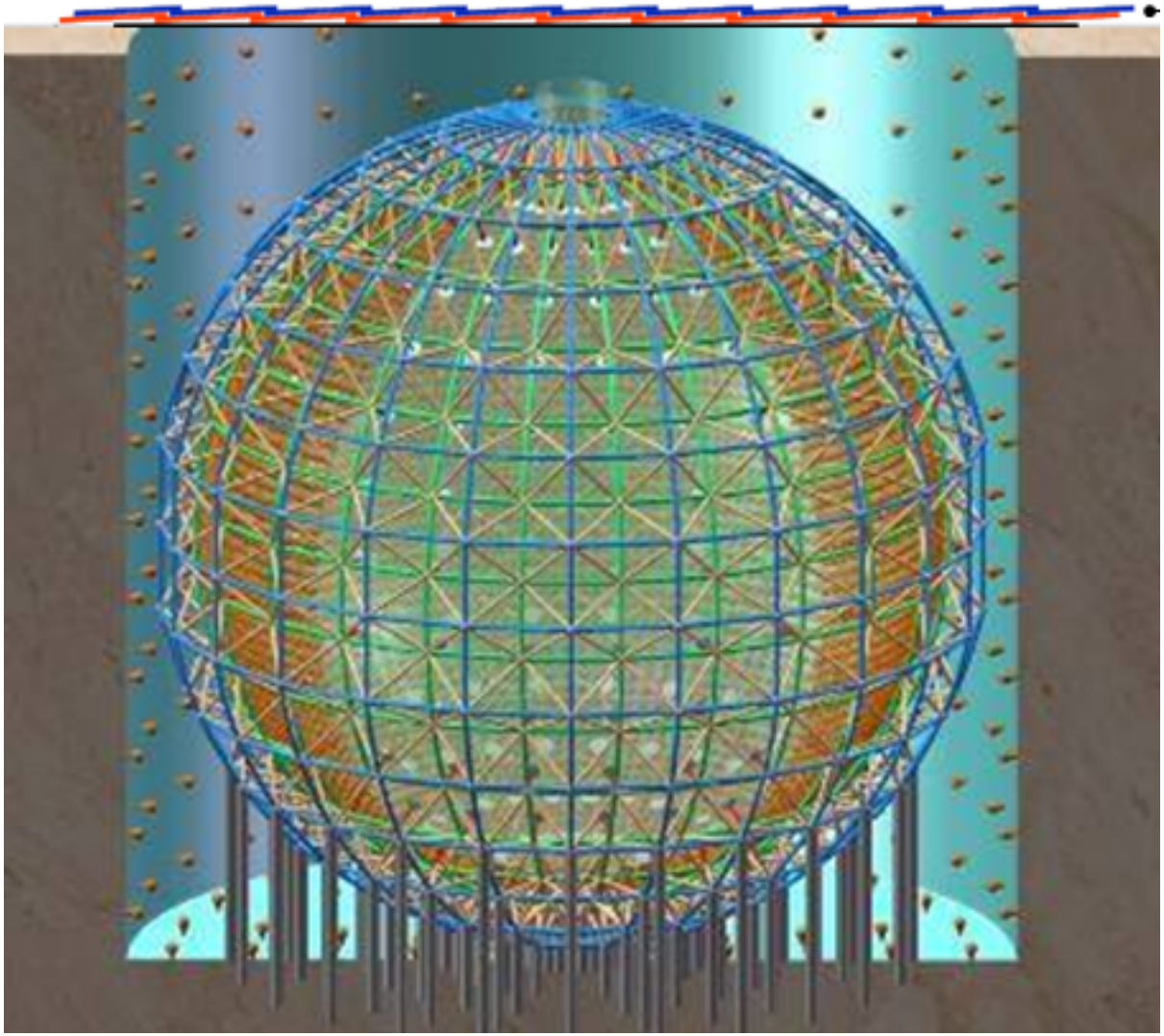
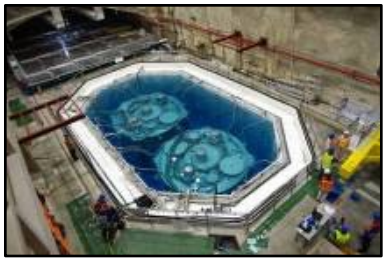
➢ 0. The Neutrino Experiment in China

➢ 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;

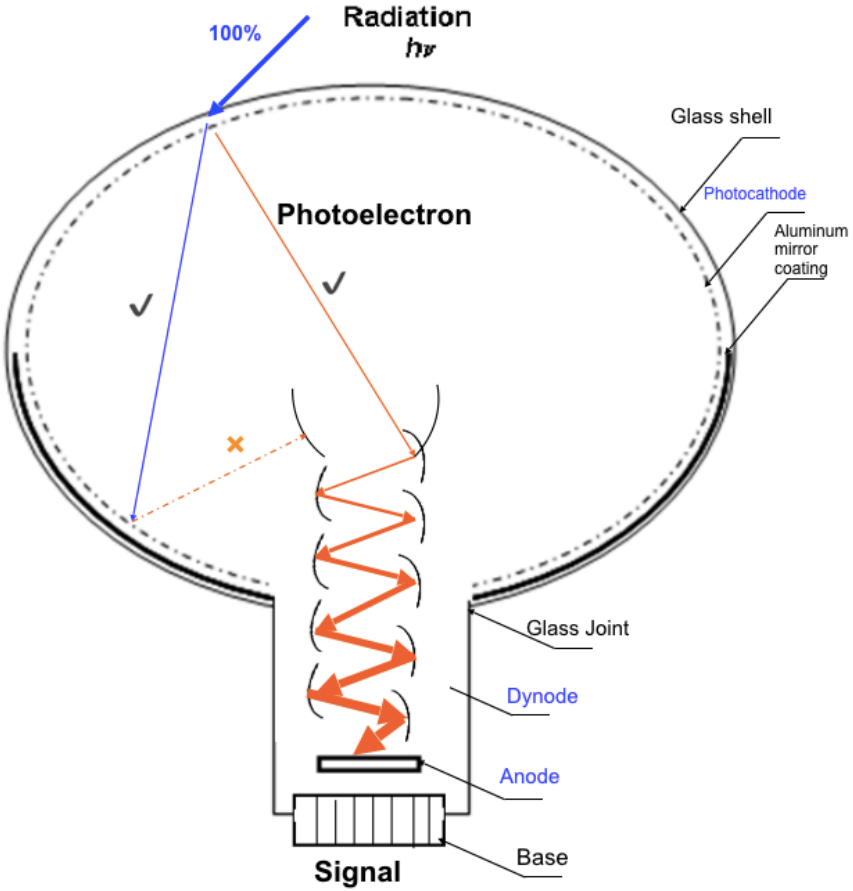
- **2. The Mass production and Batch test; (2016-2019)**

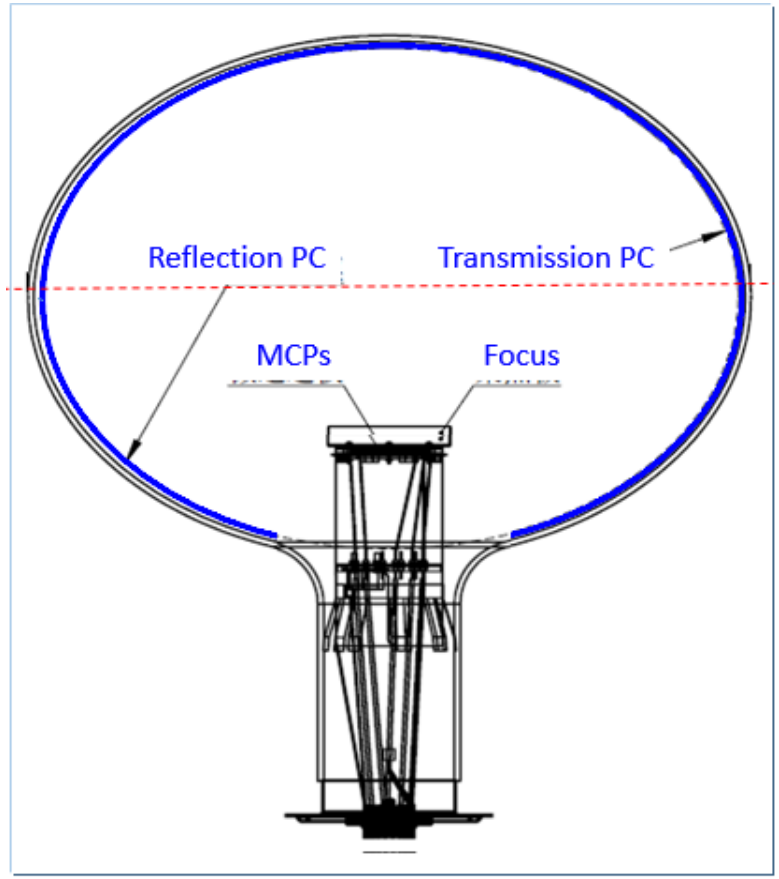
- **3. The improvement of the MCP-PMTs; (2016-2018)**

  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

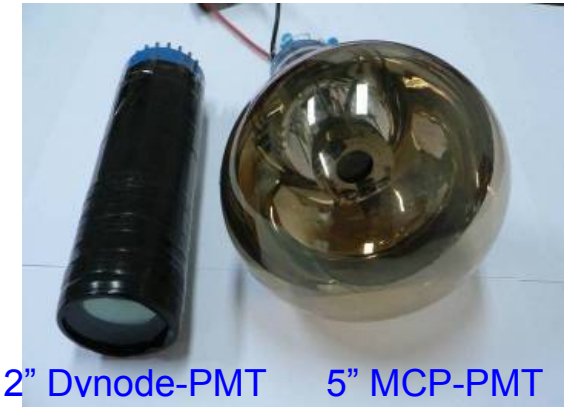
= 20% * 70% = 14% (2009)

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

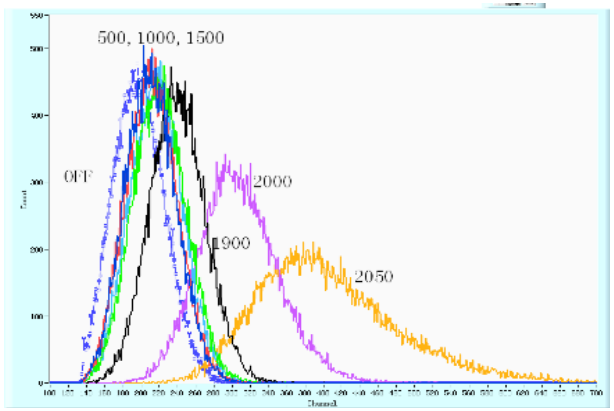
MCP :(PDE)= QE_{Trans} * CE

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

➢ 1.1 The prototypes without SPE at the beginning



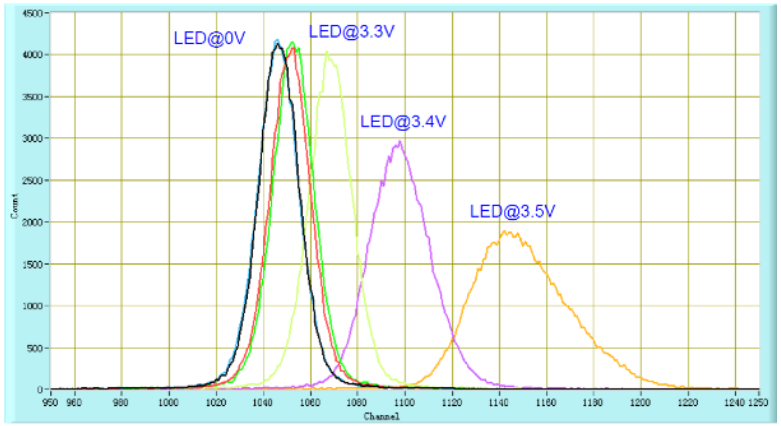
2” Dynode-PMT 5” MCP-PMT



➢ MPE vs the Voltage of the PMT

➢ 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.

5” MCP-PMT 8” MCP-PMT

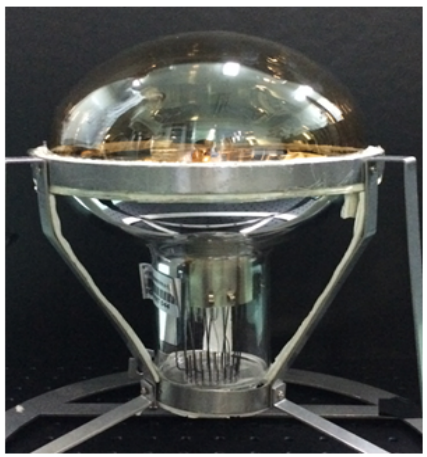


➢ MPE vs the Voltage of the LED

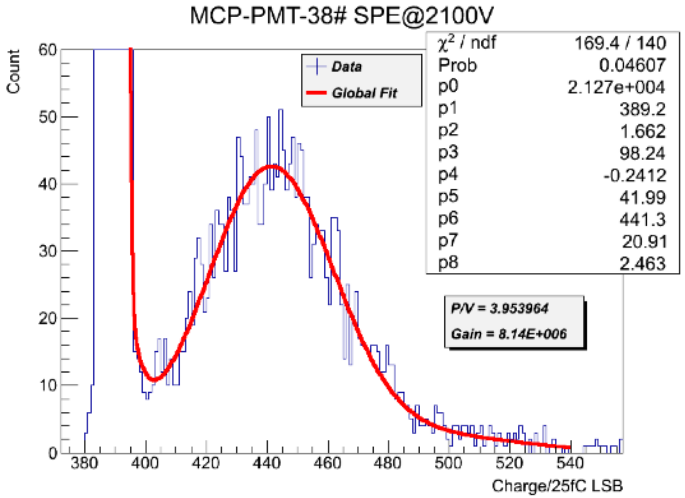
The 8 inch MCP-PMT was produced in 2012, which could get the best signal of the MCP modules, but still without the SPE anyway.

➢ 1.2 The 8 inch prototypes with normal performance--2013

➢ **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 is better than the Dynode-PMTs.



The 8 inch MCP-PMT prototype



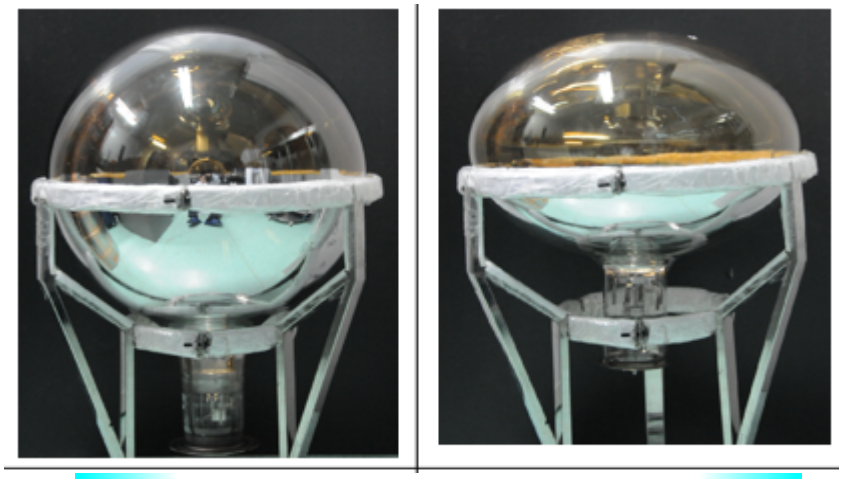
The SPE of the MCP-PMT prototype

➢ The performances of these types of 8 inch MCP-PMT were as good as the ones of normal dynode-PMTs, but the CE was only 70%, not the same as we designed.

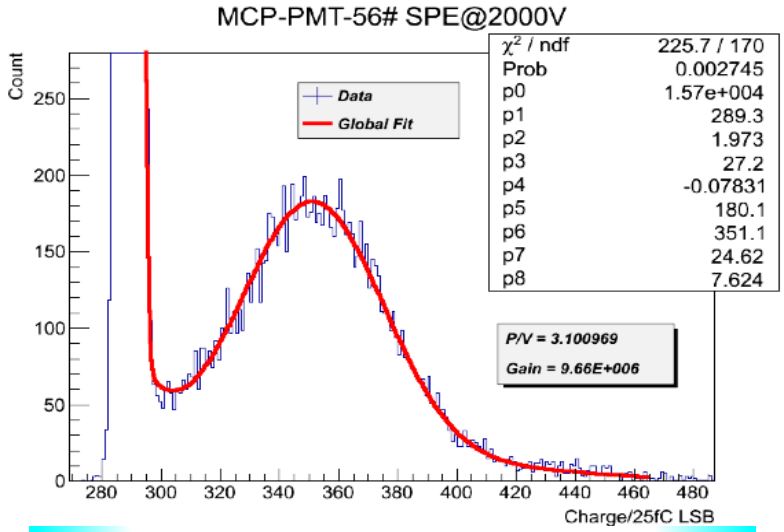
HV	Gain	P/V	Rise Time	Fall Time	Dark rate @1E7 Gain(0.25PE)	QE@400nm	CE
2100V	~1E7	~4	~1.3ns	~8.8ns	~3kHz	25%	70%

1.3 the 20 inch prototypes with normal performance--2014

- **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 8 inch MCP-PMT prototype

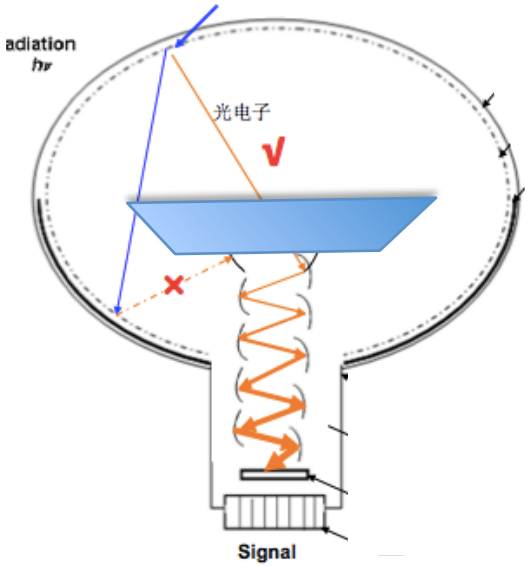


The SPE of the MCP-PMT prototype

- 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%.

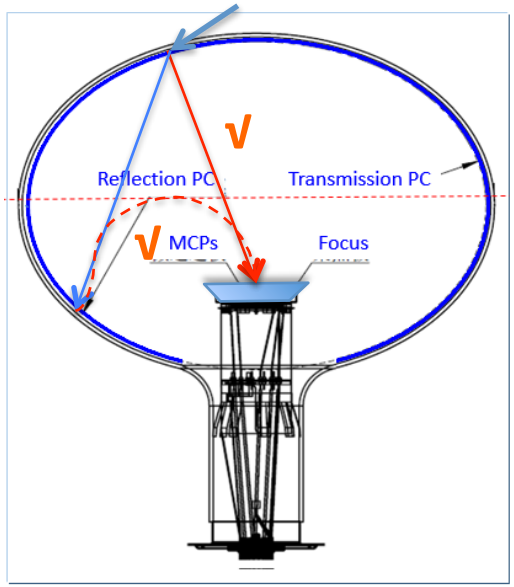
HV	Gain	P/V	Rise Time	Fall Time	Dark rate @1E7 Gain(0.25PE)	QE@400nm	CE
2000V	~1E7	~3	~1.2ns	~15ns	~50kHz	25%	70%

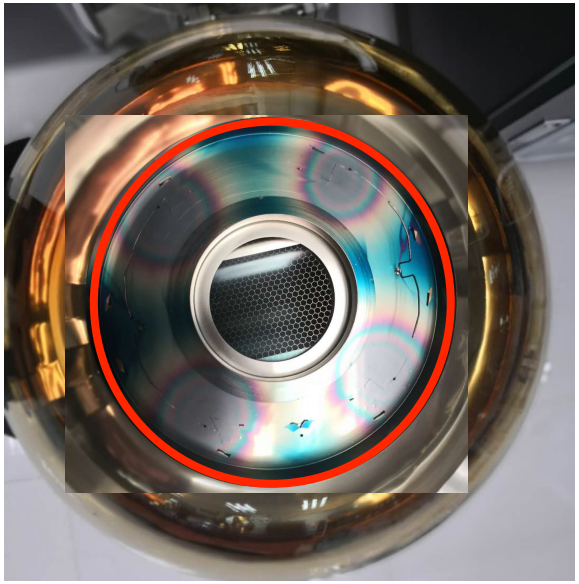
In 2015, the MCP-PMT work group did the best to improve the CE of the MCP modules, and finally, the CE of the MCP-PMTs was improved from 70% to 100% successfully.



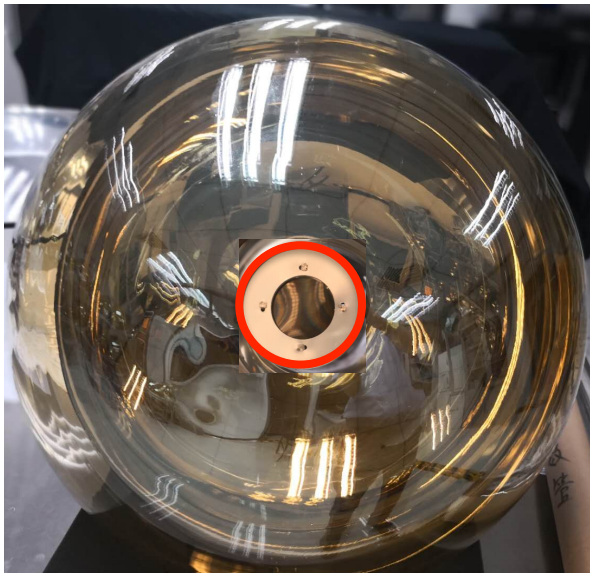
QE=20% → QE=30%

CE=70% → CE=100%

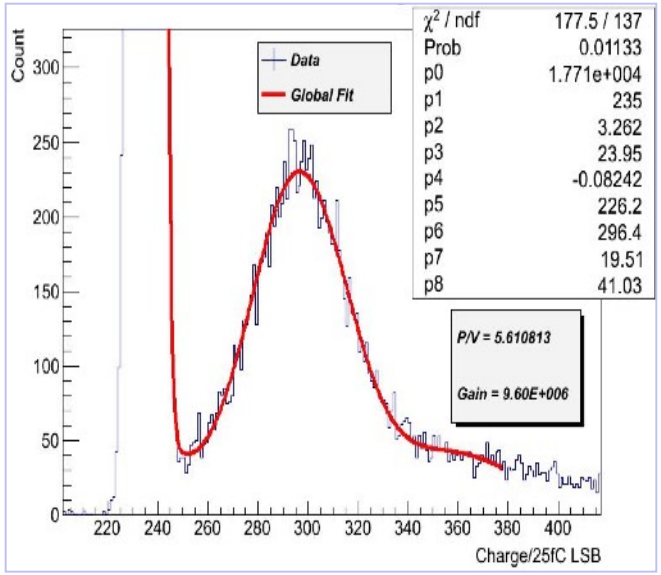




DE=14% → DE=30%



1.4 the 20 inch prototypes with HDE performance--2015



SPE of the Prototype

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

- The QE of the Trans.+Ref. photocathode together could be 30% @400nm; The CE of the MCP increased to 100%, so the total DE of the MCP-PMT could be 30%@400nm;
- The Glass of the MCP-PMT is also special with the low potassium glass to decrease the radioactivity of the PMT materials.
- Because of the large area Trans.+Ref. photocathode, the high collection efficiency MCPs, the small electronic focus, the TTS of the 20inch MCP-PMT was worse.

1.5 PMT Purchasing of JUNO

Characteristics	unit	MCP-PMT（NNVC）	R12860 （Hamamatsu）
Detection Eff.(QE*CE*area)	%	27%, > 24%	27%, > 24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2 , F~12	R~5, <7; F~9, <12
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40

Decision based on

risk,

price,

performance merit for physics

15k MCP-PMT (75%) from NNVT

5k Dynode (25%) from Hamamatzu

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;

➢ 2.1 The Batch Result —Quantum Efficiency (QE)

20 inch PMTs	Dynode-PMTs	MCP-PMT prototype	~6047 MCP-PMTs
QE.Trans @ 400nm	30%	26%	29.6%
Uni-QE @ 400nm	< 10%	7.8%	7.2%

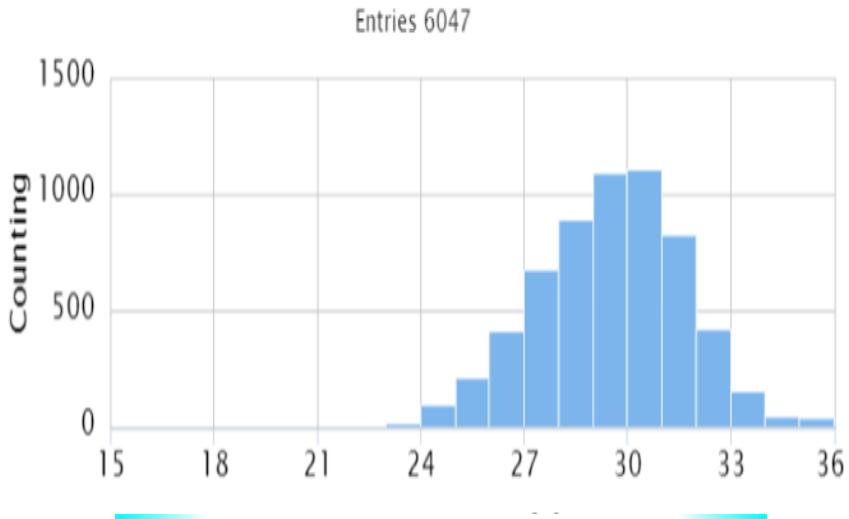
– The Quantum Efficiency of the photocathode is really improved during the mass production process.

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

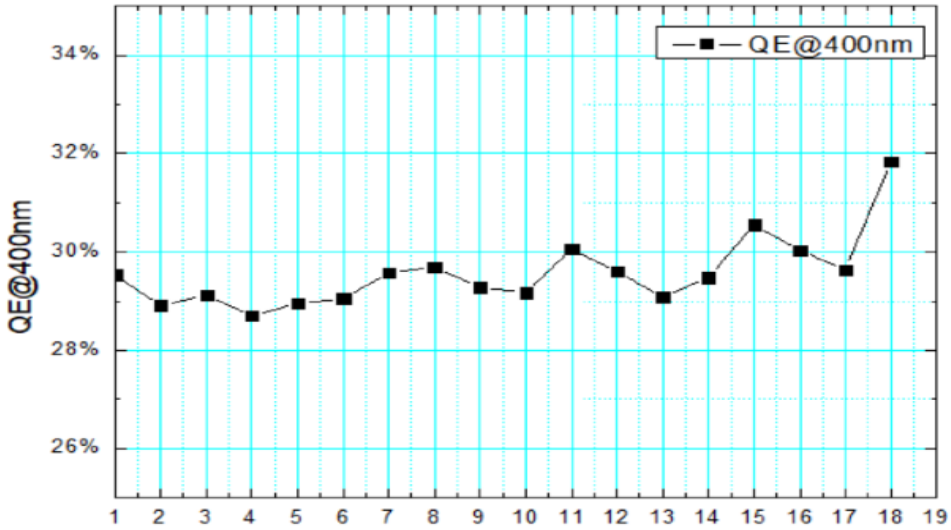
– The DE Uniformity of the PMT is affected by the QE Uniformity of the Photocathode;

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

20 inch PMTs	Dynode-PMTs	MCP-PMTprototype	~6047 MCP-PMTs
TTS @ FWHM	2.8 ns	13.2 ns	20.2ns
TTS @sigma	1.19 ns	5.62ns	8.61ns
RT @ Gain~1X10^7	6.7 ns	1.2 ns	1.4 ns
FT @ Gain~1X10^7	17.7 ns	10.2 ns	25.4 ns

—The Rise time of the MCP-PMTs is really fast within **1.4ns** for the average of 6K pics.

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

--> the large area photocathode for better QE,

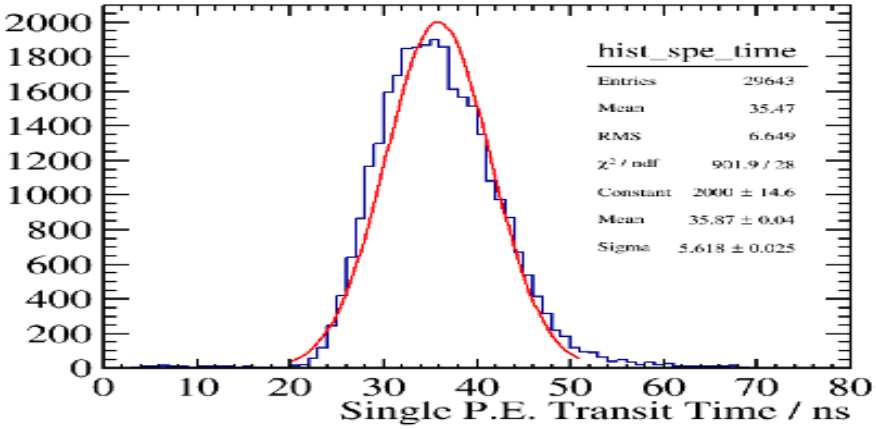
--> the special MCPs for better CE,

--> 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

Waveform of the MCP-PMT

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

20 inch PMTs	Dynode-PMTs	MCP-PMT prototype	~6047 MCP-PMTs
P/V of SPE @ Gain~1X10^7	3.7	5.6	7.0
DE @ 400nm	27%	26%	29.5%

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

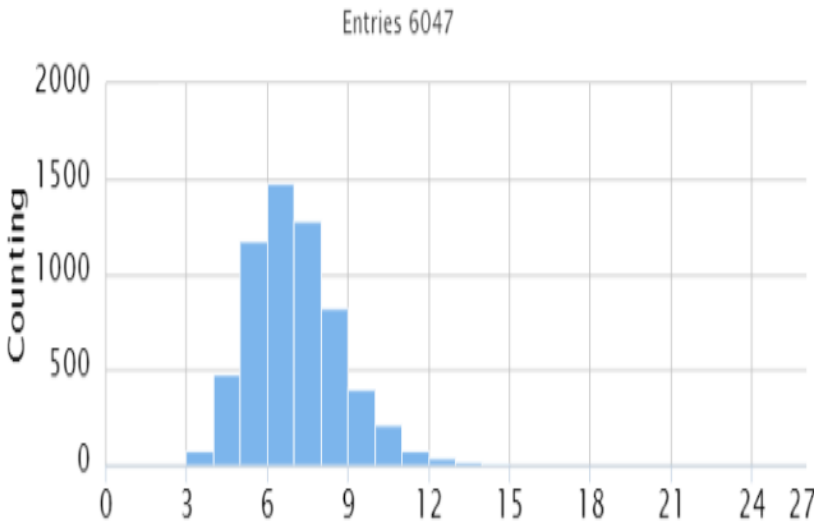
the P/V of the SPE is improved from 5 to 7 in the mass production process, better than the Dynode one.

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

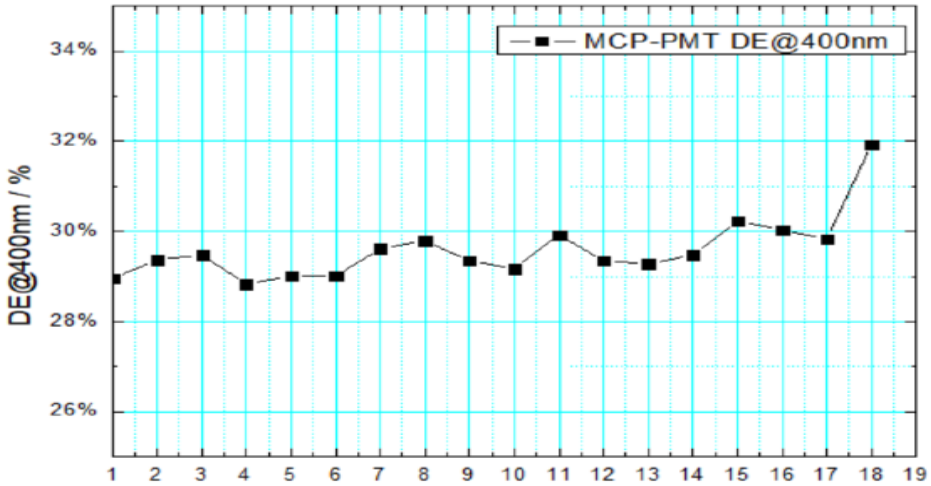
—With the improved technology of photocathode, the QE is increasing to 30%;

the DE of the MCP-PMTs is improved from 26% to nearly 30% (the average data of the 6K pics)

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



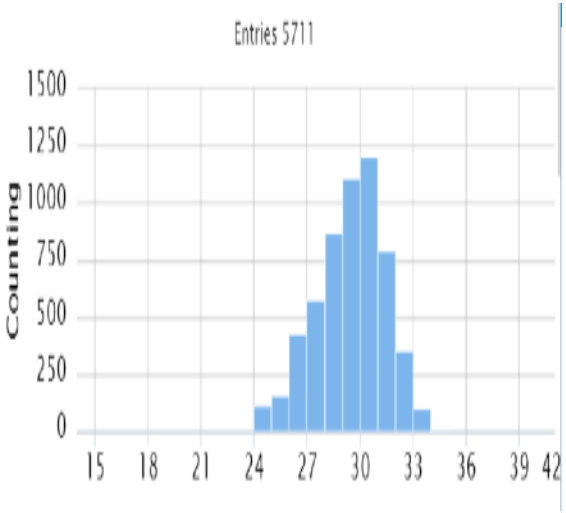
P/V of the SPE



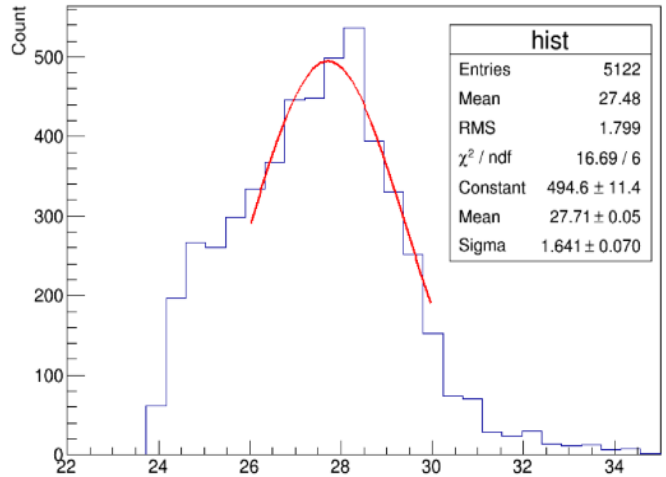
Average DE for different batch from NNVT to JUNO

—The DE of the MCP-PMTs from the NNVT bath test is about 29.46% @ 400nm;

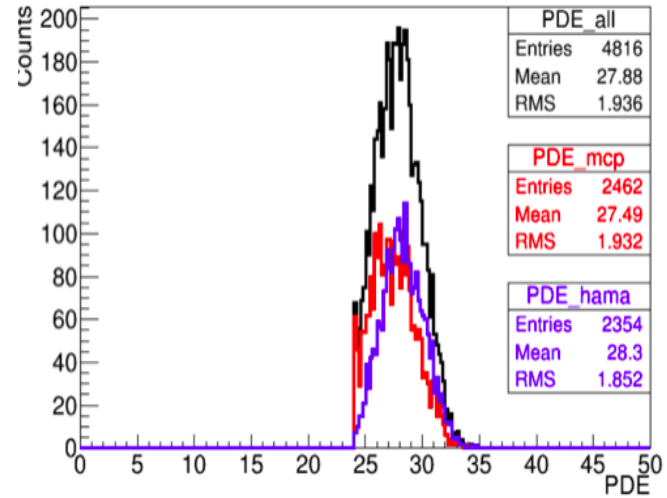
But the JUNO ordered the DE@420nm.



DE=29.46% @400nm @NNVT



DE=27.48% @420nm @NNVT



DE=27.49% @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 5K MCP-PMTs is about **27.48%** in the NNVT batch test.

—The average DE@420nm of 2.5K MCP-PMTs is about **27.49%** in the JUNO batch test;

More about the PMTs tested in JUNO, see the Wei Wang & Zhonghua Qin's talk in the Detector section.

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

PMT Parameters	data in Contract	Prototype	6000pic PMTs
Quantum Efficiency - QE@400nm	≥ 26.5%	~ 26%	29.6%
QE Uniformity	≤ 15%	≤ 10%	≤ 7.2%
SPE-P/V	≥ 2.8	~ 5.6	~ 7.0
HV@1X10^7	~ 2800V	~ 1930V	~ 1745V
Detection Efficiency @400nm	?	~ 26%@400nm	~ 29.5%@400nm
Detection Efficiency @420nm	≥ 24%@420nm	?	~ 27.5%@420nm
Dark Rate	≤ 50KHz	~ 30KHz	~ 36KHz
TTS	≤ 15ns	~12ns	~20ns
APR	≤ 5%	~ 2.5%	≤ 1%
Linearity <10%	≥ 1000pe	~ 1000pe	~ 1200pe
Rise Time	≤ 2ns	~ 1.2ns	~ 1.4ns
Fall Time	≤ 12ns	~10.2ns	~25ns

Outline

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

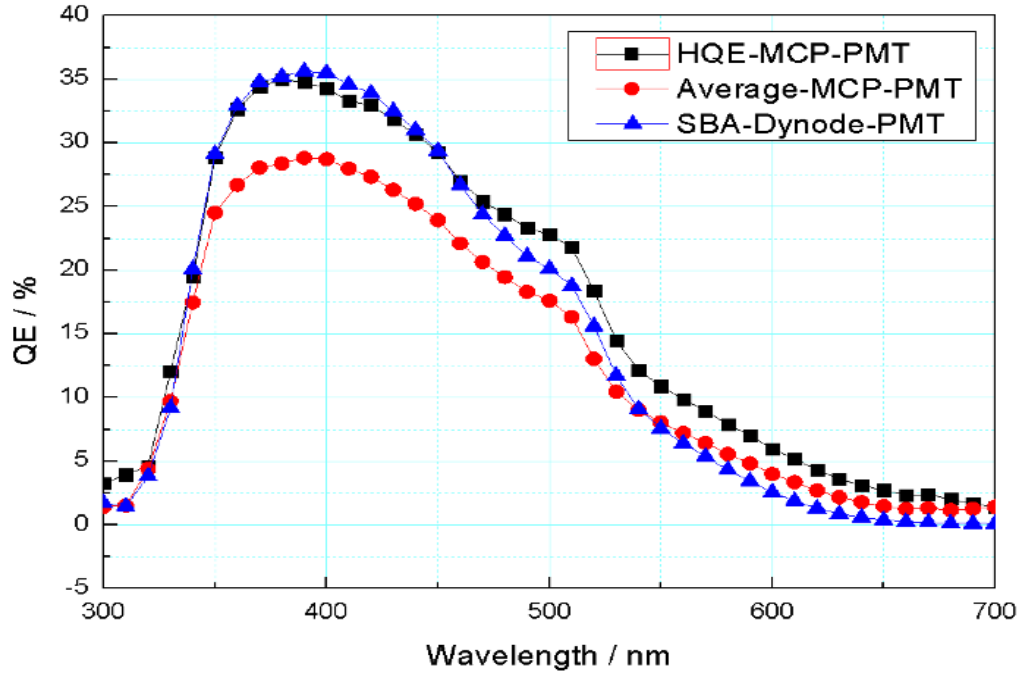
  the 8 inch， the 20 inch， the high PDE prototypes；

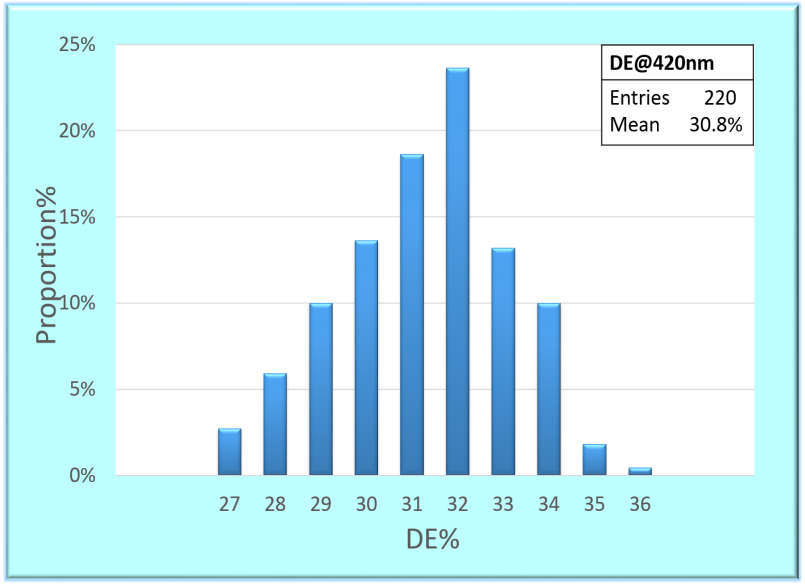
- **2. The Mass production and Batch test;（2016-2019）**

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

  the High QE prototypes, the fast prototypes;

➢ 3.1 the improvement of the QE & DE for JUNO





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

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

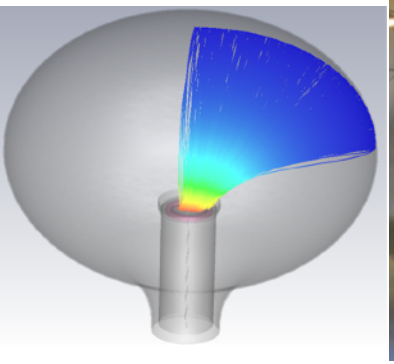
The average DE=**27.5%**@420nm of 6K pics normal MCP-PMTs

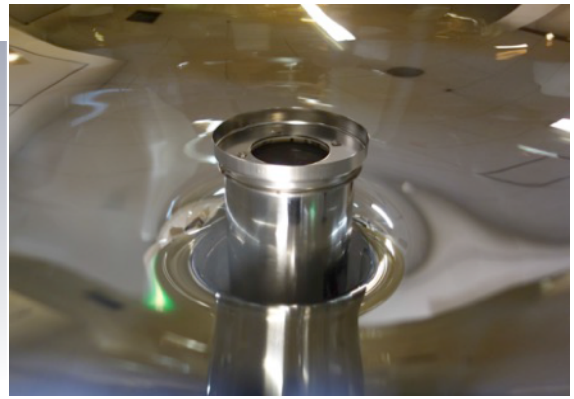
The average DE=**30.8%**@420nm of 200 pics HQE-MCP-PMTs

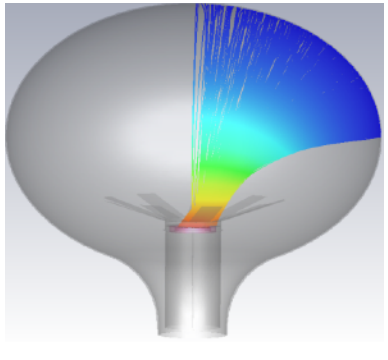
PMTs	Hamamatsu	MCP-PMT prototype	~6000 Normal MCP-PMTs	~200 HQE-MCP-PMT
QE @ 400nm	30%	26%	29.5%	32%
DE @ 420nm	28%	—	27.5%	**30.8%**

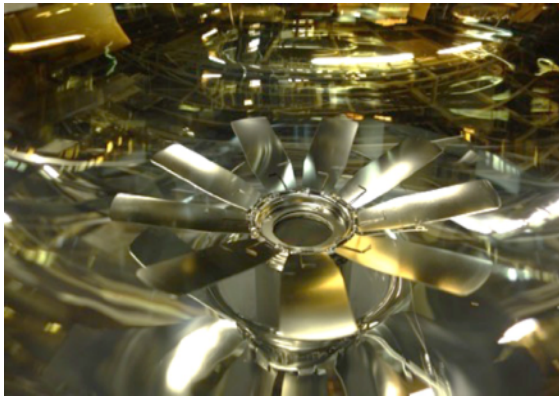
➢ 3.2 the improvement of the TTS for HyperK

Normal focusing electrode → Flower-like focusing electrode



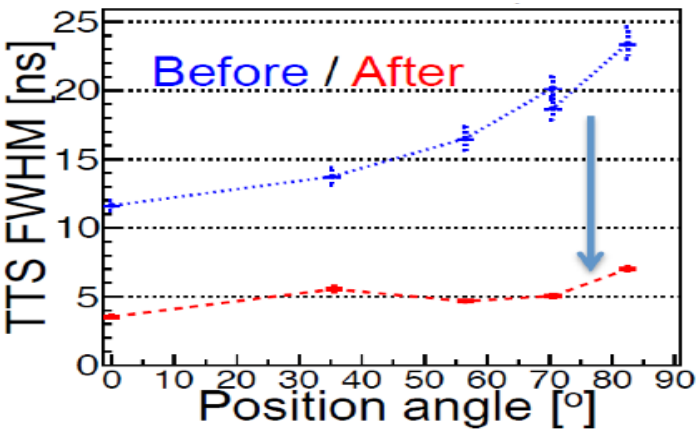






—By changing the constructer of the focusing electrode, using the flower-like one, the TTS of the PMTs is improving from 20ns to 5ns, but the CE of the prototype is decreasing to 85%,

—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

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

2009 Design

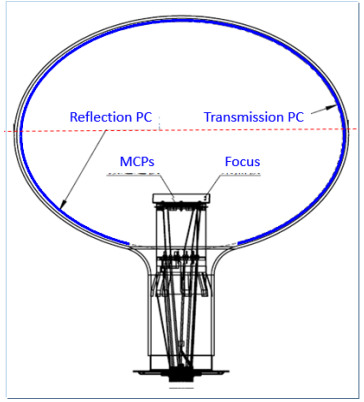
2010-2013 5”(8”) prototype Transmission +reflection

2014-2015 20” prototype Transmission +reflection

2016 Production line batch test sys

2017-2019 Mass production Batch test

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**;

Thanks for your attention!
Any comment and suggestion are welcomed!

Many Thanks!

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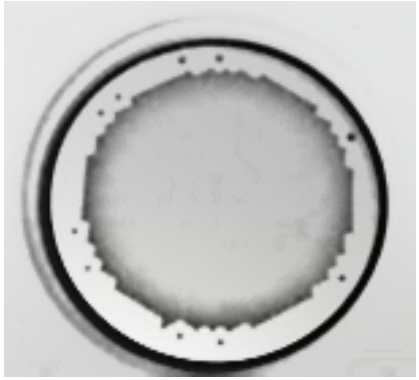
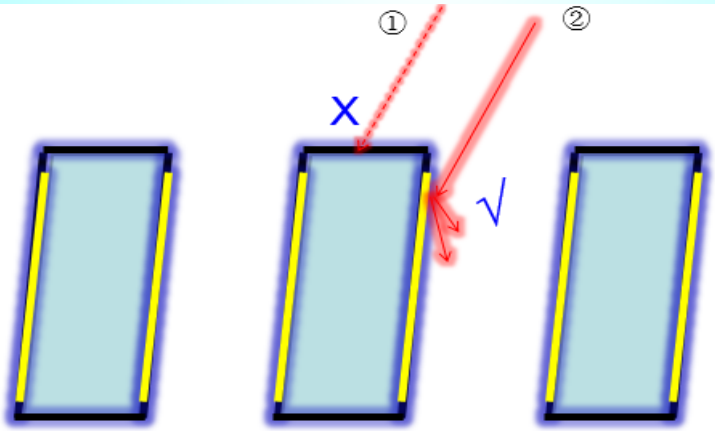
How to improve the Collection Efficiency of the MCP modules (2015)





CE = 70%

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

The Diameter of the MCP: **33mm; 50mm;**

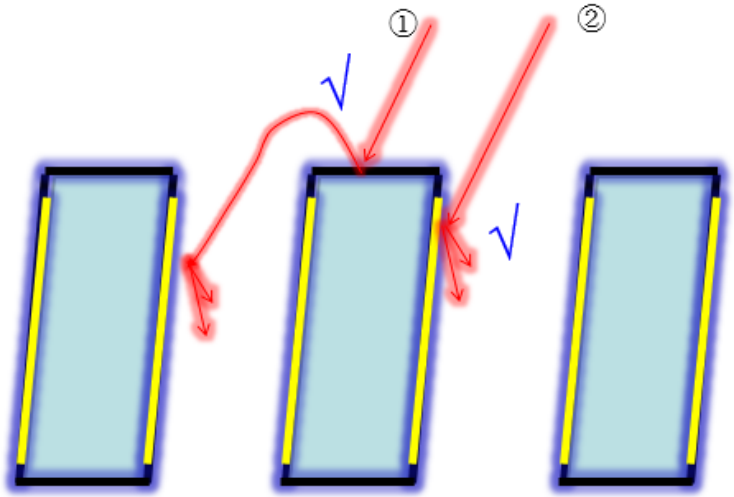
The Diameter of the Hole: **6um; 8um; 10um; 12um**;

The Inclined Angle: **0°**; **8°**; **12°**;

The Open Area Ratio: **60%**; **77%**;

The Depth of output electrode:……

change

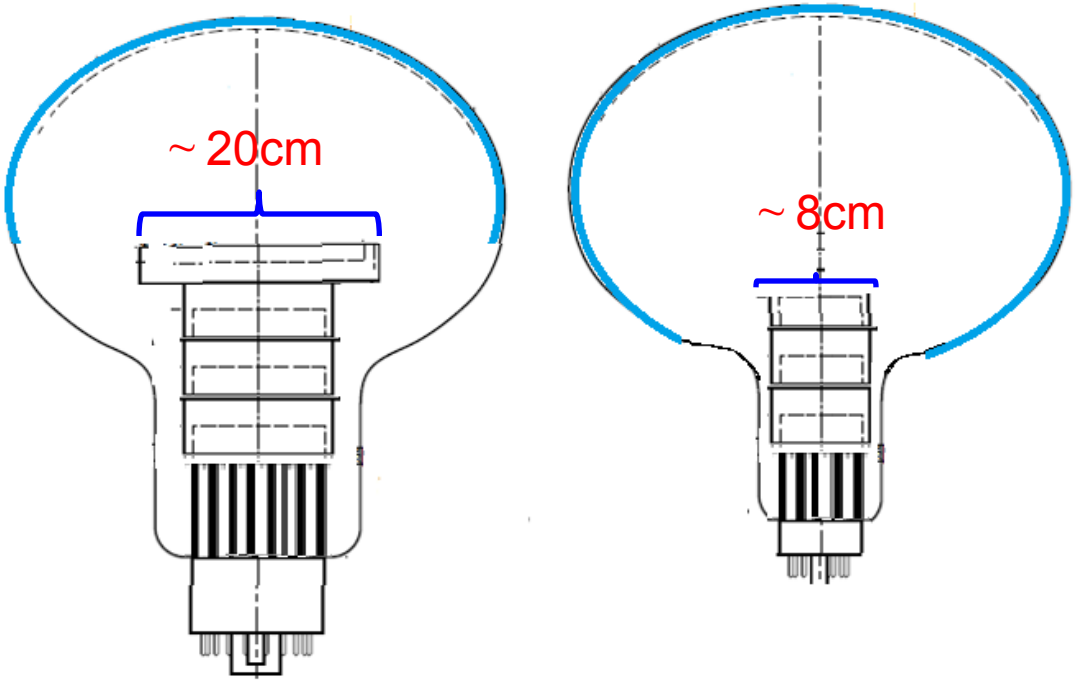


CE = 100%

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

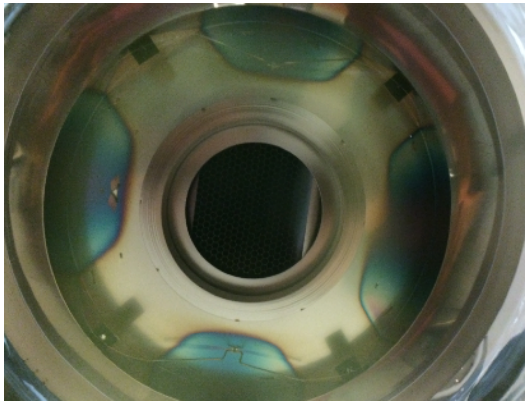
The p.e. from the electrod indirectly ~ 30%

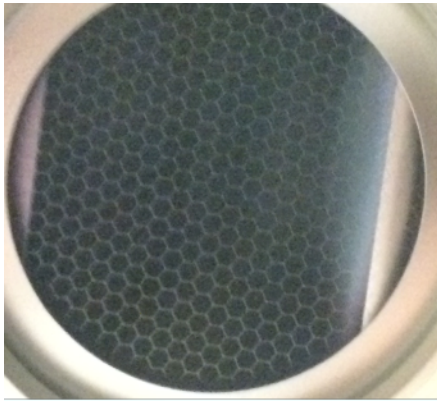
➢ MCP: Large area PC (Rrf. + Tran.)



Prototype	Relativity DE	Relativity DE
Dynode-PMT	100%	**90%**
MCP-PMT	110%	**100%**

➢ Dynode: A mesh covering the dynode

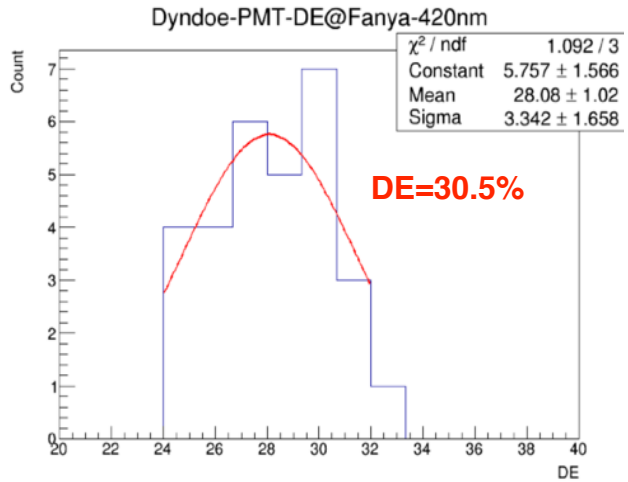


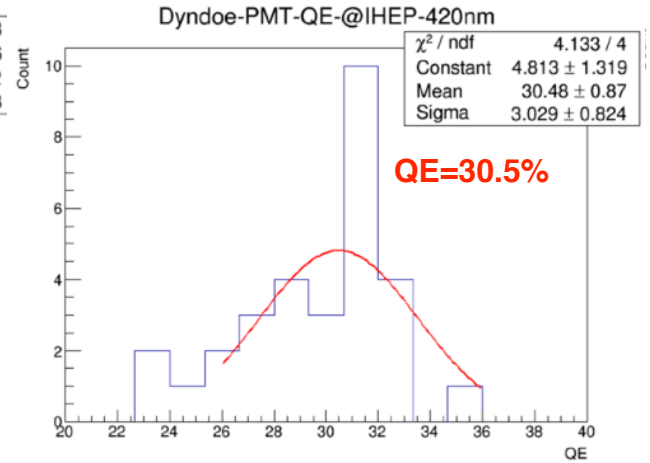


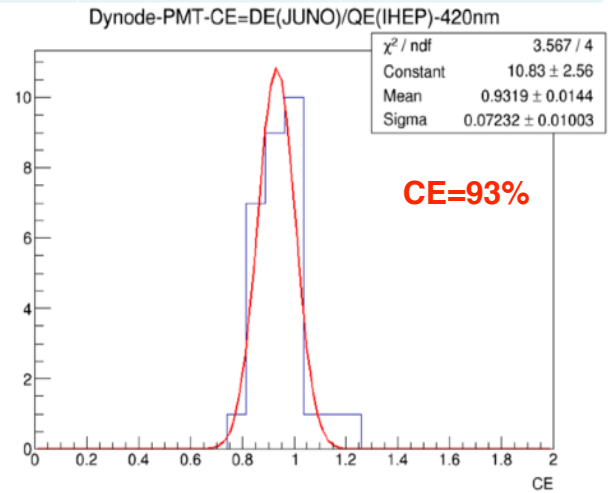
➢ MCP: Special MCP for CE~100%

➢ **~30 pics 20 inch Dynode-PMTs**

Type	QE@420nm	DE@400nm	CE@420nm
Dynode	30.5%	28.1%	**~93%**

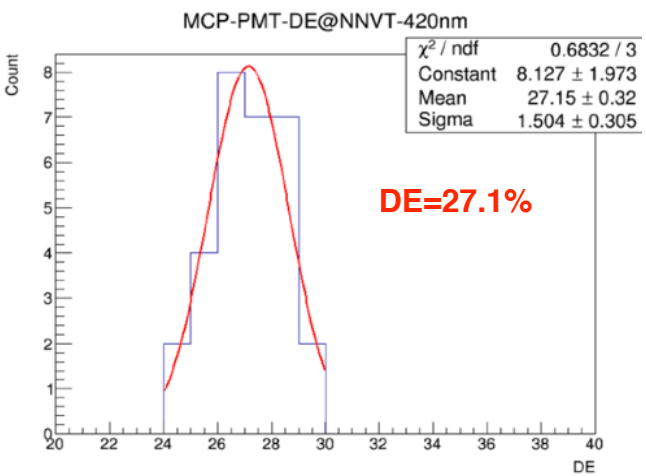


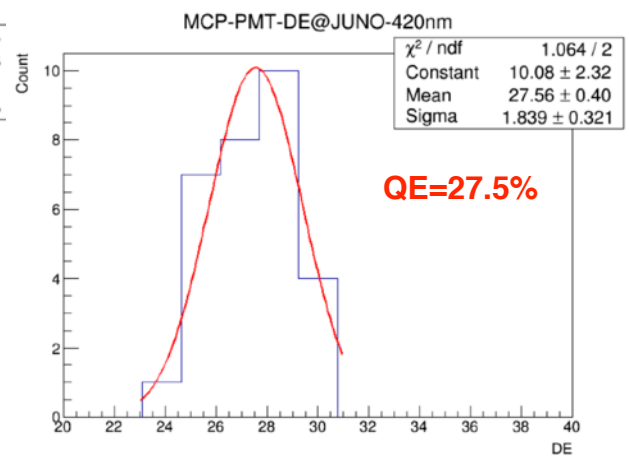


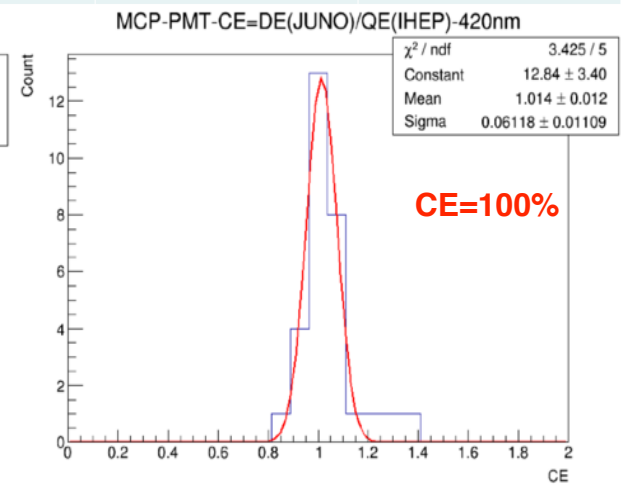


➢ **~30 pics 20 inch MCP-PMTs**

Type	QE@420nm	DE@400nm	CE@420nm
20 inch MCP-PMTs	27.5%	27.1%	**~100%**

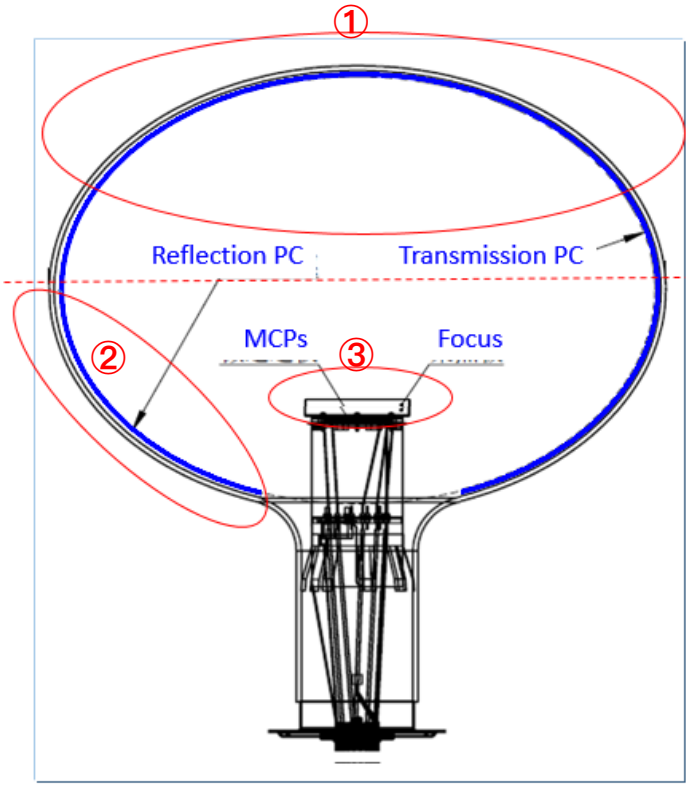


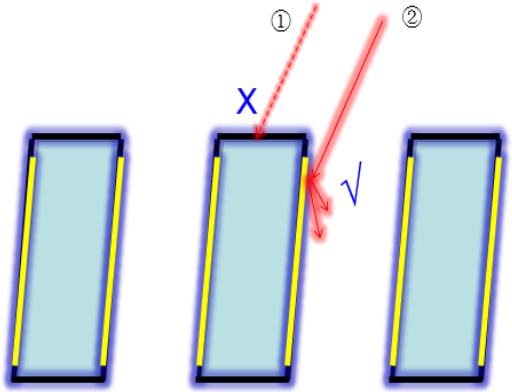


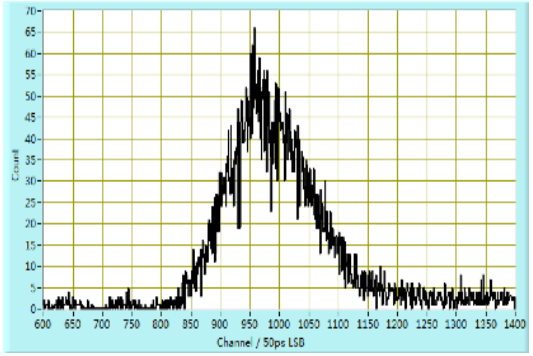


➢ How to improve the TTS

Why is the TTS so Large!

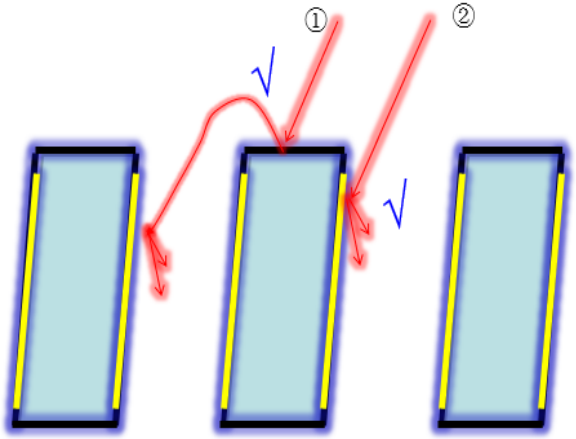


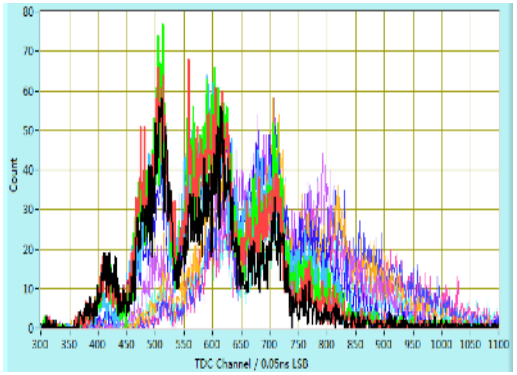




➢With the contribution of the second electron from the electrode (30%),

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





The prototype

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

--> with special MCP for better DE;

But the TTS will be worse!