The R&D of Microchannel-Plate-Based Large Area Photomultiplier (MCP-PMT) at IHEP

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On Behalf of the Workgroup

Beijing-Chicago Workshop on Detector R&D

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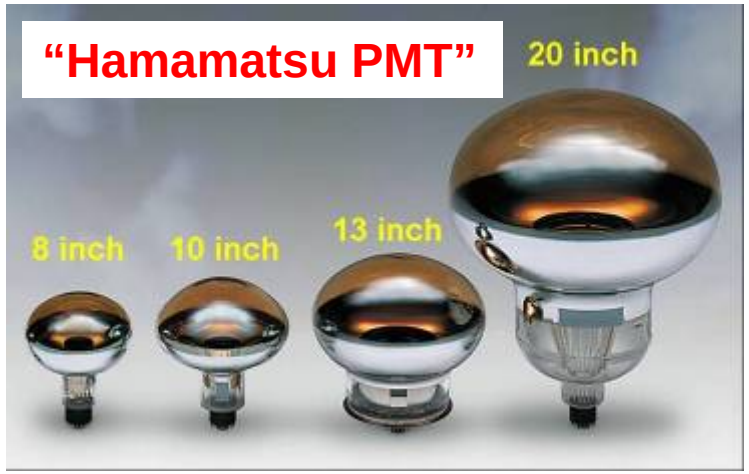
Outline

- 1. The Motivation;
- 2. The Design of the new MCP-PMT;
- 3. The Research project;
- 4. The Status of the MCP-PMT R&D;
- 5. Summary.

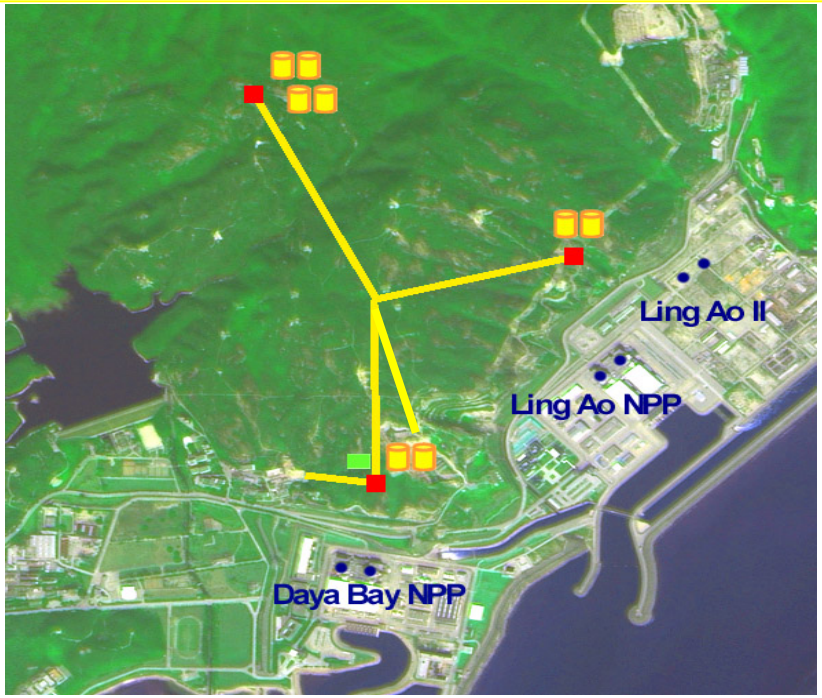
➢ Current and Future Neutrino Experiments

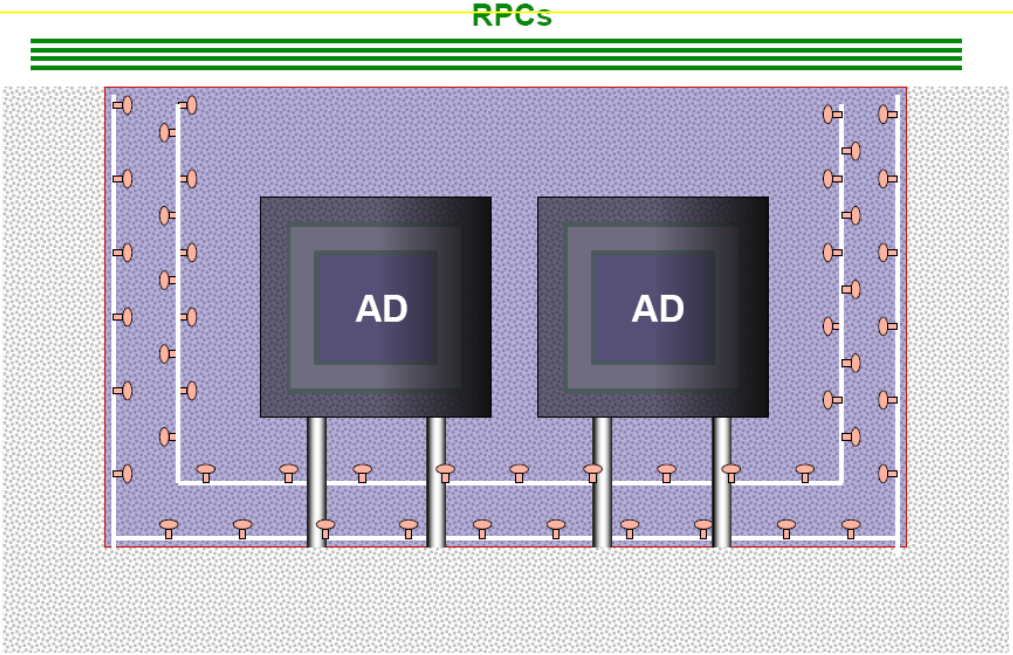


Large Format PMTs for Neutrino Experiments

- **Atmospheric neutrino exp.**
  - **SuperK**,
  - HyperK/UNO,
  - INO,TITAND,…
- **Solar neutrino exp.**
  - **SNO,**
  - GALLEX/SAGE,
  - Borexino, XMASS, …
- **Accelerator neutrino exp.**
  - **T2K,**
  - **Nova**,
  - Minos, OPERA,
  - MiniBooNE,
- **Reactor neutrino exp.**
  - **KamLAND** (Japan),
  - **Daya Bay** (China),
  - **Reno** (Korea),
  - **Double Chooz** (France)
  - **…**

➢ Daya Bay Experiment: Layout

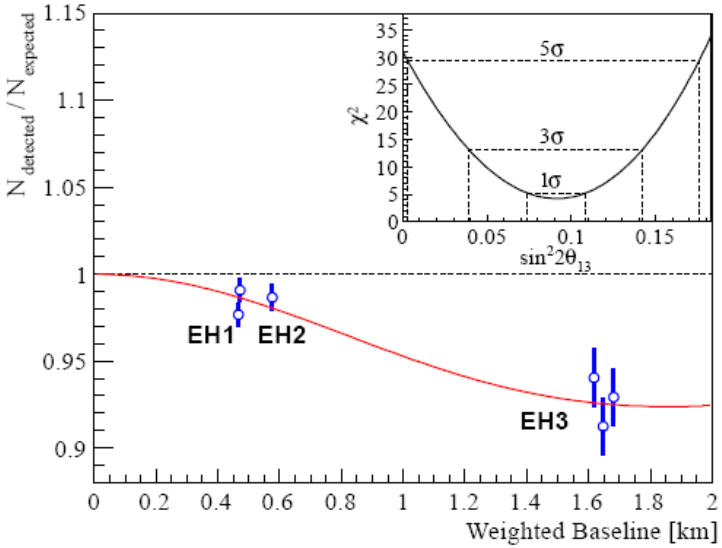




- Relative measurement to cancel Corr. Syst. Err.
  - ⇨ 2 near sites, 1 far site
- Multiple AD modules at each site to reduce Uncorr. Syst. Err.
  - ⇨ Far: 4 modules，near: 2 modules
- Multiple muon detectors to reduce veto eff. uncertainties
  - ⇨ Water Cherenkov： 2 layers
  - ⇨ RPC： 4 layers at the top + telescopes

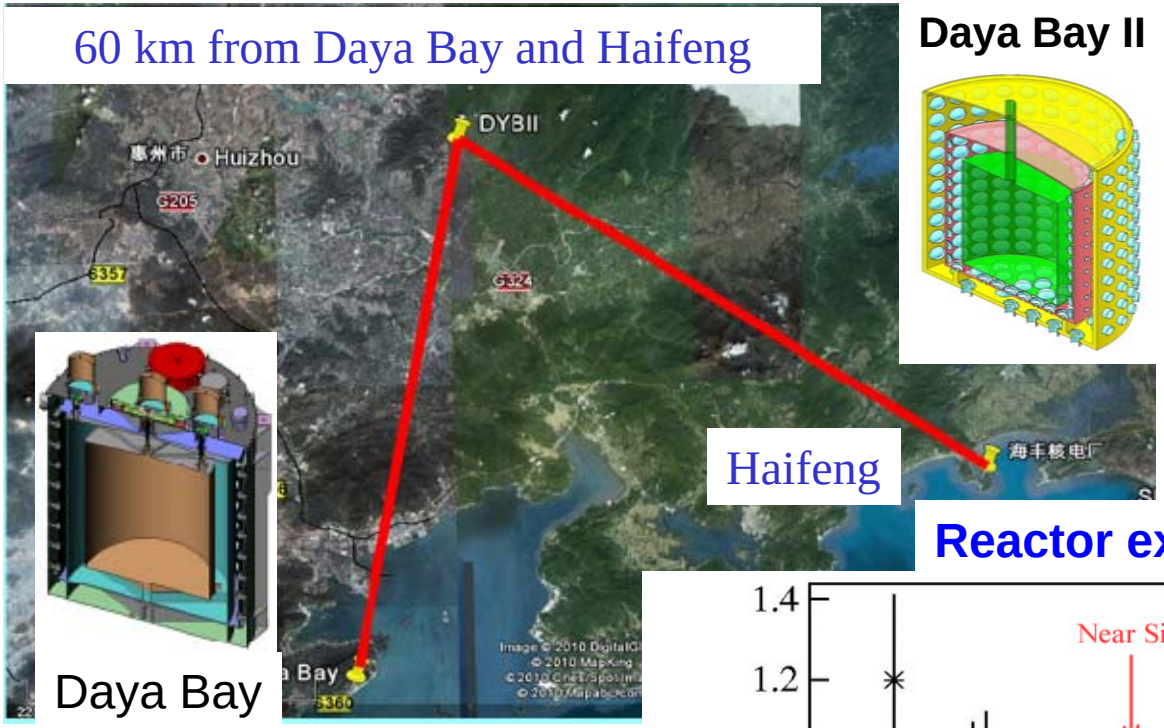
$\mathrm{Sin}^2 2\theta_{13} = 0.092 \pm 0.016(\mathrm{stat}) \pm 0.005(\mathrm{syst})$

$\chi^2/\mathrm{NDF} = 4.26/4$ 5.2 σ for non-zero θ_{13}



Neutrino Oscillation

➢ Next generation Neutrino Experiment in China

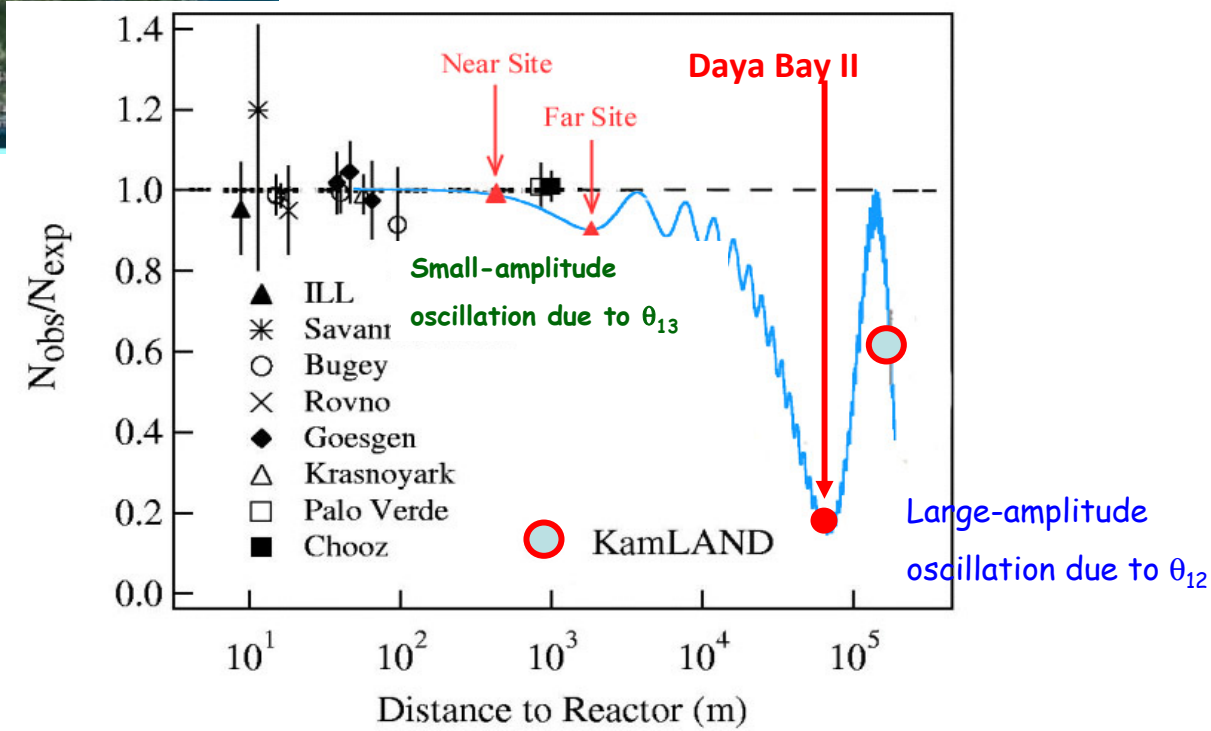


Daya Bay II

The Main Scientific goals:

- ⇨**Mass Hierarchy**
- ⇨Mixing matrix elements
- ⇨Supernovae
- ⇨geo-neutrinos

Reactor experiments:



Measuring Mass Hierarchy

Huge Detector : LS + PMT

Energy resolution ~ 3%/√E

L. Zhan, et. al., Phys.Rev.D 78:111103,2008
L. Zhan, et. al., Phys.Rev.D 79:073007,2009

	KamLAND	Daya Bay II	Daya Bay II
Detector	~1 kt Liquid Scintillator	➢10 kt Liquid Scintillator	➢10 kt Liquid Scintillator
Energy Resolution	6%/√E	2%/√E	3%/√E
Light yield	250 p.e./MeV	2500 p.e./MeV	1100 p.e./MeV

How? ×10

- **Ongoing R&D:**

– **Highly transparent LS: Attenuation length ;**

Attenuation length: 15m → 25m; the Light Yield (% standard): ×**1.5**

Attenuation length: 15m → 30m; the Light Yield (% standard): ×**2**;

– **High light yield LS: increasing PPO% ;**

KamLAND: 1.5g/l → Daya Bay II : 5g/l;

Light Yield (% standard): **30%→ 45%;** × **1.5**

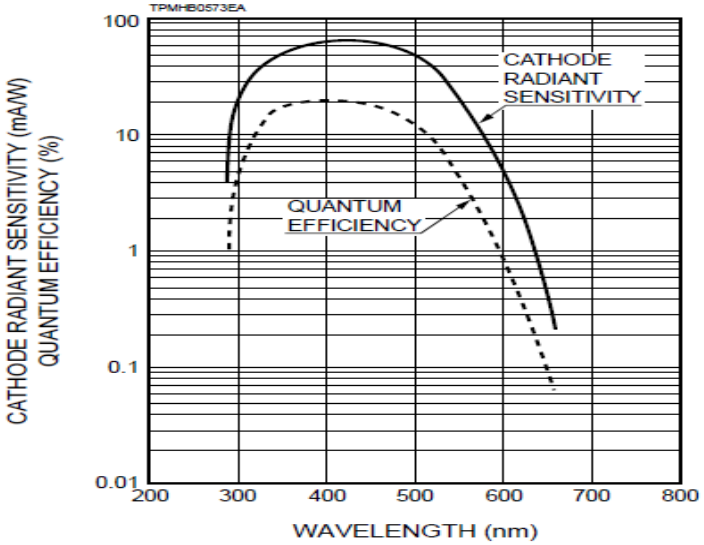
– **Photocathode coverage :**

KamLAND: 34% → Daya Bay II : ~ 80% × **2 ~ 2.5**

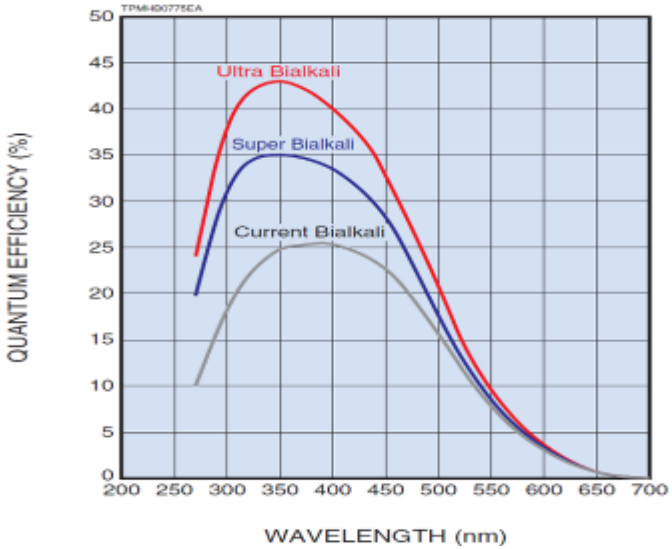
– **High QE "PMT": Quantum Efficiency (**or **Photon Detection Efficiency)**×**2**;

➢ The Quantum Efficiency of PMT

The QE of 20“ PMT-R3600



The QE of SBA/UBA



➢**High QE PMTs: SBA (35%) and UBA (43%)**

are only available in small format (< 5" diameter ?)

➢**Can we improve the Quantum Efficiency of Photocathode or Photon Detection Efficiency for the large area 20” PMT ?**

?? 20” UBA/SBA photocathode PMT from Hamamatzu ? QE: 20% → 40%

?? 20” New large area PMT ? Quantum Efficiency > 40% ?

or **Photon Detection Efficiency:** 14% → 30%

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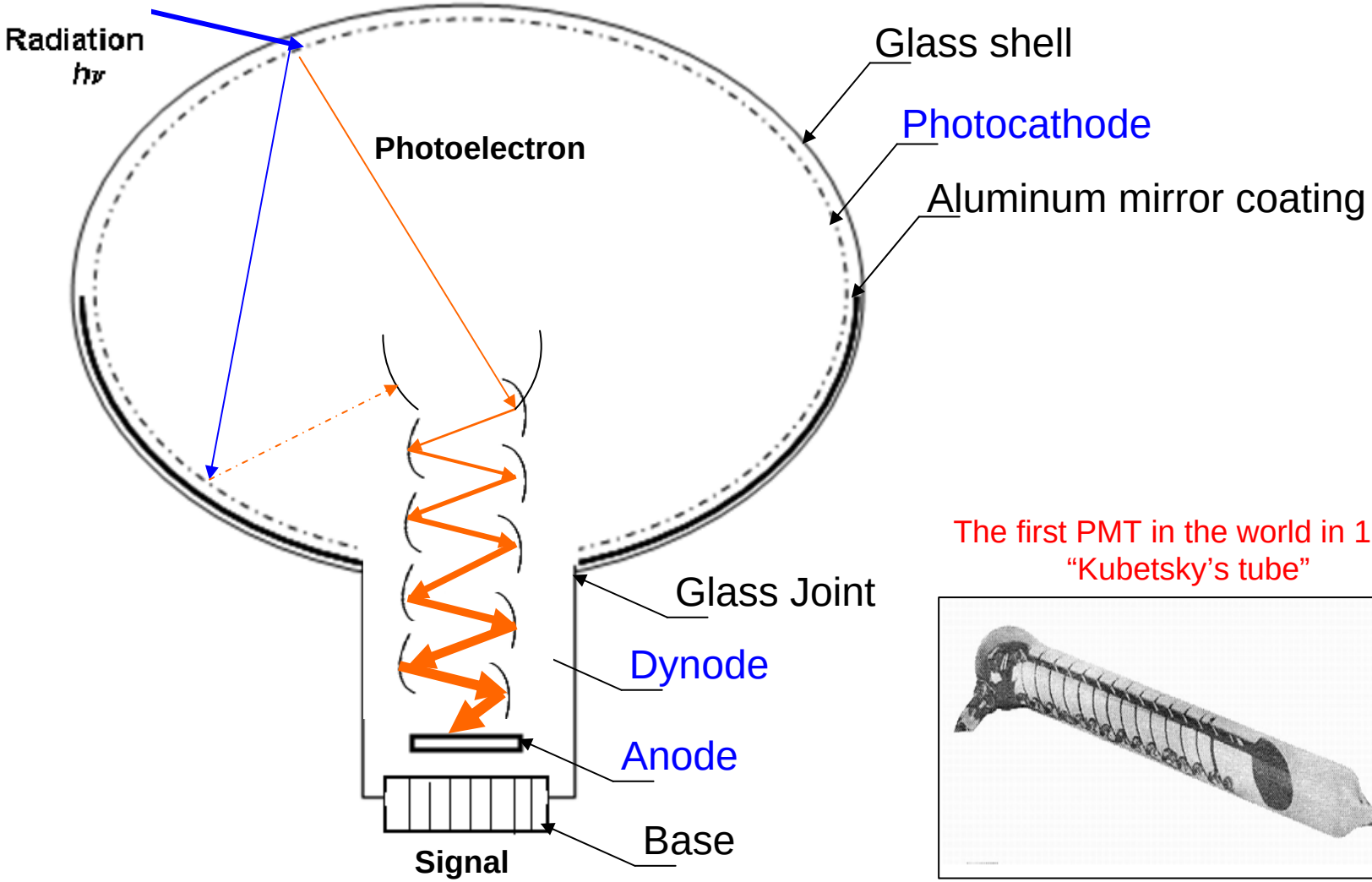
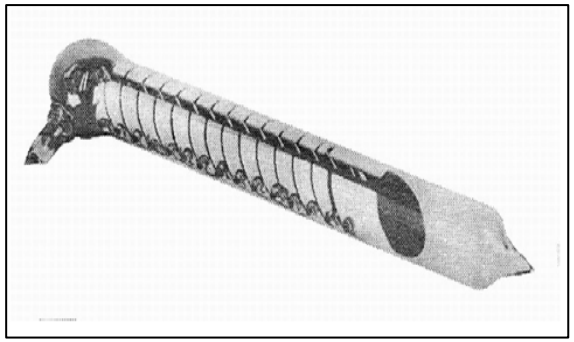
Conventional PMT



The first PMT in the world in 1933
"Kubetsky's tube"



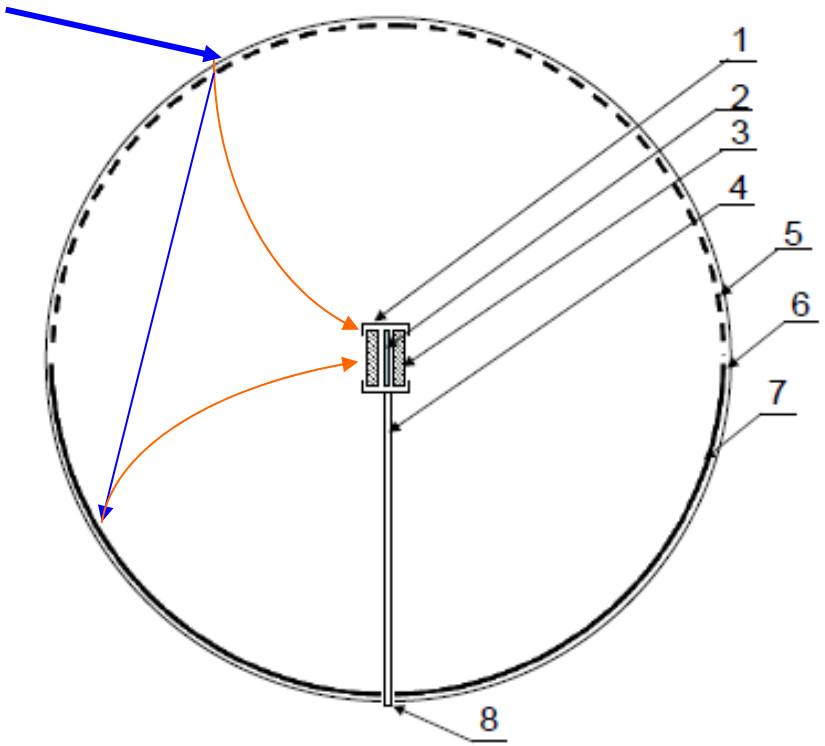
Photomultipliers are constructed from a glass envelope with a high vacuum inside, which houses a photocathode, several dynodes, and an anode.

➢ The new design of a large area PMT

High photon detection efficiency + Single photoelectron Detection + Low cost

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain

2) Using transmission photocathode (front hemisphere) and reflective photocathode (back hemisphere) } **~ 4π viewing angle!!**



1.Insulated trestle table

2.Anode

3.MCP dodule

4.Bracket of the cables

5.Transmission Photocathode

6.Glass shell

7.Reflection Photocathode

8.Glass joint

➢**Quantum Efficiency:**

Transmission photocathode: 20%

Reflection photocathode: 40%

➢**MCP Collection Efficiency: 60%**

Photon detection efficiency:

→ **20% * 60% = 12%**

→ **70% * 40% * 60% = 17%**

➢**Total Photon Detection Efficiency: ~30%**

Photon Detection Efficiency: 14% → 30% ; ×~2 at least !

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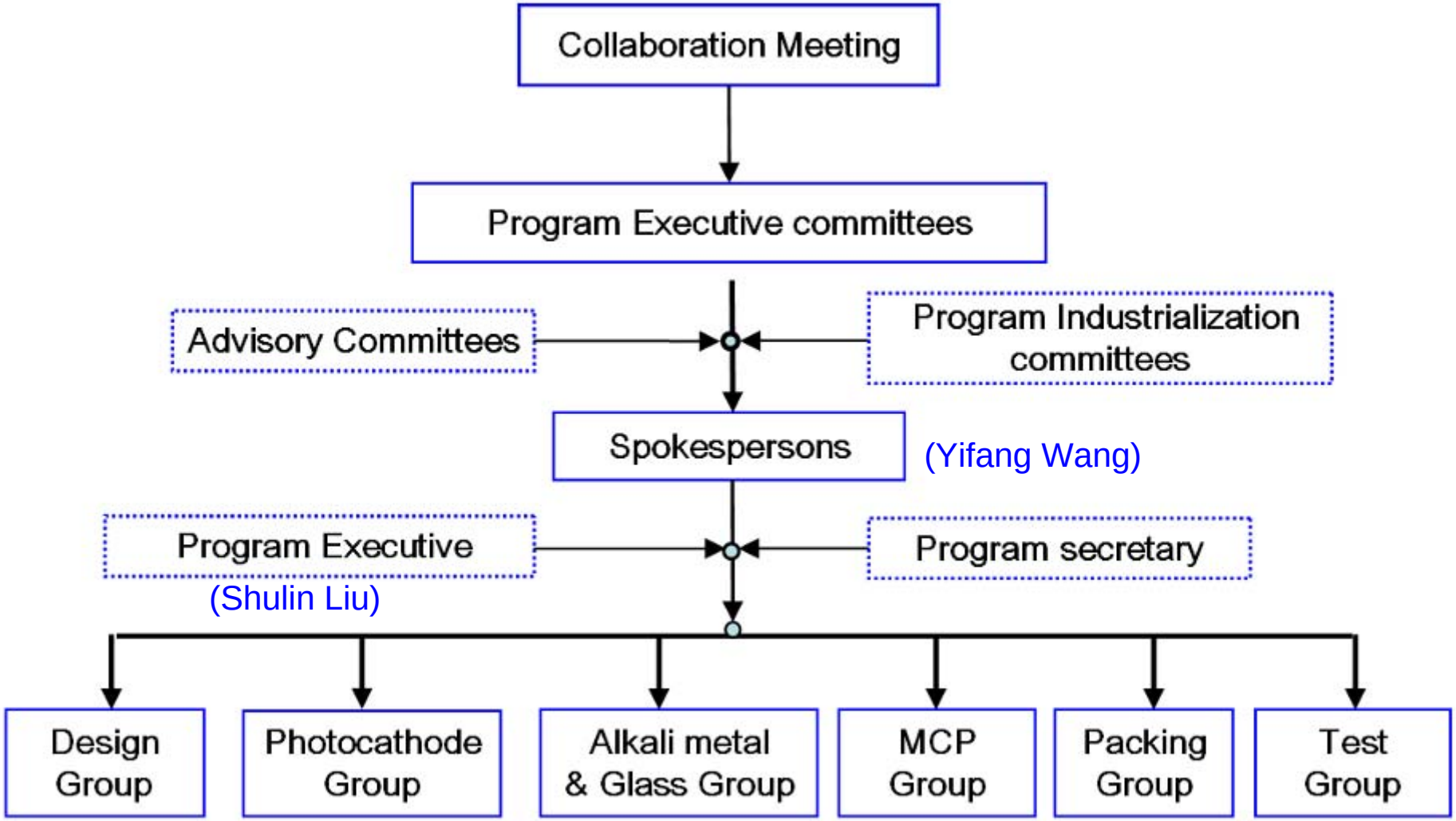
➢ The Organization Chart

Microchannel-Plate-Based Large Area Photomultiplier Collaboration (MLAPC)



Project team and Collaborators

中国科学院高能物理研究所

Institute of High Energy Physics, CAS

effort by **Yifang Wang;**

中国科学院西安光学精密机械研究所
XIAN INSTITUTE OF OPTICS AND PRECISION MECHANICS OF CAS

中核（北京）核仪器厂
CNNC Beijing Nuclear Instrument Factory

南京大学

北方夜视技术股份有限公司
NORTH NIGHT VISION TECHNOLOGY CO.,LTD

宝光股份
BAOGUANG

Other company and institute (cooperated but not join us yet)： ……

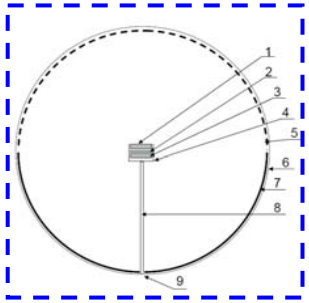
南京电子器件研究所
Nanjing Electronic Devices Institute

華東電子

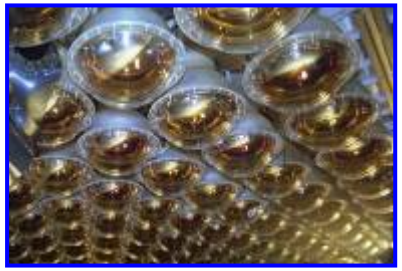
New PMT company in Hainan

➢ The R&D plan of MCP-PMT （schedule）

Design → 5”(8”) prototype transmission → 5”(8”) prototype Transmission +reflection → 20” prototype Transmission +reflection → Mass production

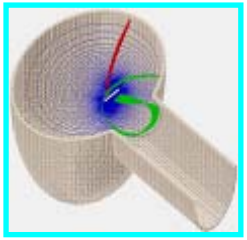


The design of the IHEP-MCP-PMT → The project of Daya Bay II



Alkali metal

Low price MCP

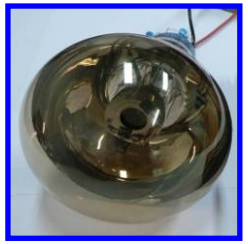


Photomultiplier

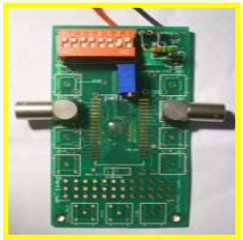
Glass Shell

Vacuum equipment

Prototype

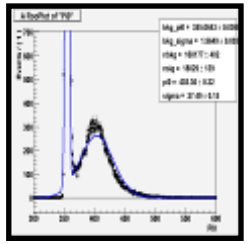


Test system



Electronic

SPE



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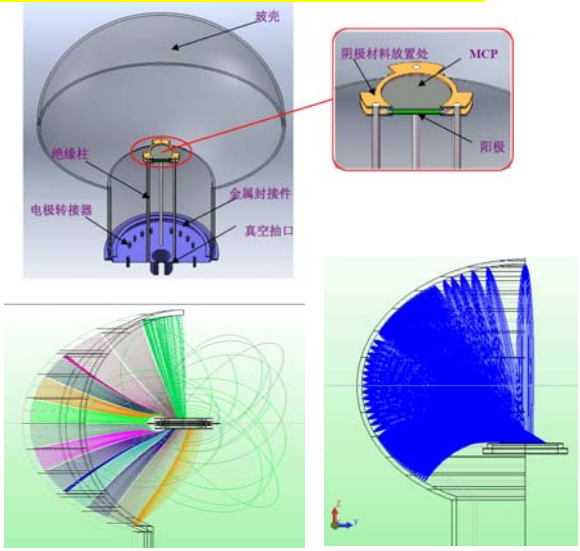
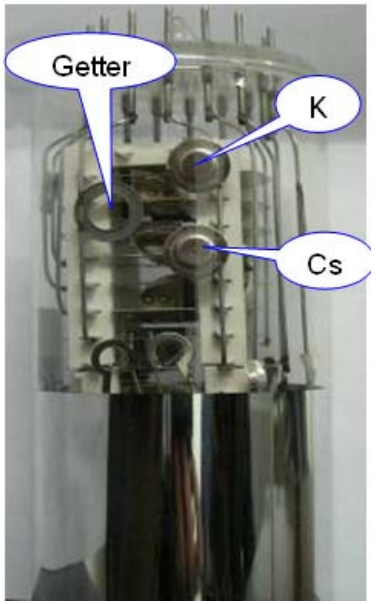
The progress:

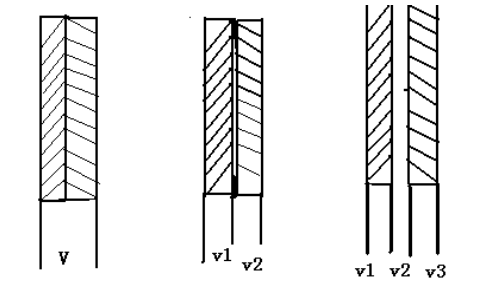


➢Simulation and design

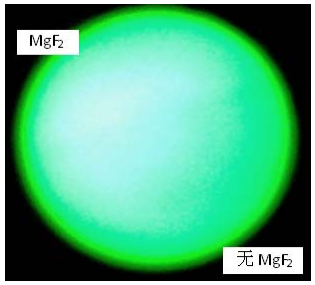


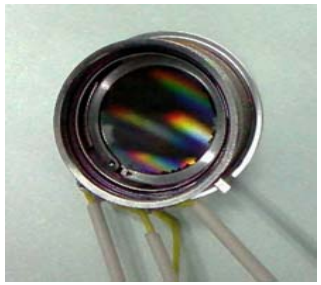
➢Alkali Metal Dispensers （AMD）

➢Glass

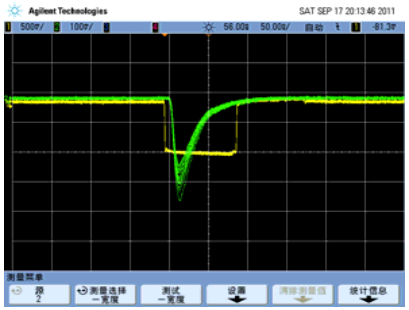


(1)直接对贴型 (2)独立加压型 (3)间隙加压型





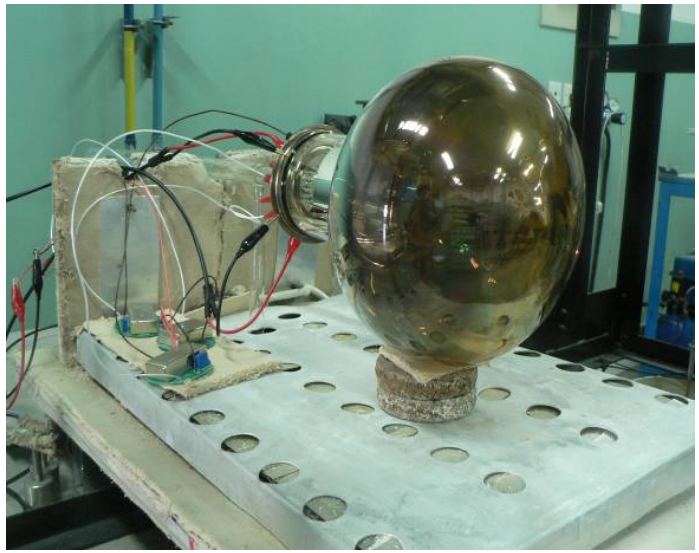
➢MCP



➢Electronic

The progress:

2” MCP-PMT



8” MCP-PMT

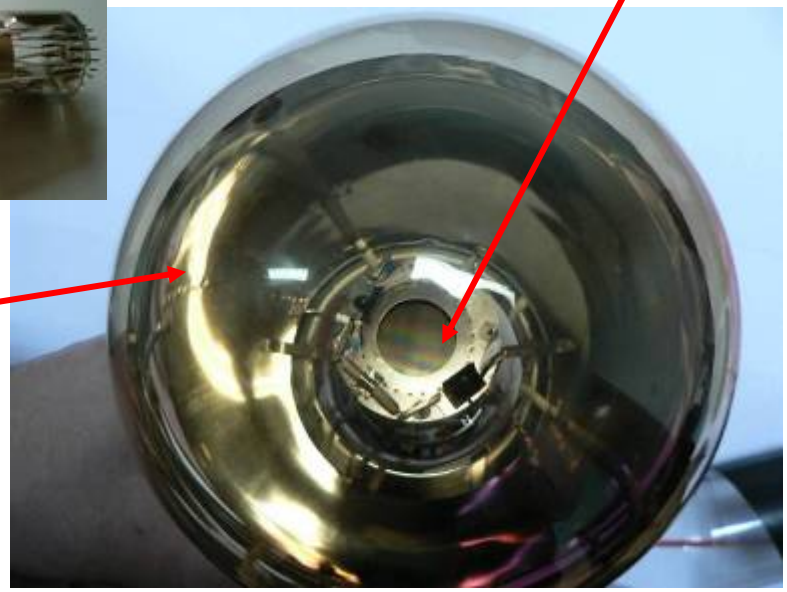
8” Dynode-PMT

5” MCP-PMT

MCP

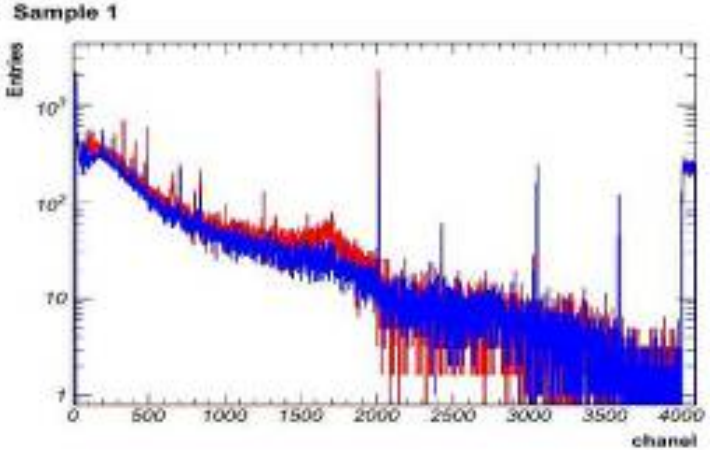
8” MCP-PMT

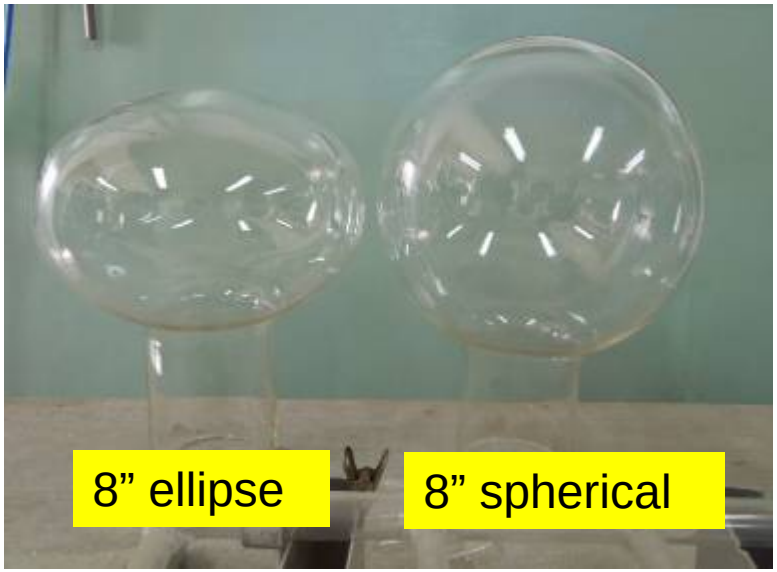
transmission photocathode



➢Challenge 1: The Low radioactive background glass

- ➢Large (8” , 20”);
- ➢Superb water-resistance characteristics；
- ➢Low radioactive background glass;





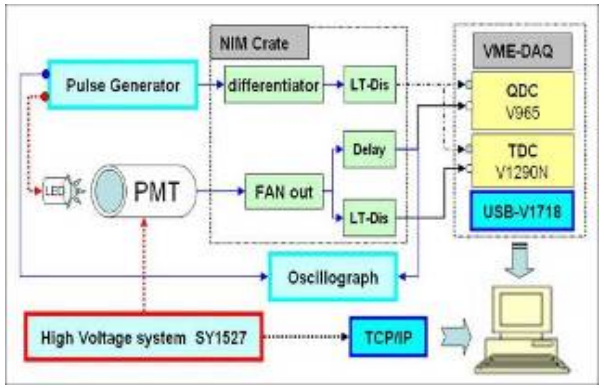
Low background gamma spectrometer in IHEP

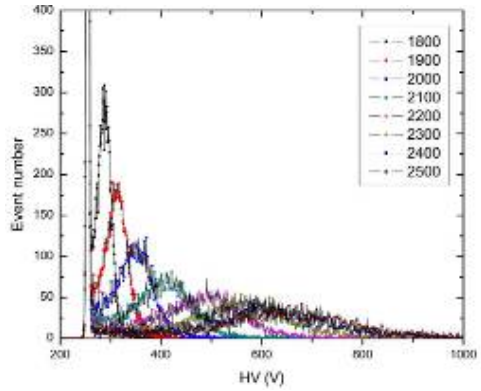
radioactive background test of different PMT glass (unit: ppb)

Glass	*DM-308*	*DM-305*	Hamamastu	*CN-2# Glass*	*CN-2# Material*
Sample Mass	211.0g	131.1g	53.8g	335.2g	280.9g
Test Time	311023	424110	598930	315394	359618
^{238}U	21.50±0.10	42.40±0.14	8.04±0.27	14.96±0.08	<0.1
^{232}Th	18.50±0.32	6.43±0.23	12.50±0.60	4.78±0.16	<0.2
^{40}K	2.50±0.01	41.01±0.03	0.3±0.02	3.11±0.01	<0.01

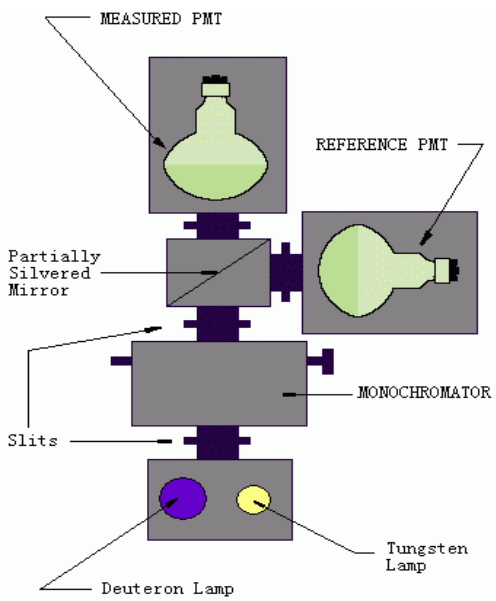
➢ Challenge 2: **Large PMT evaluation** system

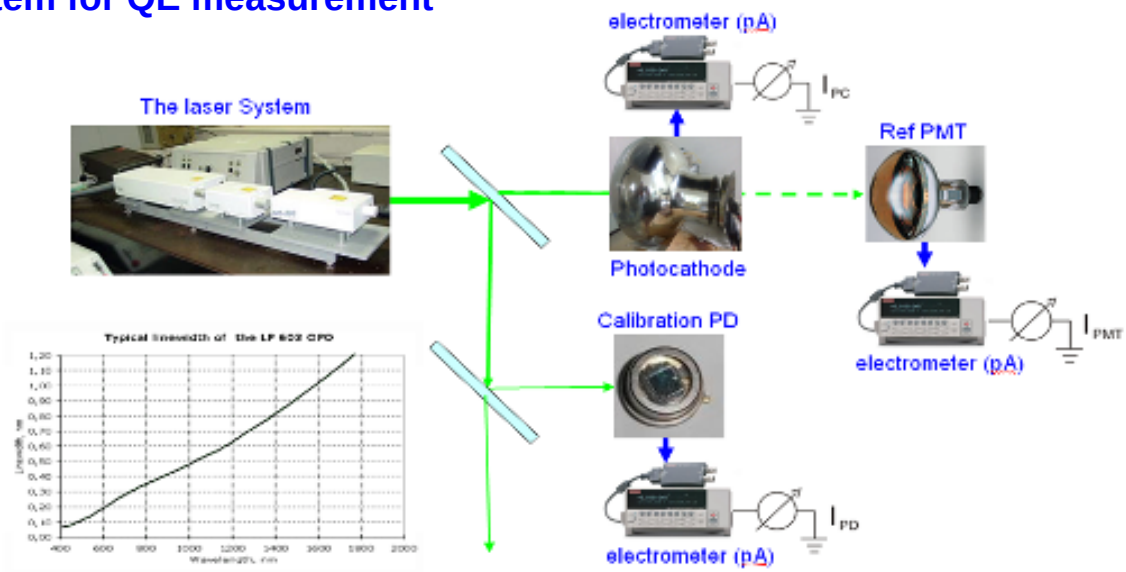
1. The typical single photoelectron spectrum (SPE) test system;





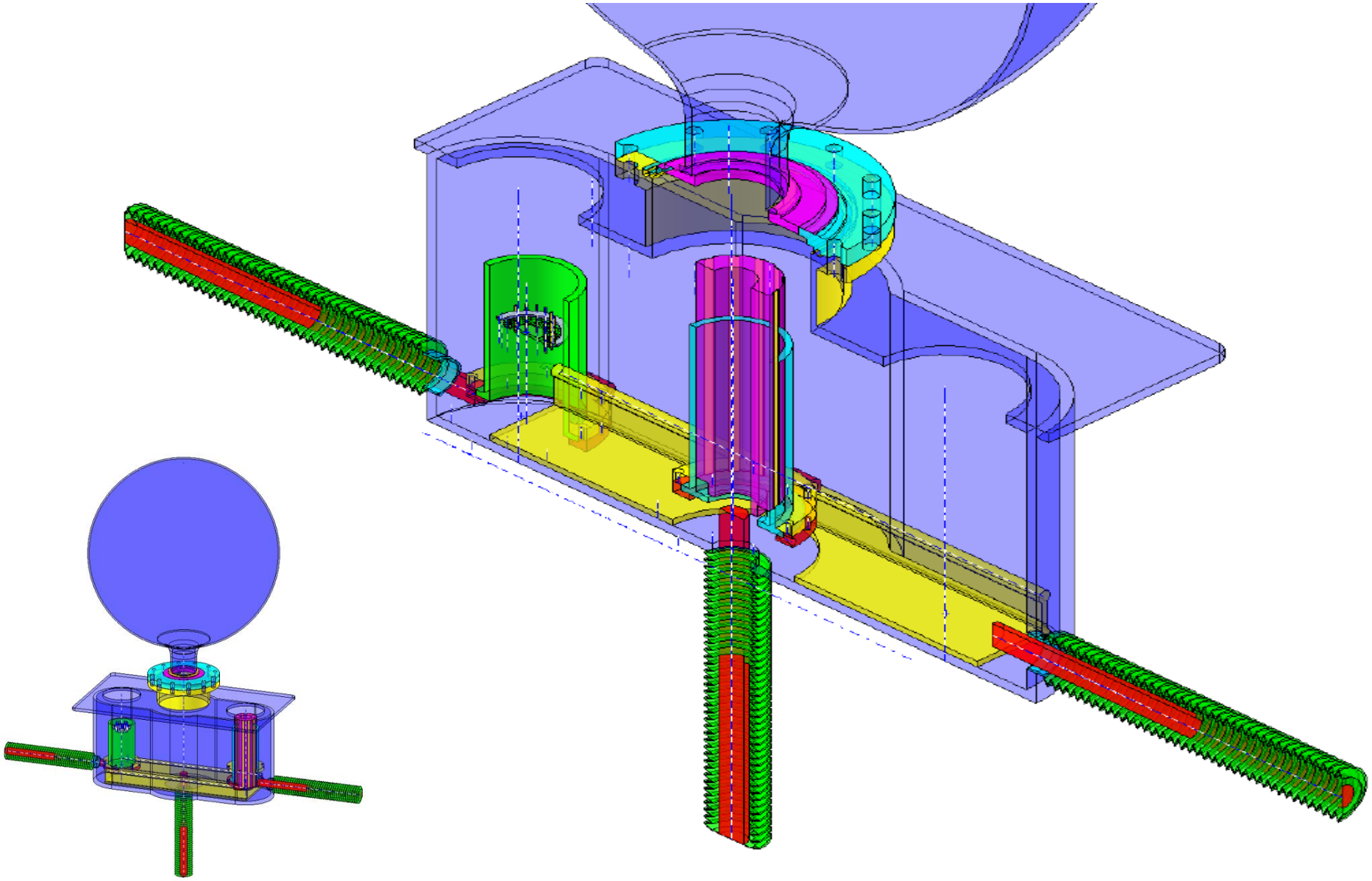
2. The system for QE measurement





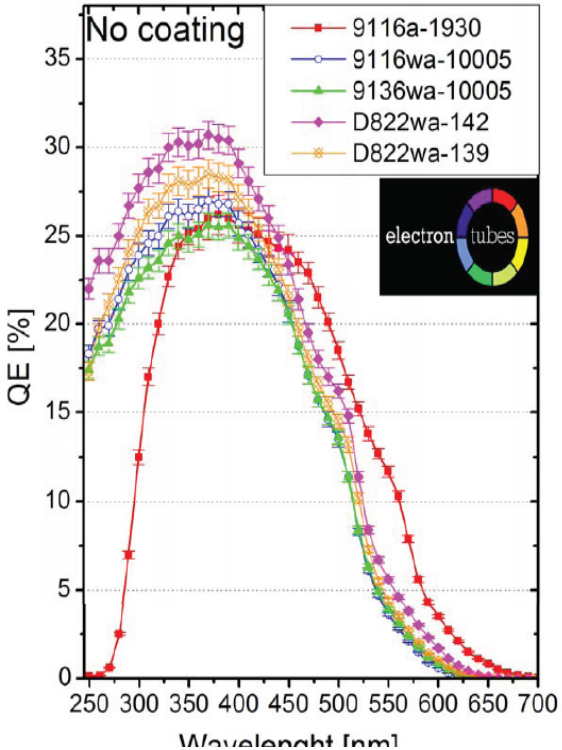
$$QE_{pc} = \frac{I_{PD.trans}}{I_{PMT.trans}} \bullet \frac{I_{PC}}{I_{PD}} \bullet QE_{PMT}$$

➢Challenge 3: The Vacuum Transfer Equipment

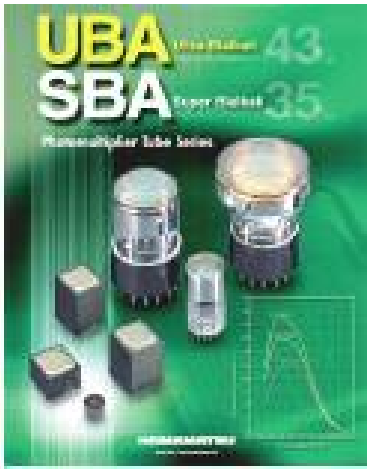


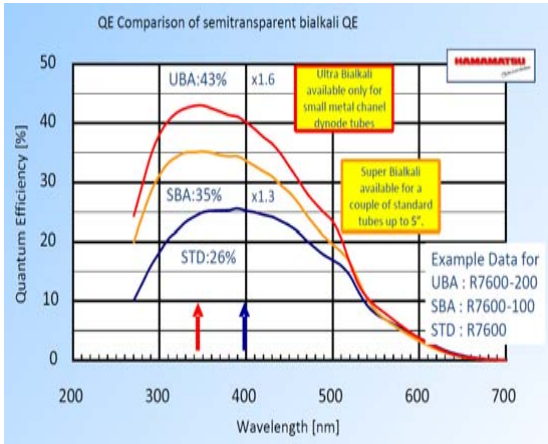
➢Challenge 4: The High QE photocathode

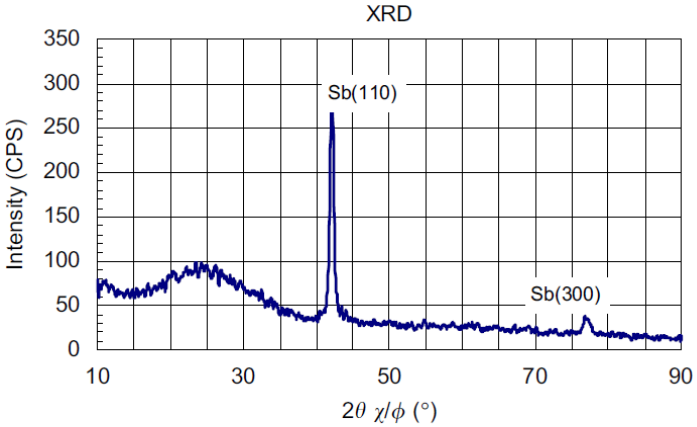
- Cs_3Sb on MnO (S11, L_{peak} @400nm, QE ~ 20%)
- $(Cs)Na_2KSb$ (S20, L_{peak} @400nm, QE ~ 30%)
- K_2CsSb (L_{peak} @400nm, QE ~ 30%)
- $K_2CsSb(O)$ (L_{peak} @400nm, QE ~ 35%)



- ➢Use of highly purified materials for the photo cathode;
- ➢Optimal tuning of the material composition;
- ➢Optimal tuning of the photo cathode thickness ;
- ➢Optimal tuning of the anti-reflective layer;
- ➢Optimal tuning of the Cs layer thickness ;







The X-ray diffraction analysis result of Sb thin film.

*K. Nakamura, et.al. Latest bialkali photocathode with ultra high sensitivity .**NIM A 623 (2010) 276***

- **Source:** SAES? Hamamastus? Others?
- **Setup position:** inner? Outlier?
- **Active method:** Current? High Frequency?
- **Purity?** Material ? Impurity?
- **The Know-How! ……**

Composition

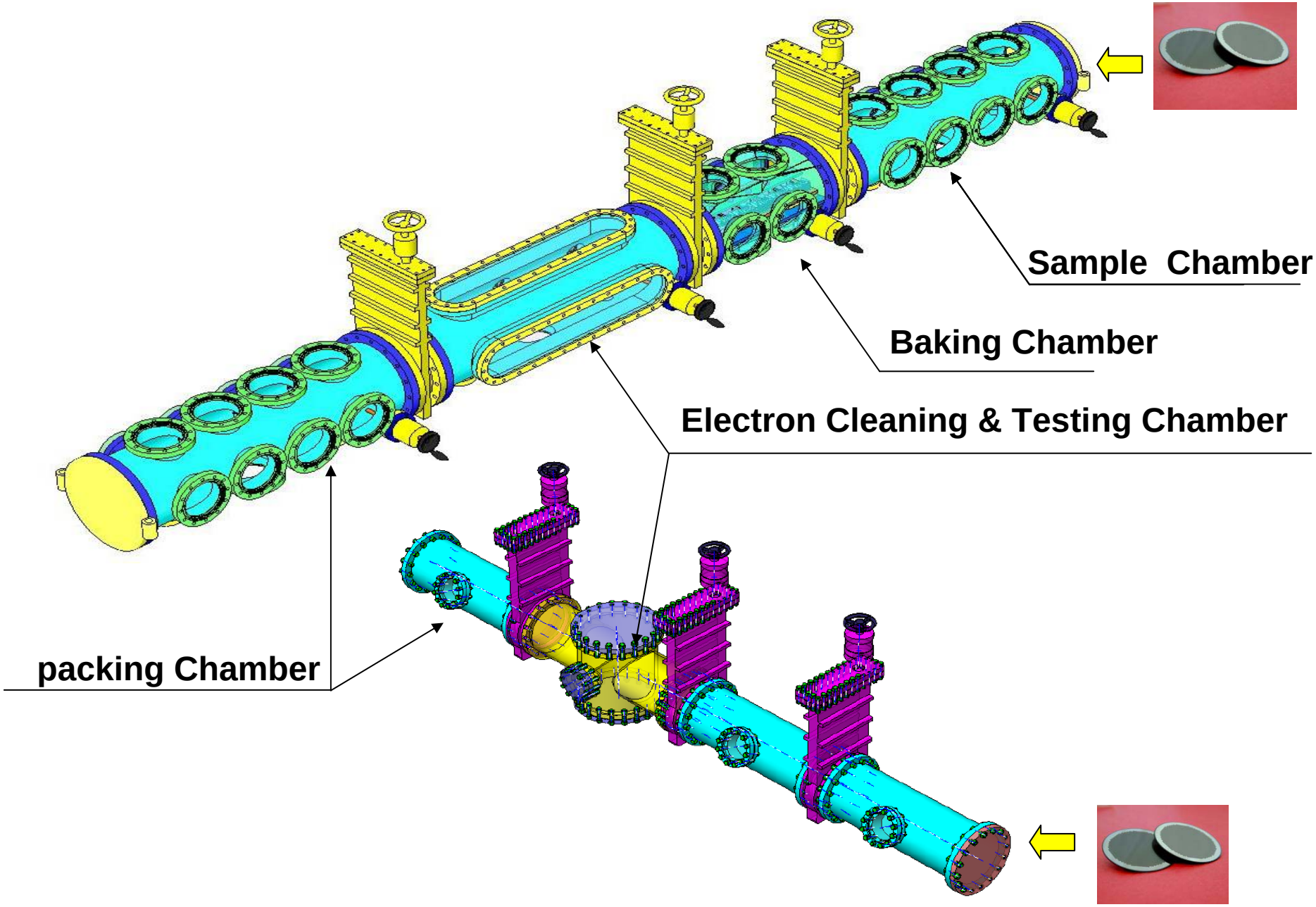
- **Oxygen Plasma:** When? How Long?
- **Baking:** temperature? Time?
- **Growth method:** fast? Slow?
- **Thickness of Sb:** monitor and control?
- **Anti-reflective layer:** Material ? Thickness?
- **Thickness of K/Cs:** Monitor and control?
- **The Know-How! ……**

The growth technology

High QE photocathode

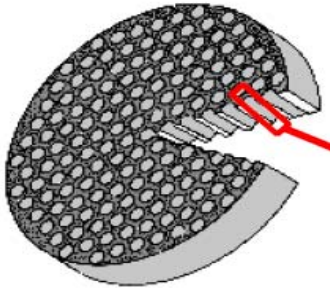
The AMD for Industry

➢Challenge 3: How to improve the performance of the MCP

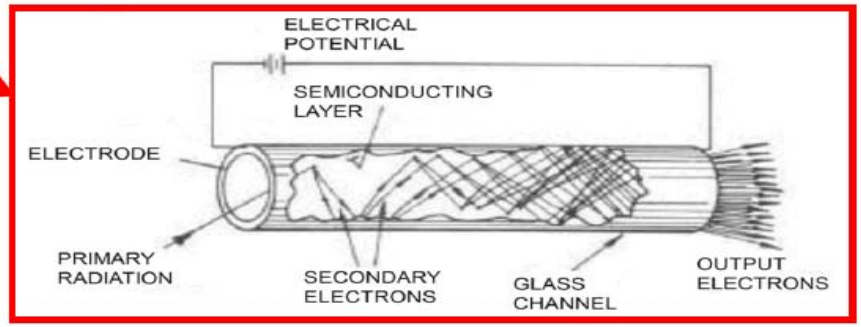


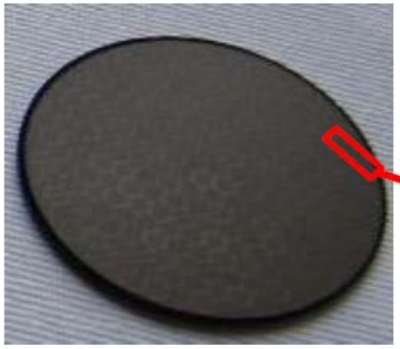
➢Challenge 3: How to improve the performance of the MCP

Microchannel plate for electron multiplier

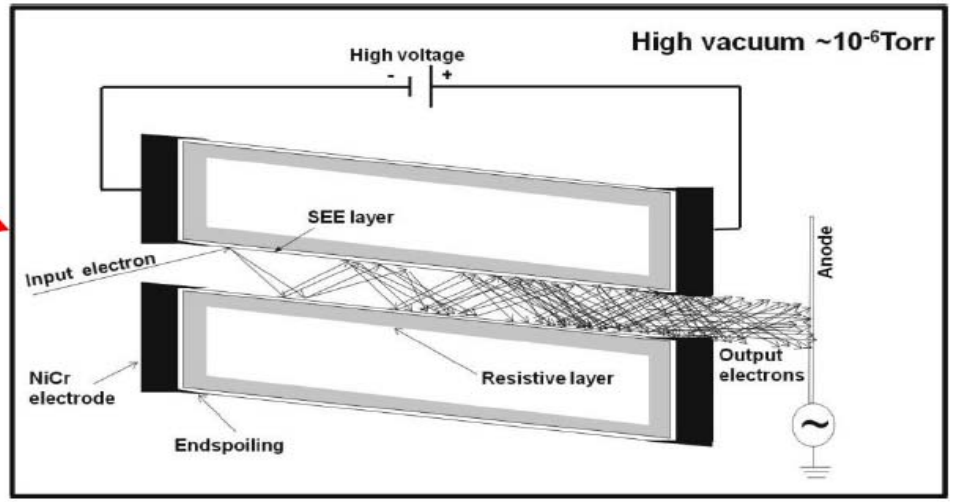


Conventional MCP pore





ALD functionalized MCP pore



Argonne MCP in TIPP2011 conference （Author：**Anil U. Manea** ）

Arradiance

BeneQ

Picosun

Keming

- 1. The Al_2O_3 (Al) film covers the MCP for reducing the ion feedback;
- 2. The MgO、ZnO、 Al_2O_3 in the MCP channel for better gain and other performance;
- 3. The Gd_2O_3 film covers the MCP channel for thermal neutron detection;
- 4. The gallium nitride (GaN) photocathode for the Gaseous PMT;
- 5. Produce the superconductive (NbTiN) material in the accelerate pipe.
- ……

ALD / MCP	ANL		CAS (Keming)		Company (BeneQ or Picosun)	
	Advantage	Drawback	Advantage	Drawback	Advantage	Drawback
Income	Cooperation Technology	cost	Cooperation	Technology cost	Technology	Cooperation cost
NNV	Technology cost	Cooperation	Cost Cooperation	Technology	Technology cost	Cooperation
Other Company In China	Cost	Cooperation Technology	Cost	Technology Cooperation	cost Technology	Cooperation

Summary

- **1. A new type of MCP-PMT is designed for the next generation neutrino exp.**
  - ✓ Large ares: ~ 20";
  - ✓ High photon detection efficiency: ~30%, al least ×2 than normal PMT;
  - ✓ Low coat: ~ low cost MCPs;
- **2. The R&D process is composing with 3 steps.**

  ① 5"(8") prototype with transmission photocathode;

  ② 5"(8") prototype with transmission and reflection photocathode;

  ③ 20" prototype with transmission and reflection photocathode;
- **3. The R&D work is divided into 7 Parts to product the prototype to detect SPE:**

  ①Photocathode; ②MCP; ③Glass; ④Photomultiplier;

  ⑤vacuum equipment; ⑥Electronic; **⑦Test system;**

There are lots of work to do!

We need any help from other institute and company!

Thank！ 谢谢！

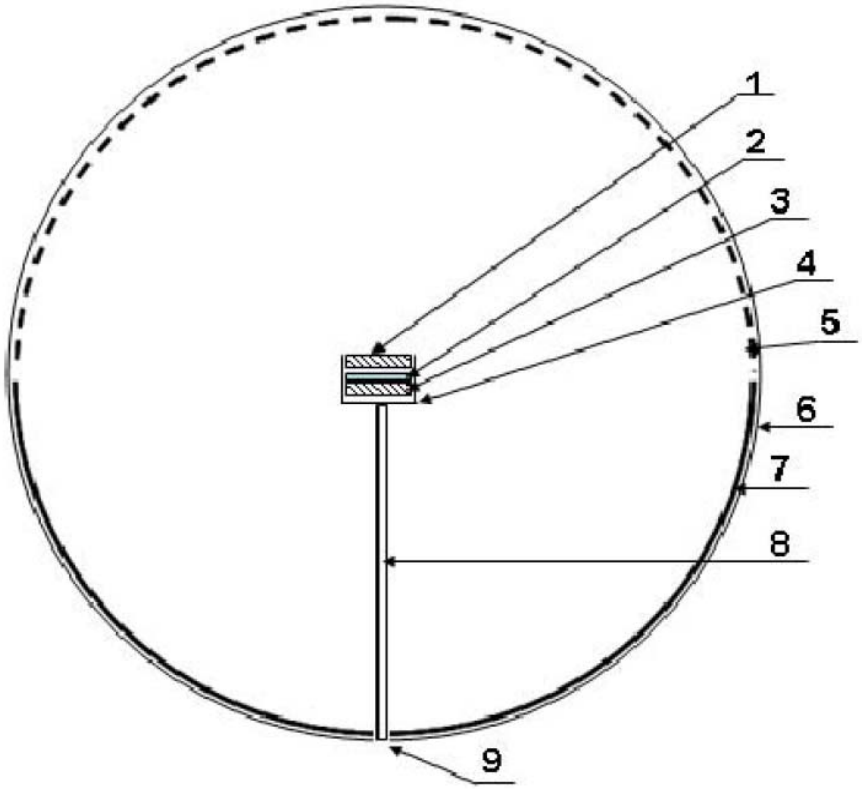
Thanks for your attention!
Any comment and suggestion are welcomed!

➢ The new design of a large area PMT

High photon detection efficiency + Single photoelectron Detection + Low cost

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain

2) Using transmission photocathode (front hemisphere) and reflective photocathode (back hemisphere) } ~ 4π viewing angle!!



1. up MCP
2. anode
3. down MCP
4. insulated trestle table
5. transmission photocathode
6. glass shell
7. reflection photocathode
8. bracket of the cables
9. glass joint

➢ **Quantum Efficiency:**

Transmission photocathode: 20%

Reflection photocathode: 40%

➢ **MCP Collection Efficiency: 60%**

Photon detection efficiency:

→ 20% * 60% = 12%

→ 70% * 40% * 60% = 17%

➢ **Total Photon Detection Efficiency: ~30%**

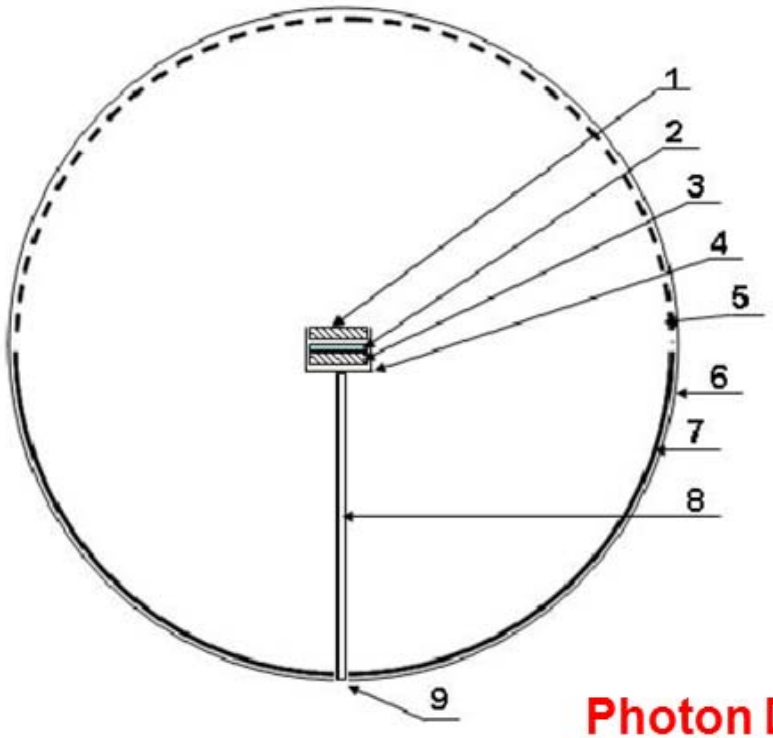
Photon Detection Efficiency: 14% → 30% ; ×~2 at least !

The new design of a large area PMT

High photon detection efficiency + Single photoelectron Detection + Low cost

1) **Using transmission photocathode (front hemisphere) and reflective photocathode (back hemisphere)** ⇨ **~ 4π viewing angle!!**

2) **Using two sets of Microchannel plates (MCPs) to replace the dynode chain**



1. up MCP
2. anode
3. down MCP
4. insulated trestle table
5. transmission photocathode
6. glass shell
7. reflection photocathode
8. bracket of the cables
9. glass joint

➢ **Quantum Efficiency:**

Transmission photocathode: 30%

Reflection photocathode: 35%

➢ **MCP Collection Efficiency:** 70%

Photon detection efficiency:

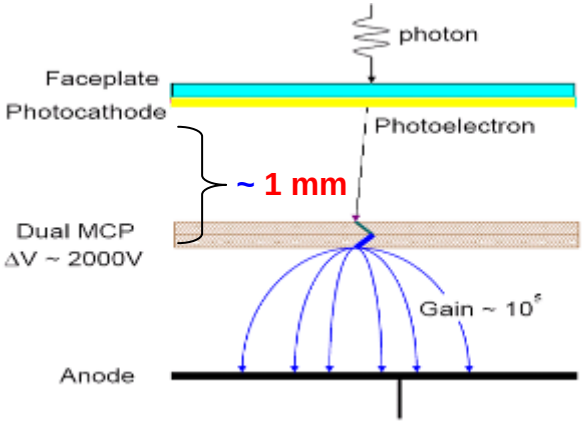
30% * 70% = 21%

40% * 35% * 70% = 9. 8%

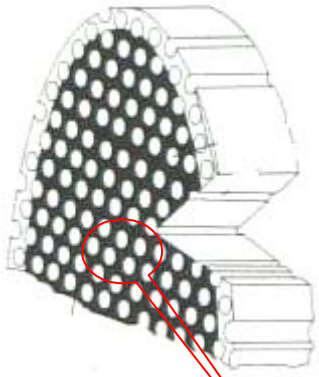
➢ **Total Photon Detection Efficiency:** ~ 30. 8%

Photon Detection Efficiency: 15. 4% → 30. 8% × ~2 **at least**

4.3 The Low cost MCP



MCP →



Why the cost of the MCP is usually high?

---- **optoelectronic imaging device**

---- **High timing resolution device**

Low production yield! ~ 20%

□ MCP-PMT Operation Principle

Channels

cost

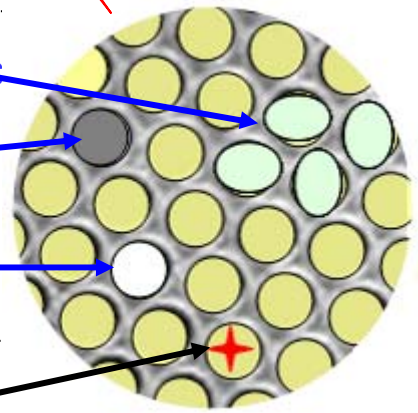
disqualified MCP for Imaging device

1。asymmetrical surfac

2。Blind channels;

3。Non-uniform gain of the channels ;

4。 emission flash



Acceptable MCP for SPE detection

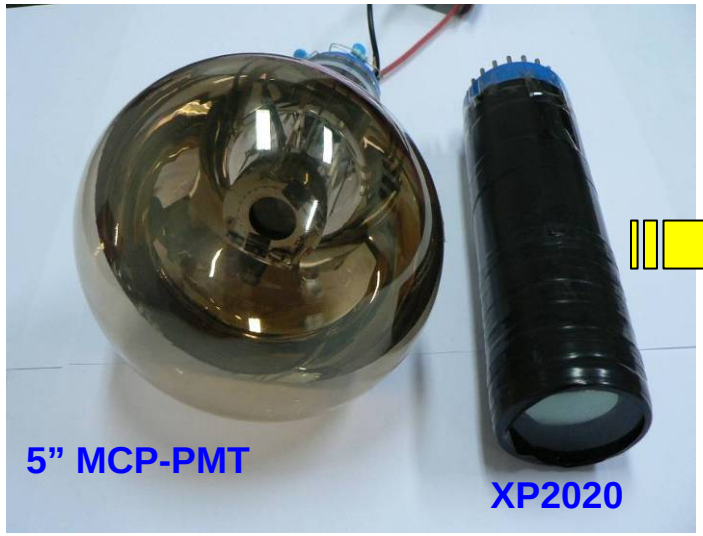
cost

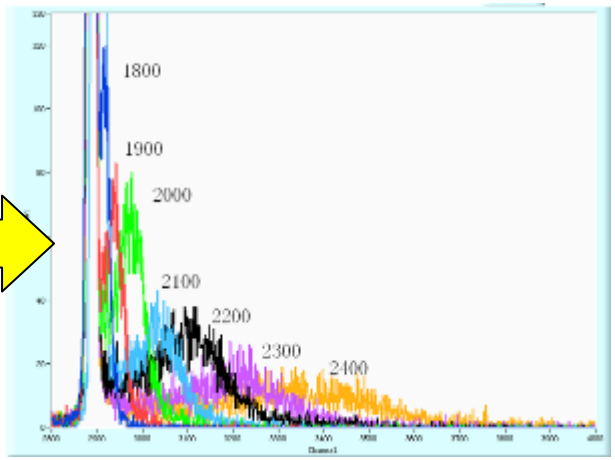
The MCP production company, which is the one of our partner has over 20 years of experience in MCP production.

Could supply us the MCP with low cost.

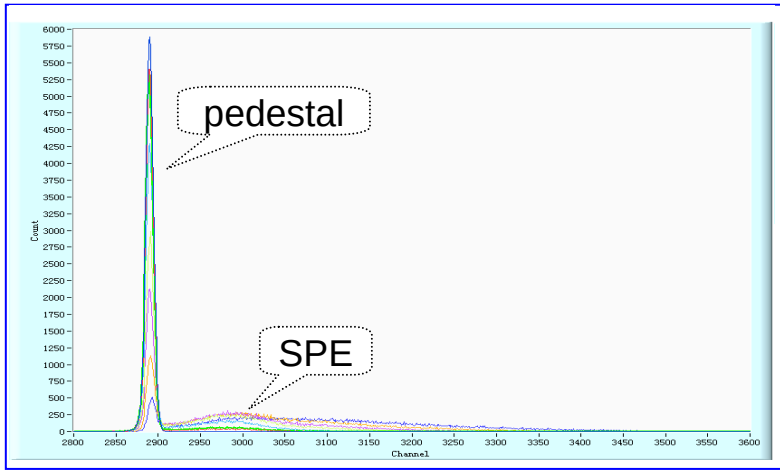
The single photoelectron spectrum and the multi-photoelectron spectrum of the PMT

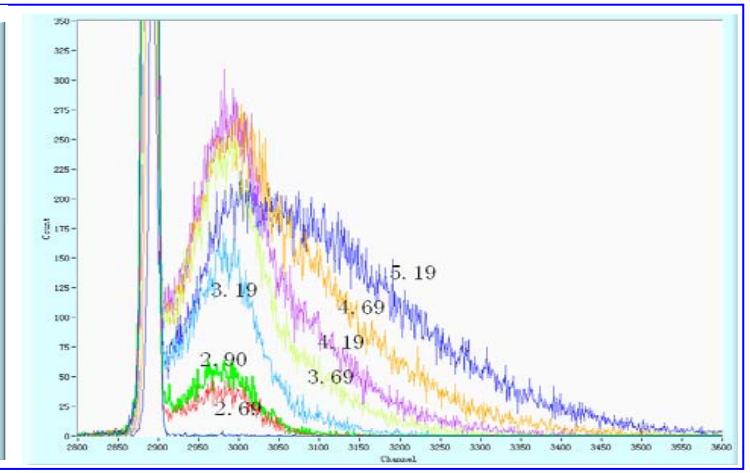
➢**The photoelectron spectrum of the XP2020 PMT**





➢**SPE vs the Voltage of the PMT**

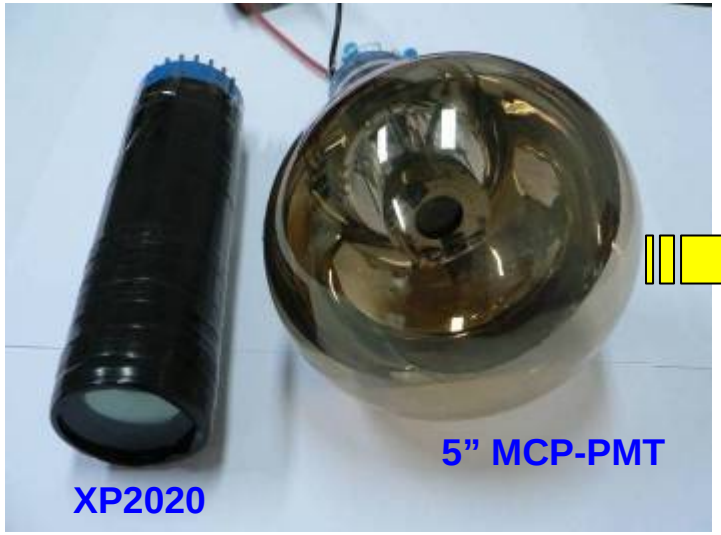


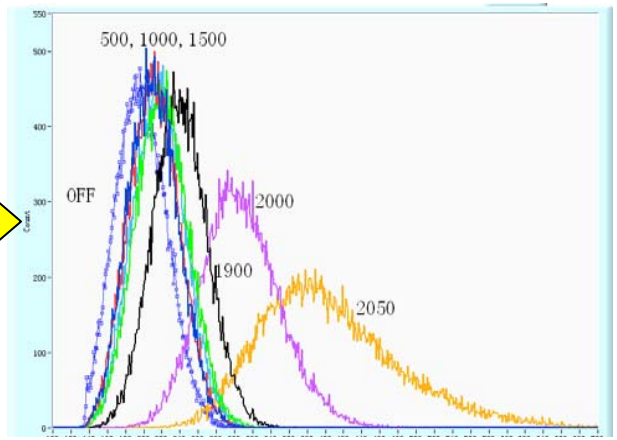


➢**SPE vs the luminance of the LED light**

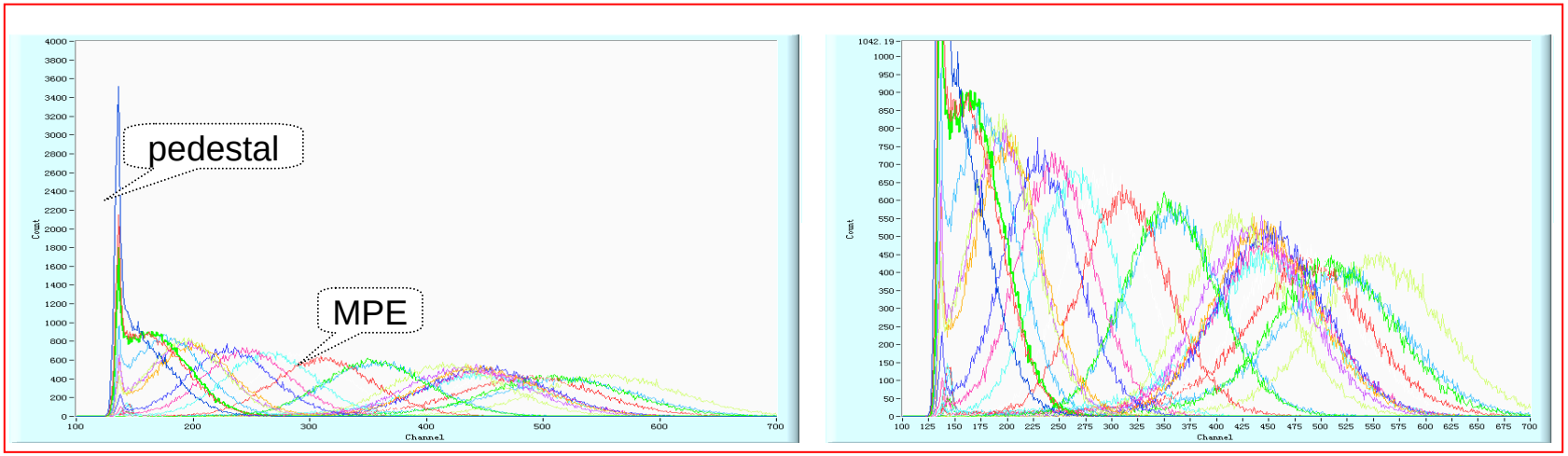
**--adjust the working voltage of the LED to adjust the luminance of the LED light.

➢**The photoelectron spectrum of a prototype: 5” IHEP-MCP-PMT**





➢**SPE vs the Voltage of the PMT**



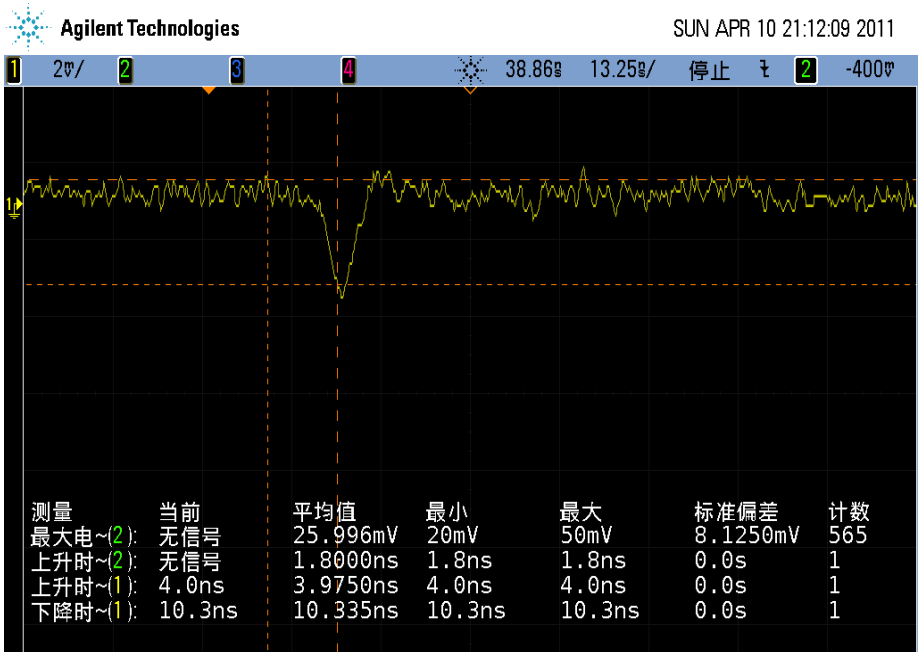
➢**MPE vs the luminance of the LED light**

**--adjust the working voltage of the LED to adjust the luminance of the LED light.

➢ The performance of the MCP-PMT

Characteristics	unit	R3809U-50 （Hamamatsu）	R5912 （Hamamatsu）	MCP-PMT-8 （IHEP）	R3600 （Hamamatsu）	MCP-PMT-20 （IHEP）
size	inch	2	8	**8**	20	**20**
Spectral Response	nm	160~850	300~650	**300~650**	300~650	**300~650**
Photocathode Material	--	Multialkali	Bialkali	**Bialkali**	Bialkali	**Bialkali**
Electron Multiplier	--	MCP	Dynode	**MCP**	Dynode	**MCP**
Gain	--	2×10^5	$\geqslant1\times10^7$	**$\geqslant1\times10^5$**	$\geqslant1\times10^7$	**$\geqslant1\times10^5$**
Photocathode mode	--	transmission	transmission	**reflection + transmission**	transmission	**reflection + transmission**
Cathode Sensitivity	uA/lm	150	70	**70**	60	**70 ~100**
Quantum Efficiency（400nm）	%	--	22	**20~40？？**	20	**20~40？？**
Electron Multiplier Collection efficiency	%	~ 60%	~ 60%	~ 70%	~ 60%	~ 60%
Efficiency of detecting photoelectron	%	--	< 13	**> 20**	<12	**> 20**
Anode Dark Current	nA	100	⩽700	**⩽100**	⩽1000	**⩽100**
Anode Pulse Rise Time	ns	0.150	3.8	⩽ 5	10	**⩽10**
Transit Time Spread (TTS)	ns	⩽0.025	2.4	**⩽1**	5.5	**⩽2**
Anti-Magnetic characteristics	--	Good	**normal**	**normal**	**normal**	**normal**
Glass	--	--	Low-Potassium Glass	**Low-Potassium Glass CN-2#**	HARIO-32	**Low-Potassium Glass- CN-2#**

Characteristics		unit	13#	16#	22#	25#
Test voltage	v	V	-2000	-2000	-1970	-2020
Cathode current	I_K	nA	-1.2	-3.46	-10.56	-31
Cathode luminous sensitivity	S_K	uA/lm	4.5	12.9	39.5	117
Anode Current	I_A	nA	12.5	42	35.7	70
Anode Dark Current	I_D	nA	0.7	16.7	2.39	18
Anode luminous sensitivity	S_A	A/lm	2.57	5.5	7.22	9.15
Gain	G	-	$5.7*10^5$	$4.2*10^5$	$1.8*10^5$	$1.01*10^5$



$$S_k = \frac{I_k}{\varphi_k} \qquad S_A = \frac{I_A - I_D}{\varphi_A}$$

$$G = \frac{S_A}{S_k}$$

luminous flux:

$\varphi_k = 2.67*10^{-4}$ lm

$\varphi_A = 4.59*10^{-9}$ lm