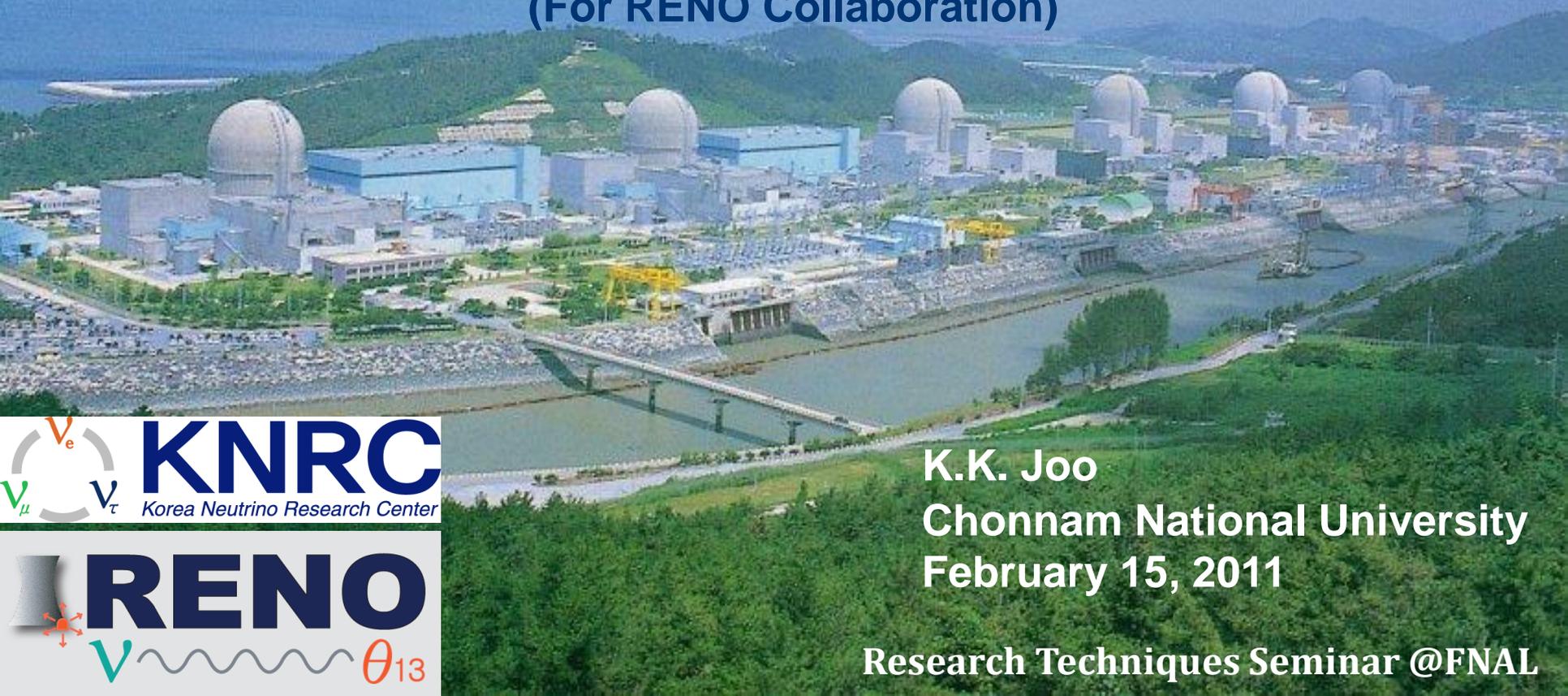


Status of the RENO Reactor Neutrino Experiment

RENO = **R**eactor **E**xperiment for **N**eutrino **O**scillation
(For RENO Collaboration)



K.K. Joo

Chonnam National University

February 15, 2011

Research Techniques Seminar @FNAL

Outline

- ❑ **Experiment Goals of the RENO Exp.**
 - **Short introduction**
 - **Expected θ_{13} sensitivity**
 - **Systematic uncertainty**

- ❑ **Overview of the RENO Experiment**
 - **Experimental Setup of RENO**
 - **Schedule**
 - **Tunnel excavation**
 - **Status of detector construction**
 - **DAQ, data analysis tools**

- ❑ **Summary**

Brief History of Neutrinos

- ❑ 1930: Pauli postulated neutrino to explain β decay problem
- ❑ 1933: Fermi baptized the neutrino in his weak-interaction theory
- ❑ 1956: First discovery of neutrino ($\bar{\nu}_e$) by Reines & Cowan from reactor
- ❑ 1957: Neutrinos are left-handed by Glodhaber et al.
- ❑ 1962: Discovery of ν_μ by Lederman et al. (Brookhaven Lab)
- ❑ 1974: Discovery of neutral currents due to neutrinos
- ❑ 1977: Tau lepton discovery by Perl et al. (SLAC)
- ❑ 1998: Atmospheric **neutrino oscillation** observed by Super-K
- ❑ 2000: ν_τ discovery by DONUT (Fermilab)
- ❑ 2002: Solar **neutrino oscillation** observed by SNO and confirmed by Kamland

What NEXT?

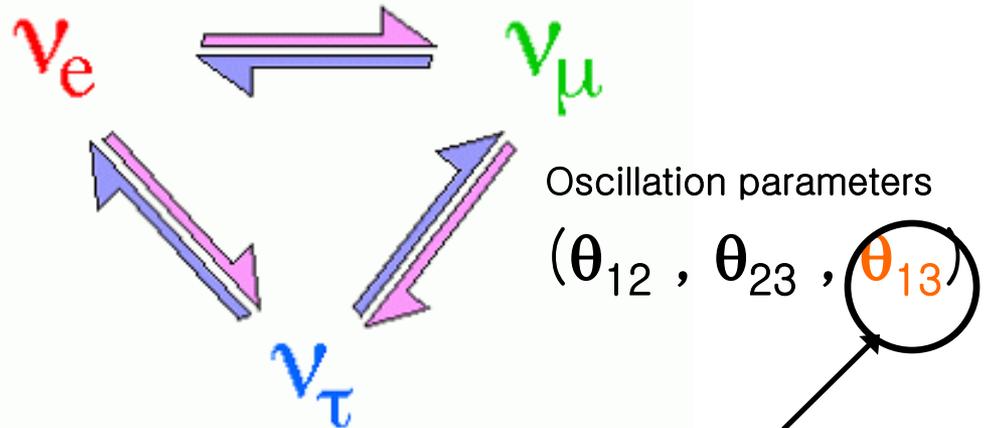
Standard Model

Neutrinos in SM

Leptons	Quarks	<i>u</i> up	<i>c</i> charm	<i>t</i> top	
		<i>d</i> down	<i>s</i> strange	<i>b</i> bottom	
		ν_e e- Neutrino	ν_μ μ - Neutrino	ν_τ τ - Neutrino	
	<i>e</i> electron	μ muon	τ tau		
	I			II	III
	The Generations of Matter				

Neutrino Oscillation

- Three types of neutrinos exist & mixing among them



Oscillation parameters

$(\theta_{12}, \theta_{23}, \theta_{13})$

Not measured yet

- Elementary particles with almost no interactions
- Almost massless: impossible to measure its mass

Neutrino Mixing Parameters

In 1962 Z. Maki, M. Nakagawa, and S. Sakata considered neutrino flavor oscillations: neutrinos of different flavors can be transformed to each other

Matrix Components:
 3 Angles (θ_{12} ; θ_{13} ; θ_{23})
 1 CP phase (δ)
 2 Mass differences

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric SK, K2K}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{SNO, solar SK, KamLAND}}$$

atmospheric SK, K2K

$$\theta_{23} \approx \theta_{\text{atm}} \approx 45^\circ$$

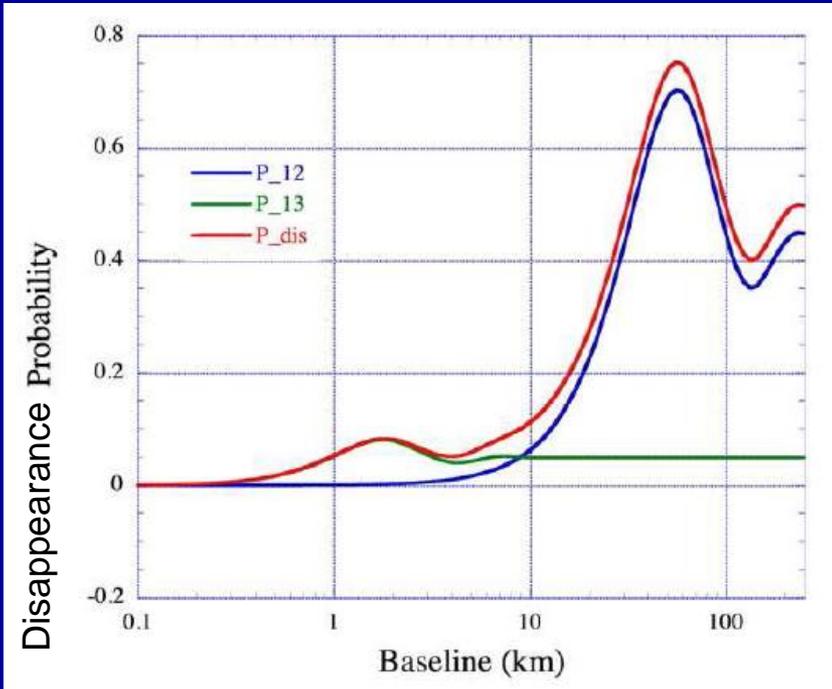
Large and maximal mixing!

The Next Big Thing?

SNO, solar SK, KamLAND

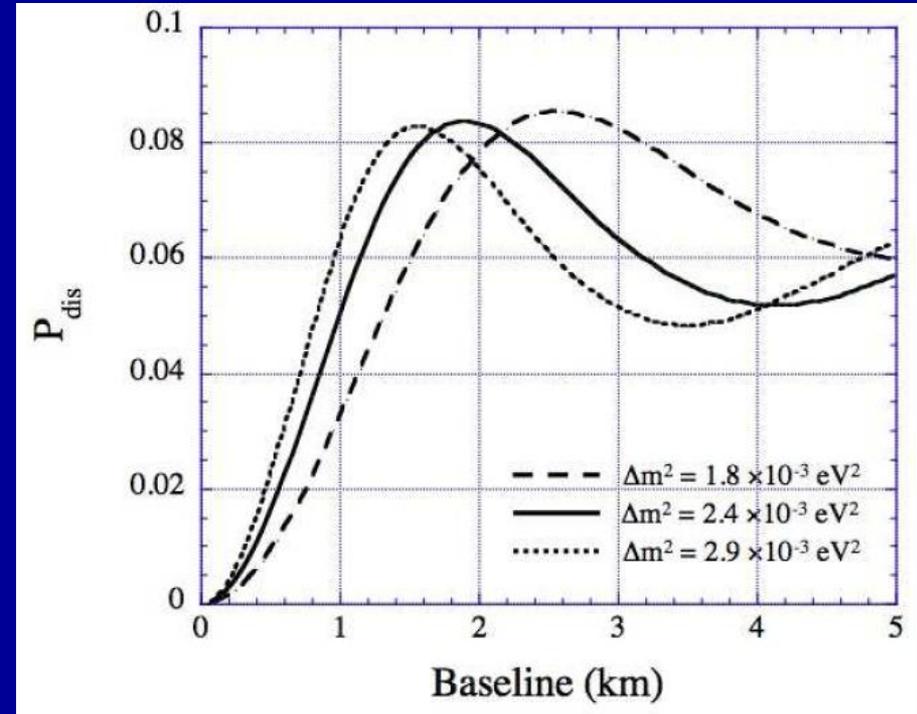
$$\theta_{12} \approx \theta_{\text{sol}} \approx 32^\circ$$

Reduction of reactor neutrinos due to oscillations



$$\sin^2 2\theta_{13} = 0.10$$

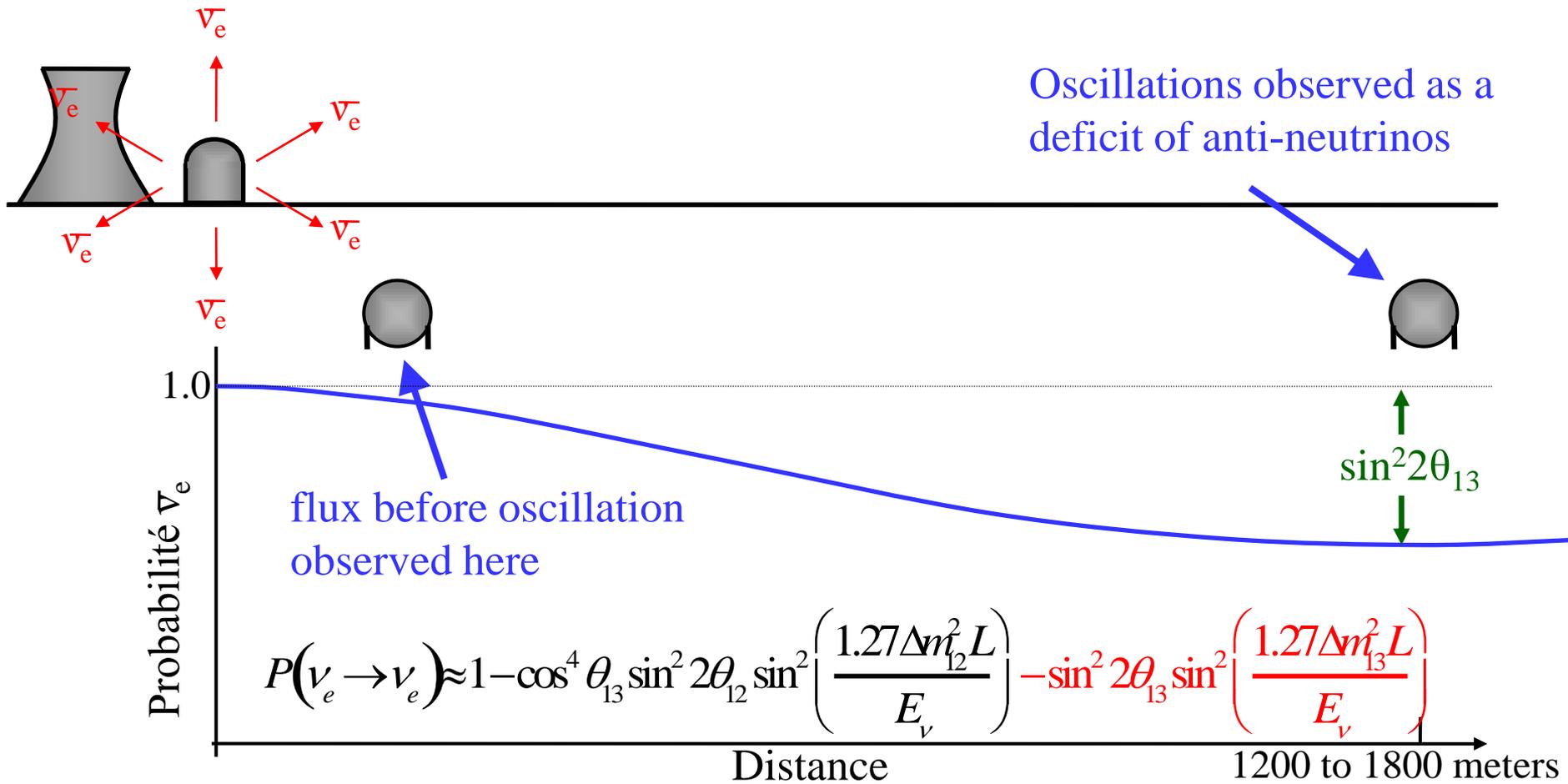
$$\theta_{12} = 34^\circ, \quad \Delta m_{21}^2 = 7.9 \times 10^{-5} \text{eV}^2, \quad \Delta m_{31}^2 = 2.5 \times 10^{-3} \text{eV}^2$$



Reactor neutrino disappearance Prob. due to θ_{13} with the allowed 2σ range in Δm_{23}^2

- $\sin^2 2\theta_{13} > 0.01$ with $10 \text{ t} \cdot 14 \text{ GW} \cdot 3 \text{ yr} \sim 400 \text{ t} \cdot \text{GW} \cdot \text{yr}$
($400 \text{ t} \cdot \text{GW} \cdot \text{yr}$: a 10(40) ton far detector and a 14(3.5) GW reactor in 3 years)

Experimental Method of θ_{13} Measurement



- Find disappearance of $\bar{\nu}_e$ fluxes due to neutrino oscillation as a function of energy using multiple, identical detectors to reduce the systematic errors in 1% level.

Expected Number of Neutrino Events at RENO

- 2.73 GW per reactor × 6 reactors
- 1.21×10^{30} free protons per targets (16 tons)

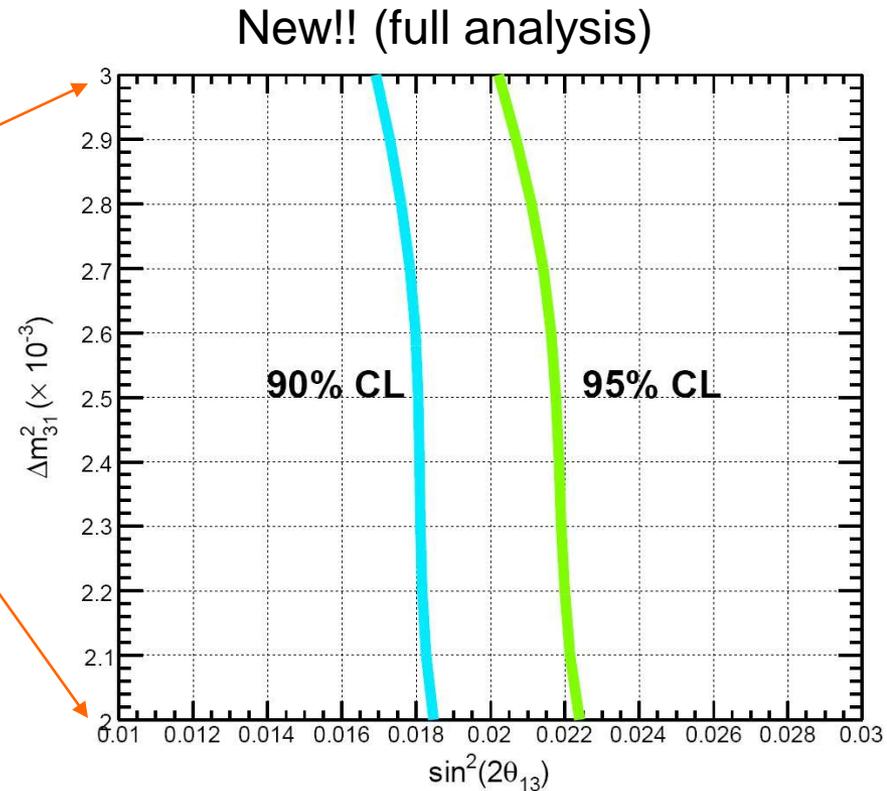
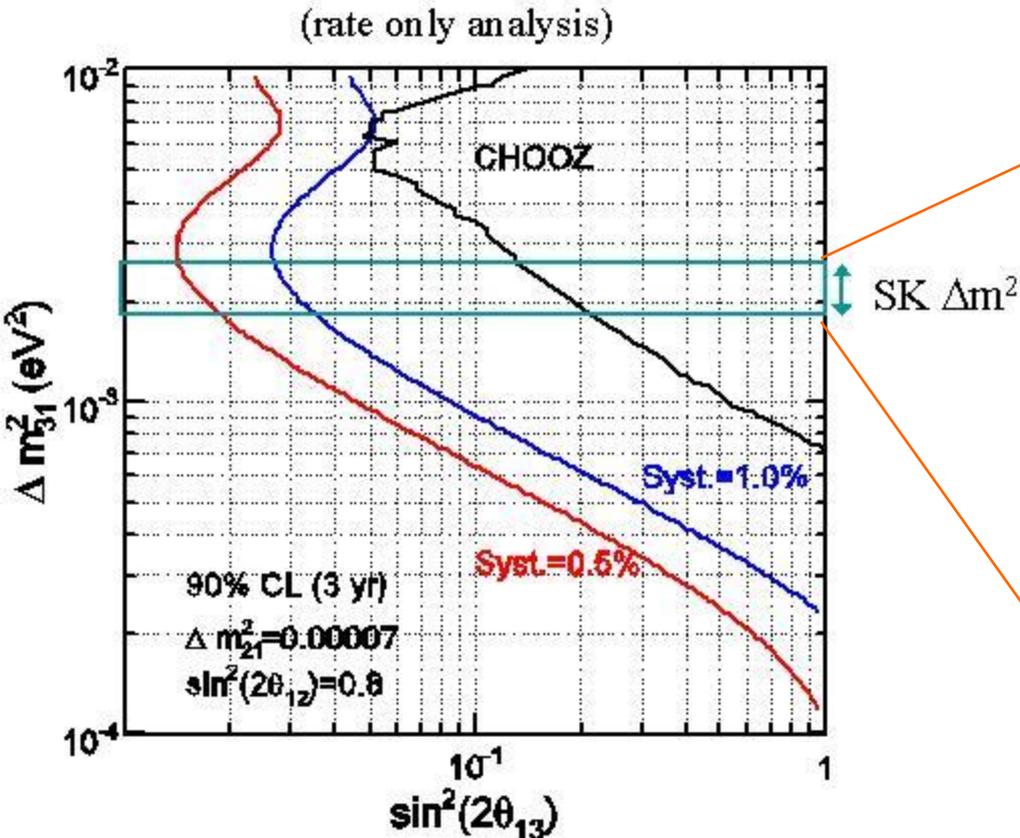
- | |
|---|
| <ul style="list-style-type: none">• Near : 1,280/day, 468,000/year• Far : 114/day, 41,600/year |
|---|

✓ 3 years of data taking with 70% efficiency

Near : $9.83 \times 10^5 \approx 10^6$ (0.1% error)

Far : $8.74 \times 10^4 \approx 10^5$ (0.3% error)

RENO Expected Sensitivity



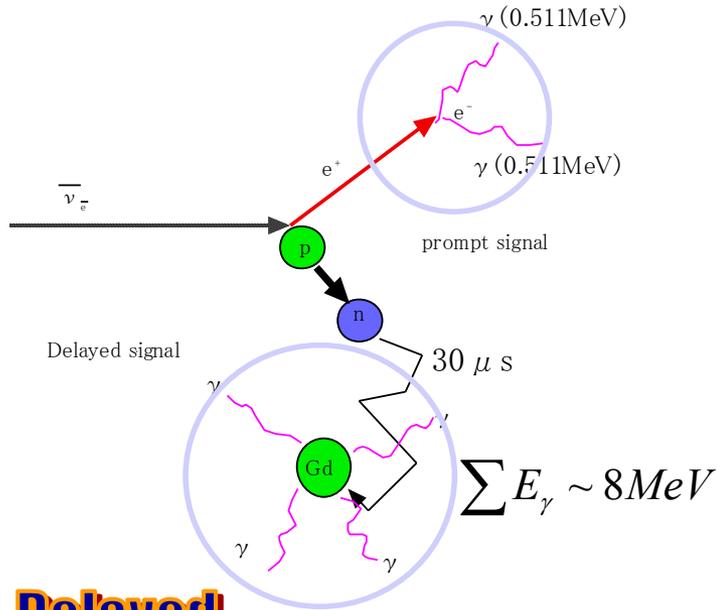
10x better sensitivity than current limit

Expected Systematic Uncertainty

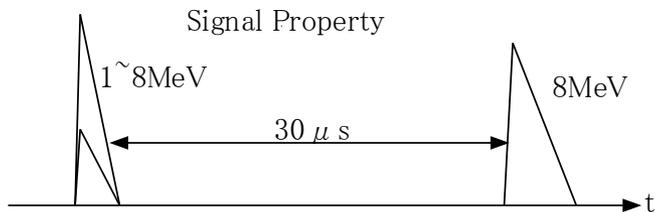
Systematic Source		CHOOZ (%)	RENO (%)
Reactor related absolute normalization	Reactor antineutrino flux and cross section	1.9	< 0.1
	Reactor power	0.7	0.2
	Energy released per fission	0.6	< 0.1
Number of protons in target	H/C ratio	0.8	0.2
	Target mass	0.3	< 0.1
Detector Efficiency	Positron energy	0.8	0.1
	Positron geode distance	0.1	0.0
	Neutron capture (H/Gd ratio)	1.0	< 0.1
	Capture energy containment	0.4	0.1
	Neutron geode distance	0.1	0.0
	Neutron delay	0.4	0.1
	Positron-neutron distance	0.3	0.0
Neutron multiplicity	0.5	0.05	
combined		2.7	< 0.5

Principle of Neutrino Detection

Prompt



Delayed



- Use inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) reaction process
- Prompt part: subsequent annihilation of the positron to two 0.511MeV γ
- Delayed part: neutron is captured
 - $\sim 200\ \mu\text{s}$ w/o Gd
 - $\sim 30\ \mu\text{s}$ w Gd
- Gd has largest n absorption cross section & emits high energy γ
- Signal from neutron capture
 - $\sim 2.2\text{MeV}$ w/o Gd
 - $\sim 8\text{MeV}$ w Gd
- Measure prompt signal & delayed signal
- “Delayed coincidence” reduces backgrounds drastically

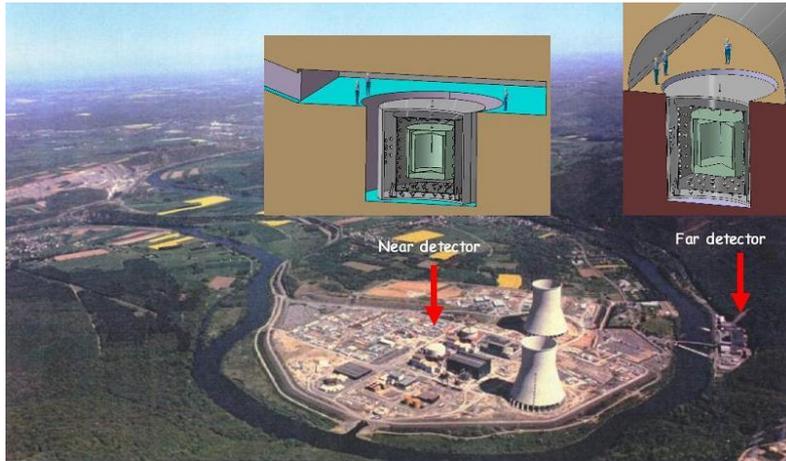
World Competition in Reactor Neutrino Experiments

Experiments	Location	Thermal Power (GW)	Distances Near/Far (m)	Depth Near/Far (mwe)	Target Mass (tons)	Cost (US \$)	# of Collaborators
Double-CHOOZ	France	8.7	410/1050	115/300	10/10	~30M	>160
RENO	Korea	17.3	290/1380	120/450	16/16	~10M	40
Daya Bay	China	11.6	360(500)/1985 (1613)	260/910	40×2/80	~60M	>230

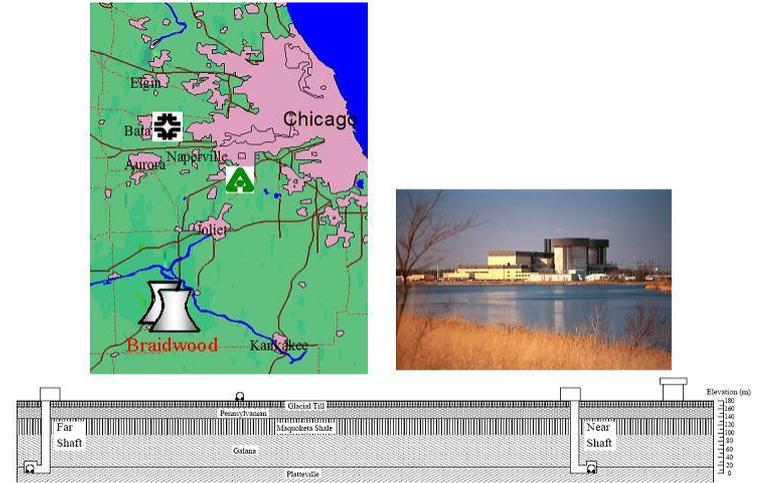
- Double-Chooz** is expected to complete construction in 2012
- RENO** will finish its construction by Feb 2011
- Daya Bay** is expected to finish its construction in 2012

Reactor Neutrino Experiments

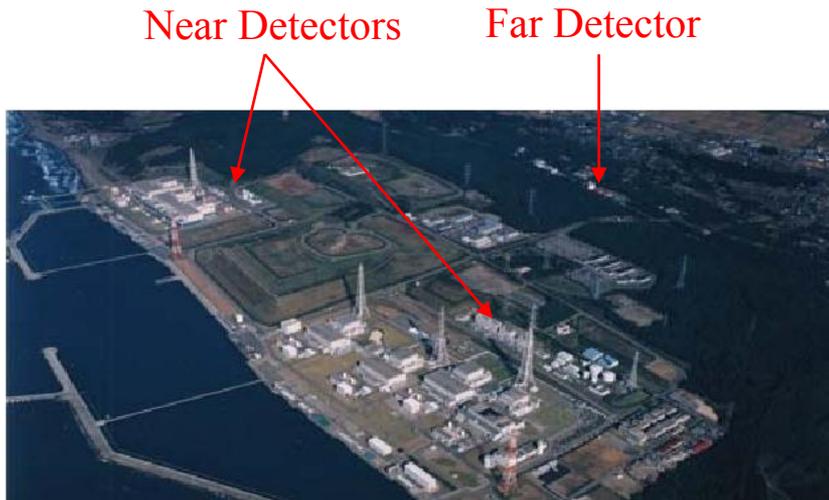
Double-CHOOZ (France)



Braidwood (USA)



KASKA (Japan)



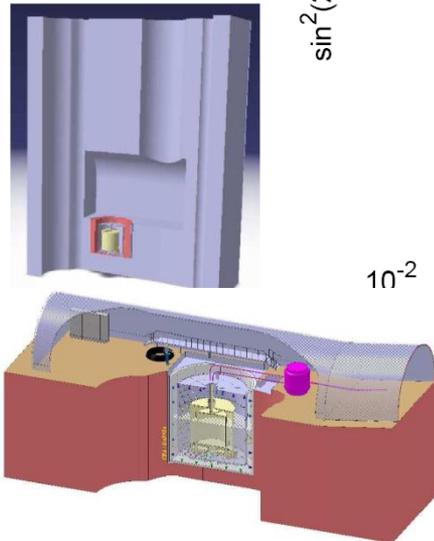
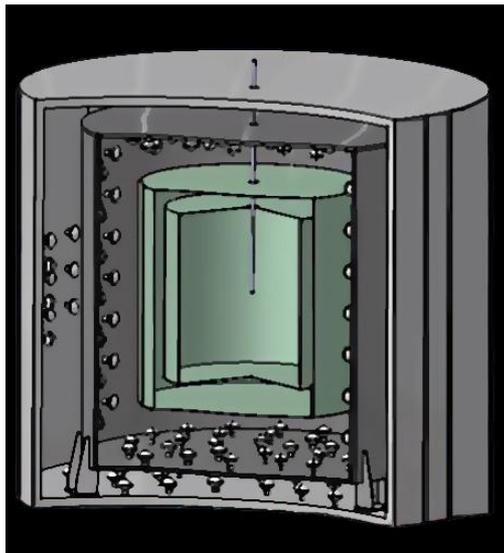
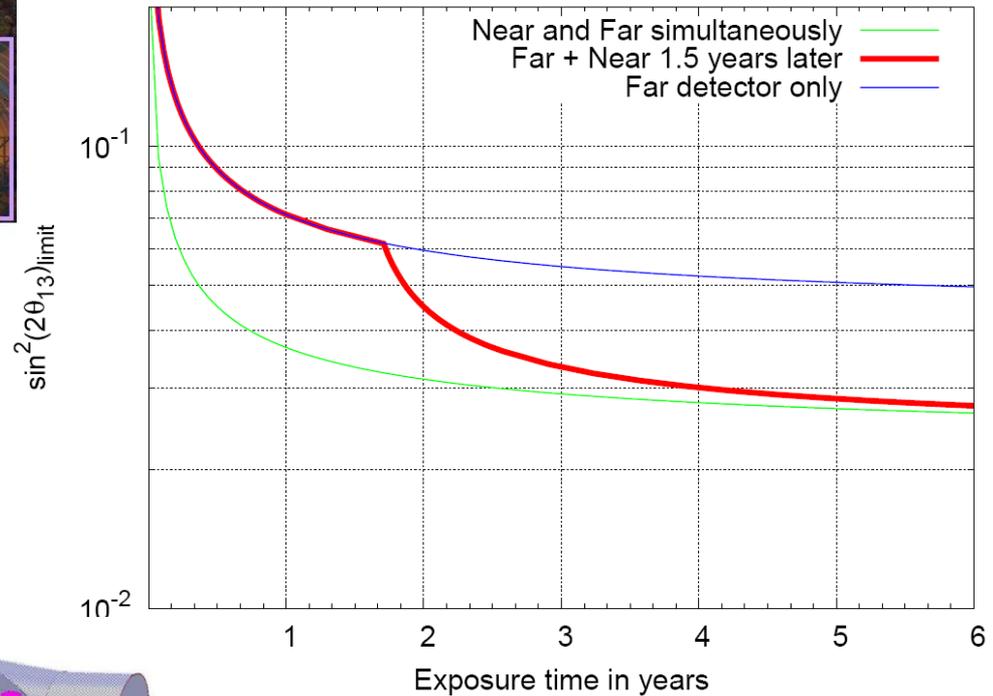
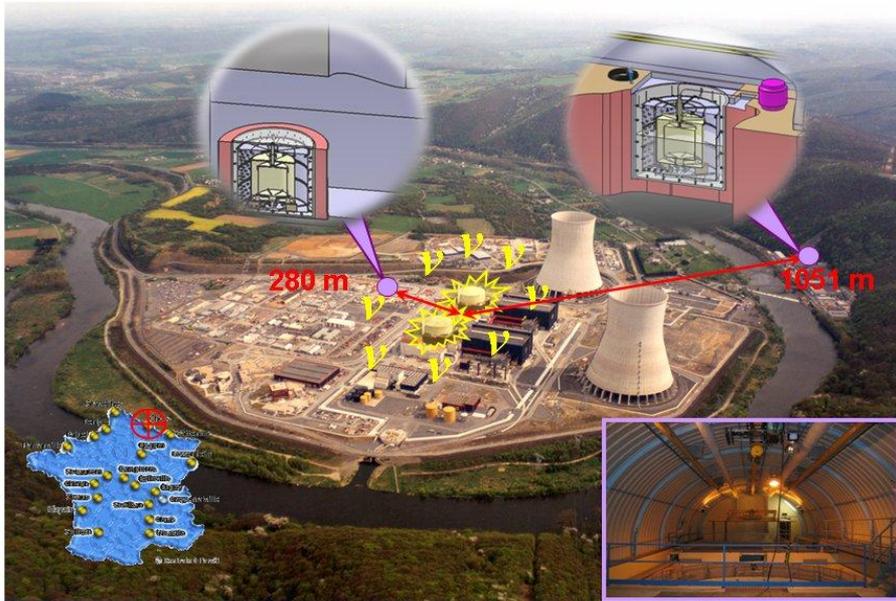
Daya Bay (China)



Double-CHOOZ

Double-Chooz Collaboration:

France, US, Germany, Italy, Japan,
Spain & Russia

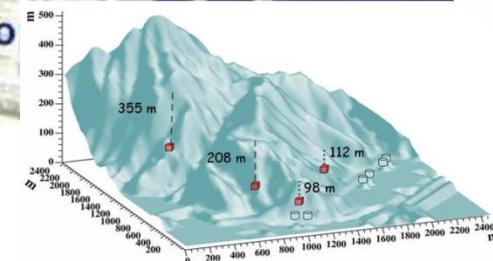
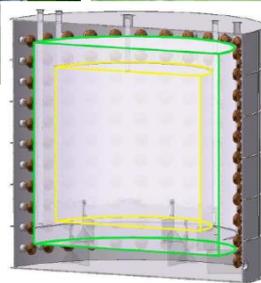
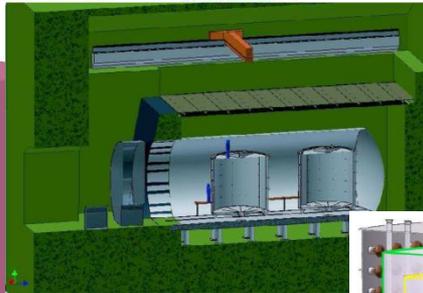
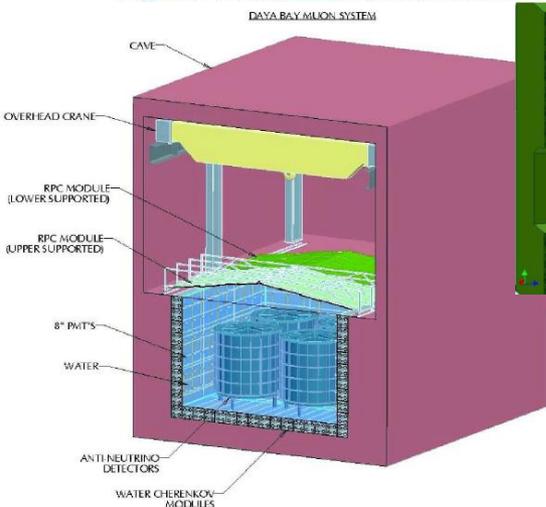
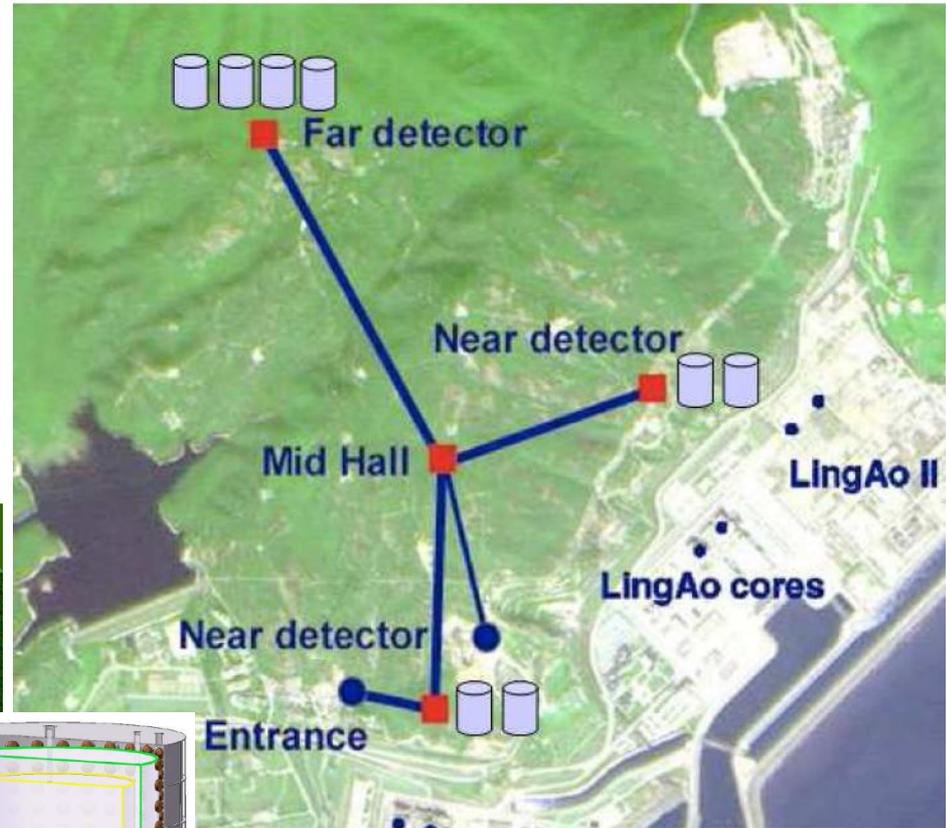


* Proposal (June 20, 2006) : hep-ex/0606025



Daya Bay

Daya Bay Collaboration: China, US, Czech Republic, Hong Kong, Russia & Taiwan



* Proposal to DOE (Jan. 15, 2007): hep-ex/0701029

RENO Collaboration

(13 institutions and 40 physicists)



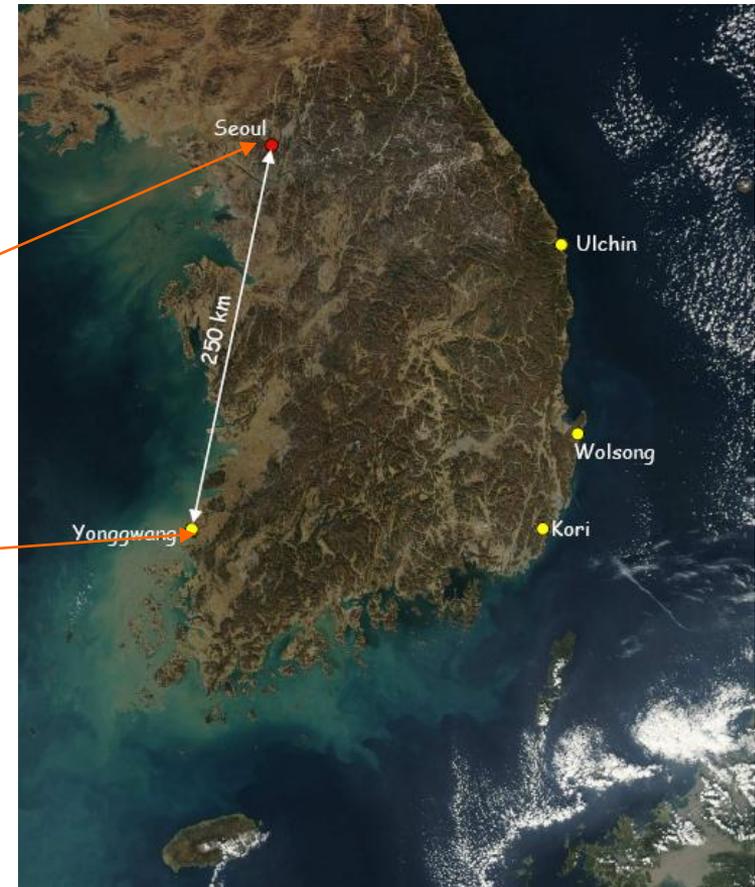
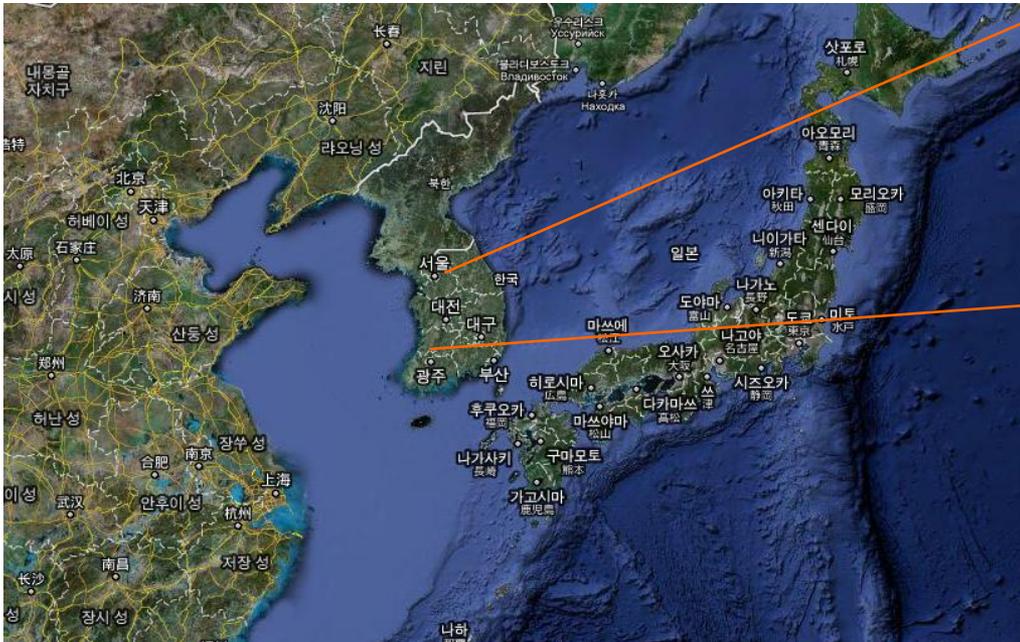
- Chonbuk National University
 - Chonnam National University
 - Chung-Ang University
 - Dongshin University
 - Gyeongsang National University
 - Kyungpook National University
 - Pusan National University
 - Sejong University
 - Seokang Information University
 - Seokyeong University
 - Seoul National University
 - Sungkyunkwan University
 - California State University Dominguez Hills, USA
- +++ <http://neutrino.snu.ac.kr/RENO>

International collaborators are being invited

YongGwang Nuclear Power Plant

- ❑ Located in the west coast of southern part of Korea
- ❑ ~400 km from Seoul
- ❑ 6 reactors are lined up in roughly equal distances and span ~1.3 km
- ❑ Total average thermal output ~16.4GW_{th} (2nd largest in the world)

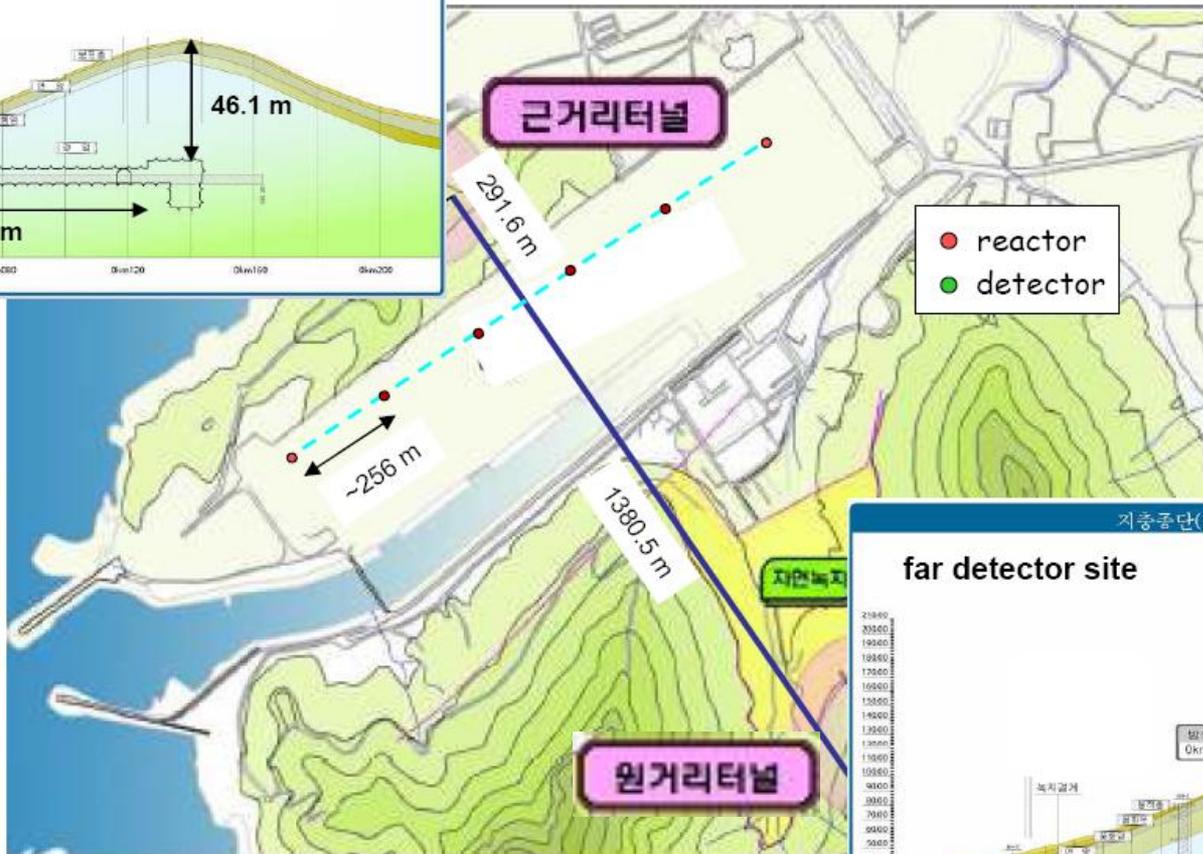
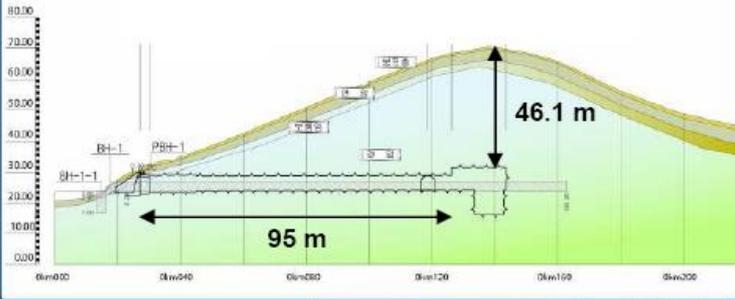
YongGwang(靈光):
= glorious[splendid] light



RENO Experimental Setup

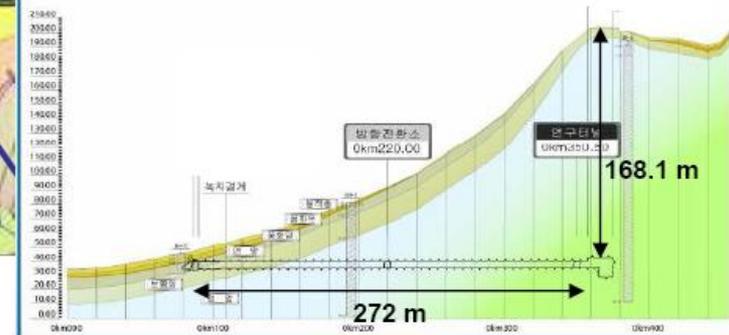
지층종단(근거리터널)

near detector site



지층종단(원거리터널)

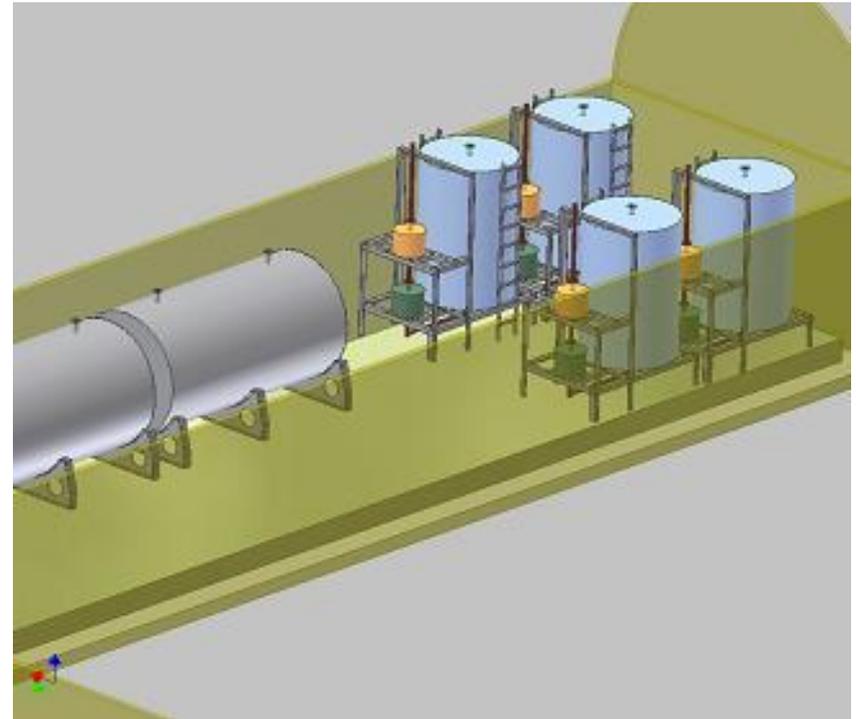
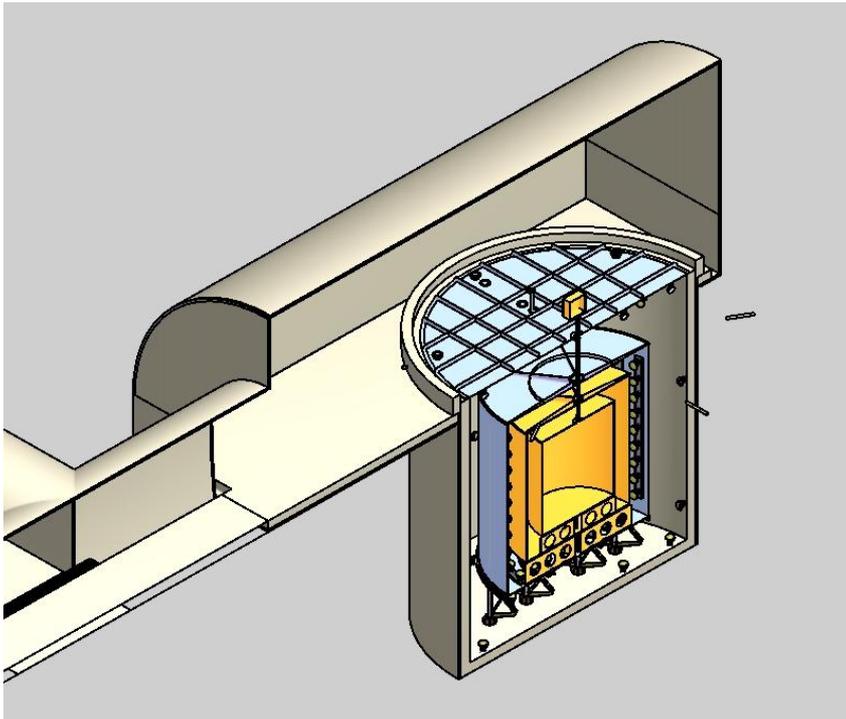
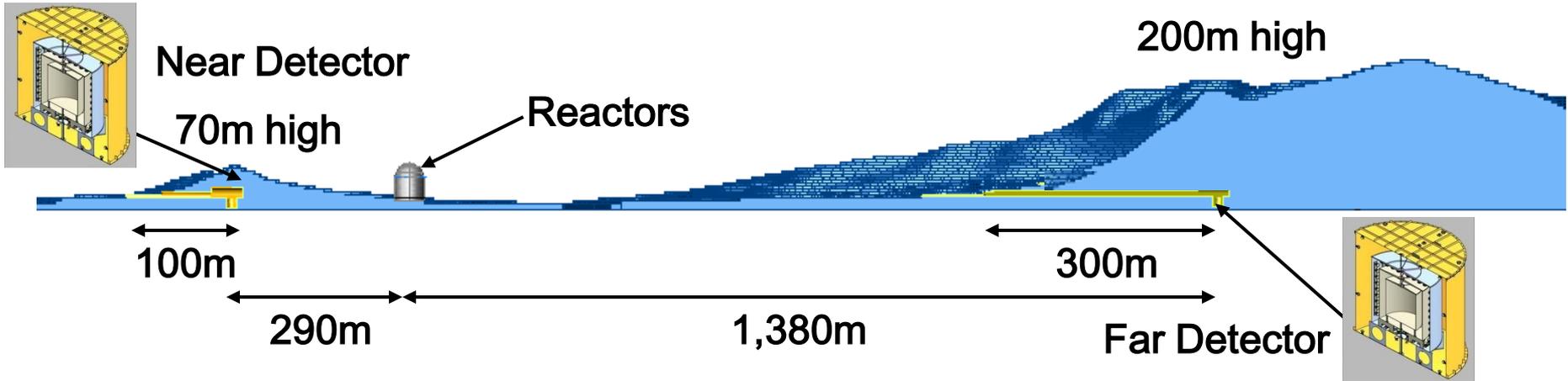
far detector site



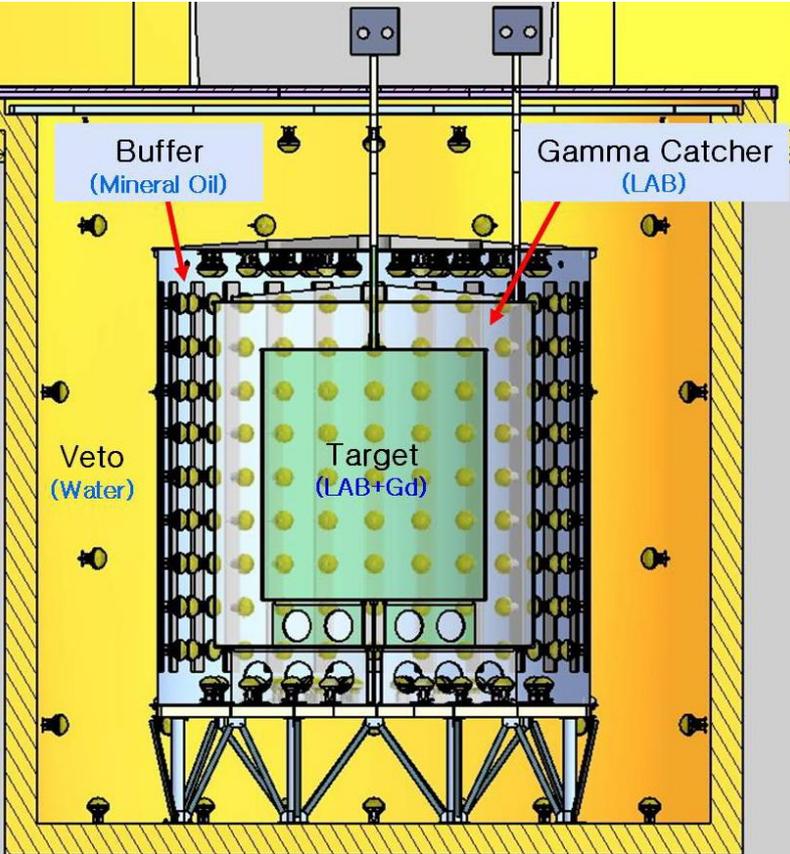
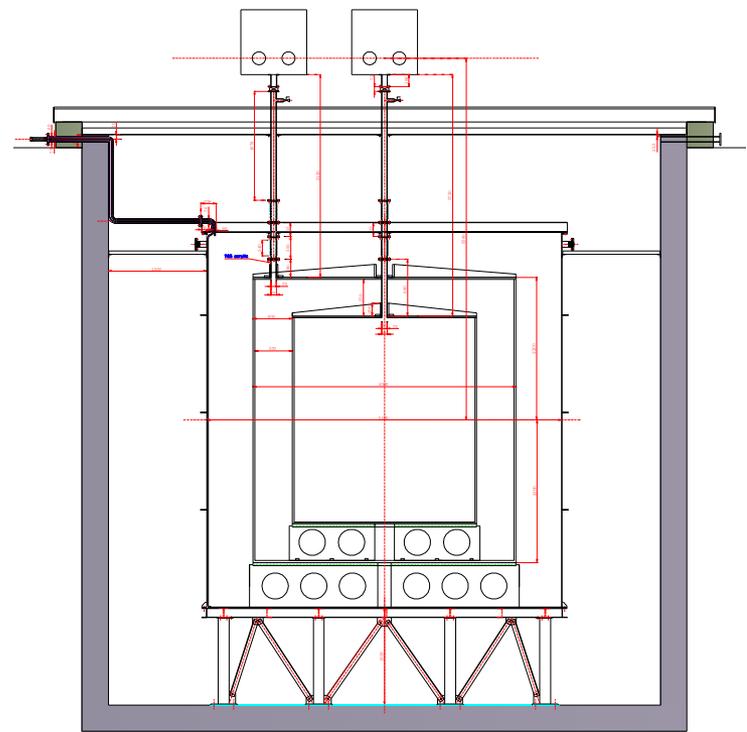
Google Satellite View of Experimental Site



Schematic View of Underground Facility



RENO Detector



	Thick (cm)	vessel	Material	Mass (tons)
Target	140	Acrylic (10mm)	Gd(0.1%) +LS	15.4
Gamma catcher	60	Acrylic (15mm)	LS	27.5
Buffer	70	SUS(5mm)	Mineral oil	59.2
Veto	150	Steel (15mm)	water	354.7

- Inner PMTs: 342 10" PMTs
 - solid angle coverage = 12.6%
- Outer PMTs: ~ 60 10" PMTs

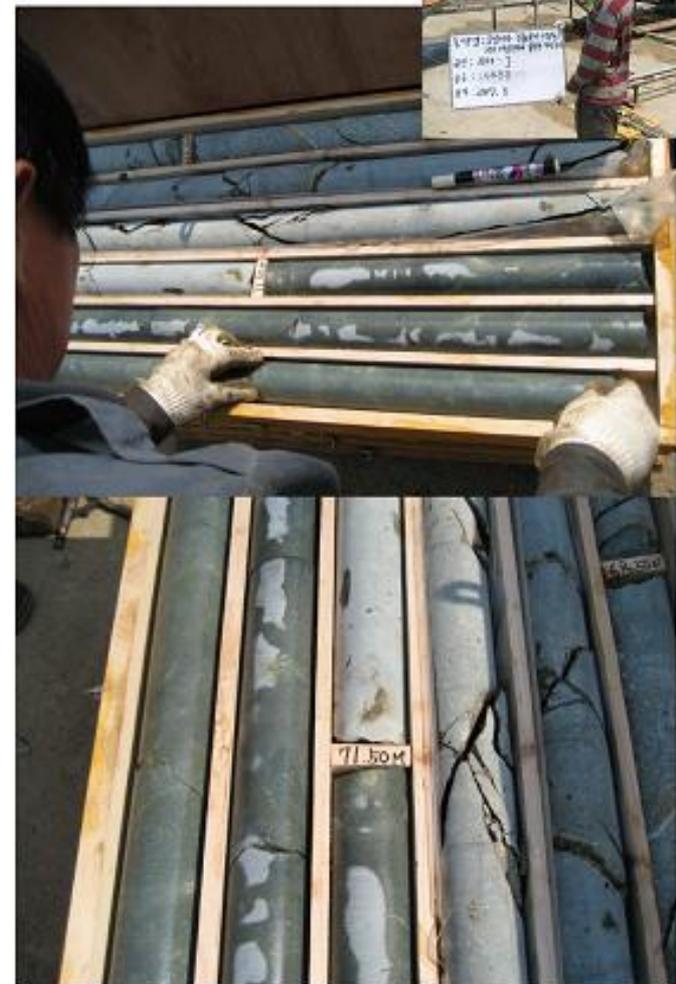
total ~460 tons

Efforts for Underground Facility

- 03~08, 2006 : Project description to local government, residents, and NGO's (endorsed by local government)
- 03, 2007 : Agreement between KHNP and SNU
- 03~10, 2007 : Geological survey and tunnel design are completed.
- 12, 2007 : Public hearing for YG residents
- 01, 2008 : Safety regulation established and accepted by the atomic energy department of MOST
- 05~11, 2008 : Tunnel construction

Rock sampling (DaeWoo Engineering Co.)

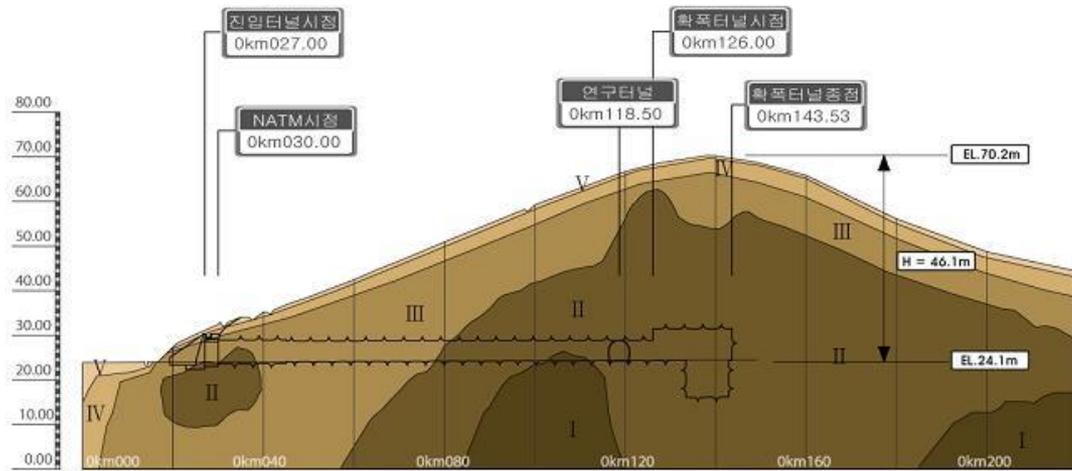
Rock samples from boring



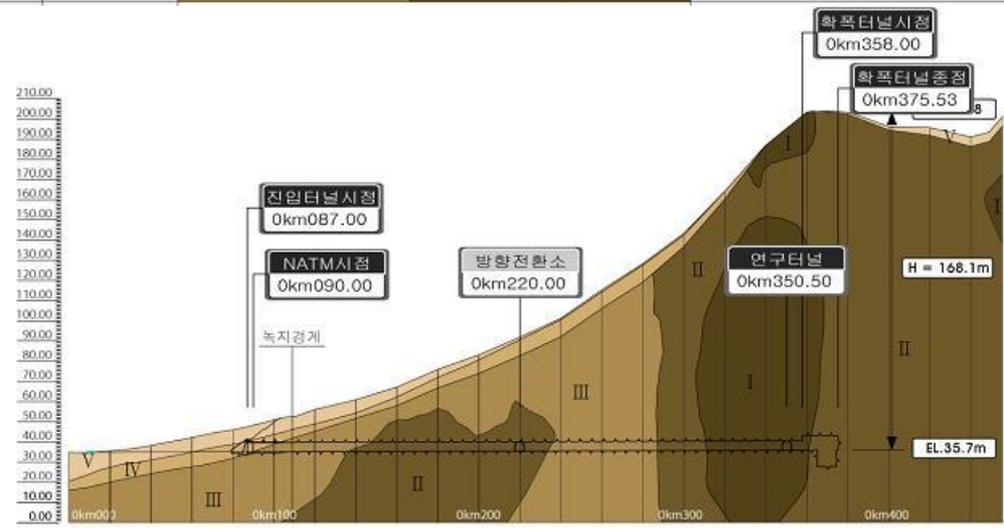
Rock Quality Map

(2007.3~2007.8)

- Near detector site:
- tunnel length : 110m
- overburden height : 46.1m



시추조사 결과	RMR	50				
	Q	100				
암반등급	상부 1.00		V	IV	III	II
	막장면				III	II



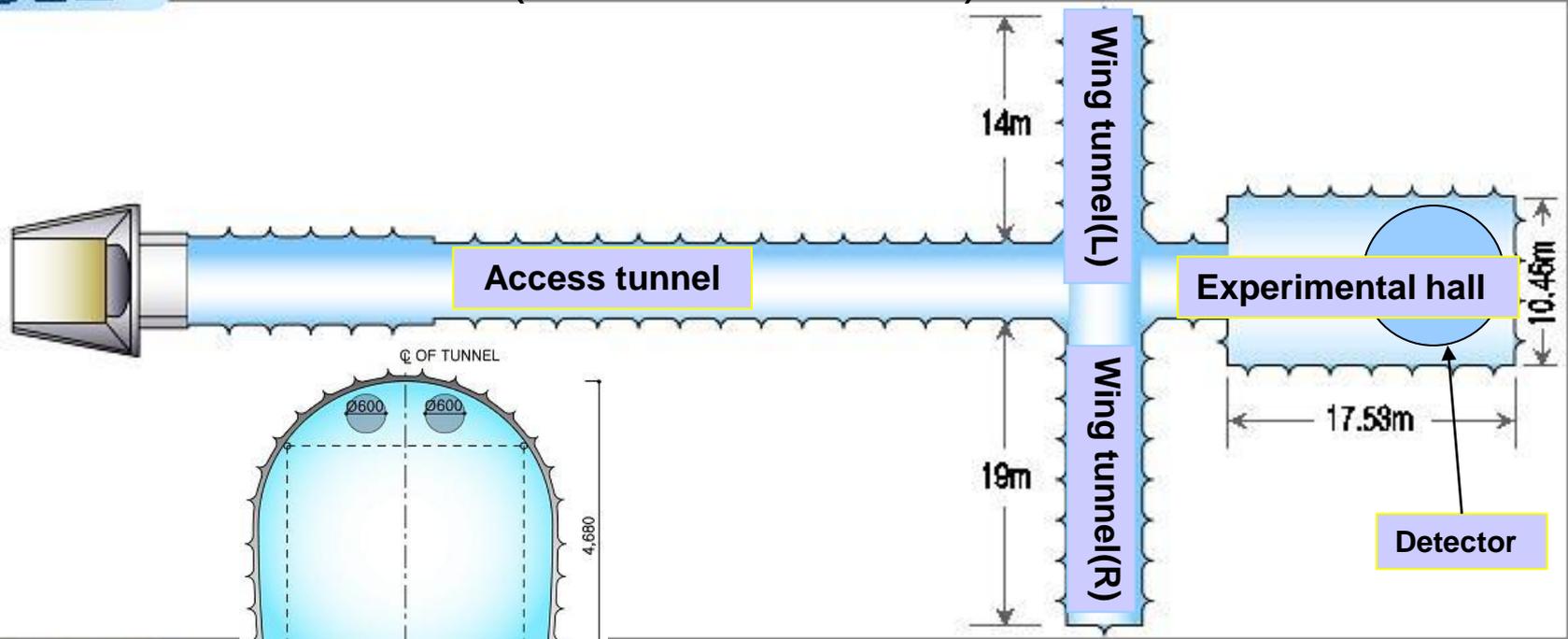
- Far detector site:
- tunnel length : 272m
- overburden height : 168.1m

시추조사 결과	RMR	상부 1.00	-	71	84		
	Q	막장면	49	72	81		
암반등급	상부 1.00		-	38	94.5		
	막장면		2.5	41.4	87.5		
			V	IV	III	II	I
			IV	III	II	I	

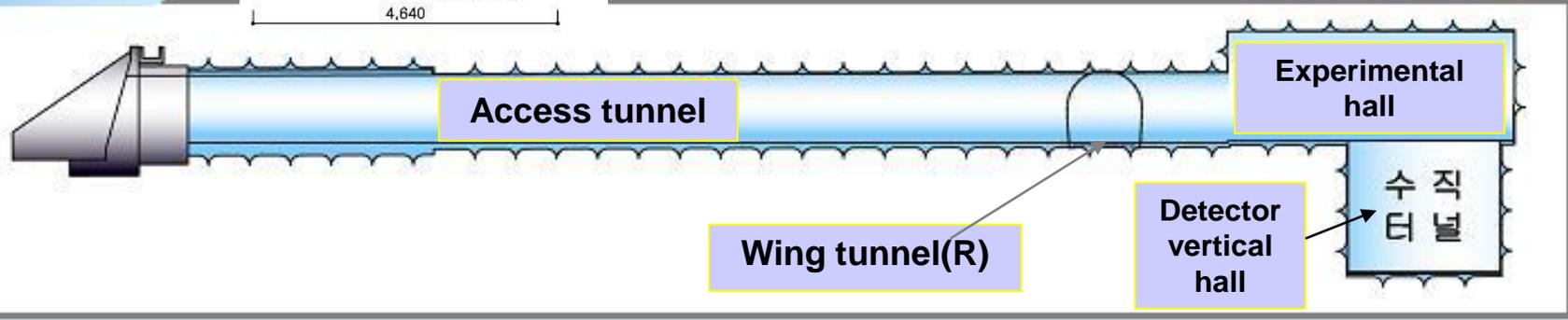
Design of Tunnel

평면도

(2007.9~2007.11)



단면도



Tunnel Construction for Underground Facility

- ❑ Approval from government regulation ('08. 01/05)
- ❑ Cleared local government regulations ('08. 01 ~ '08. 06)
- ❑ Preparation for tunnel excavation ('08. 07)



Tunnel Construction

(2008.6~2008.12)

by Daewoo Eng. Co. Korea



Near & far tunnels are completed

(2008.6~2009.3)

by Daewoo Eng. Co. Korea



Far site



Near site



Underground Peripheral Facility (2009. 7~12)

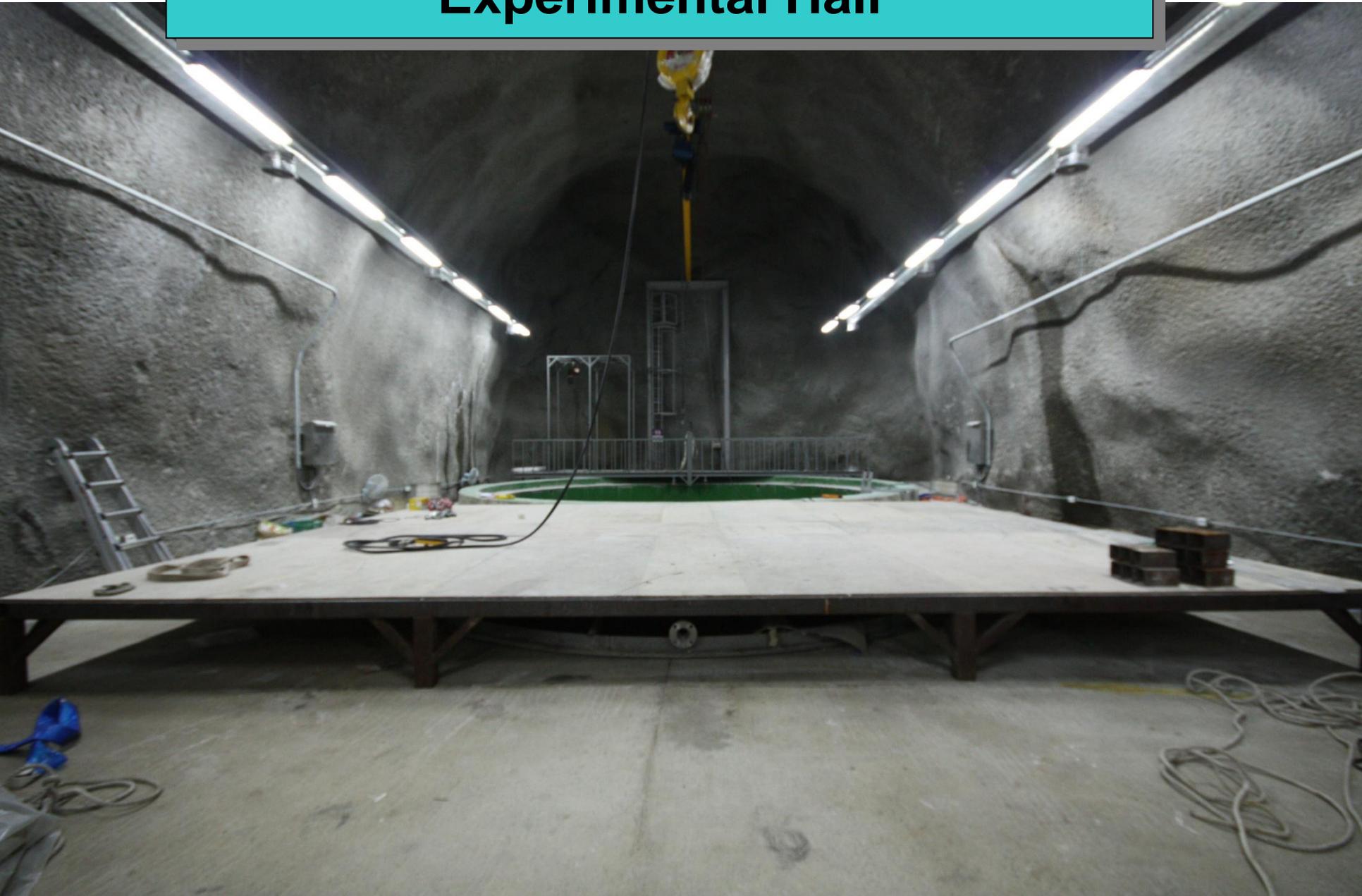
❑ Electric power and ground system



❑ Internet cable and mobile telephone network

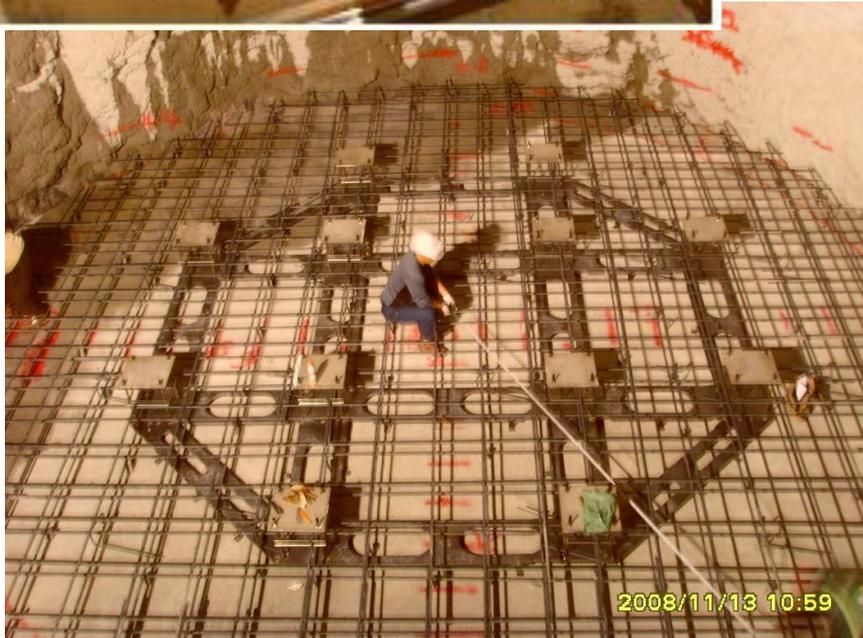


Experimental Hall



Detector vertical halls are ready

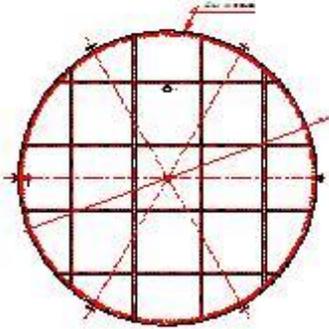
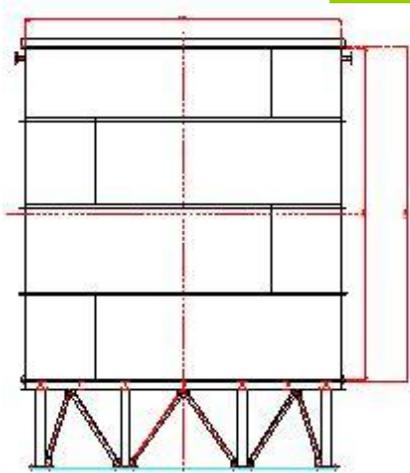
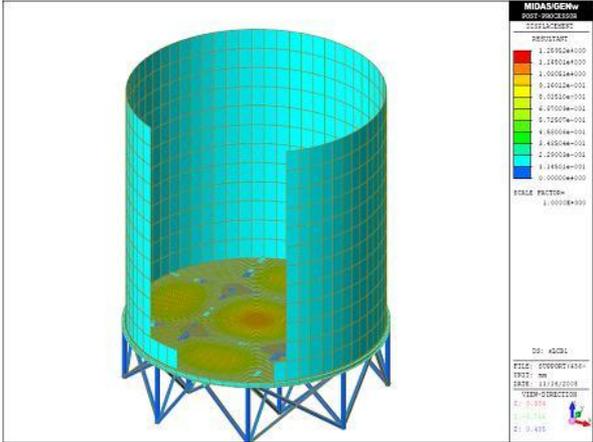
(2008.12~2009.2)



Buffer steel tanks are installed

(2009.6~2009.11)

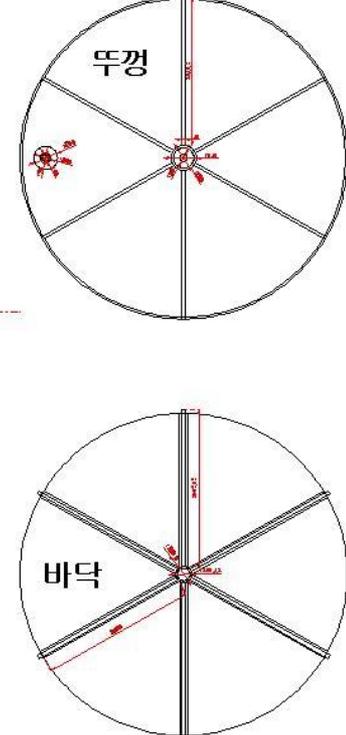
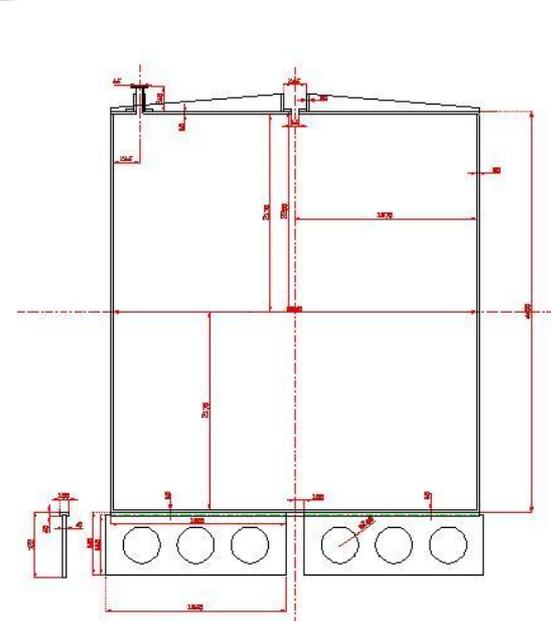
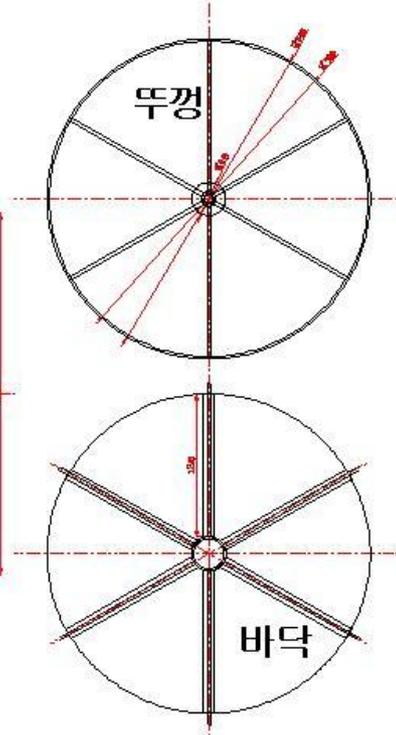
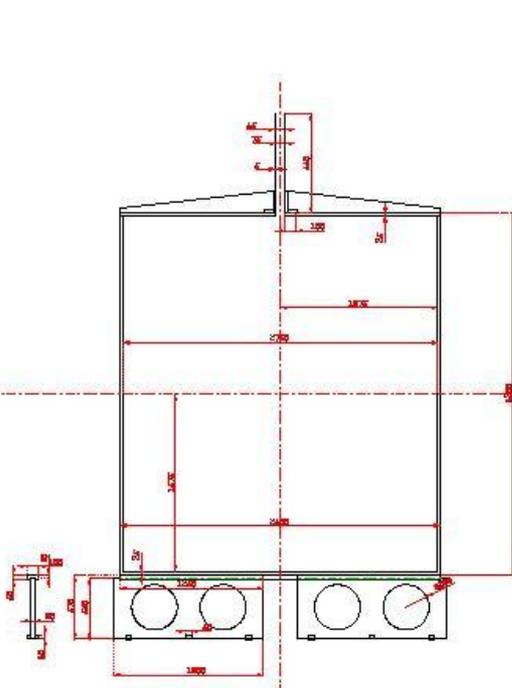
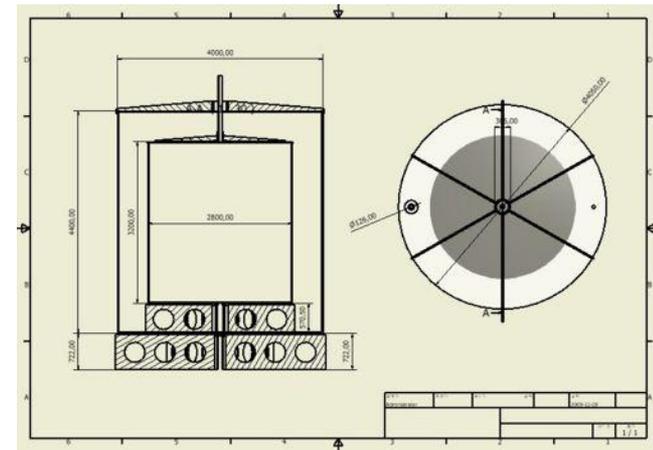
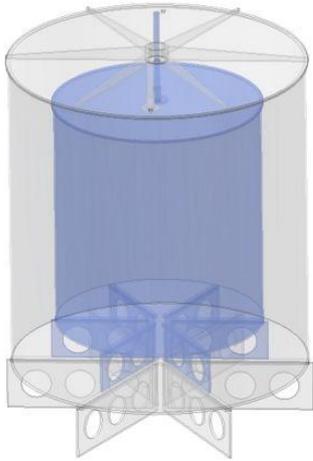
by NIVAK Co. Korea



Acrylic vessels are made and installed

(2009.7~2010.6)

by KOATECH Co. Korea



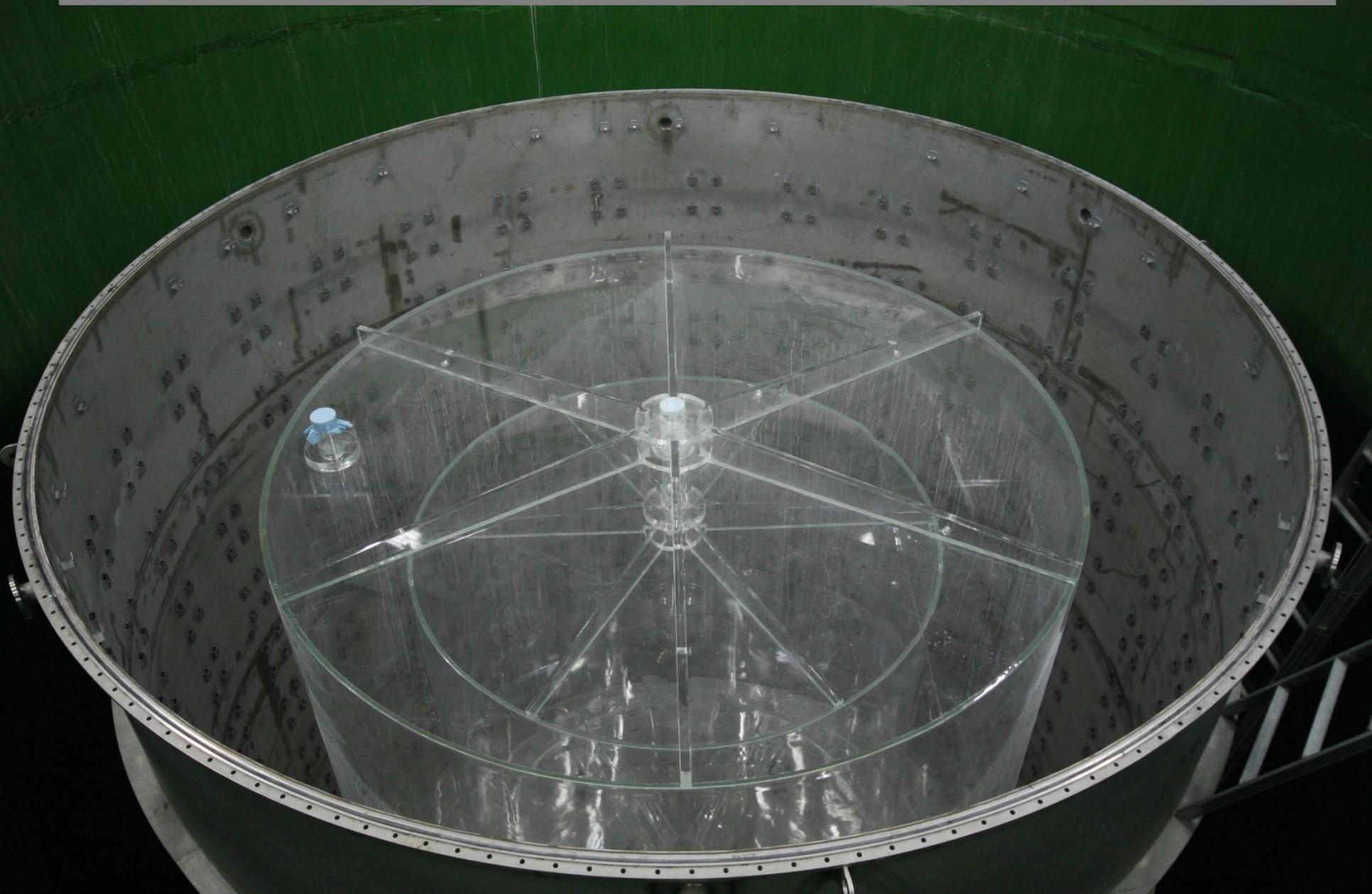
Acrylic Delivery



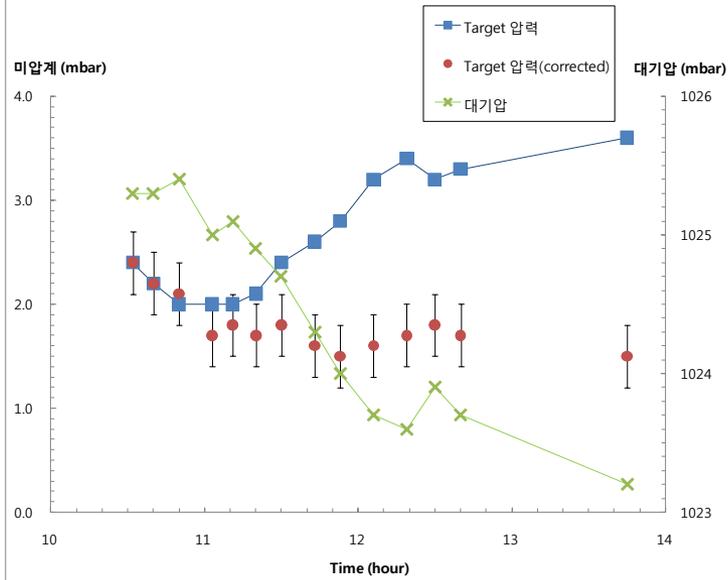


03/18/2010 13:29

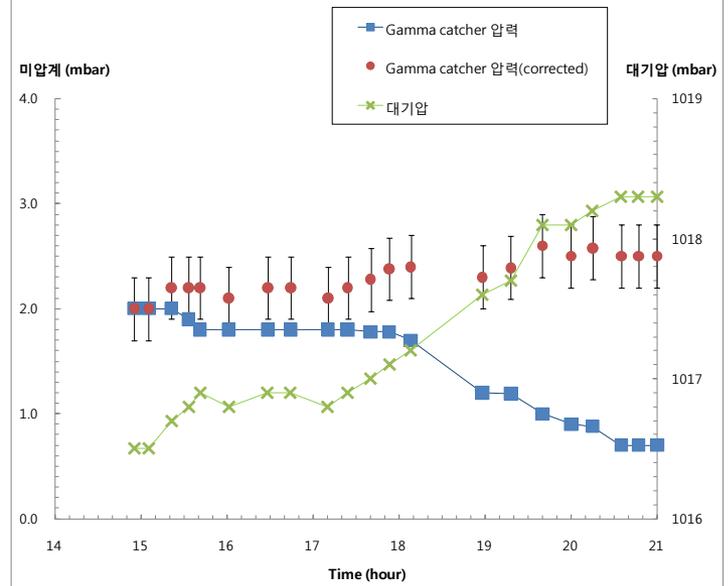
Installation of Acrylic Vessels (2010. 6)



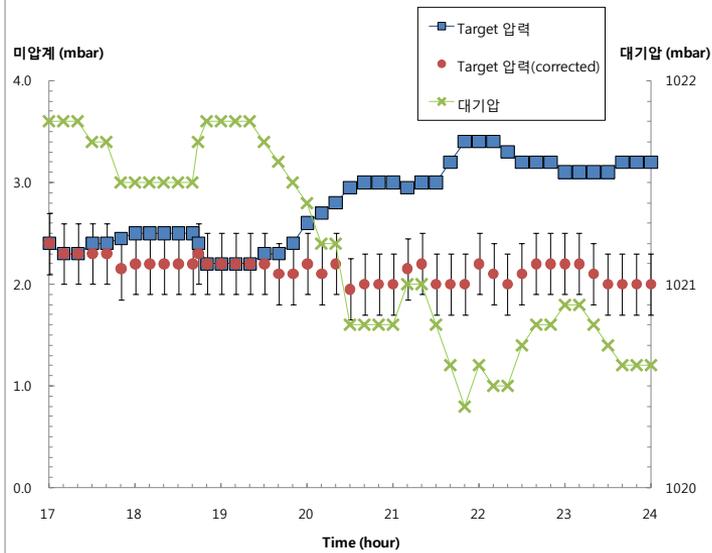
Nov.28 (Sun) 근거리 Near site



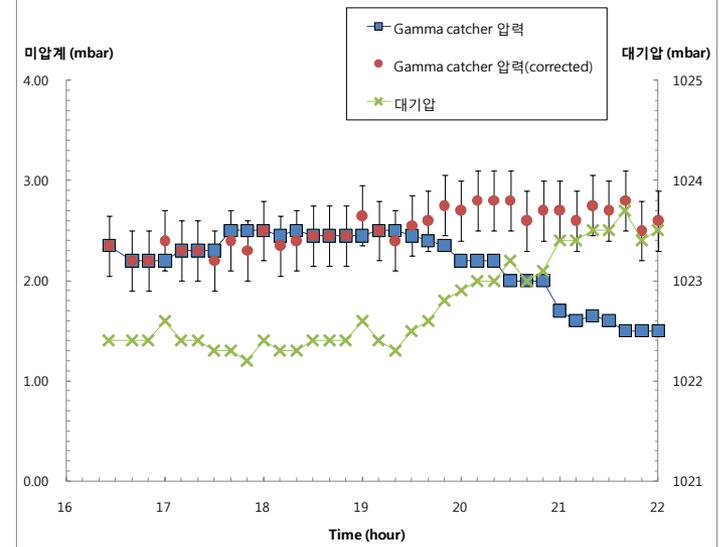
Nov.30 (Tue) 근거리 Near site



Jan.10 (Mon) 원거리 Far site



Jan.13 (Thu) 원거리 Far site



Trailer Research Facility & Guest Room (2009. 11~2010. 2)



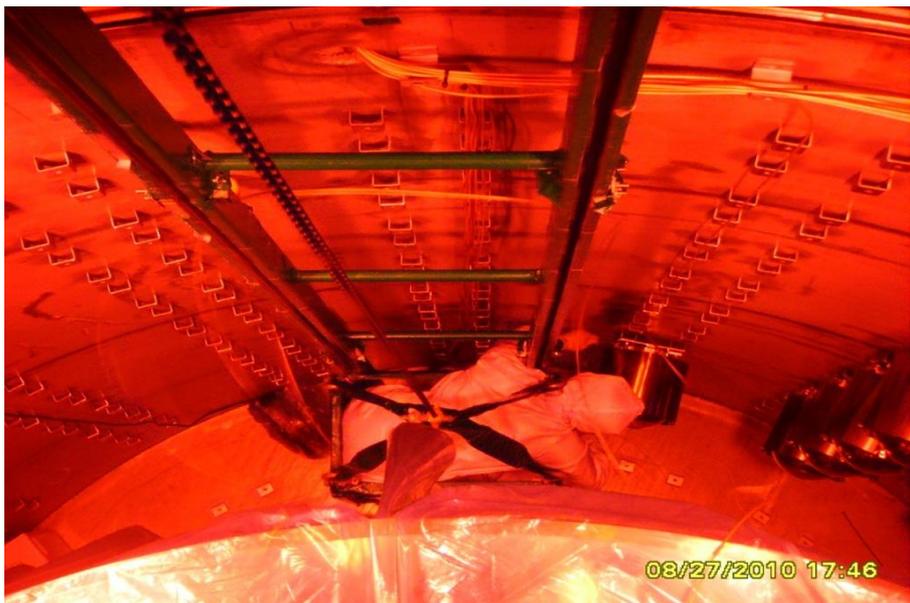
Tunnel Entrance



Construction of Vinyl House (2010. 8)



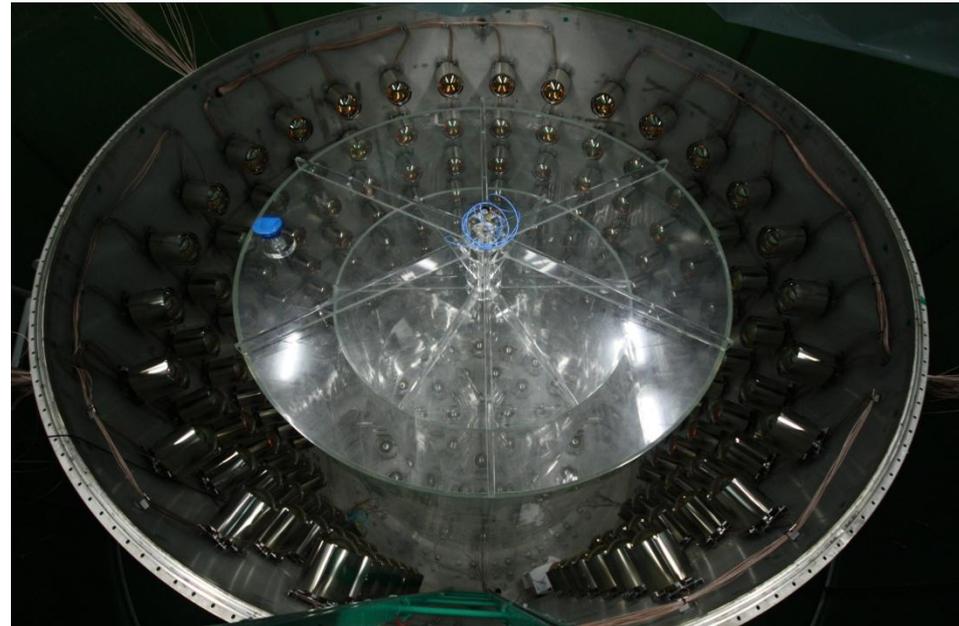
PMT Assembling & Installation (2010. 8~2011.1)



1st & Bottom PMT Mounting (2010. 8. 17)



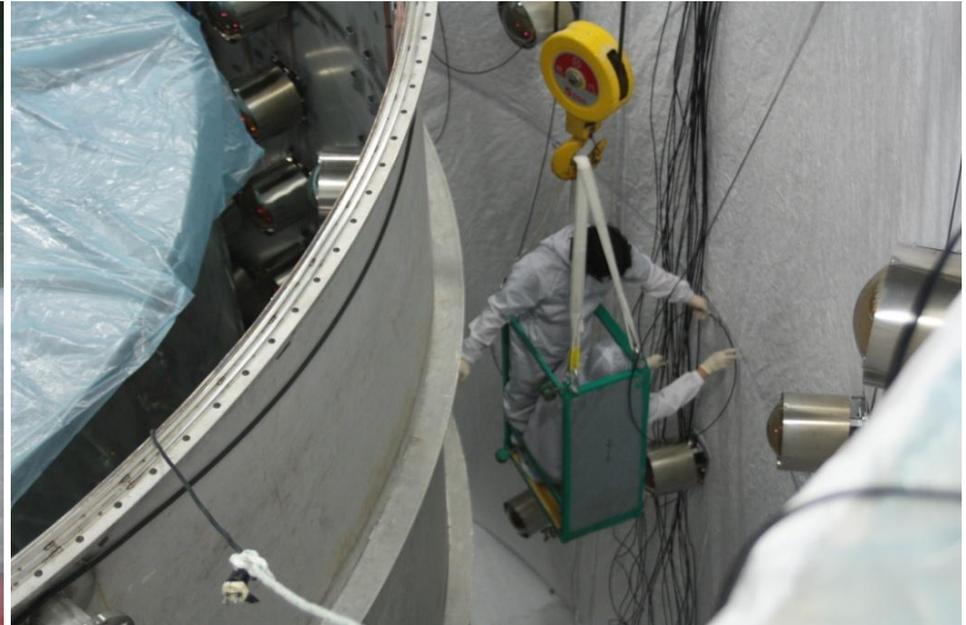
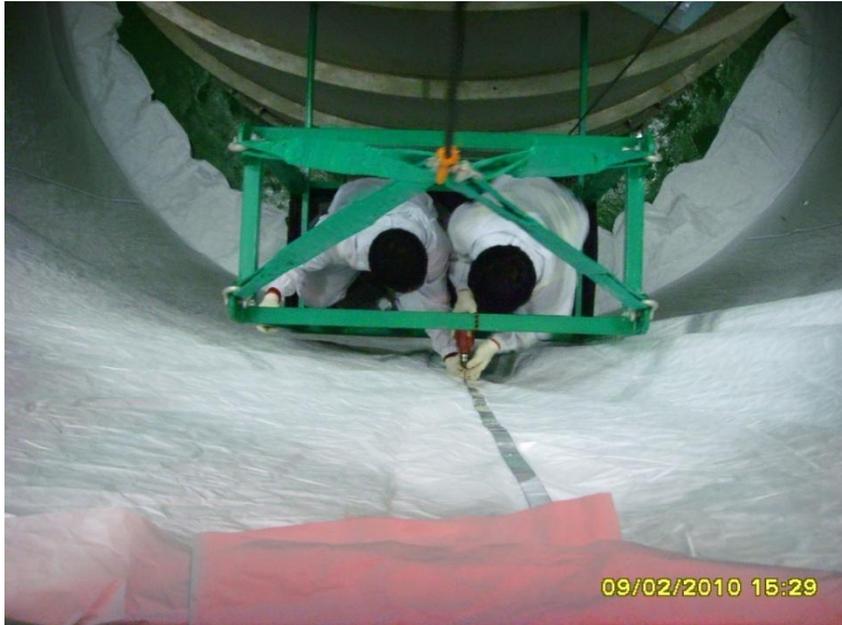
PMT Mounting (2010. 8~10)



Finishing PMT installation (2011. 1)



Veto Tyvek and PMTs (2010. 10)



Top PMT Mounting (2010. 11)



ND/FD Chimney, Tyvek, buffer Lids(2011.1)

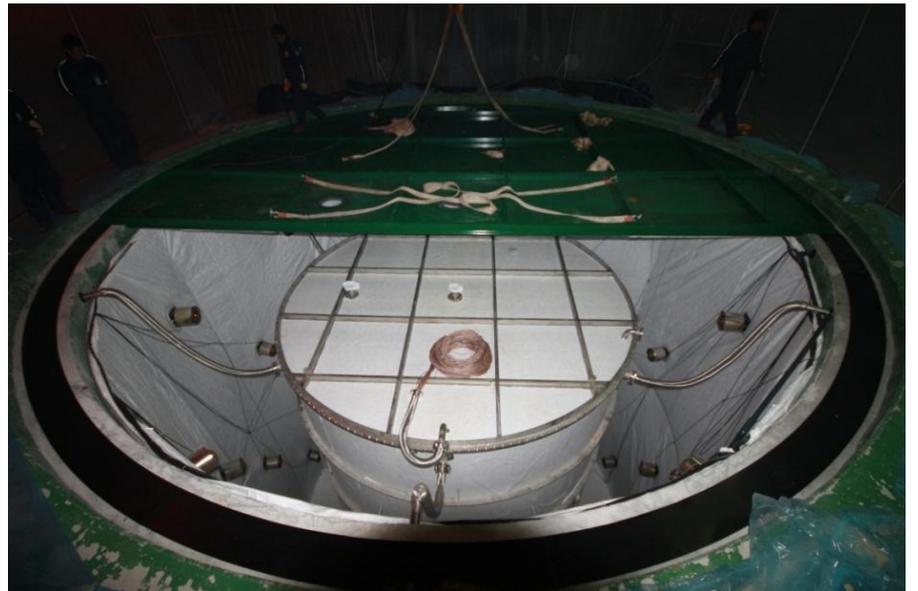
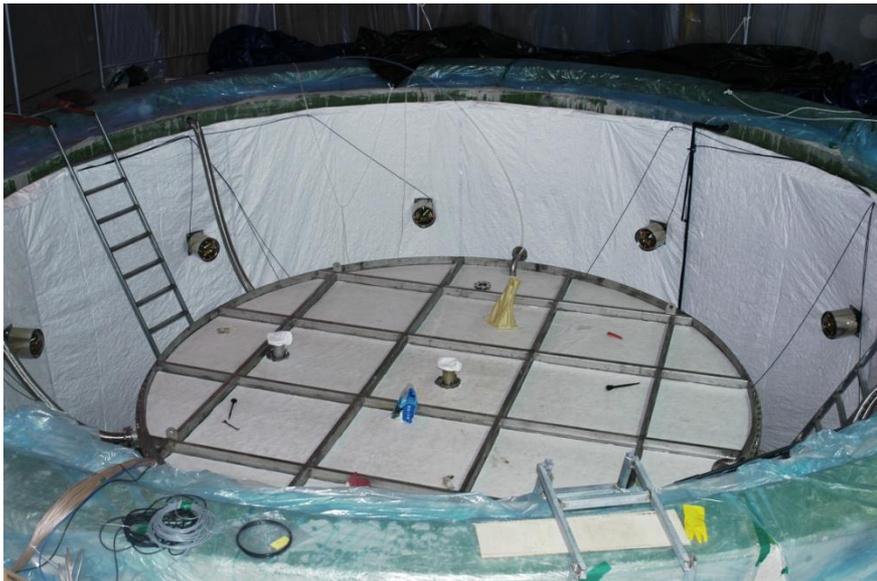
ND



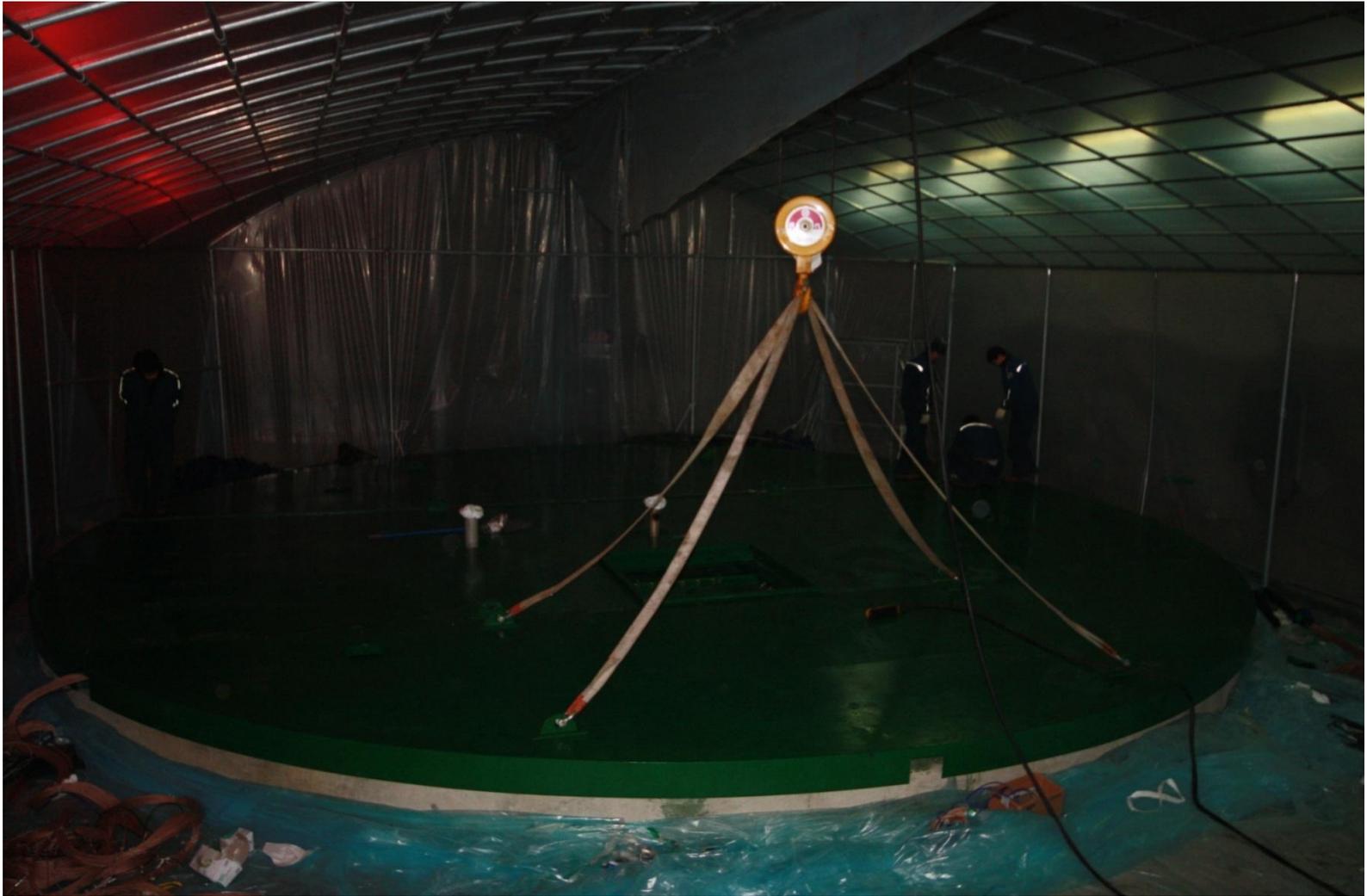
ND



Near Detector: Installing Tubes, etc (2011.1)

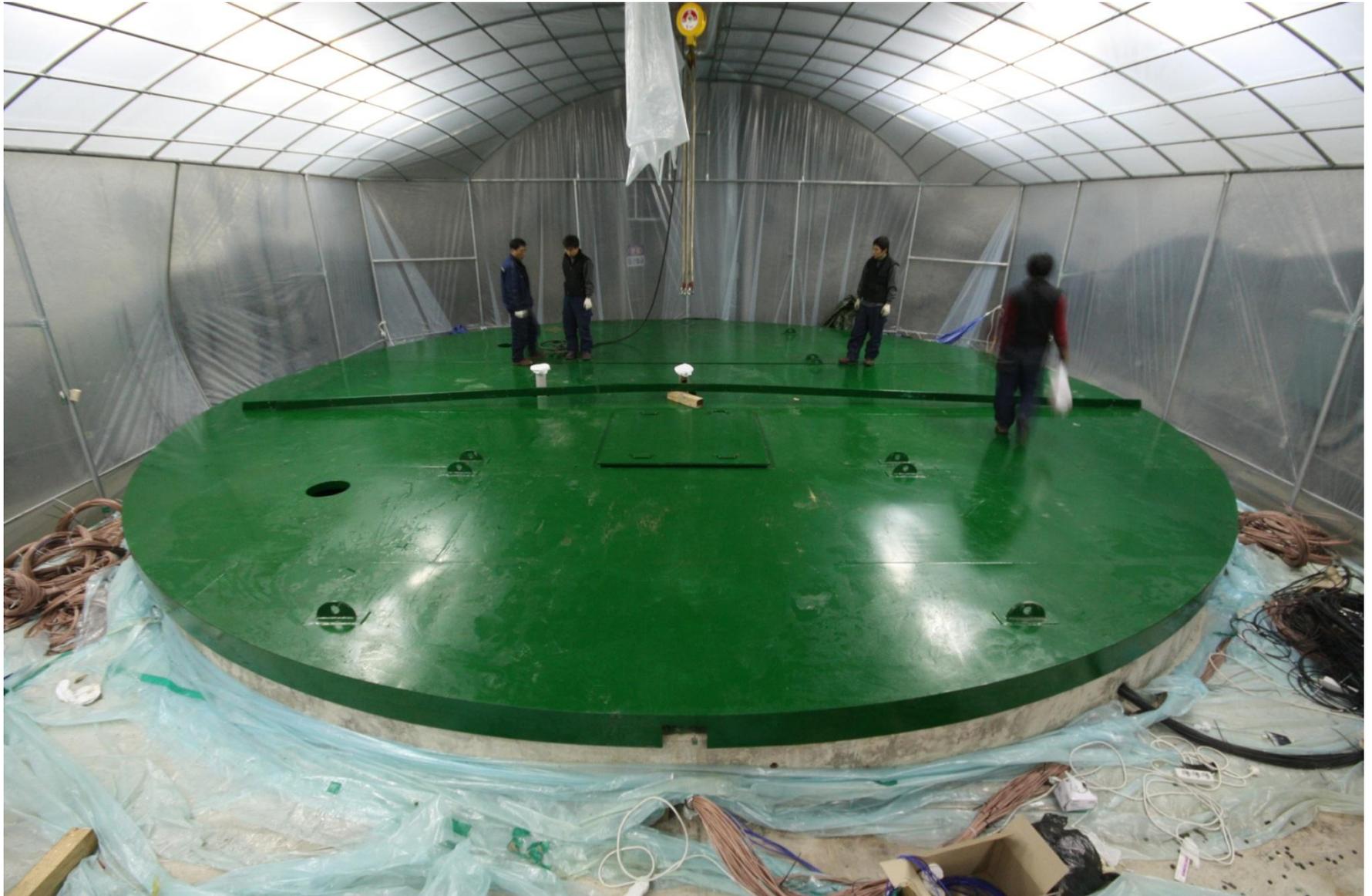


Closing Near Detector(2011.1)



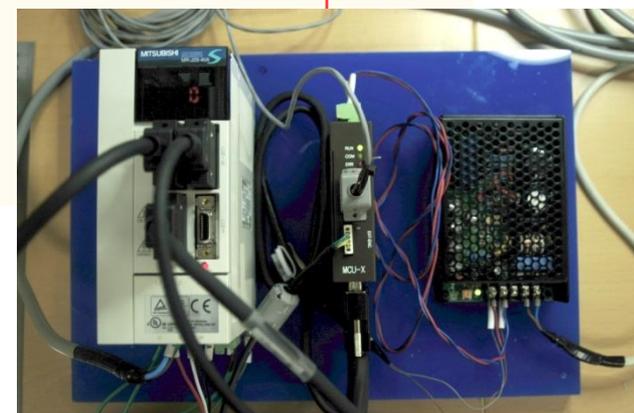
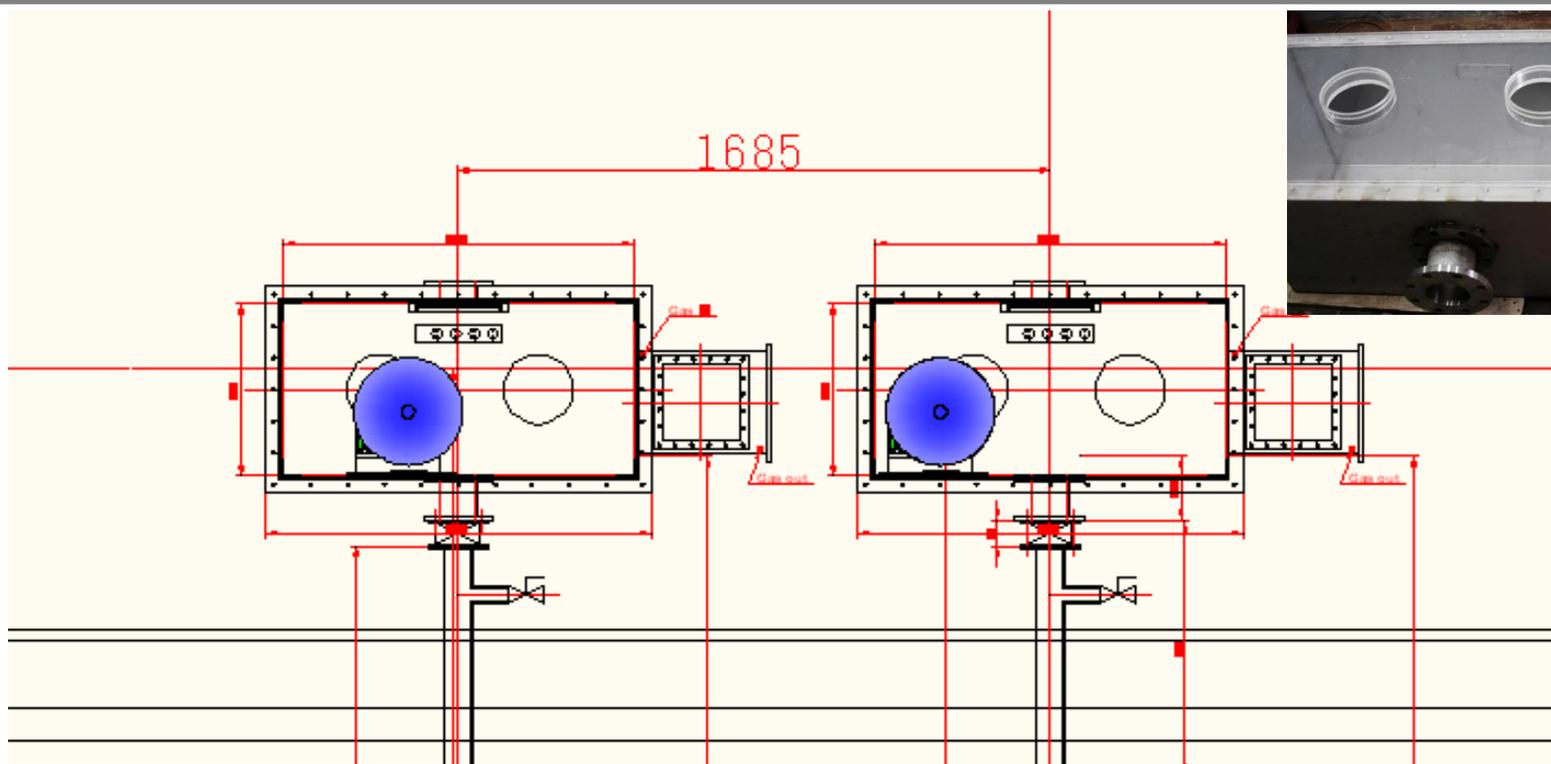
Near detector was finished (Jan 21, 2011)

Closing Far Detector(2011.1)

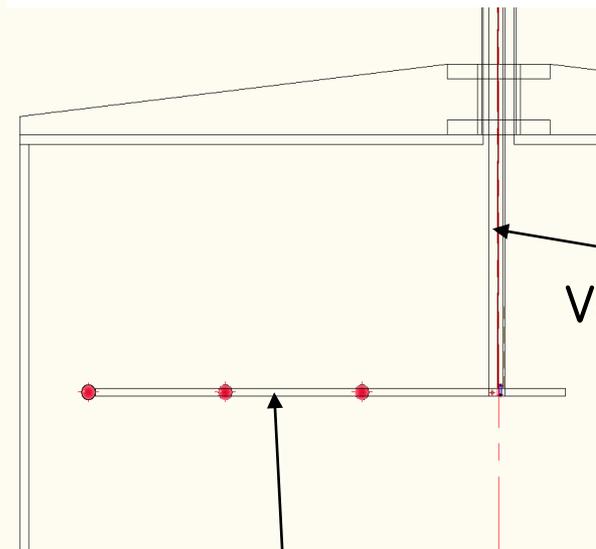
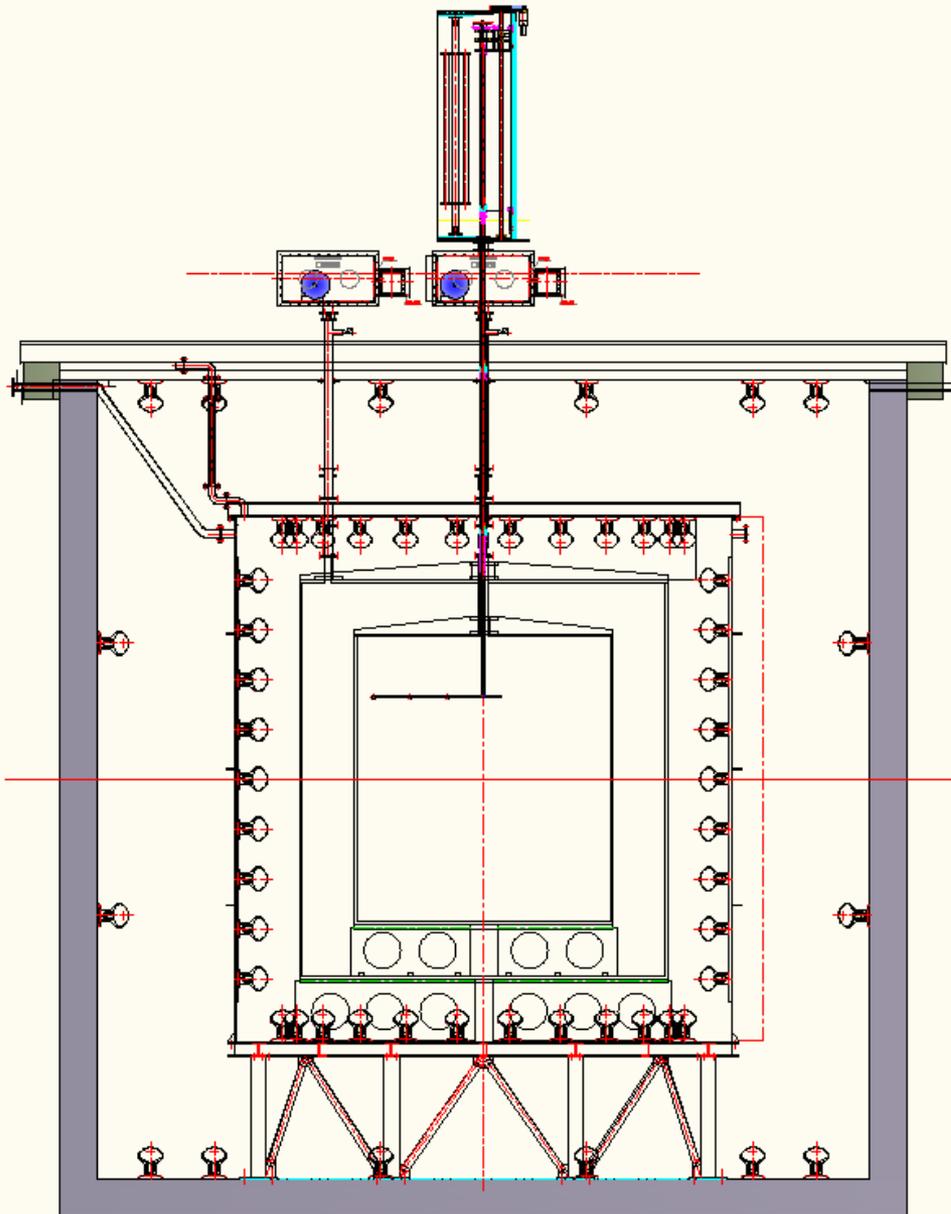


Far detector was finished (Jan 24, 2011)

Glove Box and Source Driving System (2010. 10~12)

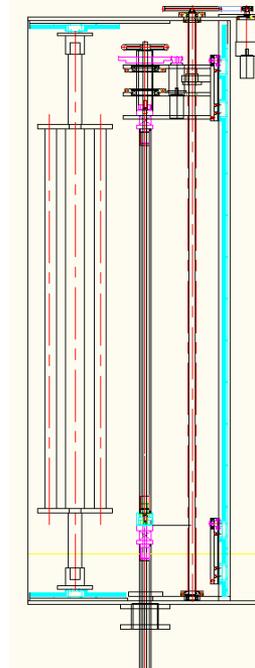


3D Calibration System (2010. 8 ~ 2011. 2)

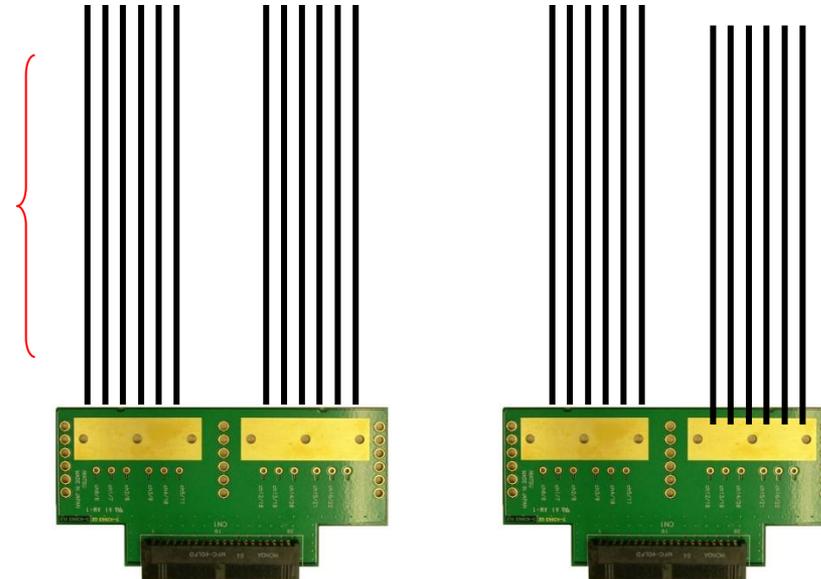
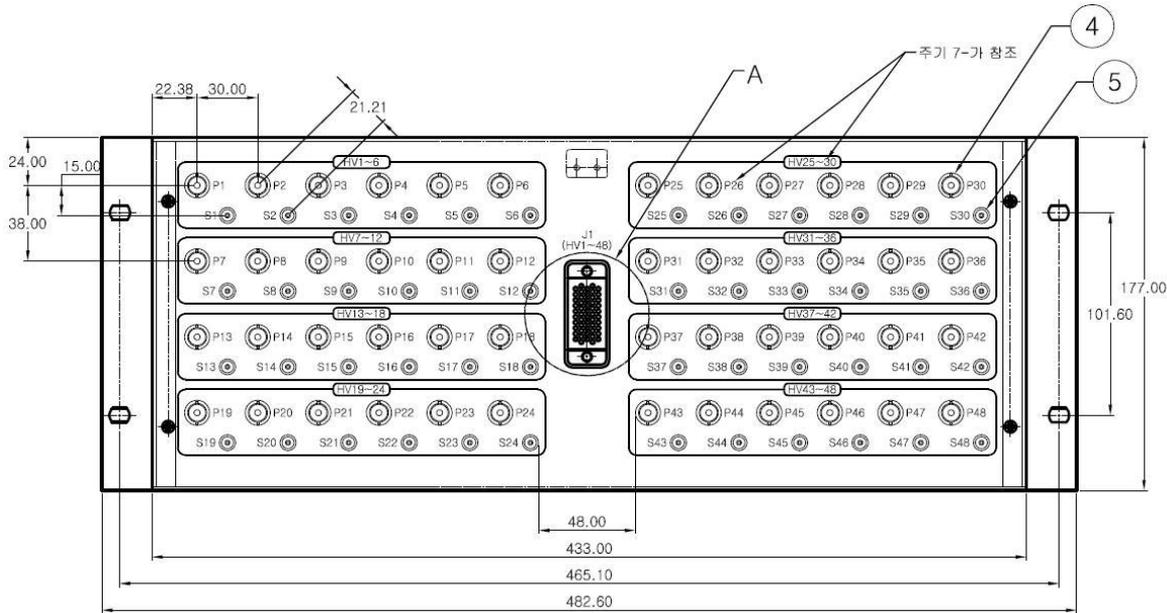


Vertical arm

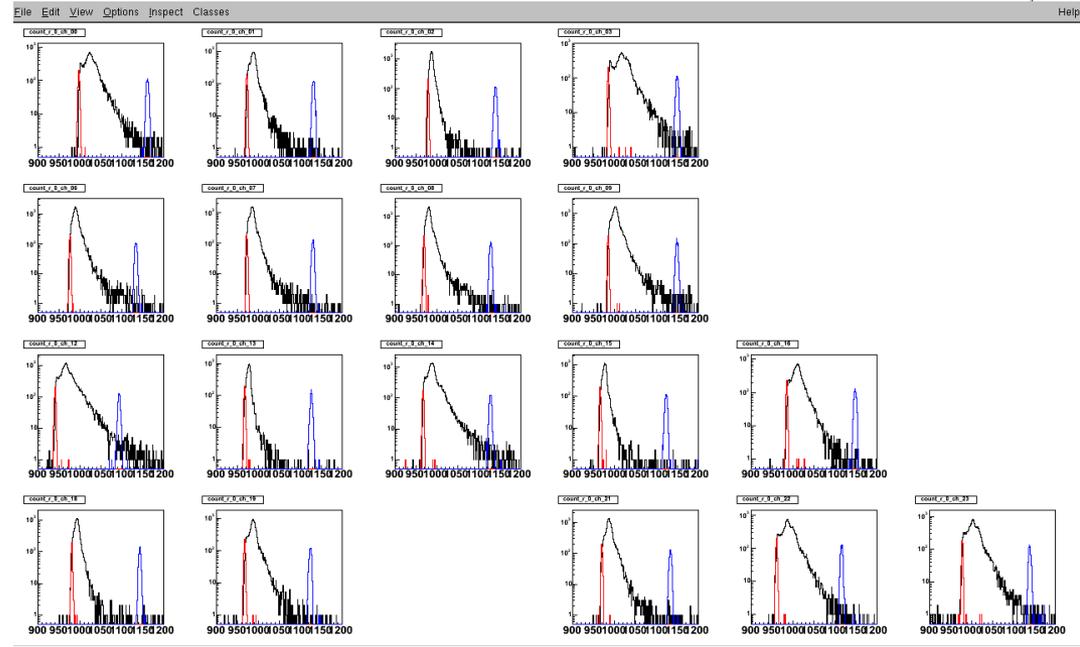
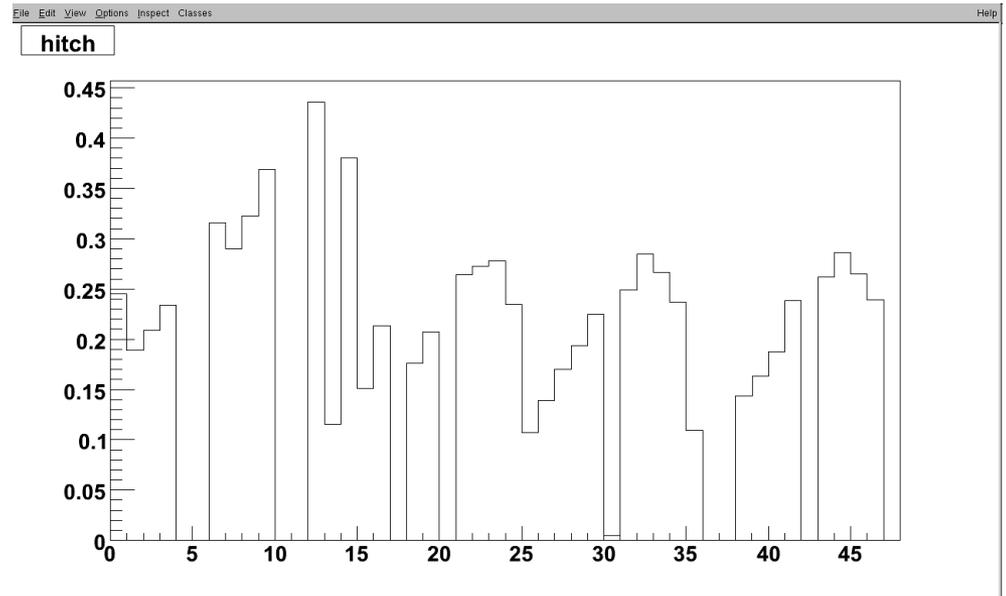
Horizontal arm



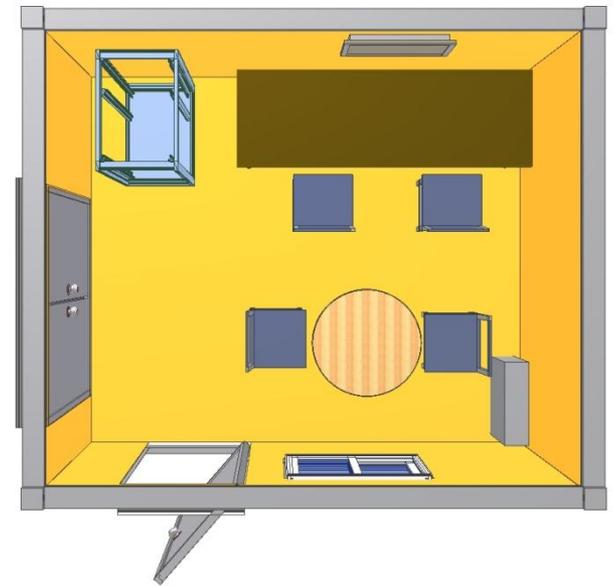
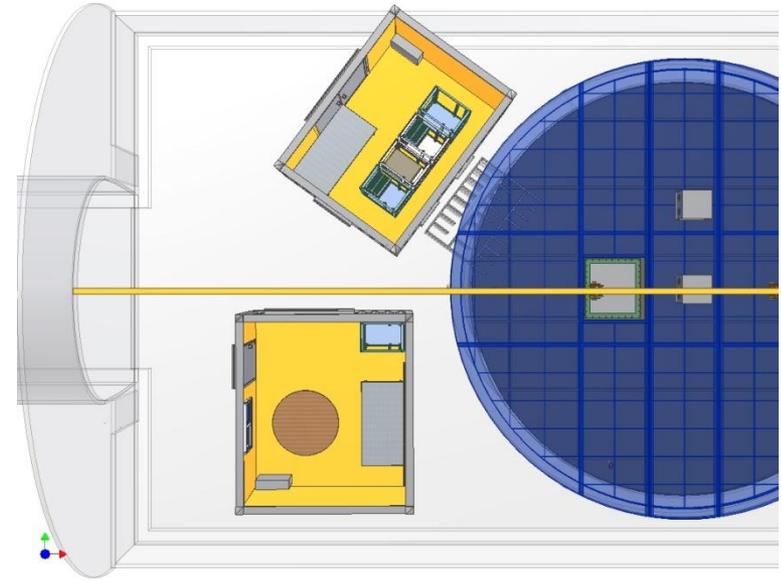
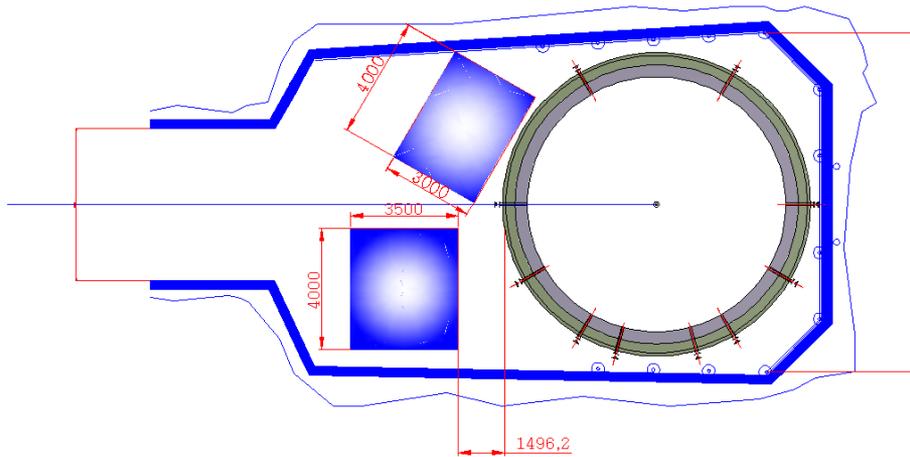
Decoupler & PMT Input Card (2010. 10~11)



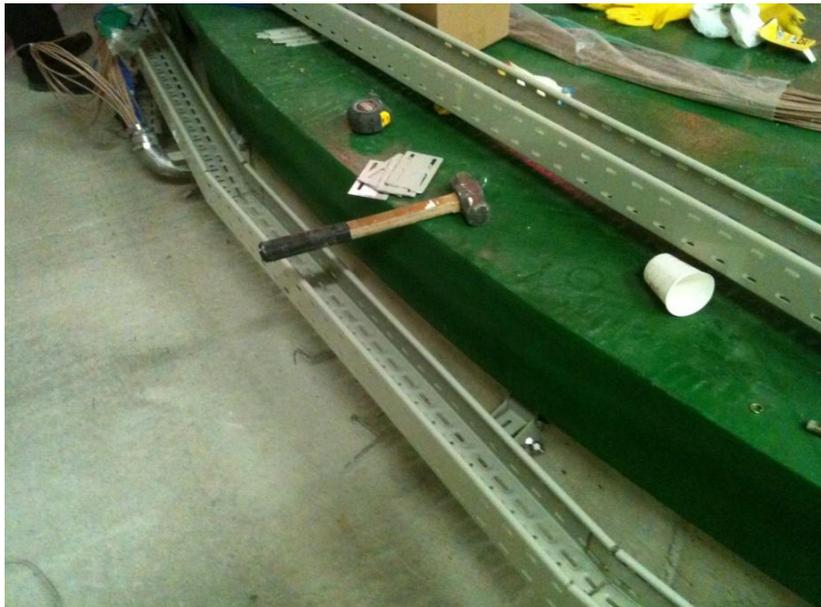
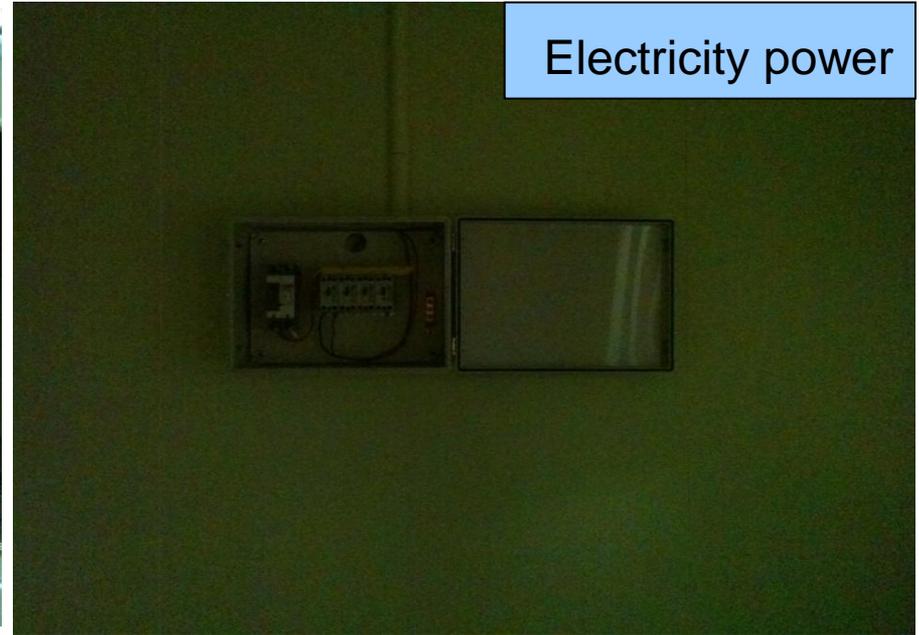
PMT Signal Check (2010. 10~12)



Design of Electronics Hut & Control Room (2010. 11)



Installing Electronics Hut & Control Room (2011. 1)



Detector Monitoring System (2010. 12~2011. 1)

SAMSUNG NETWORK ENCODER - Windows Internet Explorer

http://192.168.0.100/home/monitoring.cgi

SAMSUNG *iPOLiS* Monitoring

Profile1

MJPEG,640X480,15fps

Comp: 10



If you could do with using Digital PTZ, Please press on your mouse wheel.

Relay 1 2 3 4

다채널 온도 모니터링

실형실 온도 모니터링

Channel Parameters

- Physical Channel: cDAQ1Mod1/ai0-1
- Minimum Value (deg C): 0.00
- Maximum Value (deg C): 100.00

Timing Parameters

- Rate (Hz): 10.00

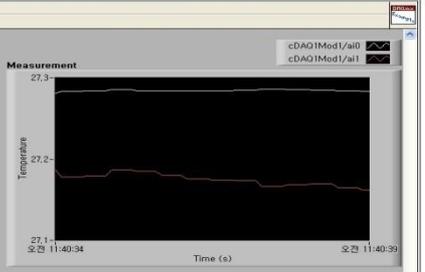
RTD Parameters

- RTD Type: Pt1000
- R (Ohms): 100.00

Resistance Parameters

- Resistance Configuration: 4-Wire
- Current Excitation Source: Internal
- Current Excitation Value: 0.00100

Measurement



STOP

CO2 농도 측정

KCD-HP500 CO2 가스센서를 이용한 이산화탄소 농도 측정입니다.

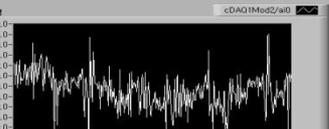
Channel Parameters

- Physical Channel: cDAQ1Mod2/ai0
- Minimum Value (Amps): 0.000
- Maximum Value (Amps): 0.020

Current Parameters

- Shunt Resistor Location: Default
- Shunt Resistor Value (Ohms): 665.0

CO2 측정

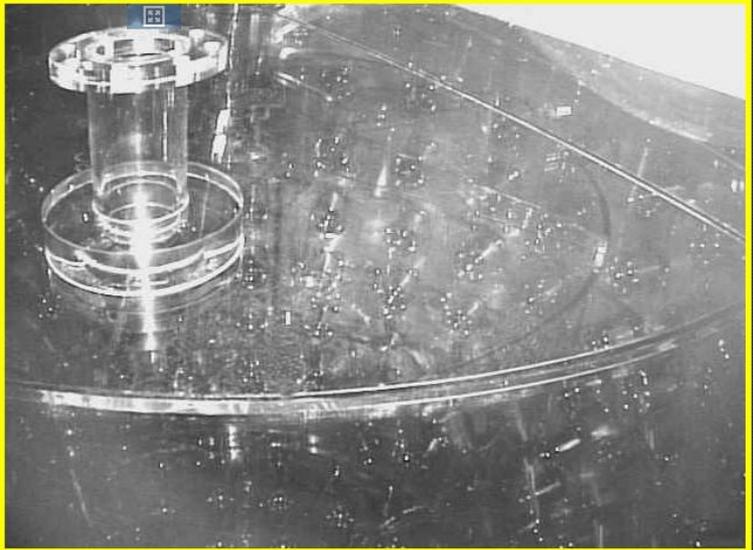


CO2 농도 ppm: 665.414

If you could do with using Digital PTZ, Please press on your mouse wheel.

Relay 1 2 3 4

Monitoring



Gd Loaded Liquid Scintillator

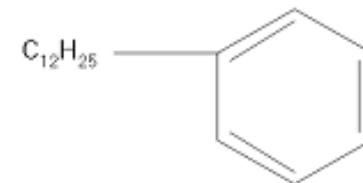
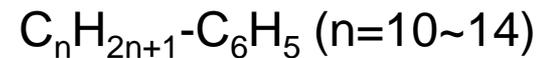
Recipe of Liquid Scintillator

Aromatic Solvent & Flour	WLS	Gd-compound
LAB	PPO + Bis-MSB	0.1% Gd+TMHA (trimethylhexanoic acid)

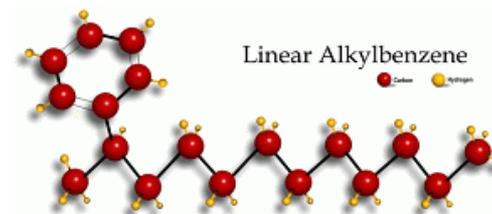
- High Light Yield : not likely Mineral oil(MO)
- replace MO and even Pseudocume(PC)
- **Good transparency** (better than PC)
- **High Flash point** : 147°C (PC : 48°C)
- **Environmentally friendly** (PC : toxic)
- **Components well known** (MO : not well known)
- **Domestically available: Isu Chemical Ltd.**

0.1% Gd compounds with CBX (Carboxylic acids; R-COOH)

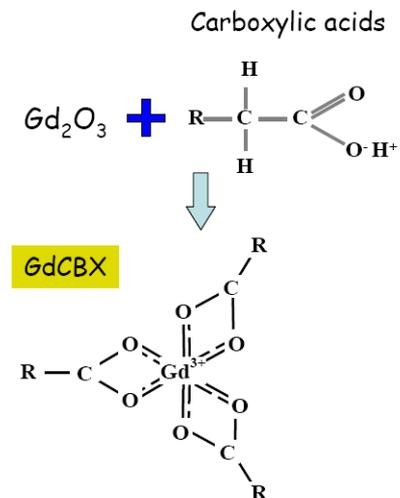
- CBX : TMHA (trimethylhexanoic acid)



Linear Alkyl Benzene (LAB)



Linear Alkylbenzene



Measurement of LAB Components with GC-MS



7.17%



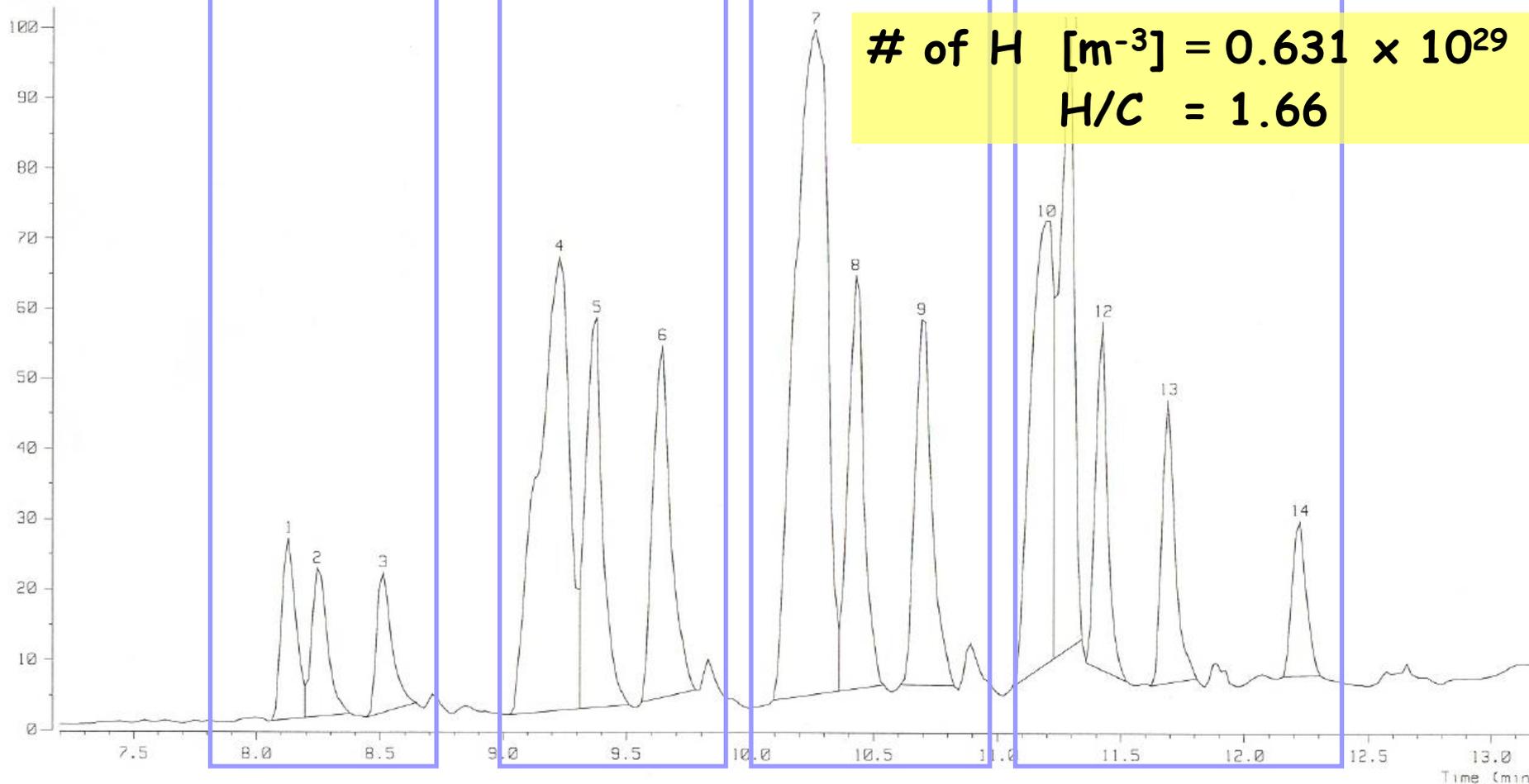
27.63%



34.97%

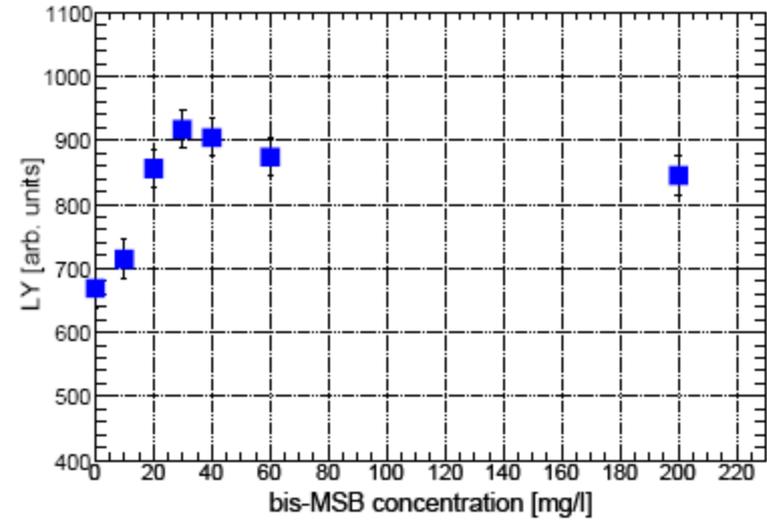
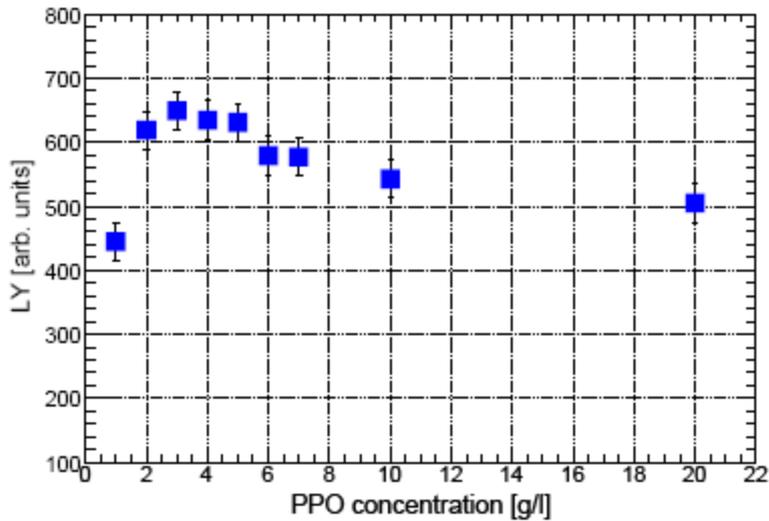
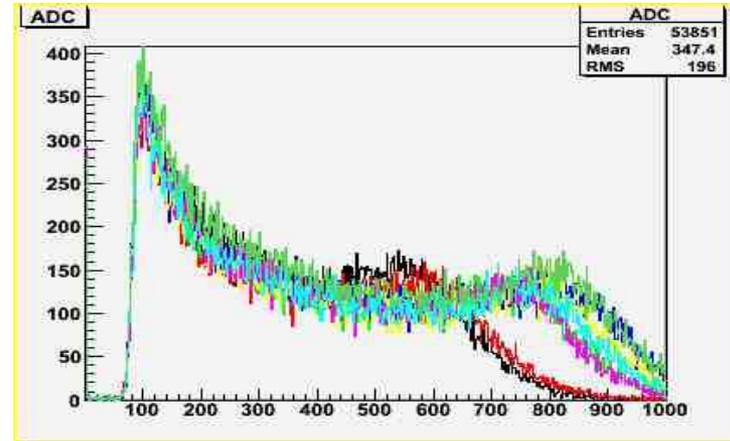
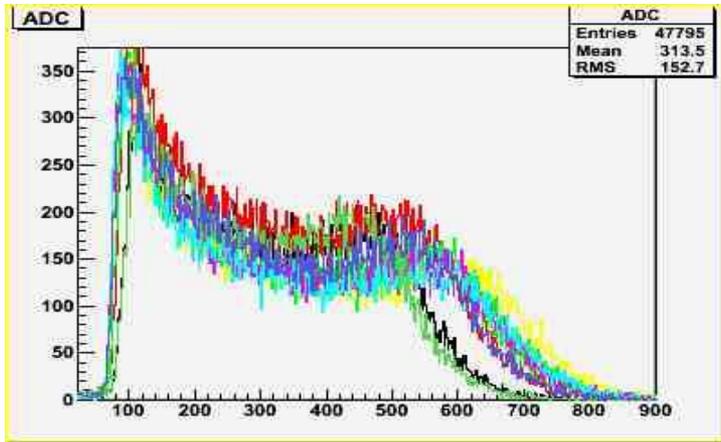


30.23%



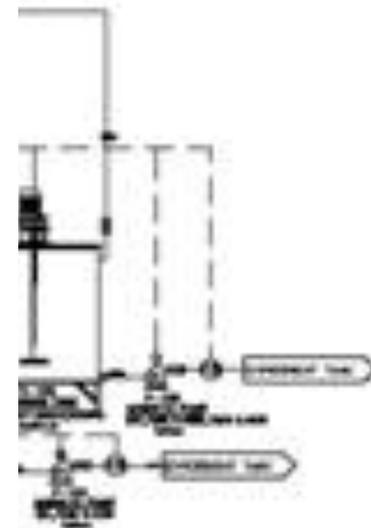
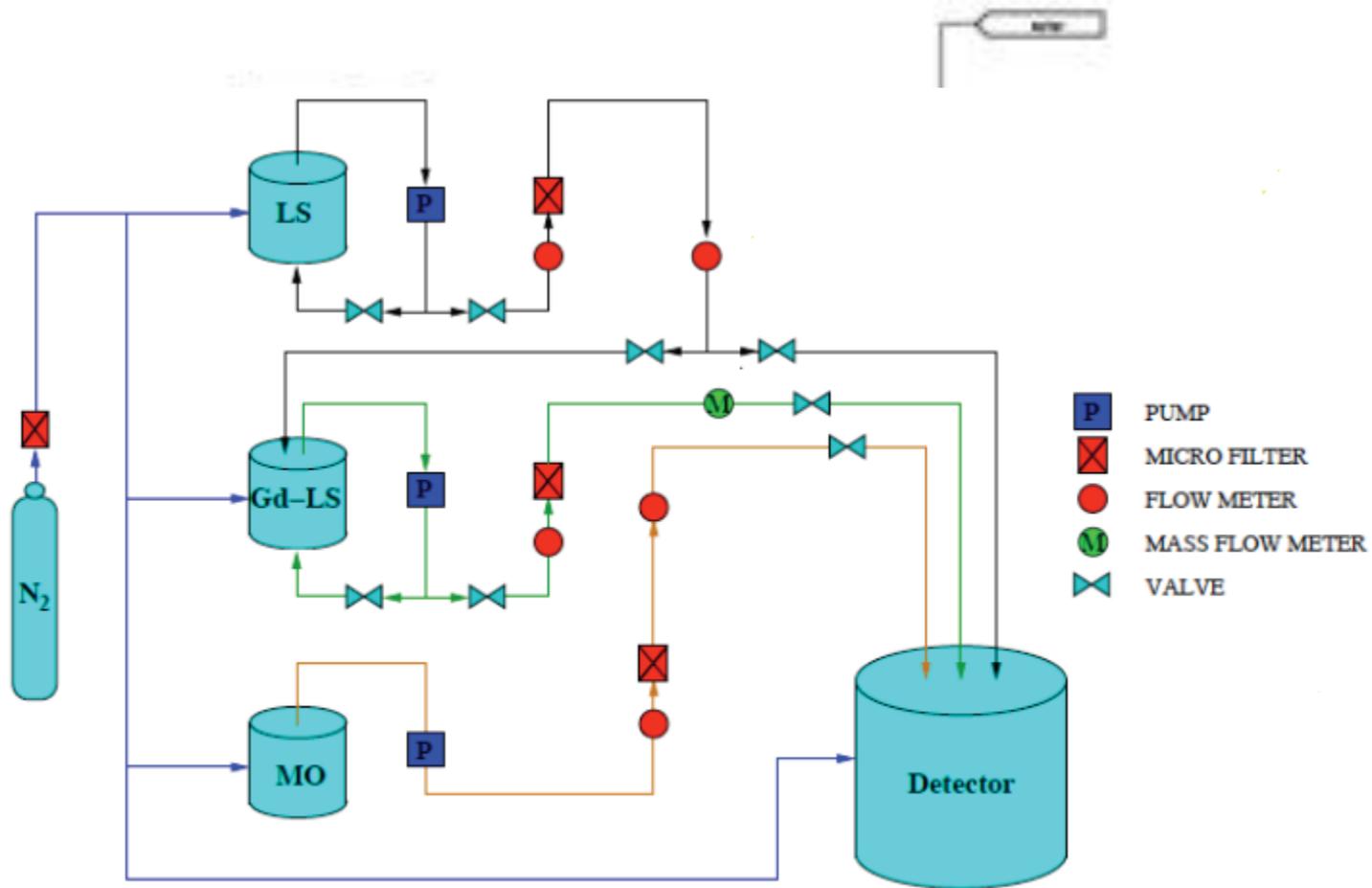
Optimization of PPO, bis-MSB Concentration

Light Yield Measurement

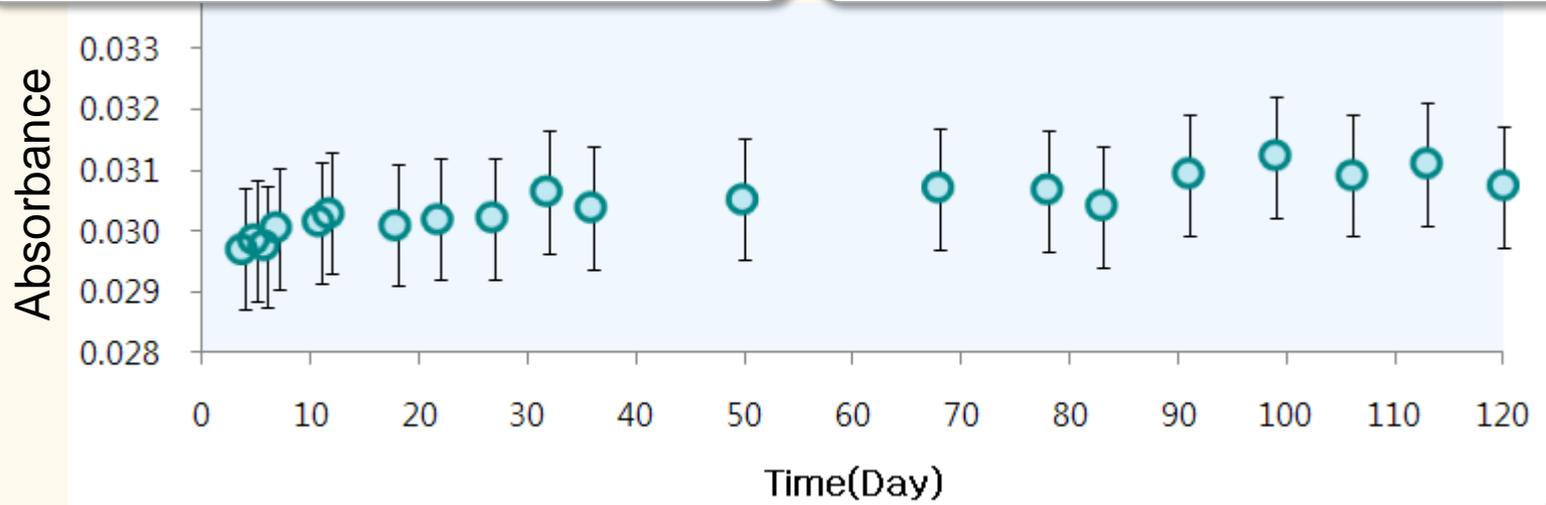
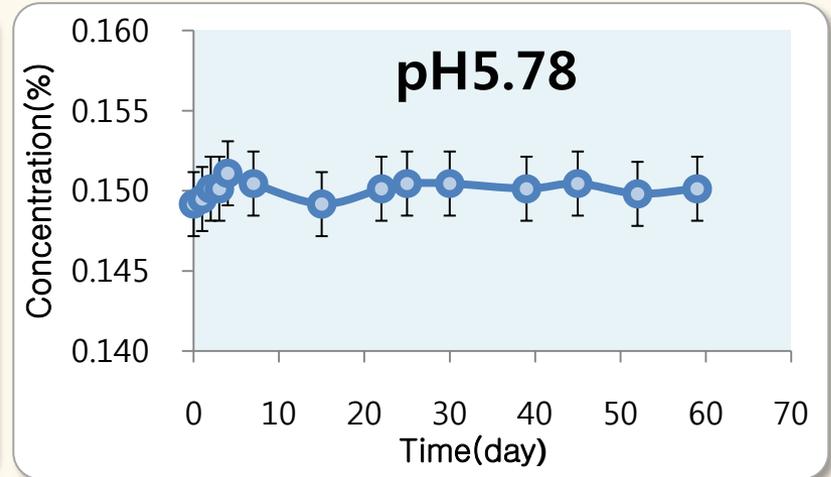
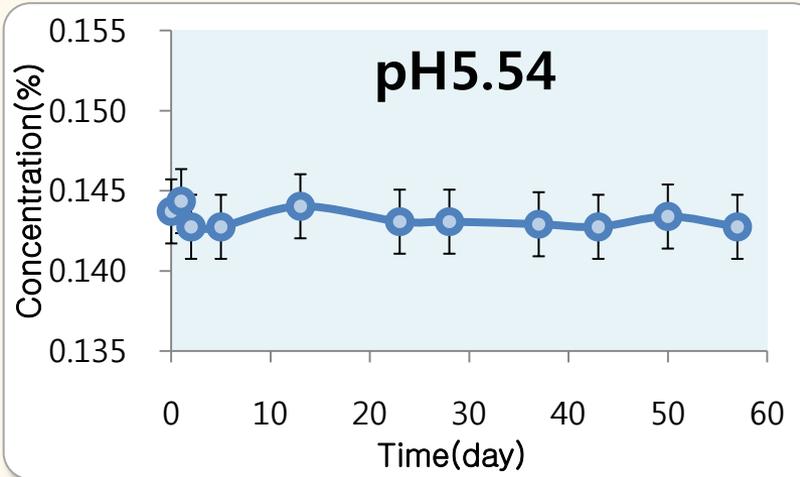


LY saturated when PPO 3g/L and bis-MSB 30mg/L

Liquid Handling System (2010. 10~2011. 2)



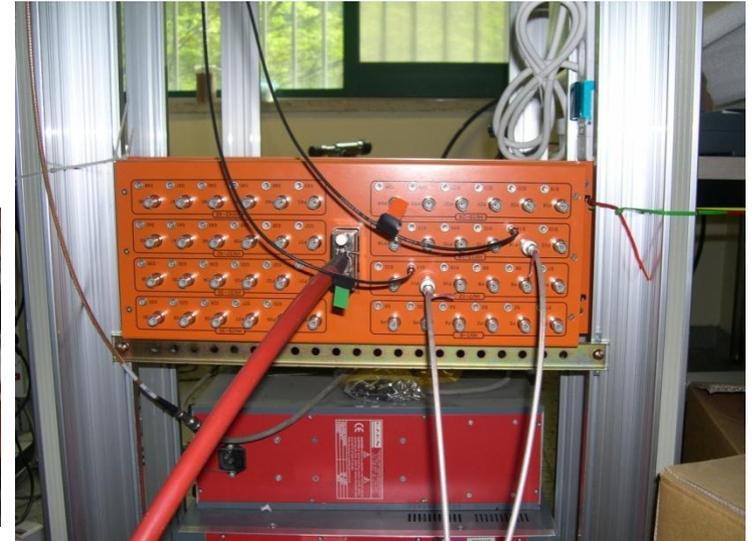
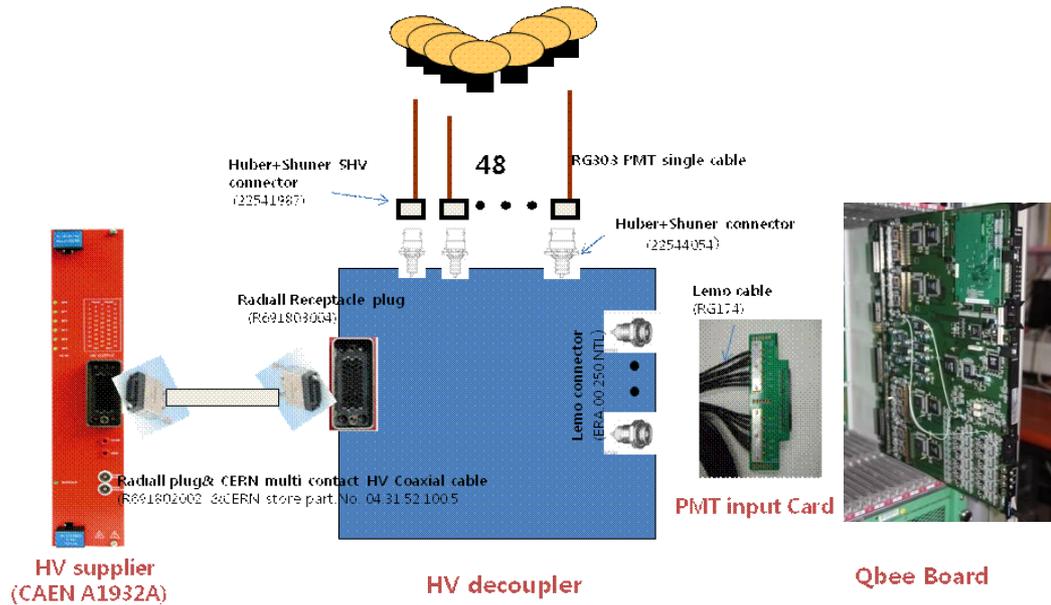
Stability Check



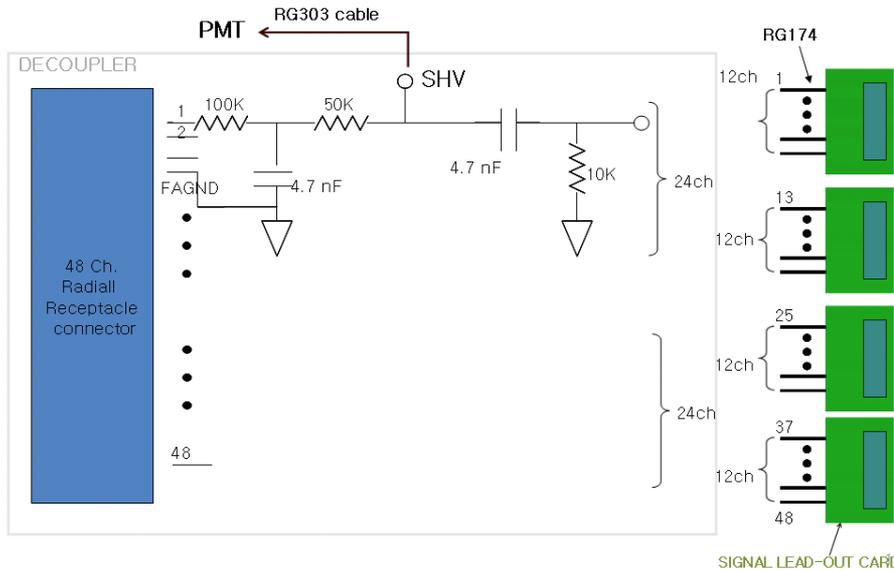
- ☐ More than 6 months, no deterioration has been found
- ☐ In Daya Bay, >3 yrs stable

Development of High Voltage System (2009. 12)

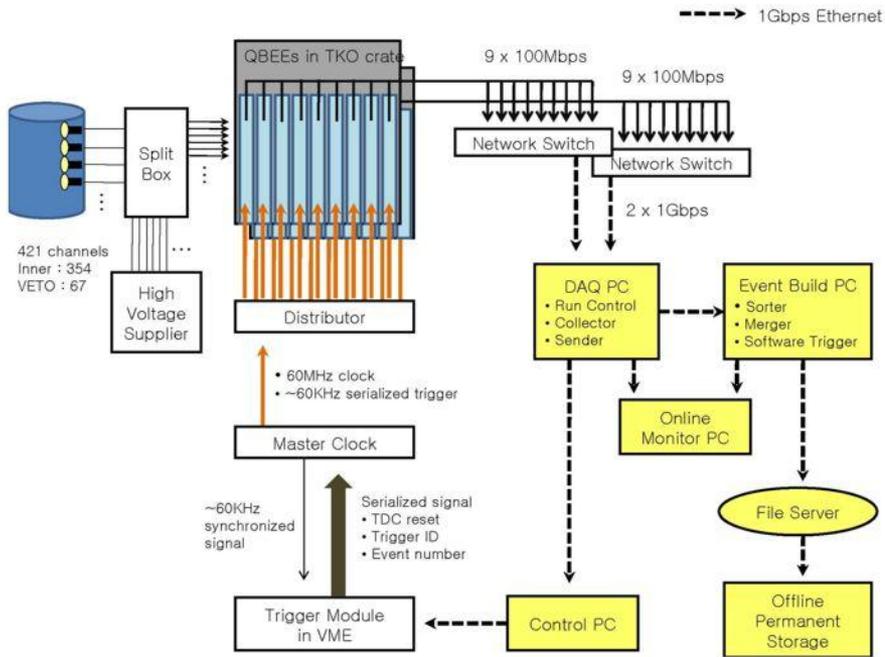
Diagram HV system to Qbee Board



DECOUPLER



DAQ System (2010. 01)



Front End PC	TKO crate & FAN	Master CLK Distributor LAN switch	TKO crate & FAN
VME			
NIM		TKO Power	
	Decoupler 1	DC AVR	
	Decoupler 2	SY1527	Decoupler 5
	Decoupler 3		Decoupler 6
	Decoupler 4	SY1527	Decoupler 7
			Decoupler 8
			Decoupler 9

Q-bee: Qtc-based Electronics with Ethernet

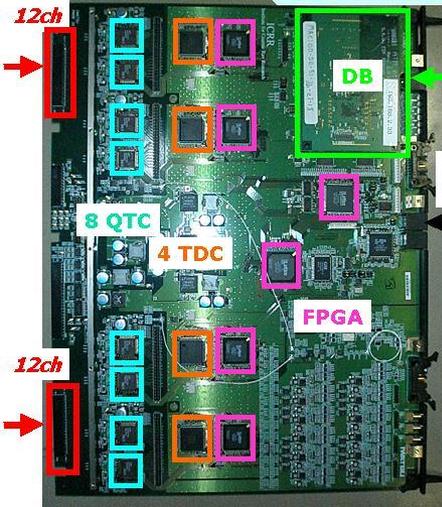
Designed by IWATSU

Ethernet R/W

Clock Input

Specifications

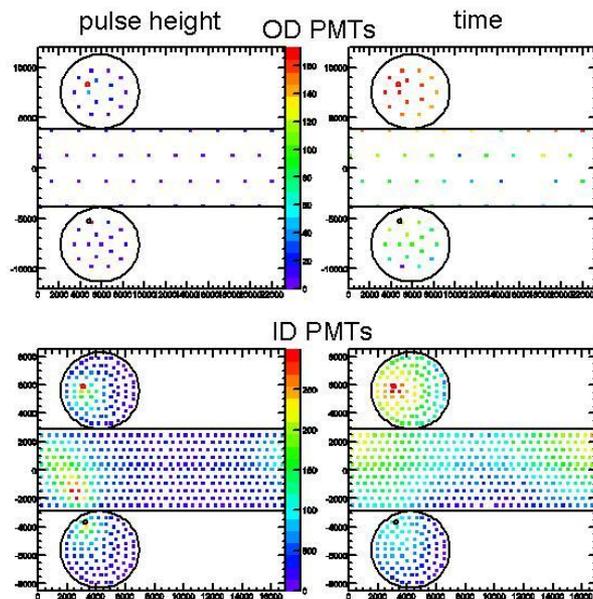
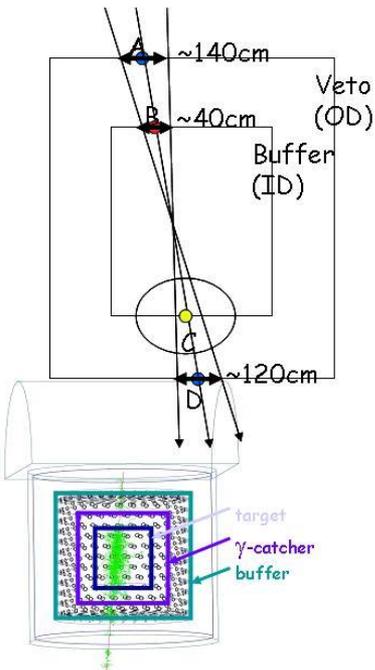
- 24 channel input
- 8 QTC
- 4 Multi-hit TDC
- External clock input (60MHz)
- Ethernet daughter board (DB)



RENO Event Display

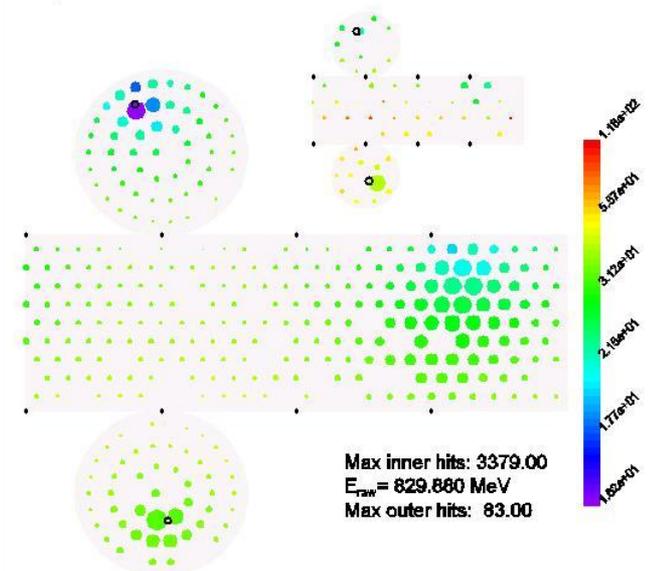
RENO Analysis Control

RACFrameWork



Run 0 Event 39 Time:2008.08.29.1301.59123

Prompt Event



To-do Lists (2011. 2)

- ❑ Jan. 14 ~ 22 : Detector closing <100%>
- ❑ Jan. 24 ~ 28 : Installation of electronics huts and control rooms
<100%>
- ❑ Jan. 24 ~ Feb. 15 : Installation of HV and DAQ
<100%>
- ❑ Jan. 24 ~ Feb. 18 : Installation of liquid scintillator handling system
<100%>
- ❑ Feb. 16 ~ 28 : Start data taking as dry run

- *** Feb. 19 ~ Apr. 15 : Make & fill liquid scintillator

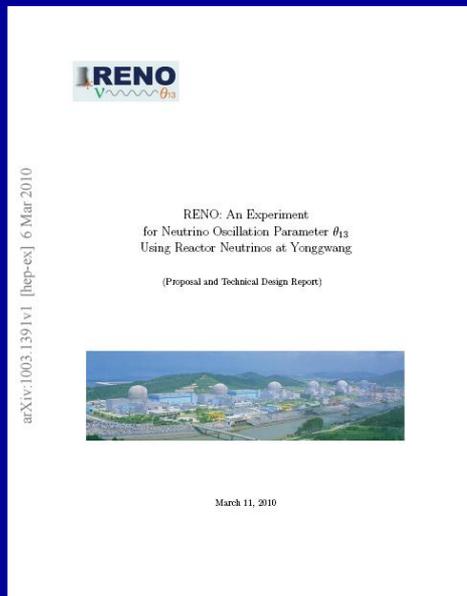
April 30, 2011: aiming for the 1st physics data taking with ND/FD detectors

RENO Completion Ceremony (2011. 04. 15)

- ❑ When: April 15, 2011
- ❑ Where: YongGwang nuclear power plant, S. Korea
- ❑ Who: Many people
 - Minister of science & technology, Power plant director,
 - University president
 - YongGwang governor
 - Science related people, professors, etc
- ❑ What:
 - tape-cutting, push the start button for data taking
 - announcement to mass-media
 - press conference
 - make/distributes booklets, brochure, etc

Summary of RENO

- ❑ RENO is suitable for measuring θ_{13} ($\sin^2(2\theta_{13}) > 0.02$)
- ❑ RENO detector is near completion.
- ❑ 126 pages of TDR was published (arXiv:1003.1391).
- ❑ Data –taking is expected to start in Apr. 2011.
- ❑ International collaborators are being invited.



서울대 김수봉 교수가 이끄는 RENO 실험팀. 30여년간 관측에 실패한 마지막 중성미자 변환상수를 밝히기 위해 프랑스 중국과 치열한 경주를 벌이고 있다.

Back-up slides

Expected Number of BG Events at RENO

source	Detected as	Near Det.	Far Det.
Radioactive Environment (⁴⁰ K, ⁶⁰ Co, ²³² Th, ²³⁸ U)	Single γ	~30 Hz	~30 Hz
Isotopes induced by cosmic μ (⁸ H, ⁹ Li)	correlated n	2.8 / day	0.7 / day
Fast n from cosmic μ	correlated n	3.0 / day	1.0 / day
Total		~6 / day ($< 0.5\%$)	~2 / day ($< 2\%$)

removable