Performance of the Mass Testing Setup for Arrays of Silicon Photomultipliers in the TAO Experiment NUCLEUS-2024

III JINR

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OUTLINE

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JUNO DETECTOR OVERVIEW

JUNO Physics Goals:

- Neutrino mass hierarchy measurements
- Oscillation parameters measurements
- Astrophysics and rare processes



Baseline:

52.5 km

Powerful source:

Yangjiang and Taishan power plants 26.6 GWth in 2020, later 35.7 GWth



The Jiangmen Underground Neutrino Observatory

Parameters:

- ø35.4m Acrylic Vessel
- 41.1m Stainless Steell Structure
- 20 kton Liquid Scintillator
- I7'6I2 large 20" photomultiplier tubes (PMTs)
- 25'600 3" small PMTs
- Water Cherenkov Veto 35 kton pure water and 2400 20" PMTs
- 700 m underground



TAO DETECTOR OVERVIEW

Taishan Antineutrino Observatory

- ~44m to core
- Ton-level fiducial mass
- N(p.e.) ~4500/MeV, ~85% SiPM cover
- Low dark noise: $-50^{\circ}C \rightarrow Low T LS$
- Energy resolution < 2%/MeV

TAO physics goals:

- measure reactor antineutrino spectrum with high energy resolution
- A new benchmark to test the nuclear database





TAO PHOTODETECTOR OVERVIEW

TAO Tile - array of 32 SI 6088 Hamamatsu MPPCs

- [NOTE]
- 1. General tolerance: ± 0.1
- 2. Connected each of 2 chips in parallel (X: A D, Y: 1 4)

16 (2 SiPMs in paralle
12 x 12 mm ² /ch
75 um
49 %
$48 \pm 2 \vee$
4.0×106
45 Hz/mm ²
12%

*at operating voltage

Light source

MASSTESTING SETUP (IHEP)

Outside view

Inside electronic rack

Electronics

Mechanics

Inside environmental chamber

MASSTESTING PROCEDURE

Single scan time ~6h 3 scans/day or 48 tiles/day Total mass testing time ~90 days

SETUP CONTROL SOFTWARE

Green -----

Monitor Settings Main-DB Light-DB

MAIN RUN

Status: OK Hardware Info:

Server status:	Web	Digit	izers	MCUpit	SiPM	Power	HV Mu	ltiplexer	L	ED	Curren	t Meter	Stage C	ontroller	Stage [Decoder		Sett	ina:		Va	ılı
Device status:	Server	erver 080C-635B 0CD9-6B60		WCOIII	connected		/dev/ttyUSB4		/dev/ttyUSB1		/dev/ttyUSB0		disconnected		/dev/tt	yUSB3	Applied	Loonfig			,	25
Tile position #:	1	2	3	4	5 6		7	8	9 10		11 12		13	14	15	16	Applied	·.	ю.		2	20
TSonsor SN:	cc705ff	4063fff	dg5gfff	d4b74ff	cd7o2ff	40505ff	f2f51ff	c5a72ff	cd8c0ff	d6cb7ff	cdefeff	48800ff	d7480ff	co2b6ff	dla6dff	d83a6ff	LED int	esity:			4	0
	0070511	4003111	0050111	04D/411	curezh	4050511	1313111	037211	cuscen	uocb/11	cueich	0889011	u748011	Cezboli	ulaouli	uosaon	Trigger	frequer	ncy:		6	0
Temperature: show	-48.69	-49.44	-48.81	-49.50	-47.50	-47.94	-49.00	-49.19	-47.56	-48.44	-47.25	-48.56	-47.75	-47.69	-48.88	-48.63	Trigger	type:				0
Tile SiPMs Voltage:				rela	y # 1							52.9	98 V				Run sta	tistics:			30	0
Reff. SiPMs Voltage:				O	N	52.919 V Start from voltage:							1	48								
LED state:				0	FF								0				Numbe	r of volta	age poin	nts:		6
Measurement mode:				Spec	trum							Cur	rent				First ov	ervoltad	e point:			1
Current multiplexer CH#:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Voltage	cton	,			1
Current meter:				Tile	#1							-5 9/32	2610-0 A				voltage	step:				-
current meter.				THE	; #4							-5.9452	1016-3 A				Reff.Sil	PM volta	ge:		52	2.9
Stage position:				#home [X:0, Y:0]					Decod	er X: 0			Decoc	er Y: 0							
Run status:	Curre	nt Multip	lexer - S	et Chanr	el: 5 - Se	erver sta	tus code	: 200 MC	:Unit: ok	,												
Run progress:	-4.0	V 1.0	DV 2.	. 0V 3	3.0V	4.0V	5.0V	CH1	CH2 C	снз сн	4 CH5	CH6	CH7	СН8 С	н9 СН	10 CH11	CH12	CH13	CH14	CH15	CH16	

LIGHT RUN STOP RUN

OSCILLOSCOPE

Run configuration Info:

ANALYSIS CONVENTIONS

Digitizer parameters

Parameters	Values
Number of channels	16
Time discretization	125 MHz
Resolution	14 bit
Voltage range	2 V
Maximum window width	l 6us

I ADC - SiPM Tile data acquisition

2 ADC - continuous monitoring of LF with Reff. SiPMs

Run parameters:

Parameters	Values
Number of oscillograms	30k
Time window for light pulses	0.5 us/oscillogram
Time window for dark pulses	10 us/oscillogram
Voltage scan range	I - 6V
Voltage scan step	$I \vee$

Single oscillogram

PHOTON DETECTION EFFICIENCY

Accuracy: ±0.5%

GAIN & BREAKDOWN VOLTAGE

Gain-Voltage dependence

PO - pedestal position PI - position of the 1st peak K_{amp} - coeff. of the amplifier - elementary charge

Gain Accuracy: $\pm 0.4\%$

Branching Poisson crosstalk process

Random primary (Photo) events

Generalized Poisson distribution

$$P(n|\mu,\lambda) = \frac{\mu(\mu+n\lambda)^{n-1}e^{-(\mu+n\lambda)}}{n!}$$

More details in: S.Vinogradov, (2011). Analytical models of probability distribution and excess noise factor of Solid State Photomultiplier signals with crosstalk. NIM A 695. 10.1016/j.nima.2011.11.086.

Crosstalk evaluation

- Building charge spectra Extracting and calculation of
- values:
 - Mean of spectrum Pedestal position of spectrum Number of photoelectrons (μ)

 - Gain of pixel (Q_1)
 - Average SiPM response $S = Mean_{spectrum} - Pos_{pedestal}$
 - Crosstalk probability

$$\lambda = 1 - \frac{\mu Q_1}{S}$$

 $P_{crosstalk}$

CROSSTALKS

$$\delta_{\lambda} = \frac{1}{S} \sqrt{(Q_1 \delta_{\mu})^2 + (\mu \delta_{Q_1})^2 + (\frac{Q_1 \mu}{S} \delta_S)^2}$$

$$= 1 - exp(-\lambda)$$

DARK COUNT RATE

DCR curve reconstruction by means of software analysis ADC data file

$$DCR = \frac{C}{W \times N \times S}, \qquad \sigma_{DCR} = \frac{1}{V}$$

C - number of counts over threshold W - width of analysis window (10us) N - number of oscillogram (30k) S - SiPM area (144mm²) Accuracy: $\pm 1.5\%$

Eval. DCR @ diff.thresholds Building DCR Curve DCR Value @ required threshold

LIGHT FIELD SCAN PERFORMANCE The light field map Light stability overall scans

).21 0.2	2 0.23	0.25	0.25	0.26	0.26	0.28	0.3	0.31	0.31	0.31	0.32	0.31	0.32	0.31	0.31	0.31	0.3	0.3	0.31	0.31	0.31	0.31	0.27	0.26	0.25	0.24	0.23	0.22	0.21	0.2
.22 0.23	3 0.24	0.26	0.26	0.28	0.29	0.29	0.32	0.32	0.32	0.32	0.33	0.33	0.33	0.33	0.33	0.32	0.33	0.33	0.33	0.33	0.32	0.32	0.28	0.28	0.26	0.26	0.25	0.23	0.23	0.22
.24 0.2	5 0.26	0.27	0.28	0.29	0.3	0.3	0.34	0.34	0.33	0.35	0.35	0.34	0.35	0.35	0.34	0.35	0.34	0.35	0.35	0.34	0.35	0.34	0.3	0.28	0.28	0.27	0.26	0.24	0.24	0.22
.24 0.2	5 0.27	0.28	0.29	0.3	0.31	0.32	0.35	0.36	0.36	0.35	0.36	0.37	0.37	0.37	0.35	0.36	0.36	0.36	0.37	0.37	0.37	0.36	0.31	0.3	0.29	0.28	0.27	0.26	0.25	0.23
.25 0.20	6 0.28	0.3	0.3	0.31	0.32	0.33	0.37	0.38	0.38	0.38	0.38	0.39	0.39	0.39	0.37	0.38	0.37	0.37	0.37	0.38	0.37	0.37	0.32	0.32	0.3	0.29	0.28	0.26	0.26	0.25
.27 0.2	9 0.3	0.32	0.32	0.33	0.35	0.35	0.39	0.39	0.4	0.39	0.4	0.4	0.4	0.4	0.39	0.39	0.39	0.39	0.39	0.38	0.38	0.39	0.32	0.32	0.3	0.29	0.28	0.26	0.25	0.26
.28 0.3	8 0.3	0.32	0.32	0.33	0.34	0.35	0.4	0.41	0.42	0.42	0.42	0.42	0.41	0.41	0.4	0.4	0.39	0.4	0.4	0.4	0.41	0.4	0.34	0.33	0.31	0.3	0.3	0.29	0.28	0.26
.28 0.3	8 0.3	0.32	0.34	0.34	0.36	0.37	0.41	0.41	0.43	0.43	0.42	0.43	0.42	0.43	0.42	0.41	0.42	0.42	0.41	0.42	0.41	0.41	0.36	0.35	0.34	0.32	0.31	0.3	0.29	0.27
.29 0.3	1 0.34	0.35	0.36	0.39	0.39	0.4	0.46	0.47	0.48	0.47	0.47	0.49	0.48	0.48	0.47	0.47	0.47	0.47	0.47	0.46	0.46	0.45	0.39	0.38	0.37	0.37	0.35	0.34	0.32	0.31
0.3 0.3	2 0.34	0.36	0.37	0.39	0.4	0.41	0.46	0.48	0.48	0.48	0.49	0.48	0.48	0.49	0.49	0.48	0.47	0.47	0.47	0.47	0.47	0.47	0.4	0.39	0.37	0.36	0.35	0.34	0.33	0.3
.31 0.3	3 0.34	0.36	0.38	0.39	0.4	0.42	0.48	0.49	0.48	0.49	0.48	0.49	0.49	0.49	0.49	0.48	0.49	0.48	0.48	0.48	0.48	0.47	0.41	0.4	0.39	0.37	0.36	0.36	0.34	0.31
.31 0.3	3 0.35	0.37	0.38	0.4	0.42	0.43	0.49	0.49	0.5	0.49	0.49	0.49	0.49	0.5	0.5	0.49	0.49	0.49	0.49	0.49	0.48	0.48	0.41	0.4	0.39	0.37	0.37	0.35	0.34	0.33
.31 0.34	4 0.36	0.36	0.38	0.4	0.41	0.42	0.49	0.49	0.5	0.5	0.5	0.51	0.5	0.5	0.5	0.51	0.5	0.5	0.49	0.5	0.49	0.49	0.42	0.41	0.4	0.39	0.37	0.36	0.35	0.33
33 0.3	5 0.37	0.39	0.4	0.41	0.43	0.43	0.5	0.5	0.51	0.51	0.51	0.5	0.51	0.51	0.51	0.51	0.5	0.51	0.51	0.5	0.48	0.49	0.42	0.41	0.39	0.38	0.37	0.35	0.33	0.34
34 0.3	6 0.38	0.39	0.38	0.41	0.42	0.44	0.5	0.51	0.51	0.51	0.51	0.51	0.52	0.5	0.52	0.51	0.51	0.51	0.51	0.5	0.51	0.49	0.42	0.42	0.4	0.39	0.39	0.37	0.36	0.34
32 0.34	4 0.36	0.38	0.4	0.4	0.42	0.43	0.49	0.5	0.51	0.52	0.51	0.52	0.51	0.52	0.52	0.52	0.51	0.51	0.52	0.5	0.51	0.5	0.43	0.42	0.41	0.4	0.39	0.37	0.36	0.34
33 0.3	6 0.38	0.39	0.4	0.42	0.43	0.44	0.5	0.5	0.5	0.5	0.5	0.52	0.51	0.52	0.52	0.52	0.52	0.51	0.51	0.52	0.5	0.5	0.45	0.44	0.44	0.42	0.41	0.4	0.38	0.36
33 0.3	6 0.37	0.39	0.42	0.42	0.43	0.44	0.49	0.5	0.5	0.52	0.52	0.5	0.51	0.51	0.51	0.52	0.53	0.52	0.52	0.51	0.51	0.5	0.44	0.44	0.43	0.42	0.41	0.39	0.38	0.36
35 0.3	6 0.38	0.4	0.4	0.43	0.43	0.45	0.49	0.5	0.5	0.5	0.52	0.51	0.5	0.51	0.52	0.51	0.52	0.52	0.51	0.51	0.5	0.5	0.46	0.44	0.44	0.42	0.4	0.39	0.38	0.35
34 0.3	6 0.37	0.39	0.4	0.42	0.43	0.44	0.48	0.49	0.49	0.5	0.51	0.51	0.5	0.5	0.52	0.51	0.52	0.51	0.51	0.5	0.5	0.49	0.45	0.44	0.43	0.42	0.4	0.39	0.37	0.36
.33 0.3	5 0.37	0.39	0.4	0.42	0.43	0.44	0.48	0.49	0.49	0.5	0.49	0.49	0.5	0.49	0.52	0.51	0.51	0.51	0.49	0.5	0.49	0.49	0.43	0.44	0.42	0.4	0.39	0.39	0.37	0.36
36 0.3	7 0.39	0.4	0.42	0.43	0.44	0.44	0.48	0.49	0.49	0.48	0.49	0.49	0.5	0.5	0.51	0.51	0.5	0.5	0.49	0.49	0.48	0.49	0.42	0.42	0.41	0.4	0.39	0.37	0.35	0.35
.35 0.3	7 0.38	0.4	0.39	0.41	0.43	0.42	0.47	0.48	0.48	0.48	0.48	0.48	0.49	0.49	0.5	0.5	0.5	0.5	0.48	0.49	0.49	0.48	0.42	0.41	0.4	0.39	0.39	0.37	0.37	0.35
32 0.3	5 0.37	0.38	0.39	0.41	0.42	0.43	0.46	0.46	0.46	0.48	0.47	0.48	0.48	0.49	0.49	0.5	0.49	0.49	0.5	0.49	0.48	0.47	0.43	0.42	0.41	0.4	0.39	0.37	0.36	0.34
.29 0.29	9 0.32	0.33	0.35	0.36	0.37	0.37	0.43	0.43	0.44	0.44	0.44	0.45	0.45	0.45	0.47	0.47	0.47	0.46	0.46	0.45	0.45	0.44	0.39	0.37	0.37	0.35	0.35	0.33	0.32	0.3
.27 0.2	9 0.31	0.32	0.33	0.34	0.36	0.36	0.42	0.41	0.41	0.42	0.43	0.43	0.44	0.44	0.45	0.45	0.44	0.45	0.45	0.44	0.44	0.43	0.37	0.37	0.35	0.34	0.33	0.32	0.3	0.28
27 0.2	8 0.3	0.31	0.33	0.34	0.34	0.35	0.4	0.41	0.41	0.41	0.41	0.42	0.43	0.43	0.44	0.44	0.44	0.43	0.43	0.44	0.43	0.42	0.36	0.35	0.35	0.33	0.31	0.3	0.29	0.28
25 0.2	7 0.28	0.29	0.31	0.32	0.32	0.34	0.39	0.39	0.39	0.4	0.4	0.41	0.4	0.41	0.42	0.42	0.42	0.42	0.42	0.42	0.41	0.4	0.35	0.33	0.32	0.31	0.3	0.29	0.28	0.26
25 0.2	5 0.27	0.28	0.29	0.3	0.31	0.32	0.37	0.37	0.38	0.38	0.39	0.39	0.39	0.39	0.4	0.4	0.41	0.39	0.4	0.4	0.38	0.38	0.33	0.32	0.32	0.3	0.29	0.28	0.27	0.25
24 0.20	6 0.27	0.28	0.29	0.3	0.3	0.3	0.36	0.36	0.37	0.37	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.37	0.38	0.37	0.36	0.36	0.31	0.3	0.29	0.27	0.26	0.26	0.24	0.24
23 0.24	4 0.26	0.27	0.27	0.28	0.29	0.29	0.34	0.34	0.36	0.36	0.35	0.36	0.36	0.36	0.37	0.37	0.35	0.36	0.35	0.35	0.35	0.34	0.29	0.28	0.27	0.26	0.26	0.25	0.24	0.23
.21 0.2	2 0.23	0.24	0.25	0.26	0.27	0.27	0.32	0.32	0.33	0.33	0.34	0.33	0.34	0.34	0.34	0.35	0.34	0.34	0.33	0.33	0.32	0.32	0.28	0.28	0.27	0.26	0.25	0.24	0.23	0.22

MAIN SCAN PERFORMANCE

Single scan

MAIN SCAN PERFORMANCE

Single scan

SUMMARY

- The setup design has been developed
- The testing procedures and methods have been developed and applied
- The testing setup has been produced and putt into operation in China
- Two papers related to the setup have been published in PEPAN Letters and JINST
- All tiles have already been tested
- •The data analysis is in progress