MTD BTL based on LYSO and SiPM at CMS experiment

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Outline

- CMS Phase-II MTD detector for HL-LHC
- BTL : MTD barrel timing layer
- BTL Work and Local Lab Setups at PKU
- Summary

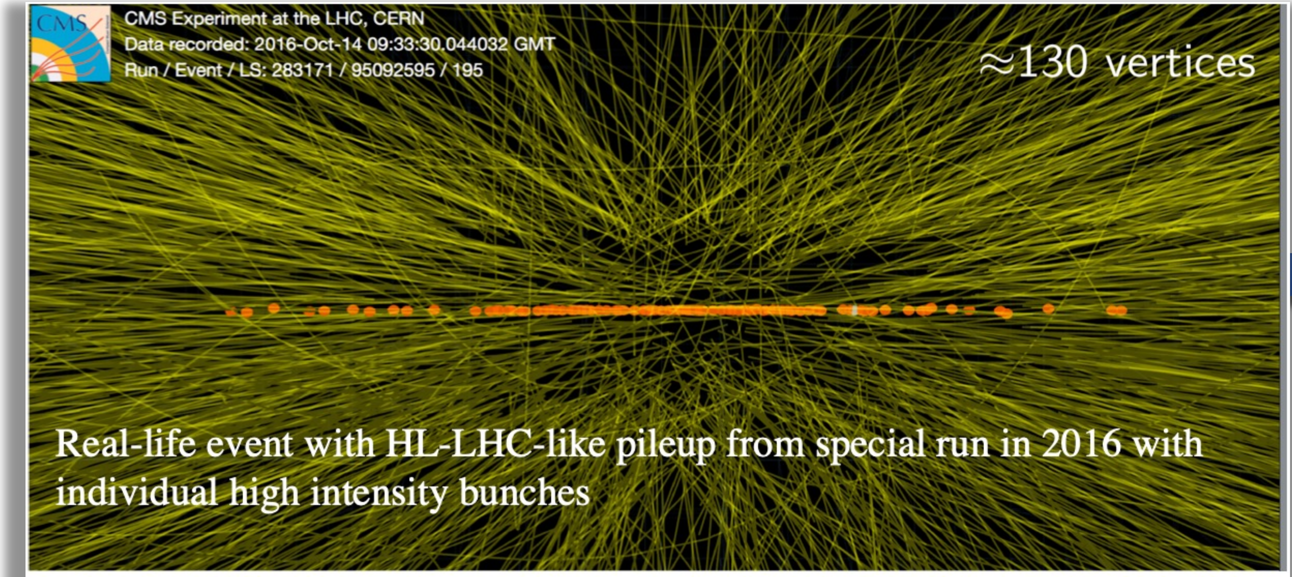
01 CMS Phase-II MTD detector for HL-LHC

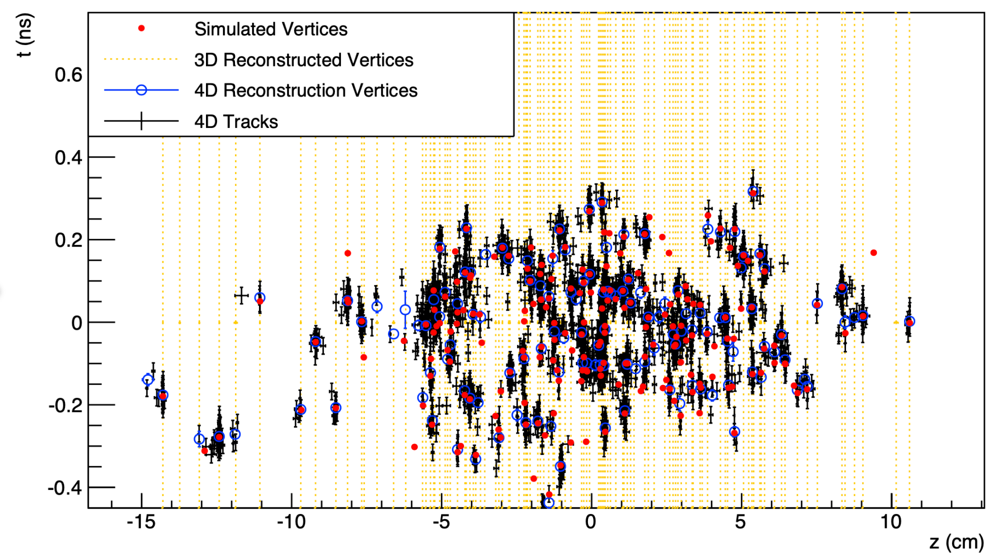
Physics motivation of MTD

High luminosity → High pileup

The MTD is a new CMS Phase-II detector for the HL-LHC.
It will be added to CMS to help meet the challenge of high luminosity.

- HL-LHC, 3000 fb^{-1} at the cost of 140-200 simultaneous collisions (PU)
- MTD + upgraded tracker = Run2-esque PU mitigation





Physics motivation of MTD

MTD can effectively suppress pileup, improving the overall accuracy of physical measurements.

- It improves the precision of single Higgs measurements by 20-30%.
- It increases the acceptance of Di-Higgs signals by 20%.

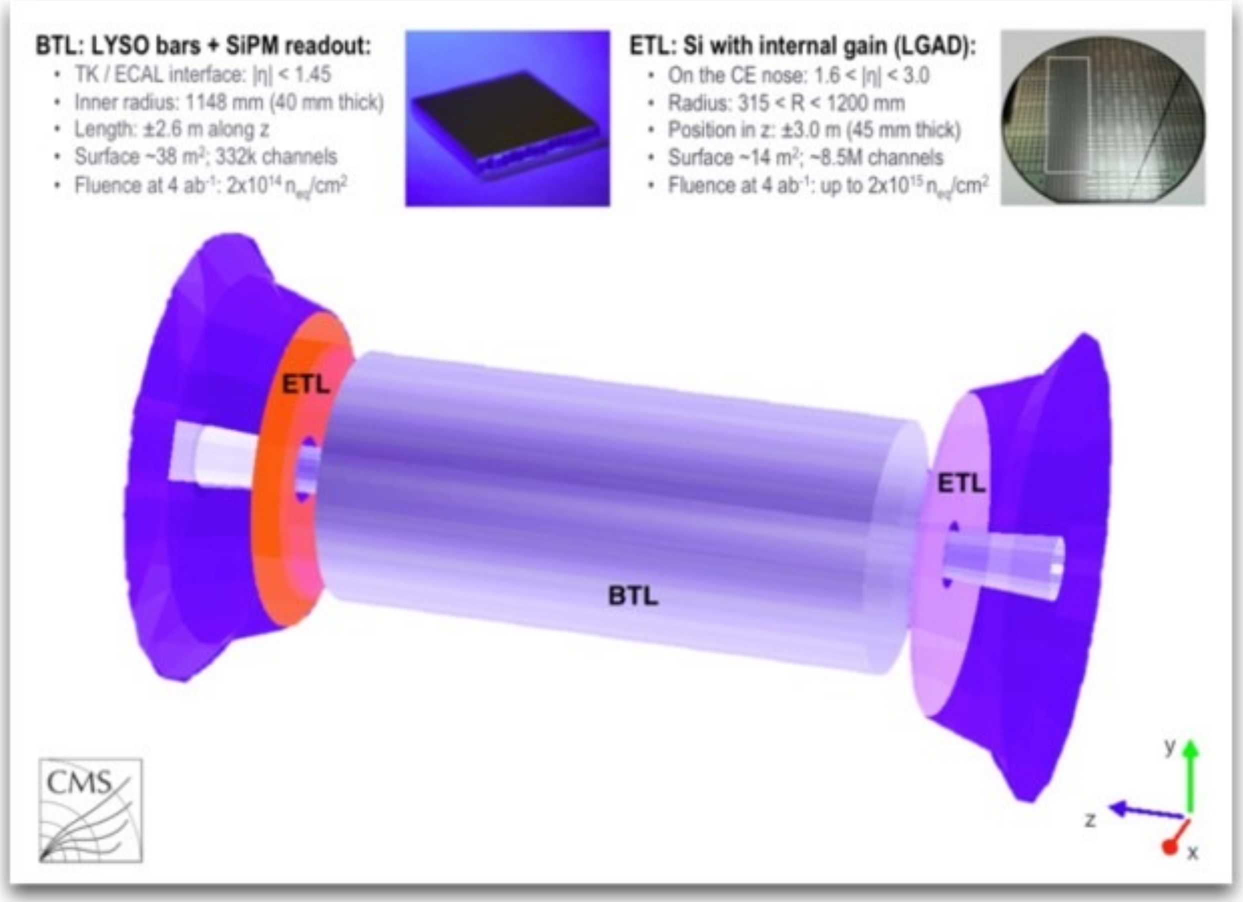
MTD provides TOF information.

- It reduces reducible background by 40% in the search for SUSY particles.
- It significantly enhances sensitivity to long-lived particles.

Composition and highlights of MTD

BTL and ETL

- Choice of sensor technologies for barrel and endcap timing layers driven by technology maturity, radiation hardness, power consumption, and cost and schedule considerations.



Highlights

✓ The MTD BTL is the first time that CMS barrel has achieved a time resolution of tens of picoseconds

✓ CMS will be the only large-scale universal detector on the LHC that measures tens of picoseconds of time in the barrel section

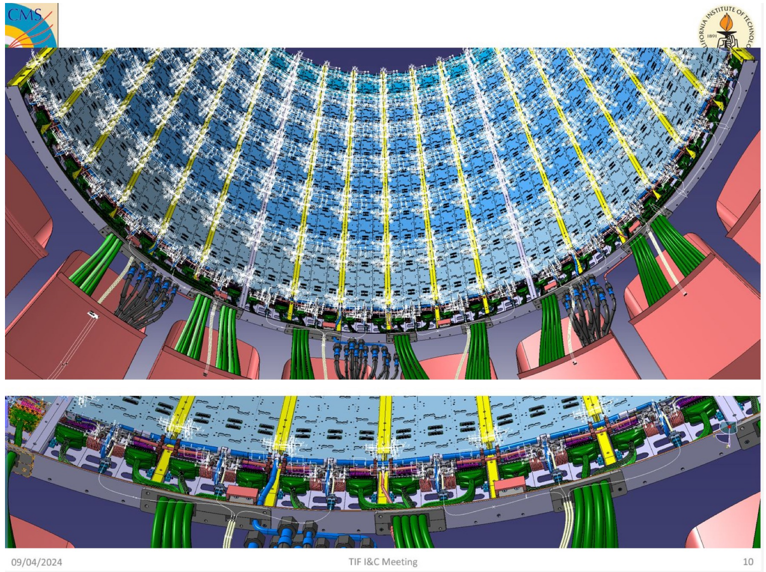
02 BTL : MTD barrel timing layer

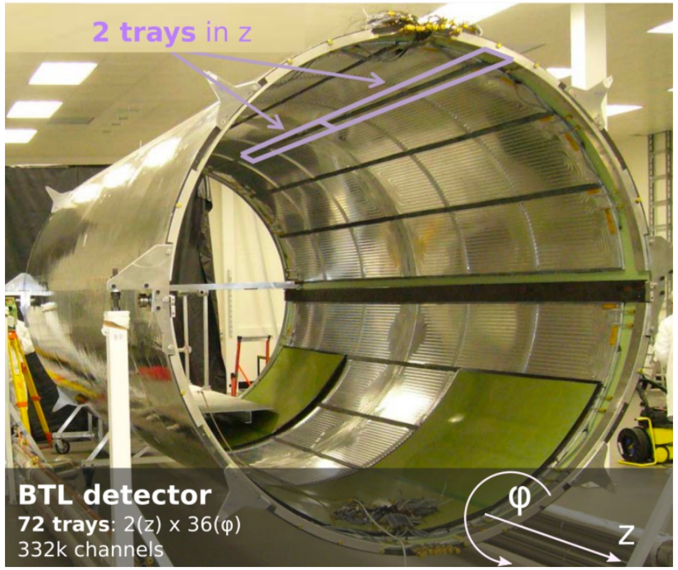
What is MTD BTL ?

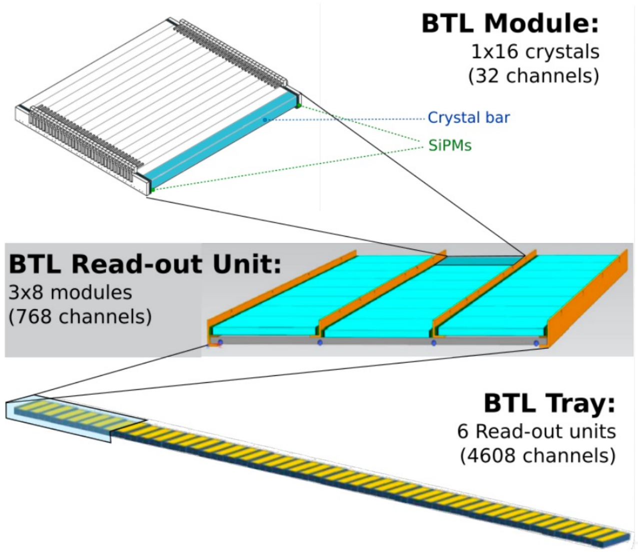
BTL is a single-layer MIP detector located in-between the outer tracker (OT) and the inner wall of the BTL-Tracker Support Tube (BTST).

It will measure time with ~30-60ps resolution.

- Thin (< 4 cm), large area (38 m^2) detector covering $|\eta| < 1.5$
- ~10k Sensor Modules, each containing 16 LYSO crystal bars and two 16-channel SiPM arrays
- Read out with custom TOFHIR2 ASIC
- Mounted on CO2 cooled trays and installed on inner surface of BTL Tracker Support Tube (BTST)





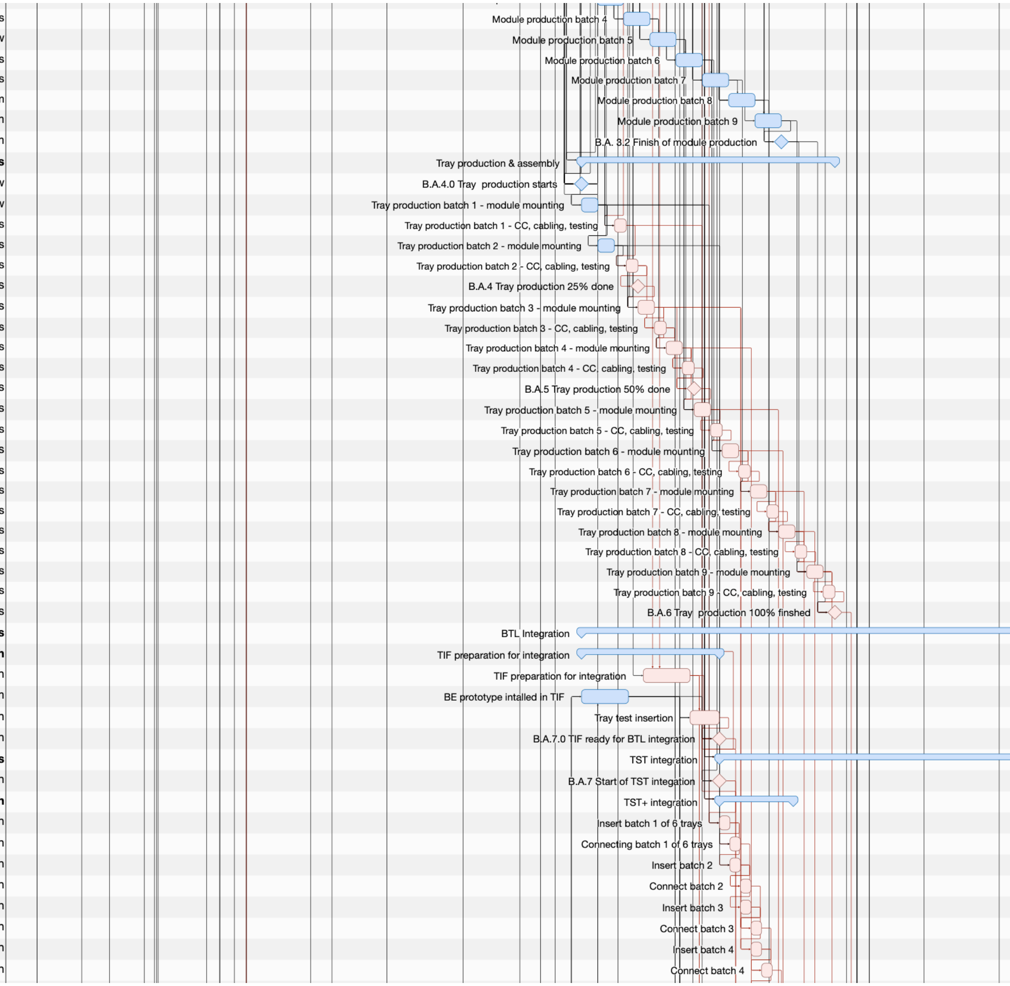


Schedule of MTD BTL

Assembly timeline

- Testbeam of sensor in 2023
- Improved the assembly and QA/QC in 2023 & 2024
- Assembly Center Certification in 2024
- Start batch assembly in the Autumn of 2024
- End assembly in 2025

382	Module production batch 4	January 7, 2025	Feb 7, 2025	2.76 weeks
383	Module production batch 5	Feb 7, 2025	Mar 11, 2025	3.1w
384	Module production batch 6	March 11, 2025	April 11, 2025	3.38 weeks
385	Module production batch 7	April 11, 2025	May 13, 2025	3.7 weeks
386	Module production batch 8	May 13, 2025	June 12, 2025	1m
387	Module production batch 9	June 12, 2025	July 15, 2025	1.1m
388	B.A. 3.2 Finish of module production	July 15, 2025	July 15, 2025	1.1m
389	**Tray production & assembly**	**Nov 18, 2024**	**Sep 16, 2025**	**0 days**
390	B.A.4.0 Tray production starts	Nov 18, 2024	Nov 18, 2024	2w
391	Tray production batch 1 - module mounting	Nov 18, 2024	Dec 6, 2024	2w
392	Tray production batch 1 - CC, cabling, testing	Dec 27, 2024	Jan 9, 2025	0 days
393	Tray production batch 2 - module mounting	Dec 6, 2024	Dec 26, 2024	2.02 weeks
394	Tray production batch 2 - CC, cabling, testing	Jan 10, 2025	Jan 23, 2025	0 days
395	B.A.4 Tray production 25% done	Jan 23, 2025	Jan 23, 2025	0 days
396	Tray production batch 3 - module mounting	Jan 24, 2025	Feb 12, 2025	0 days
397	Tray production batch 3 - CC, cabling, testing	Feb 13, 2025	Feb 26, 2025	0 days
398	Tray production batch 4 - module mounting	Feb 27, 2025	Mar 18, 2025	0 days
399	Tray production batch 4 - CC, cabling, testing	March 19, 2025	April 1, 2025	0 days
400	B.A.5 Tray production 50% done	April 1, 2025	April 1, 2025	0 days
401	Tray production batch 5 - module mounting	April 2, 2025	April 21, 2025	0 days
402	Tray production batch 5 - CC, cabling, testing	April 22, 2025	May 5, 2025	0 days
403	Tray production batch 6 - module mounting	May 6, 2025	May 23, 2025	0 days
404	Tray production batch 6 - CC, cabling, testing	May 26, 2025	June 6, 2025	0 days
405	Tray production batch 7 - module mounting	June 9, 2025	June 26, 2025	0 days
406	Tray production batch 7 - CC, cabling, testing	June 27, 2025	July 10, 2025	0 days
407	Tray production batch 8 - module mounting	July 11, 2025	July 30, 2025	0 days
408	Tray production batch 8 - CC, cabling, testing	July 31, 2025	Aug 13, 2025	0 days
409	Tray production batch 9 - module mounting	Aug 14, 2025	Sep 2, 2025	0 days
410	Tray production batch 9 - CC, cabling, testing	Sep 3, 2025	Sep 16, 2025	0 days
411	B.A.6 Tray production 100% finshed	Sep 16, 2025	Sep 16, 2025	0 days
412	**BTL Integration**	**Nov 18, 2024**	**Mar 8, 2028**	**0 days**
413	**TIF preparation for integration**	**Nov 18, 2024**	**May 1, 2025**	**-4.2h**
414	TIF preparation for integration	Jan 30, 2025	Mar 27, 2025	-4.2h
415	BE prototype intalled in TIF	Nov 18, 2024	Jan 13, 2025	2.6m
416	Tray test insertion	Mar 27, 2025	May 1, 2025	-4.2h
417	B.A.7.0 TIF ready for BTL integration	May 1, 2025	May 1, 2025	-4.2h
418	**TST integration**	**May 1, 2025**	**July 29, 2027**	**0 days**
419	B.A.7 Start of TST integration	May 1, 2025	May 1, 2025	-4.2h
420	**TST+ integration**	**May 1, 2025**	**July 29, 2025**	**-4.2h**
421	Insert batch 1 of 6 trays	May 1, 2025	May 14, 2025	-4.2h
422	Connecting batch 1 of 6 trays	May 14, 2025	May 27, 2025	-4.2h
423	Insert batch 2	May 14, 2025	May 27, 2025	-4.2h
424	Connect batch 2	May 27, 2025	June 9, 2025	-4.2h
425	Insert batch 3	May 27, 2025	June 9, 2025	-4.2h
426	Connect batch 3	June 9, 2025	June 20, 2025	-4.2h
427	Insert batch 4	June 9, 2025	June 20, 2025	-4.2h
428	Connect batch 4	June 20, 2025	July 3, 2025	-4.2h



Test beam for BTL Module research and selection

Analysis of the time resolution of BTL module using minimum ionizing particles.

Setup:

- ➢ Conducted on CERN (180 GeV pion) and FNAL (120 GeV proton) beams

The time resolution is well modeled as a function of few SiPM parameters:

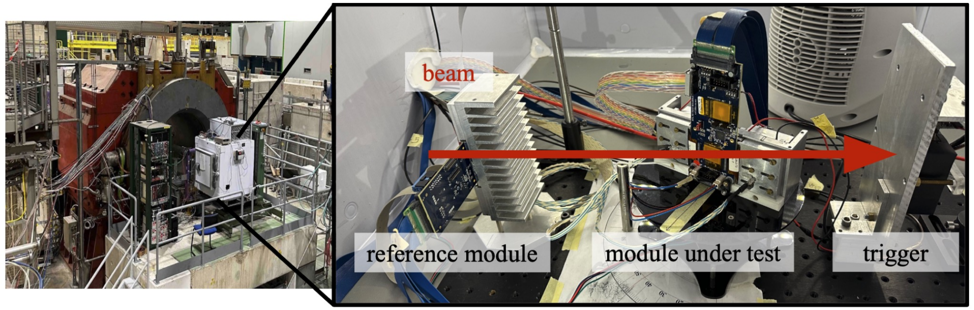
- gain, PDE and DCR

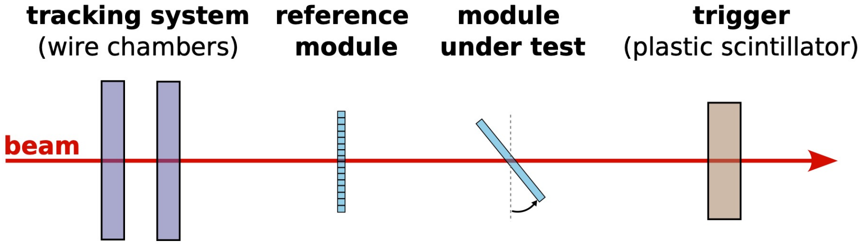
The optimal choice of SiPM and LYSO:

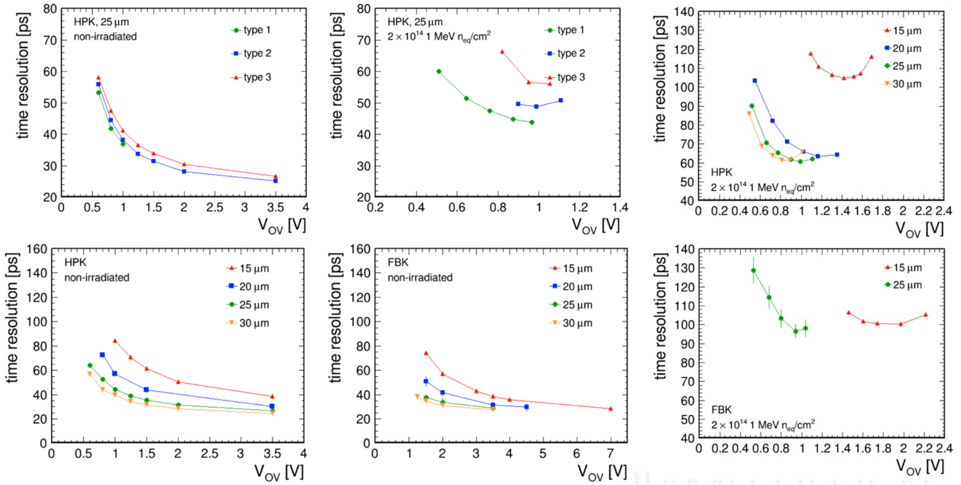
- ➢ 25 μm SiPM cell size from HPK SiPM and 3.75 mm thick LYSO

Such a sensor module configuration achieves a time resolution of about

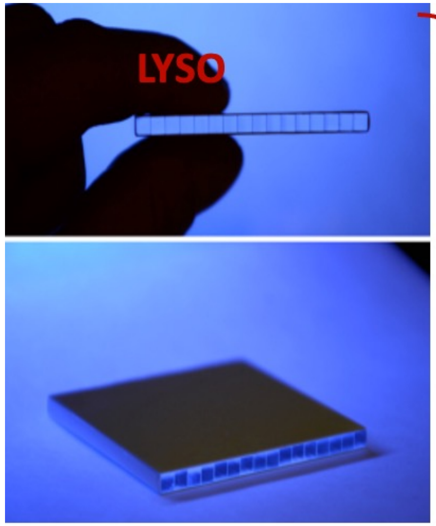
- ➢ 25 ps with non-irradiated SiPMs
- ➢ 60 ps under the irradiation, annealing and temperature conditions representative of the end of the BTL detector operation

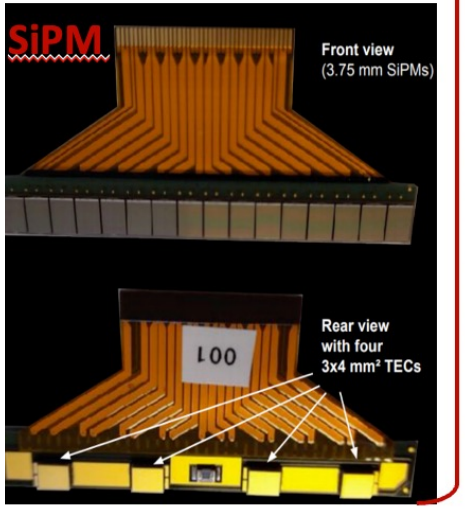


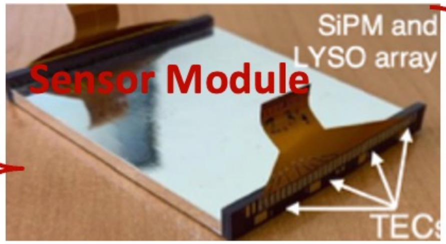


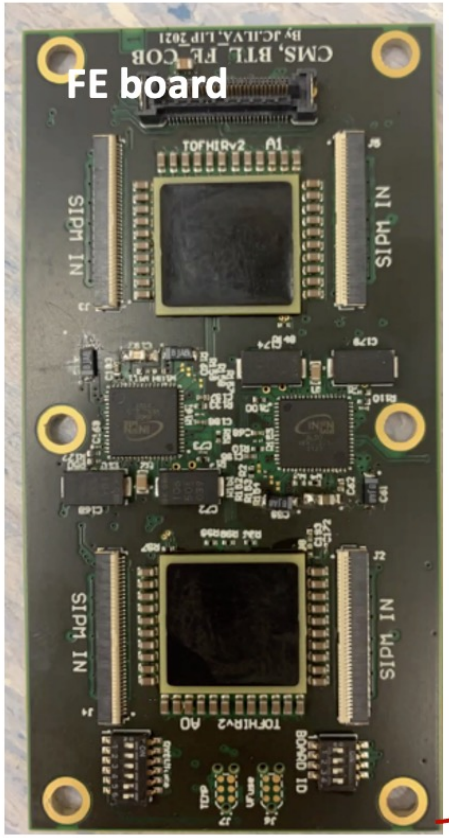


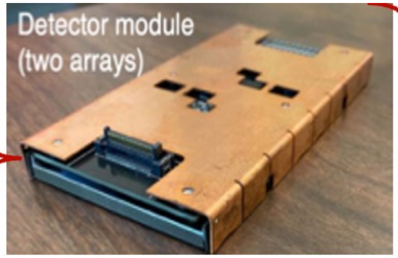
Assembly of MTD BTL from Sensor Modules

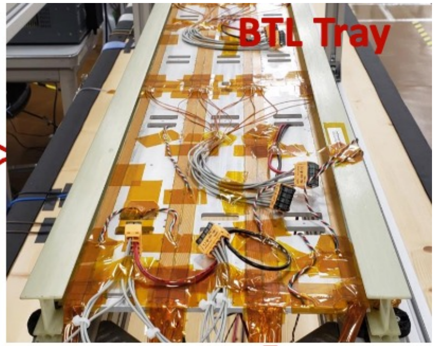


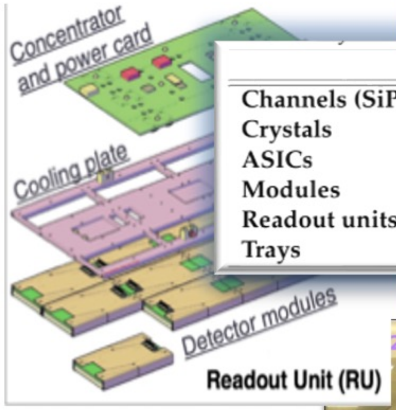




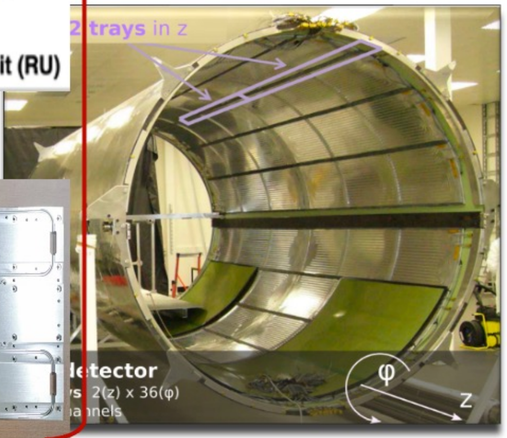








	Module	RU	Tray	Total
Channels (SiPMs)	32	768	4608	331776
Crystals	16	384	2304	165888
ASICs	1	24	144	10368
Modules	-	24	144	10368
Readout units (RU)	-	-	6	432
Trays	-	-	-	72



All components will be assembled and validated at 4 global BTL Assembly Centers (BACs)

Trays will be shipped to CERN, integrated into the BTST and commissioned in the Tracker Integration Facility

BTL Assembly “Scheme”

CERN
Cooling plate assembly and QC

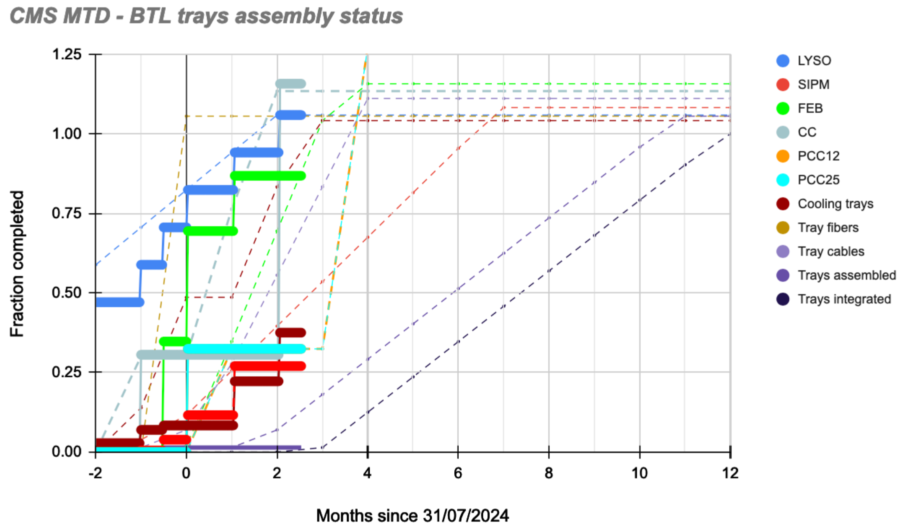
BACs
SM assembly and QC.
DM assembly and QC.
Tray population with DMs, on detector electronics & cables.
Fully assembled tray QA/QC procedures.
Sample tray QA/QC

CERN
Tray installation into BTST & commissioning

BTST (Tracker and BTL) installed at P5

Four Main assembly of the detector trays is carried out at four BTL Assembly Centers (BACs)

- Milano-Bicocca.
- University of Virginia.
- Caltech.
- Peking University.



Assembly and QA/QC of Sensor Module

Assembly of Sensor Module

Assembly materials

- RTV with a high refractive index close to that of LYSO

Assembly tool : GAMBIT

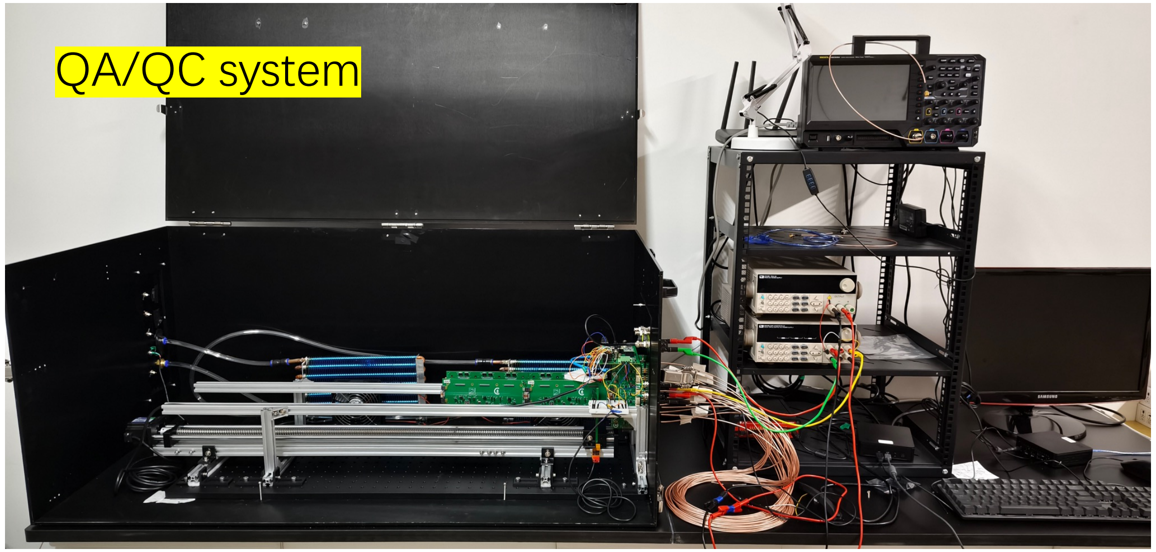
- **Control RTV thickness, SiPM/LYSO alignment, and others**

Standardization of Assembly flow

- The humidity, time, and other ranges for placing the module

QA/QC of Sensor Module

- measure the light yield of each channel to show the assembly quality
- Components: Electronic module, constant temperature dark box, data collection system, and source movement system



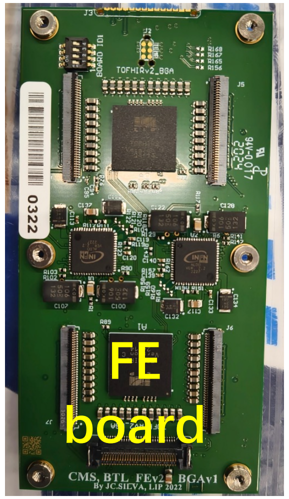
Assembly and QA/QC of Detector Module

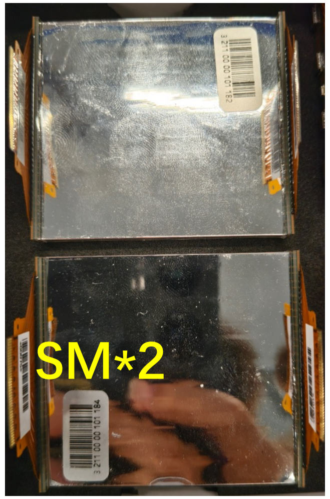
Detector Module : Sensor module, FE front-end electronic board, and copper shell for heat exchange

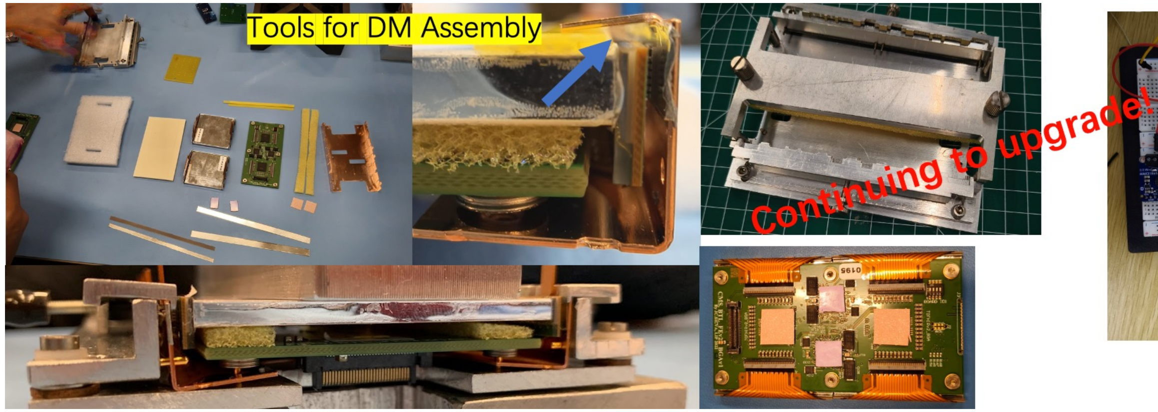
Assembly process of DM: **Thermal contact**

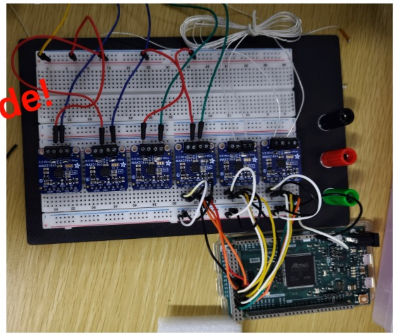
- ➢ Good contact between the outer end of TEC on SiPM and the copper
- ➢ Coverage of thermal pads on important chip surfaces on FE board
- ➢ Avoid contact between LYSO crystals and other components

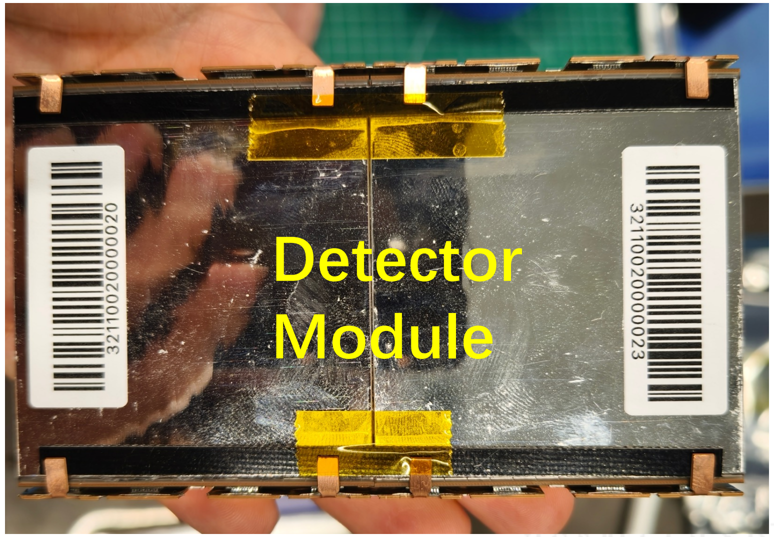
QA/QC of the DM mainly involves thermal coupling testing











Assembly and QA/QC of BTL Tray

MTD BTL Tray

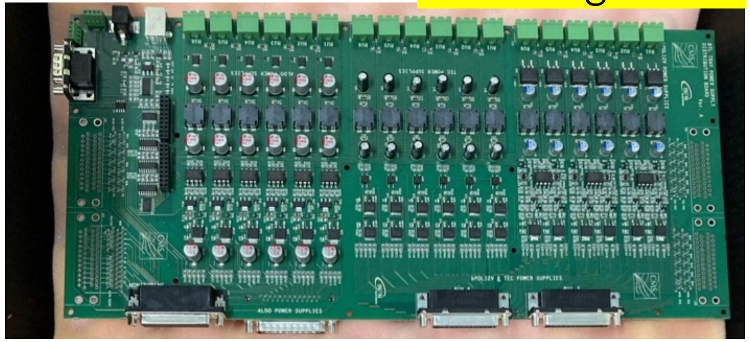
- A BTL Tray will cover a detector range of 10 degrees and 2.5 meters at η
- A total of 72 Trays cover the entire barrel of the MTD time detector

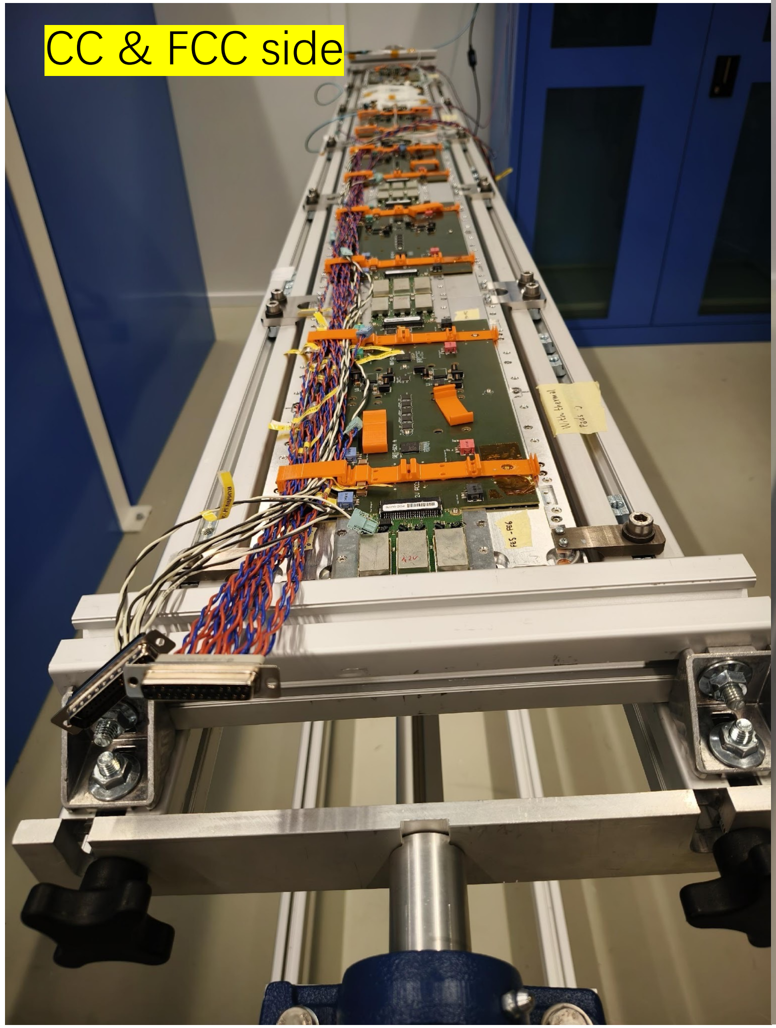
Assembly of BTL Tray

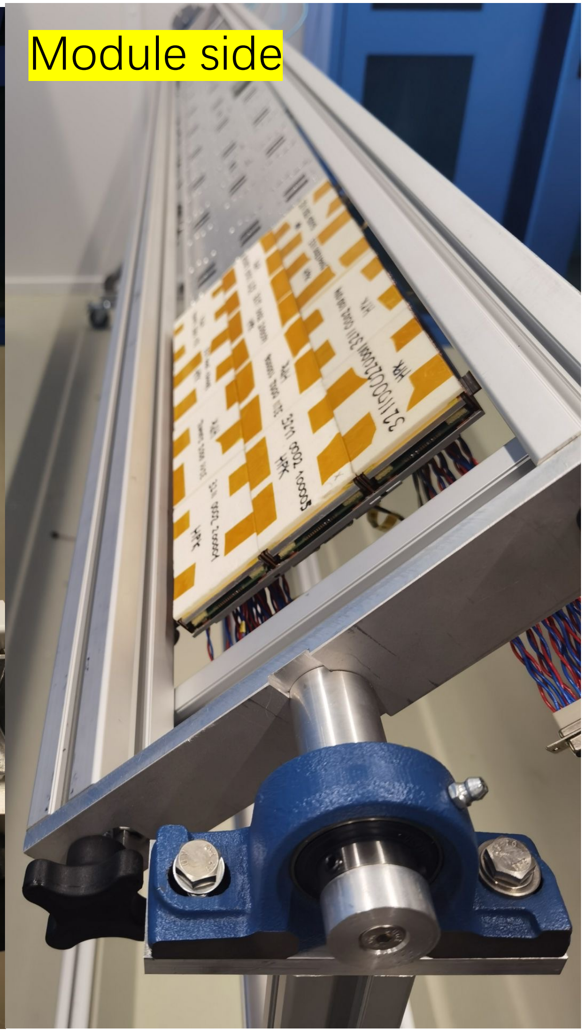
- 6 RUs, each includes a cooling plate, CC board, PCC board, and 12 DMs.

The tray QA/QC system based on Serenity board and custom tray powering board is currently being established.

Powering board







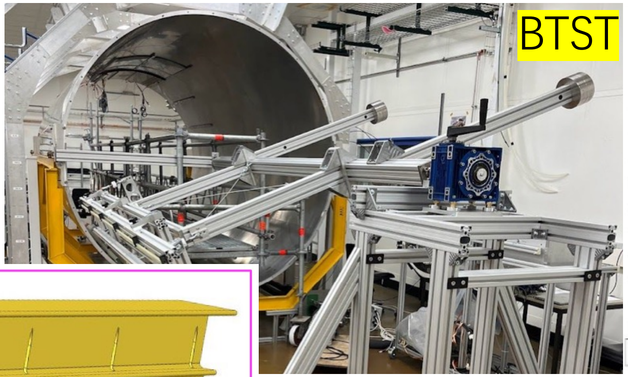
Cooling-plate, BTST at CERN

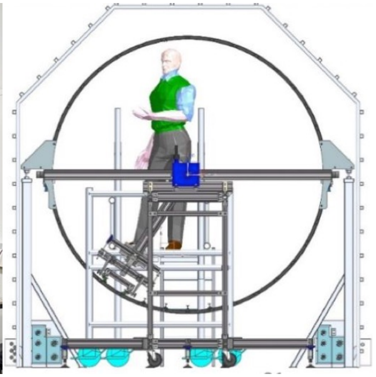
Cold-tray assembly at CERN

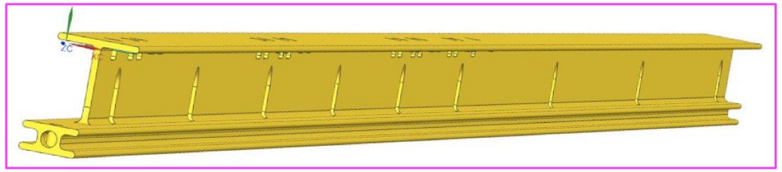
- Components received and QCed at CERN
- Finished cold-trays placed in the shipping cradles
- Currently operating at 2 trays/day (3 trays/day possible).

BTL-BTST mechanical interface consists of

- 1’368 threaded inserts embedded into the BTST (2 per foot)
- 684 aluminium feet (9 per I-beam)
- 76 glass-fiber I-beams (BTL rails)







Research and discussion on BTL assembly

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The first complete **detector module** was produced **at CERN by the end of 2023**

for the **manufacturing process** of detector modules

In March 2024 at CERN,
Complete the assembly of **the whole RU** for the first time

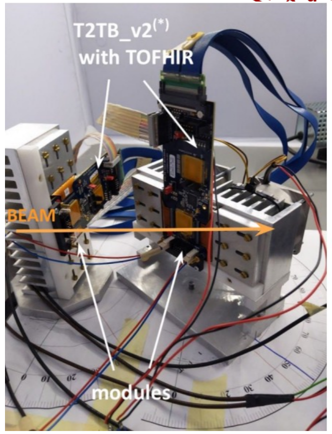
In July 2024, at CERN,
Completed the **assembly of the entire Tray** for the first time,
QA/QC was carried out, and **the assembly process** was basically determined

- BTL production is moving ahead according to the latest schedule!
- For the latest progress on BTL work, please refer to Karlis .

03 BTL Work and Local Lab Setups at PKU

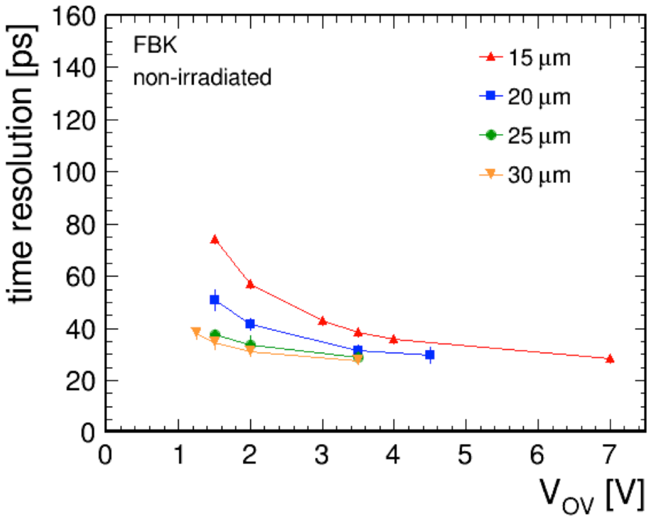
Some Test Beam Study by PKU (1)

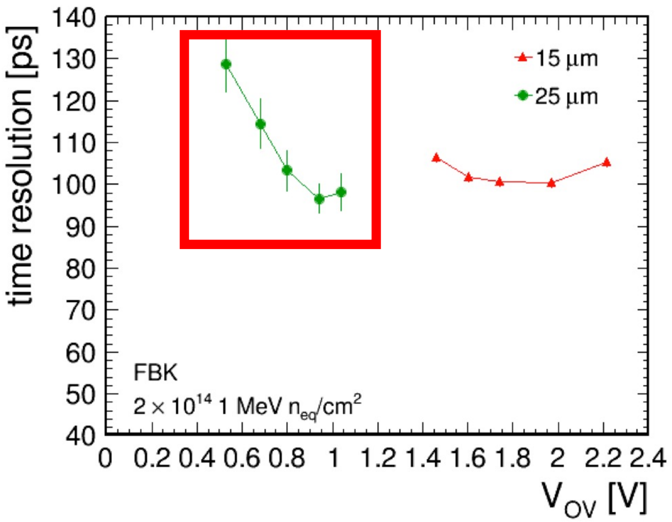
Conducted on CERN (180 GeV pion) and FNAL (120 GeV proton) beams

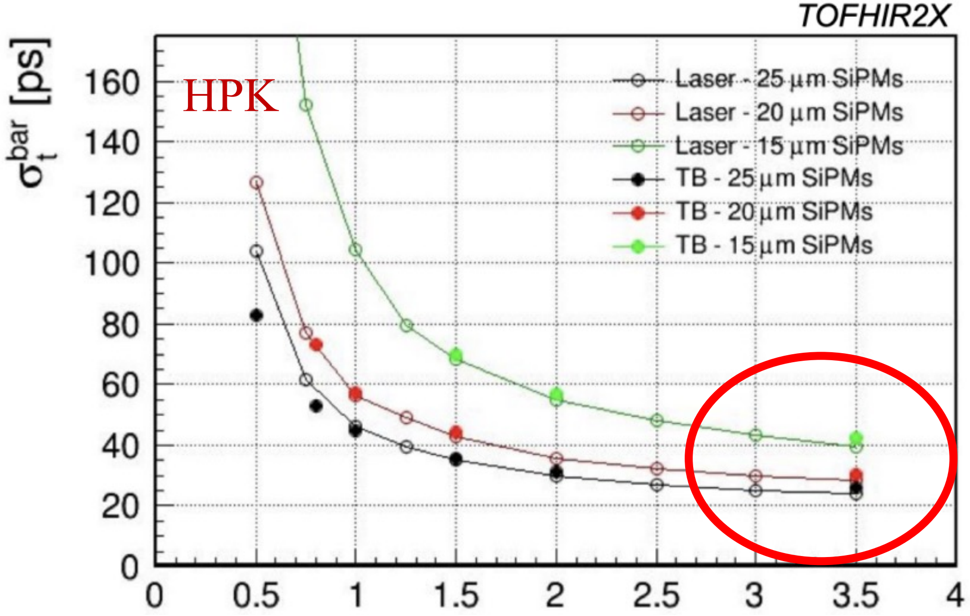


SiPM

- Main optimization and research parameters: Cell size of SiPM
  - The time resolution for modules with non-irradiated SiPMs of different cell-sizes (15, 20, 25 μm)
  - 25 μm has the best time resolution
- More tests were conducted, such as comparing the time resolution of SiPM from different manufacturers
- Optimization of SiPM parameters has been completed







Some Test Beam Study by PKU (2)

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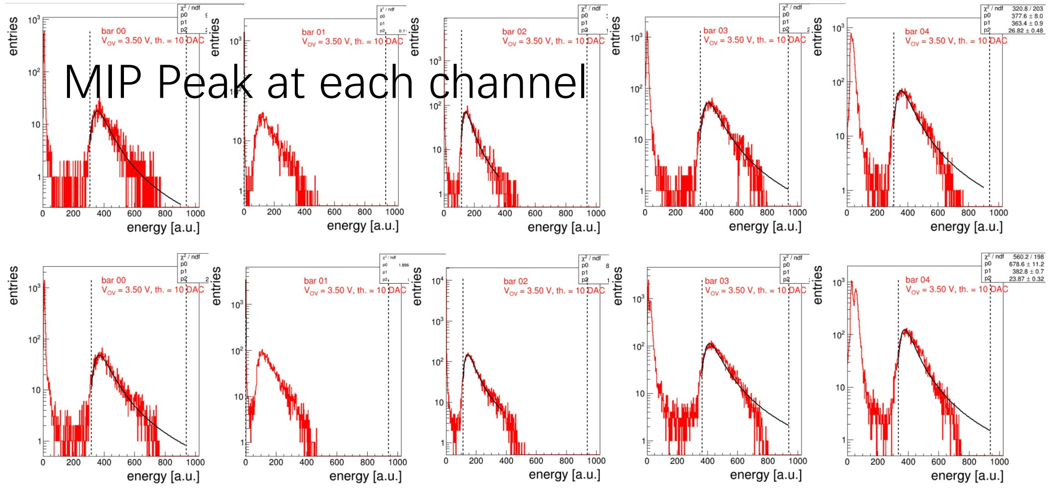
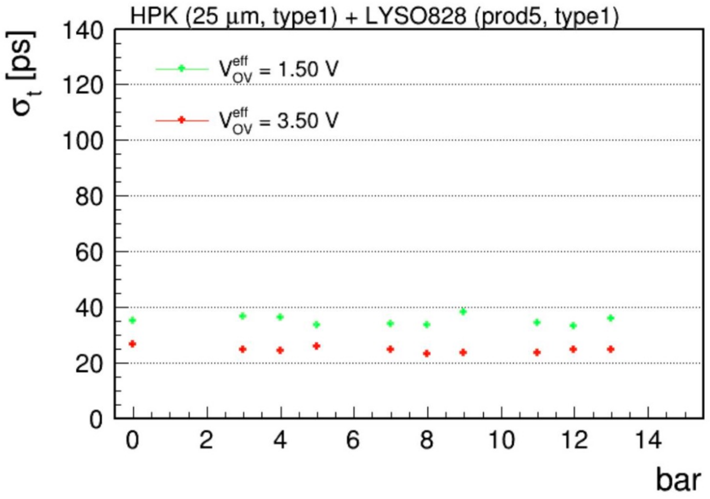
LYSO

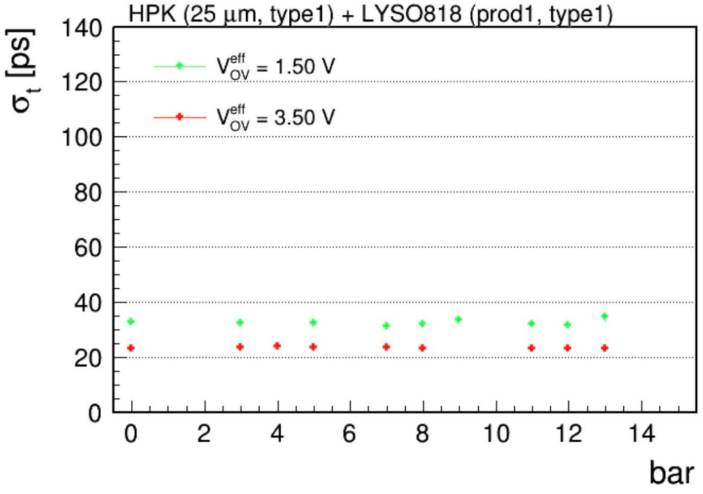
- Preliminary comparative tests were conducted on the quality of LYSO (size, yield, etc.) from various manufacturers
- Finally, perform time resolution testing on high-performance manufacturers using beam current
- The time resolution of manufacturers Prod1 and Prod5 was compared as follows
- LYSO optimization has been completed



prod5 52deg



prod1 52deg



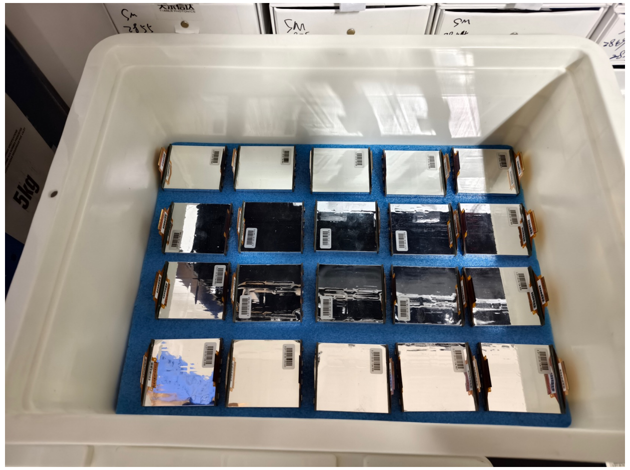
Results are measured at the optimal threshold

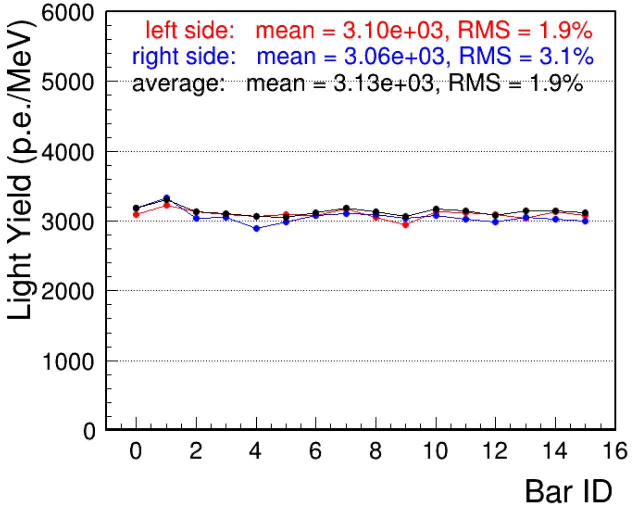
LYSO	Vov/V	angle/deg	t_{Res}/ps	error/%
prod1	1.50	32	38.2	6.9
		52	**32.2**	3.1
		64	30.9	9.0
	3.50	32	25.7	2.1
		52	**23.5**	1.2
		64	23.6	7.2
prod5	1.50	52	**35.1**	4.3
	3.50		**24.6**	4.0

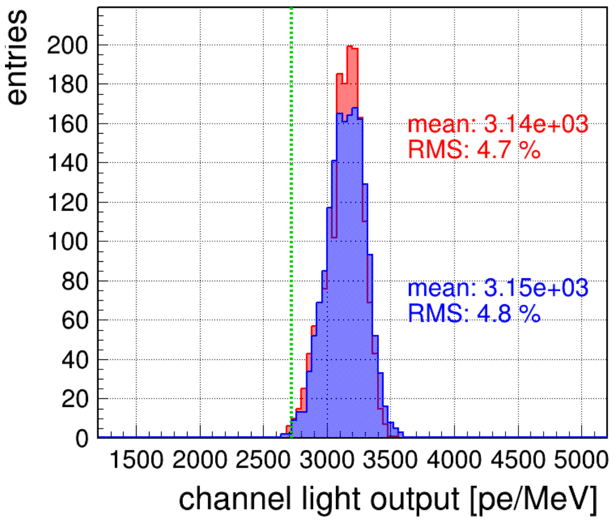
BTL Assembly and QAQC at PKU

- For each Assembly Center, our task is to complete the full assembly process from LYSOs & SiPMs to the Tray.
- Assembly will span this year and the first half of next year, ~2600 Modules (18 BTL Trays) at PKU.

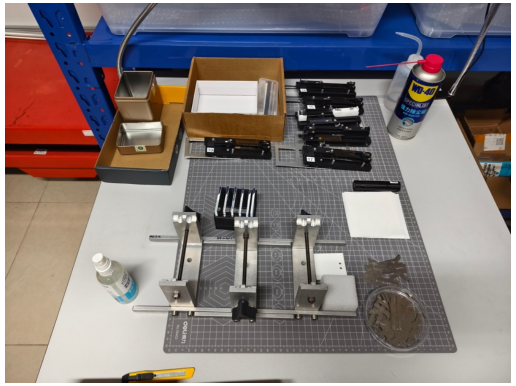
- Recently, we
  - ✓ The assembly and QAQC of sensor module required for the first tray have been completed
  - ✓ The assembly and QAQC of the first batch of detector modules are about to begin
  - ✓ Setting up the Tray testing platform

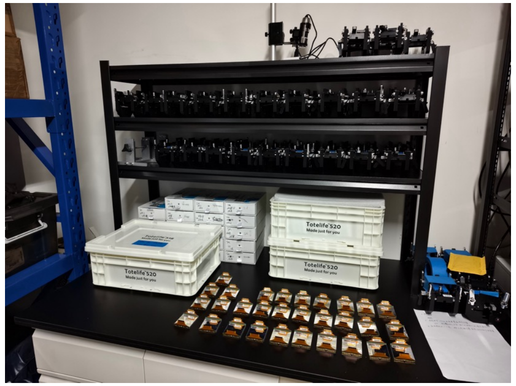


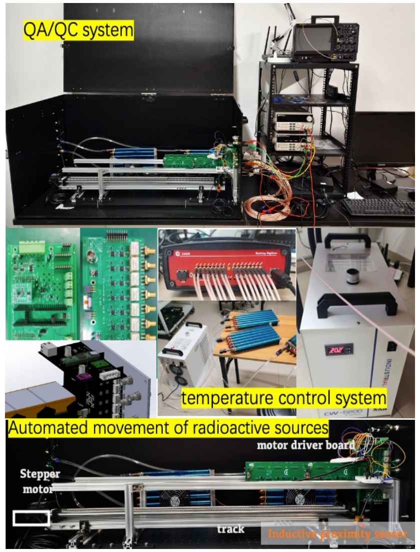


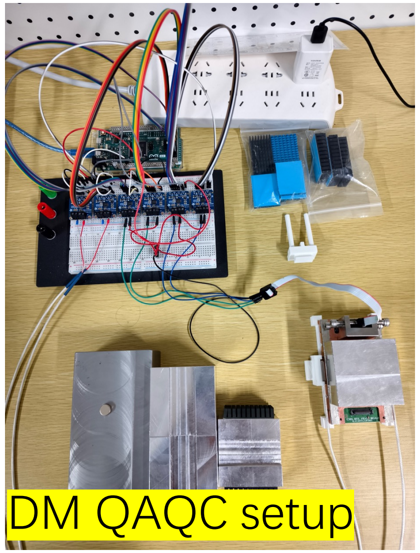


PKU Lab Setups


SM Assembly


SM glued and tools




DM QAQC setup


Tray shelf for Tray assembly and QAQC

04 Summary

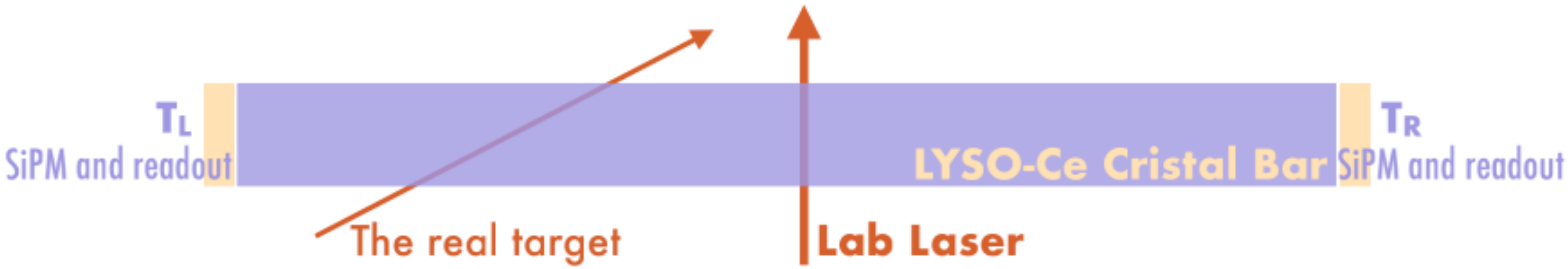
Summary

北京大学

- MTD, a new CMS Phase-II detector for the HL-LHC will be added to CMS to help meet the challenge of high luminosity.
  - ✓ BTL is a single-layer MIP detector which will measure time with ~30-60 ps resolution.
- BTL is not "moving to production", BTL is "in production".
  - ✓ We are confident that BTL will be the first fully completed CMS Phase-2 sub-detector come 4th November 2025.
- For PKU, We actively participate in the comprehensive work of MTD BTL , and, as one of the assembly centers, undertake 1/4 of the assembly work.
  - ✓ Assembly and QAQC work is currently underway at PKU !

Thanks for your attention!

Back up



$$T_{ave} = 1/2(T_L + T_R) \qquad \sigma_{ave} = 1/2\sqrt{\sigma_L^2 + \sigma_R^2}$$

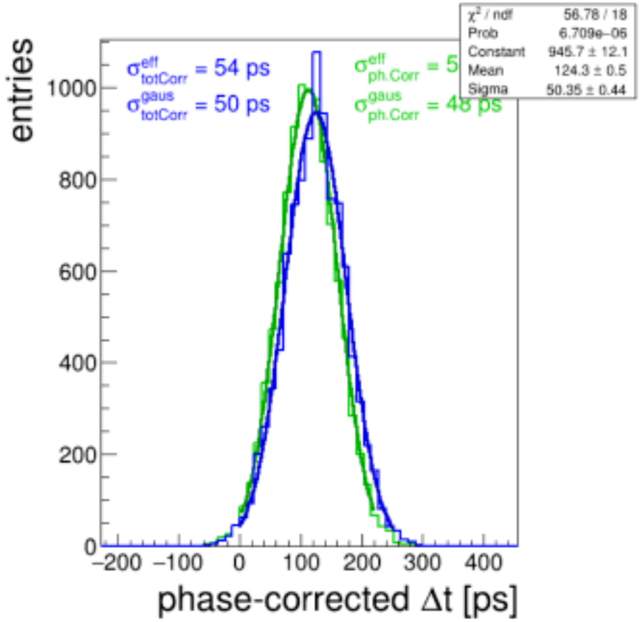
$$\sigma_{diff} = 2 \times \sigma_{ave}$$

$$T_{diff} = T_L - T_R \qquad \sigma_{diff} = \sqrt{\sigma_L^2 + \sigma_R^2}$$

- CMS clock distribution: 15 ps;
- Digitization: 7 ps;
- Electronics: 8 ps;
- Photo-statistics: 25–30 ps;
- Noise (SiPM dark counts): negligible at startup, 50 ps after 3000 fb^{-1};

summarized in the equation:

$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR} .$$



Experiment	r (m)	σ_T (ps)	r/σ_T ($\times 100$) ($m \times ps^{-1}$)
STAR-TOF	2.2	80	2.75
ALICE-TOF	3.7	56	6.6
CMS-MTD	1.16	30	3.87

Table 1.3: Nominal radiation doses and fluences at various locations of the timing layers after $3000\,fb^{-1}$. The last two columns show the radiation levels providing a safety margin of a factor 1.5. The fluence is normalized to 1 MeV neutron equivalent in silicon.

				$3000\ fb^{-1}$		$1.5 \times 3000\ fb^{-1}$	
Region	$\|\eta\|$	r (cm)	z (cm)	n_{eq}/cm^2	Dose (kGy)	n_{eq}/cm^2	Dose (kGy)
Barrel	0.0	116	0	1.65×10^{14}	18	2.48×10^{14}	27
Barrel	1.15	116	170	1.80×10^{14}	25	2.70×10^{14}	38
Barrel	1.45	116	240	1.90×10^{14}	32	2.85×10^{14}	48
Endcap	1.6	127	303	1.5×10^{14}	19	2.3×10^{14}	29
Endcap	2.0	84	303	3.0×10^{14}	50	4.5×10^{14}	75
Endcap	2.5	50	303	7.5×10^{14}	170	1.1×10^{15}	255
Endcap	3.0	31.5	303	1.6×10^{15}	450	2.4×10^{15}	675

Table 1.1: Expected scientific impact of the MIP Timing Detector, taken from Ref. [8].

Signal	Physics measurement	MTD impact
$H \to \gamma\gamma$ and $H \to 4$ leptons	+15–25% (statistical) precision on the cross section $\to$ Improve coupling measurements	Isolation and Vertex identification
VBF$\to$H$\to \tau\tau$	+30% (statistical) precision on cross section $\to$ Improve coupling measurements	Isolation VBF tagging, p_T^{miss}
HH	+20% gain in signal yield $\to$ Consolidate searches	Isolation b-tagging
EWK SUSY	+40% background reduction $\to$ 150 GeV increase in mass reach	MET b-tagging
Long-lived particles (LLP)	Peaking mass reconstruction $\to$ Unique discovery potential	β_{LLP} from timing of displaced vertices

GAMBIT performance tests and upgrade in the pre-production

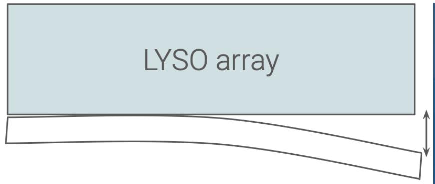
- Alignment of Crystal and SiPM → Adjust the height of the platform to approximately 200 µm
- Uneven adhesive thickness → Increasing the thickness of the Stencil and applying rubber bands for assistance

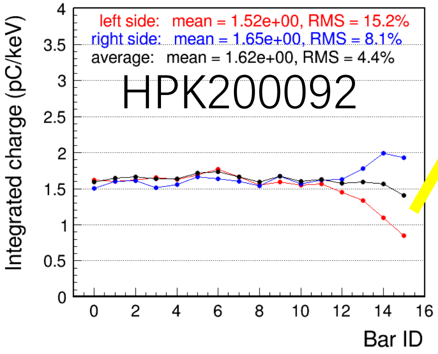
Standardization of Assembly flow

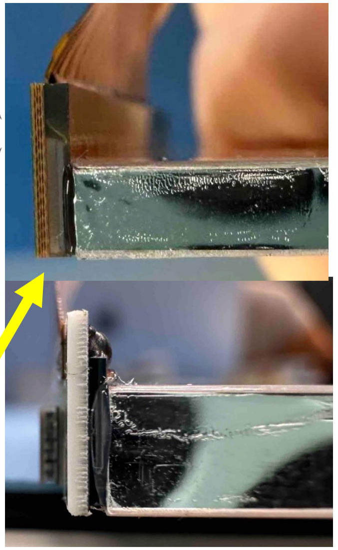
- Referring to the conditions that are most conducive to the uniform and smooth hardening of the RTV

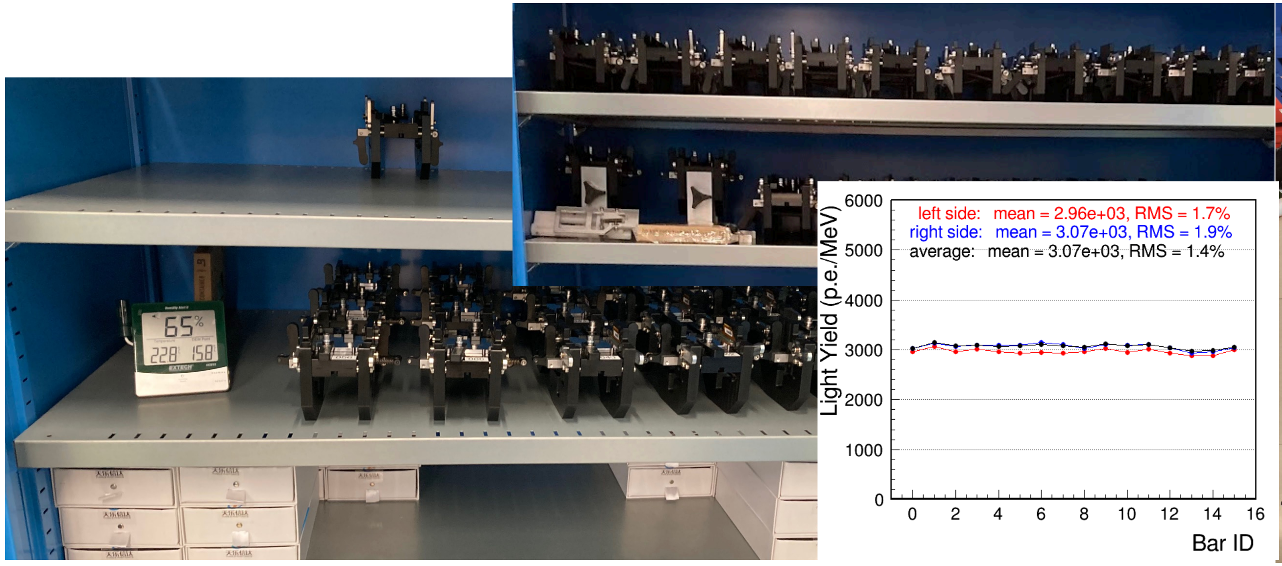
→ The humidity, time, and other ranges for placing the module after assembly have been standardized

The development of LYSO+SiPM assembly tools GAMBIT has been completed and shipped to PKU









LYSO Intrinsic Spectrum

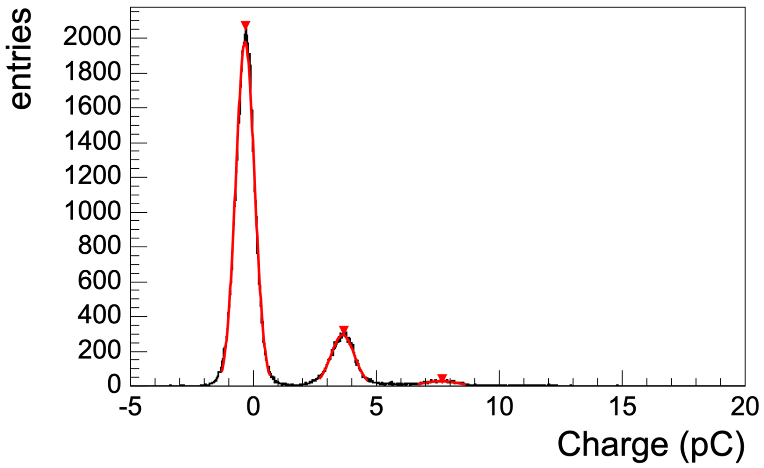
- ^{176}Lu: β decay → ^{176}Hf excited state: γ cascade decay
- 88 keV, 202 keV, 307 keV

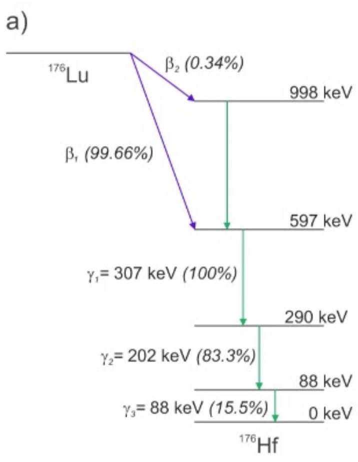
$$P(E) = \alpha_{88}\beta(E-88) + \alpha_{202}\delta(E-202) + \alpha_{290}\beta(E-290) + \alpha_{307}\delta(E-307) + \alpha_{395}\beta(E-395) + \alpha_{509}\delta(E-509) + \alpha_{597}\beta(E-597)$$

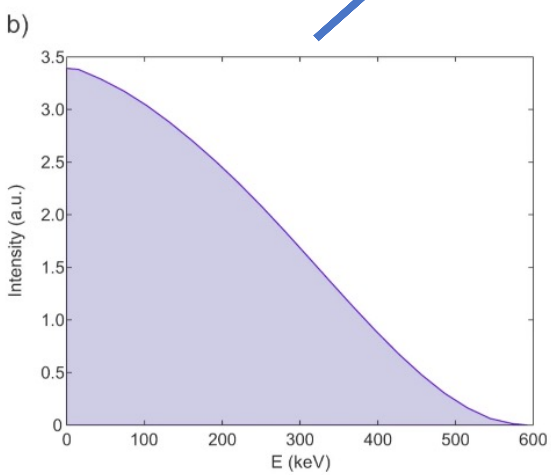
Single Photoelectron Charge

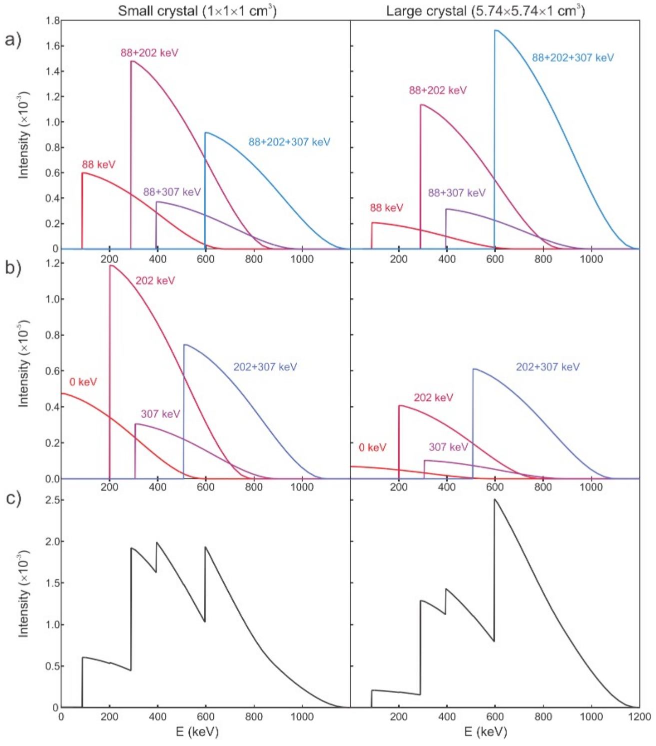
- SPE histogram presents the amount of charge carried by a single photon

The ratio is proportional to the light yield

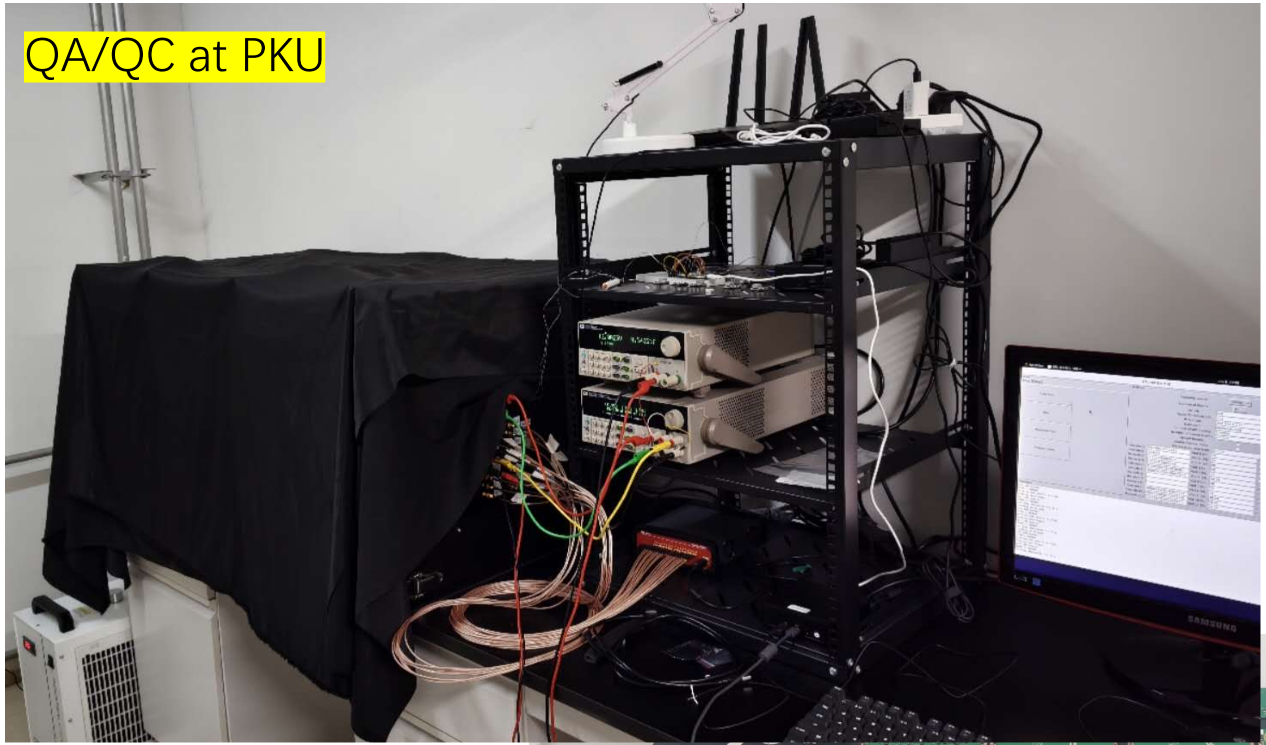


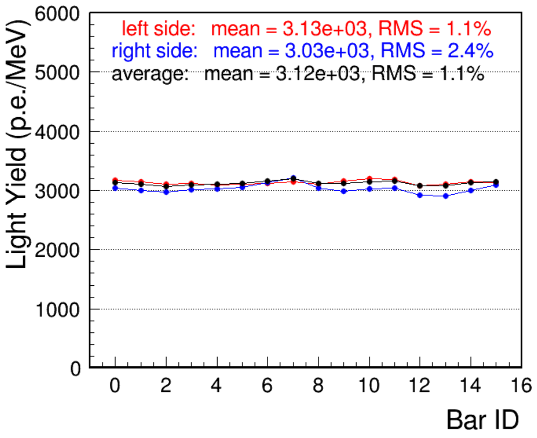


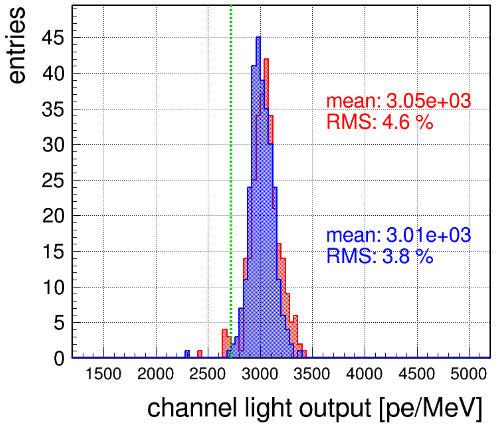




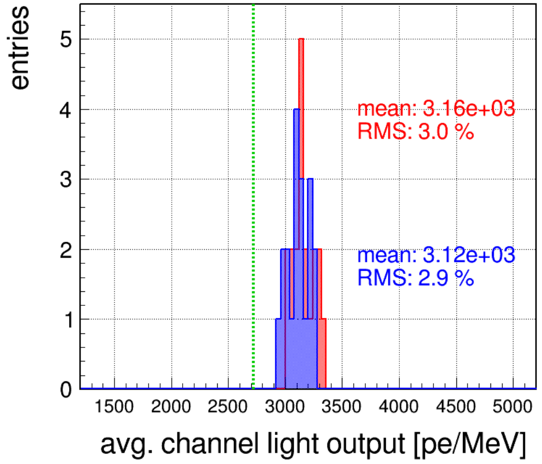
QA/QC at PKU

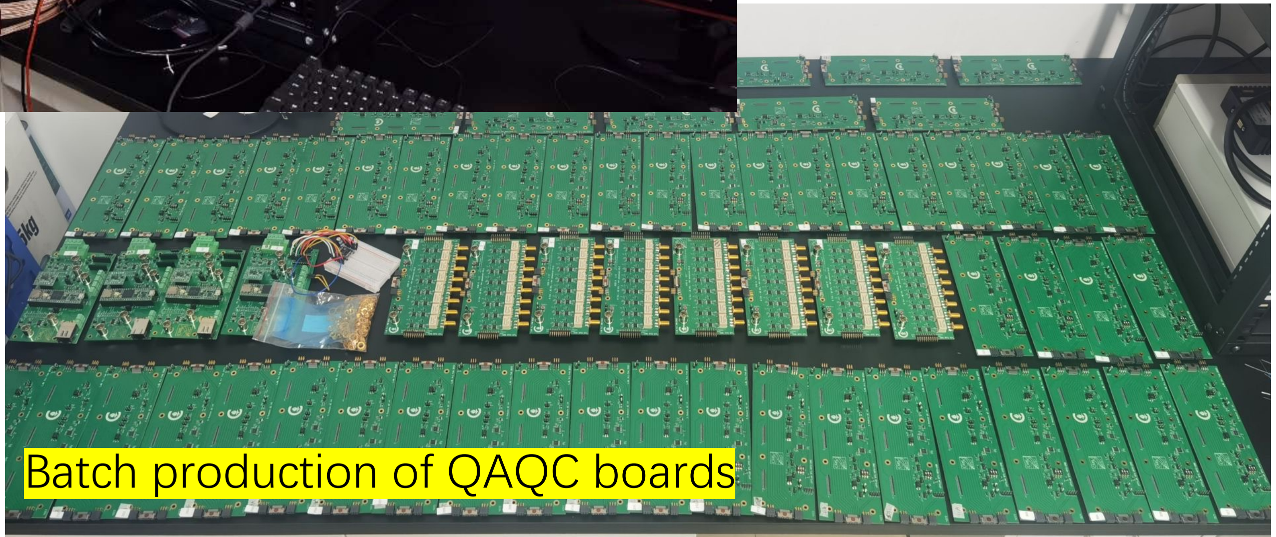






QAQC result of the SM for tray 1





Batch production of QAQC boards