中国物理学会高能物理分会第十二届全国会员代表大会暨学术年会

# The CMS MTD Barrel Timing Layer for the High Luminosity LHC

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Date: 2026/7/15

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# HL-LHC 挑战

## ◆ HL-LHC运行条件

- HL-LHC的累计积分亮度将超过 **3000 fb$^{-1}$**，为标准模型精确测量和稀有新物理过程搜索提供更大的数据样本。
- 每次束团交叉预计同时发生约 **140–200**个质子—质子碰撞，远高于当前LHC的运行条件。

## ◆ 高堆积带来的影响

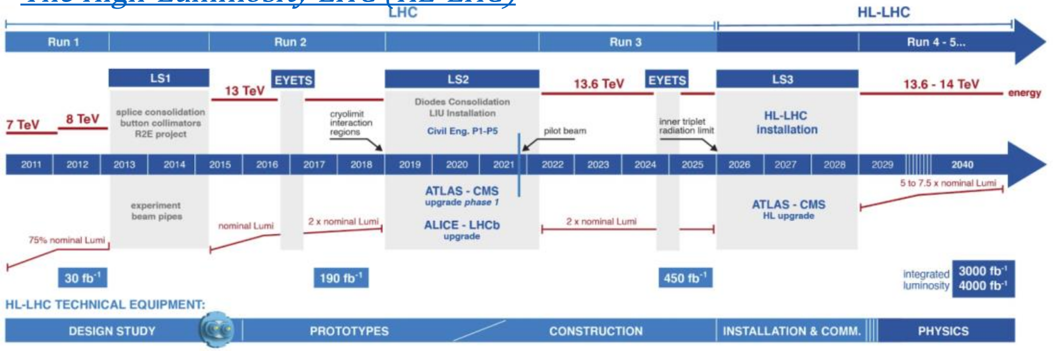
- 大量碰撞顶点在空间上相互重叠，使径迹与产生顶点之间的关联更加困难。
- 来自堆积碰撞的额外粒子会影响喷注、轻子隔离以及缺失横动量的重建。
- 仅依靠空间位置信息，难以在HL-LHC条件下保持现有的粒子重建性能。

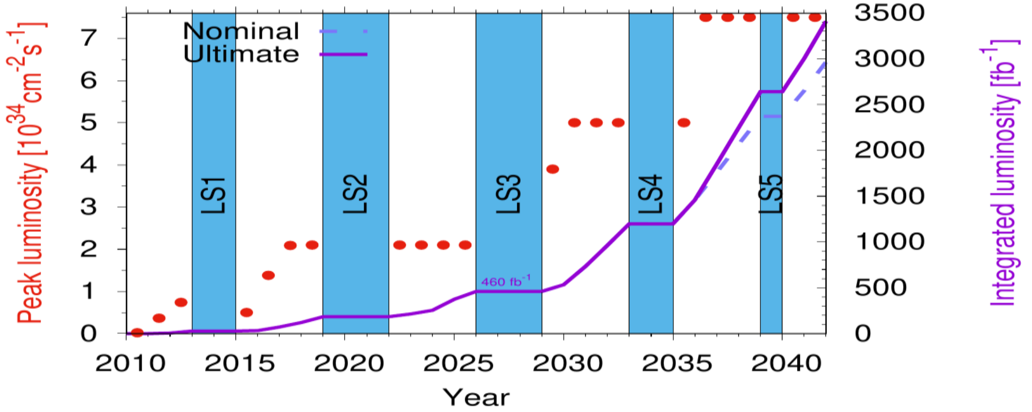
**高精度timing detector是大型粒子对撞实验探测器的发展趋势**

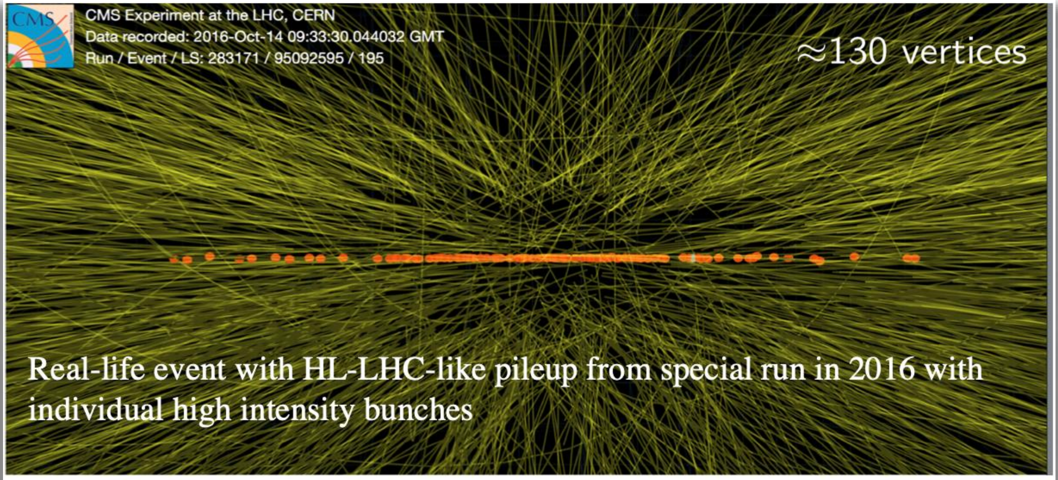
**MTD: 为每条带电粒子径迹增加30–60 ps量级的时间信息，实现四维顶点重建。**

*Physics Reports 1156 (2026) 1–39*

*The High-Luminosity LHC (HL-LHC)*



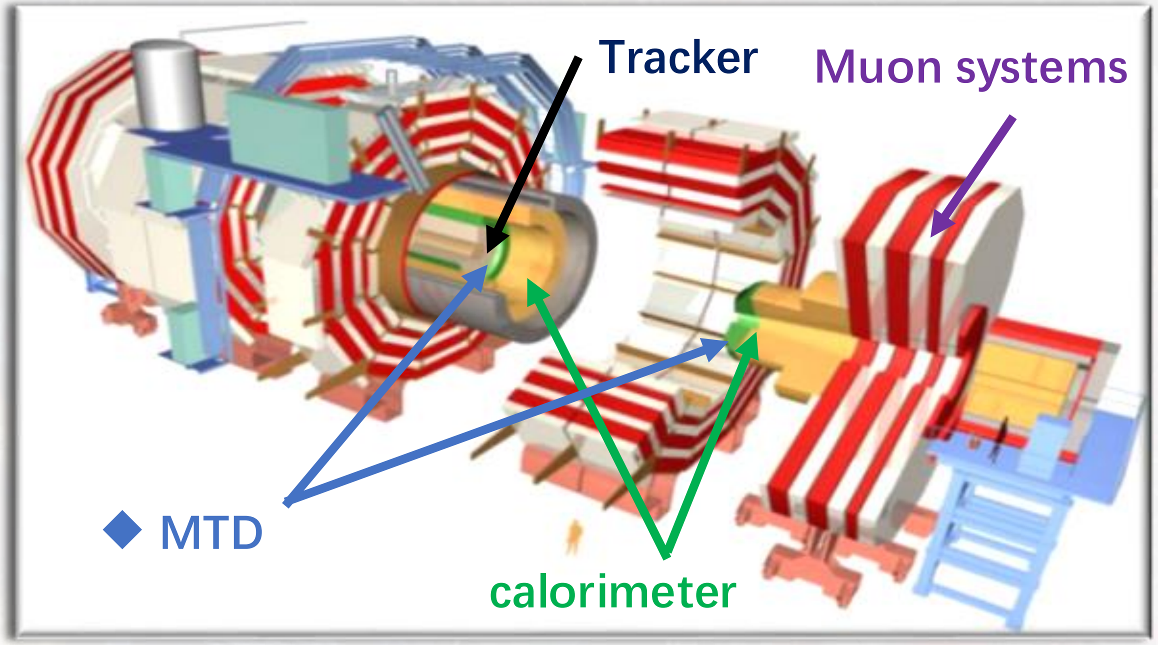




Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches

# CMS 升级 & MTD 时间探测器

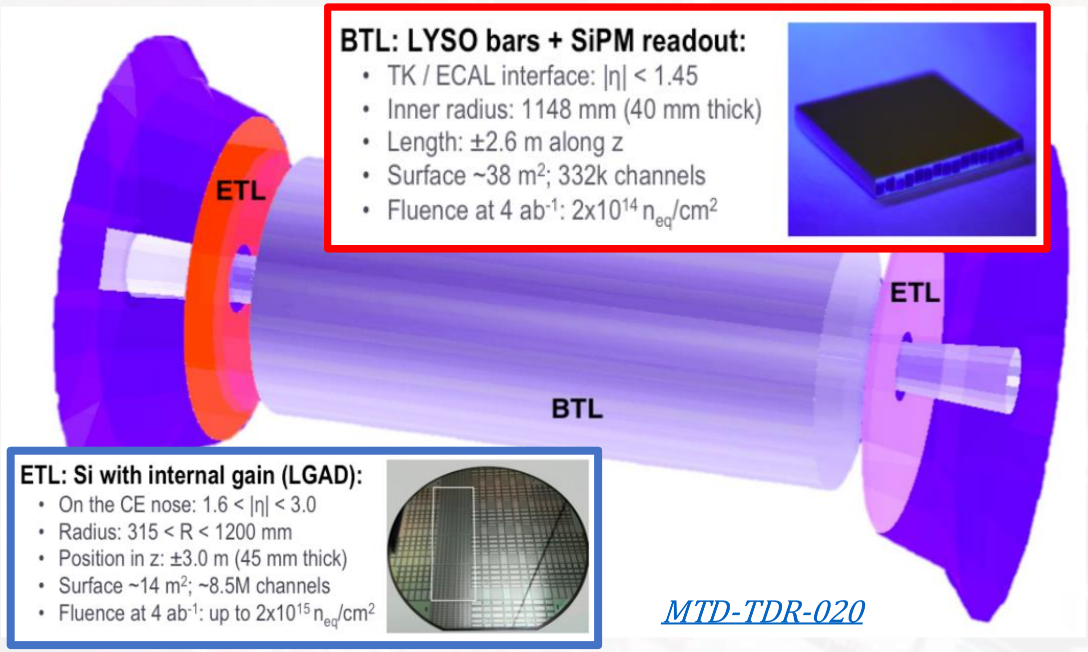
◆ **MIP Timing Detector**

- **MTD是CMS Phase-II升级中新增加的精密时间子探测器，用于测量带电粒子到达探测器的时间。**
- 设计目标是在整个**HL-LHC**运行周期内提供 **30–60 ps**的单径迹时间分辨率。




◆ **探测器组成**

- **Barrel Timing Layer (BTL): |η| < 1.45**
- **Endcap Timing Layer (ETL): 1.6 < |η| < 3**




*MTD-TDR-020*

◆ **物理作用**

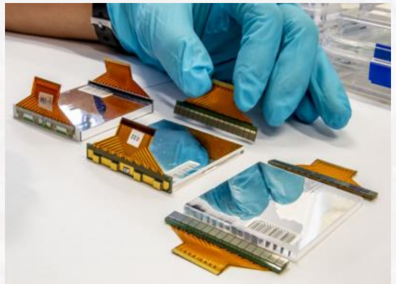
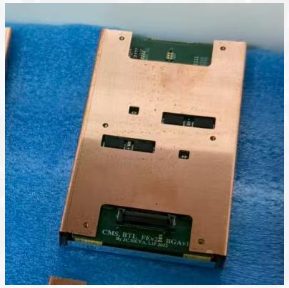
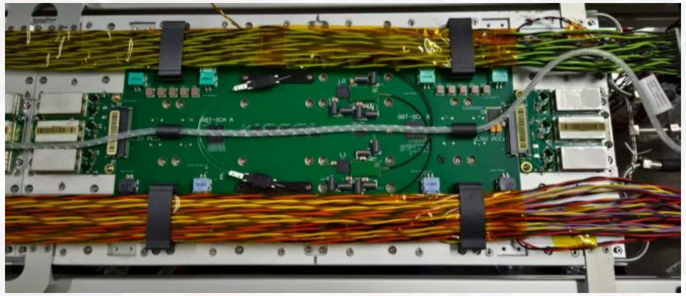
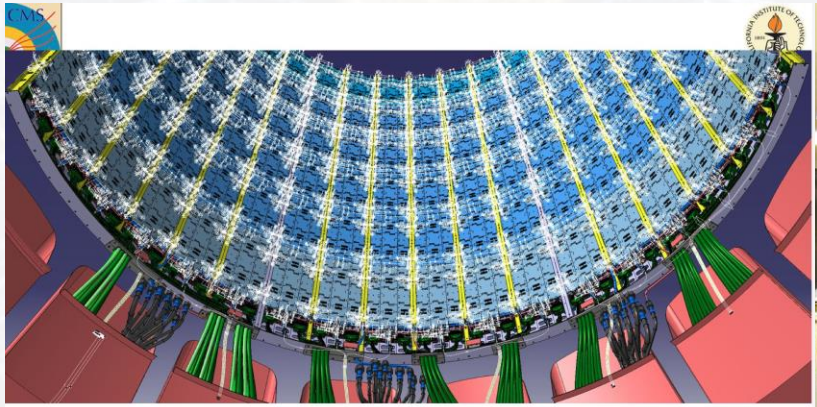
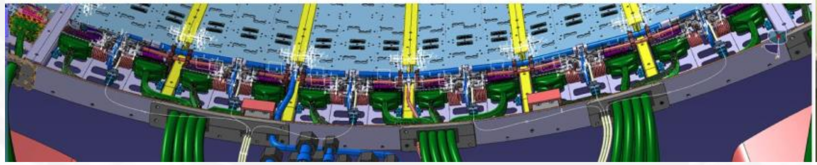
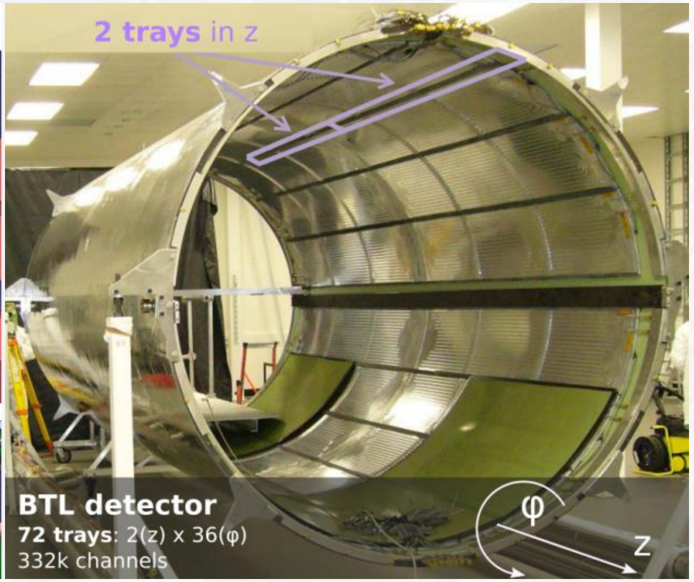
- 改善碰撞顶点重建和堆积抑制能力。
- 提升喷注重建、**b-tagging**、轻子隔离和缺失横动量的性能。
- 提供飞行时间信息，拓展对长寿命粒子的搜索。

**MTD为CMS增加了时间维度，是HL-LHC高堆积条件下保持物理性能的重要升级。**

# BTL桶部探测器

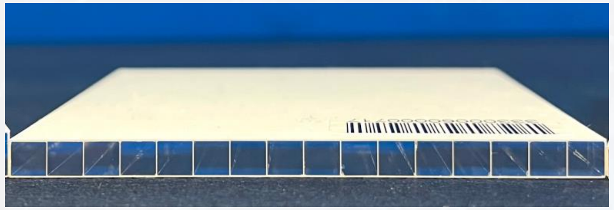
## ◆BTL Barrel Timing Layer

- **BTL是覆盖CMS桶部区域的单层MIP计时探测器，安装在外径迹探测器与BTL径迹探测器支撑筒内壁BTST之间。**
- 可用径向空间不足 **4 cm**，整个探测器需要在有限空间内完成传感器、读出电子学和冷却系统的集成。
- **BTL总覆盖面积约为 38 m²，包含约 10,000个Sensor Modules。**
- **每个Sensor Module由 16根LYSO晶体条 和两组16通道SiPM阵列组成。**
- 探测器模块由定制的 **TOFHIR2 ASIC** 读出，并安装在搭载$CO_2$冷却的托盘上。

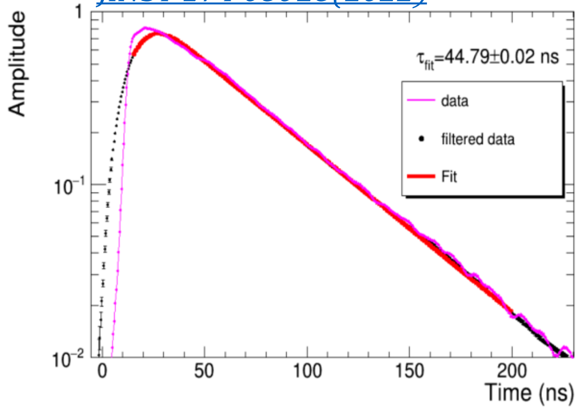
# BTL传感器模块

## ◆LYSO:Ce 晶体



- LYSO晶体具有约 **40k photons/MeV**之高的光产额，可以为最小电离粒子产生足够强的闪烁信号。
- 约 **40 ns** 的快速闪烁衰减有利于获得良好的时间分辨率。
- LYSO密度高、机械性能稳定，并具有较好的抗辐照能力，适合HL-LHC长期运行。

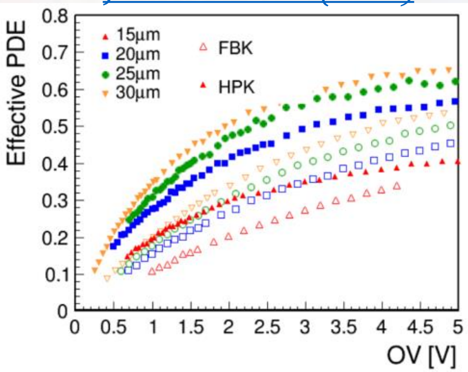
JINST 17 P08028(2022)

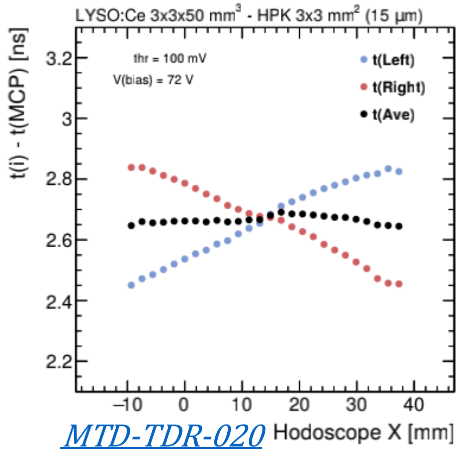



## ◆SiPM 双端读出

- 每根LYSO晶体的两端分别连接一组SiPM阵列。
- 双端读出可以提高光子统计量，并减小粒子击中位置对时间测量的影响。
- 最终选择 **25 µm cell-size SiPM**，在光子探测效率和辐照后暗计数率之间取得平衡。

JINST 19 12020(2024)



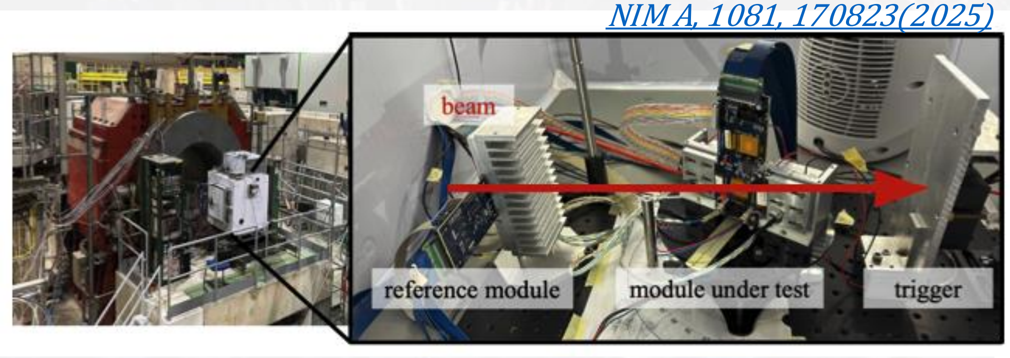



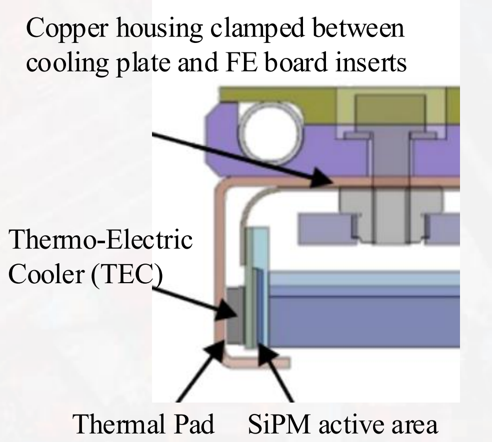

MTD-TDR-020


LYSO晶体与SiPM双端读出兼顾了时间性能、机械尺寸和抗辐照要求。

# BTL性能验证：束流与辐照测试

[NIM A, 1081, 170823(2025)]



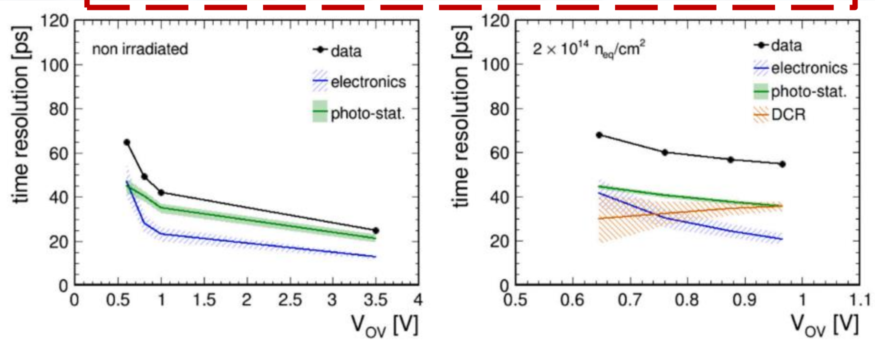



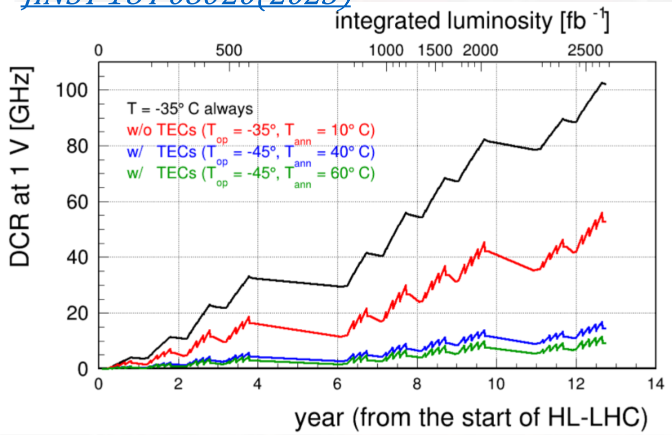

[JINST 18 P08020(2023)]

## ◆ 束流与辐照测试

- **BTL原型模块在辐照前后均进行了高能π束流测试，辐照水平覆盖HL-LHC预期的完整运行周期。**
- **LYSO晶体在目标辐照剂量下没有观察到明显的光产额退化。**
- **TOFHIR2 ASIC在测试过程中保持稳定读出。**

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



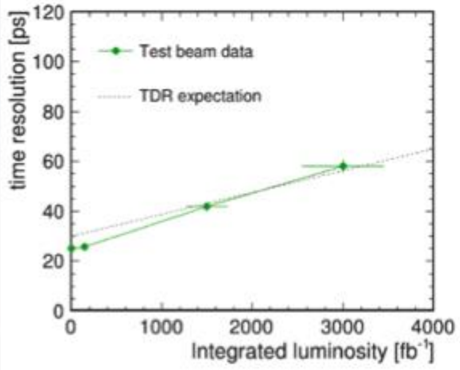

## ◆ 辐照后的主要影响

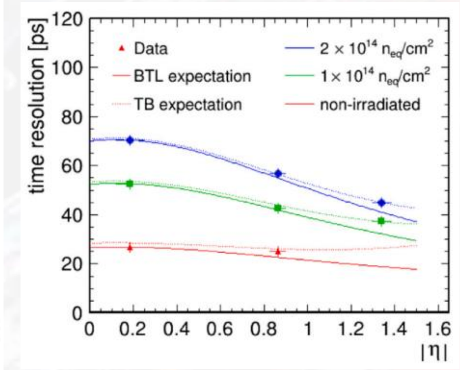
- **BTL性能退化主要来自SiPM辐照后暗计数率的增加。**
- **双相$CO_2$冷却与TEC共同将SiPM维持在低温工作状态，以降低暗计数噪声。**
- **周期性的 60 C annealing 可以恢复部分辐照损伤，减缓性能退化。**

## ◆ 时间分辨率

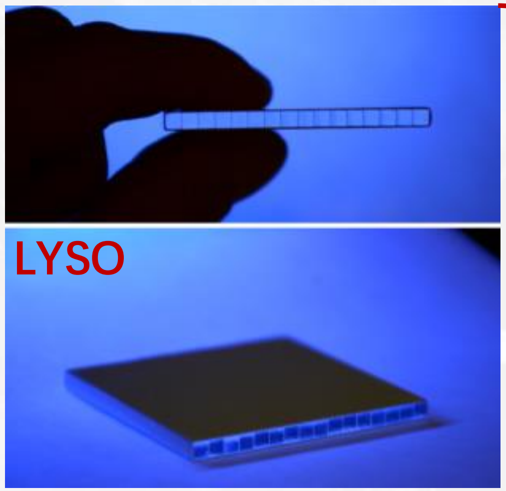
- **辐照前: ~25–30 ps**
- **HL-LHC预期寿命末期: ~55–60 ps**

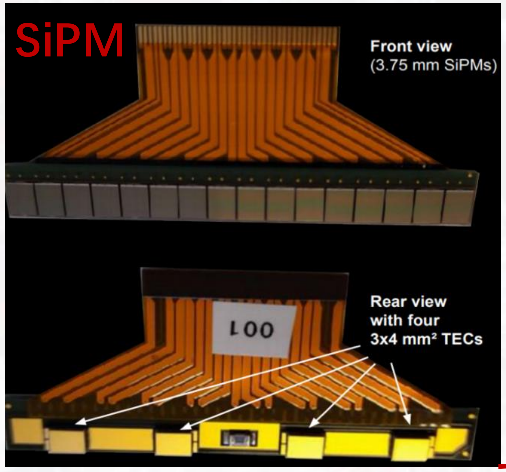
***束流与辐照测试表明，BTL可以在整个HL-LHC运行周期内满足30–60ps时间分辨率要求。***

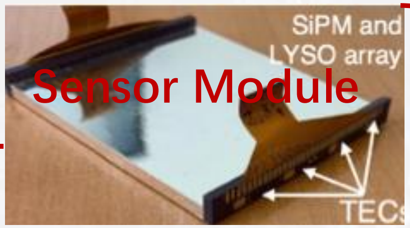


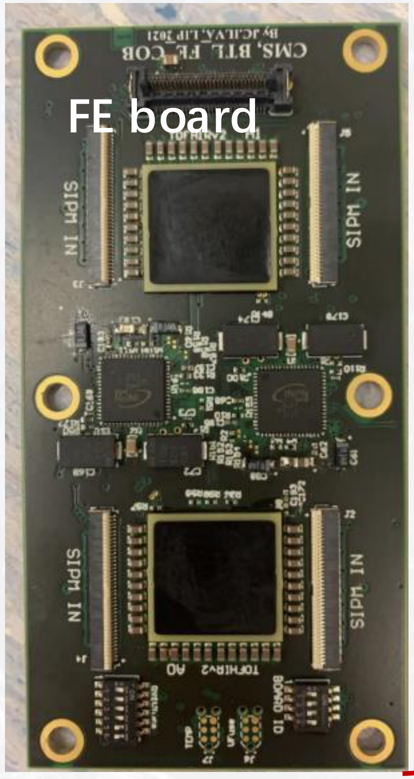



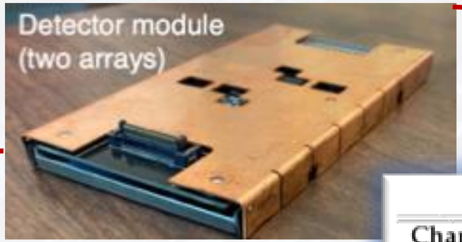
# BTL模块装配概况

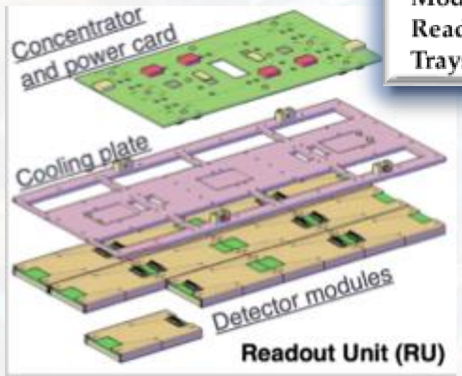


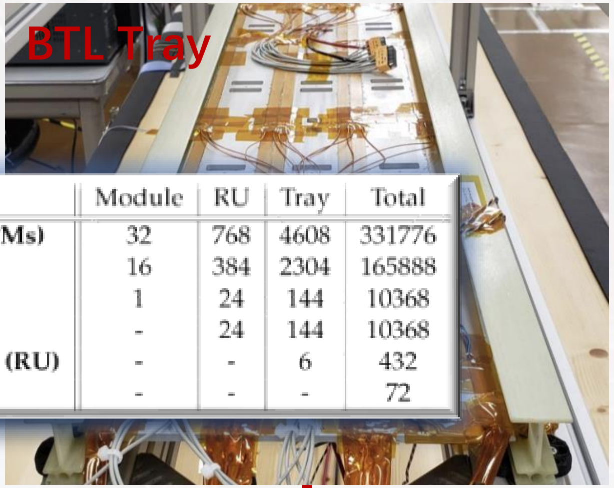



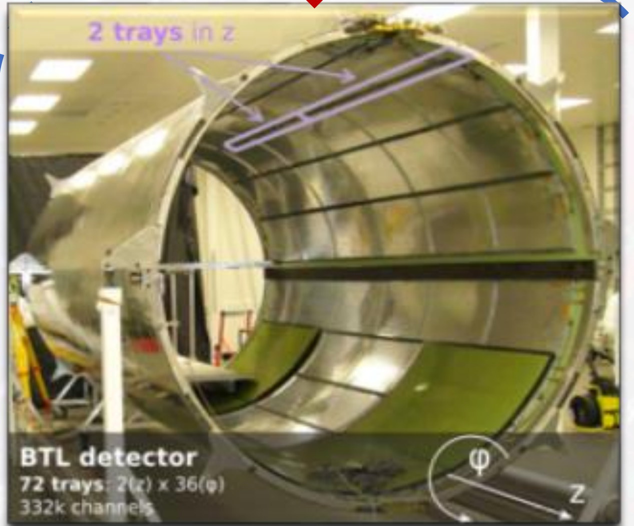








| | Module | RU | Tray | Total |
|---|---|---|---|---|
| Channels (SiPMs) | 32 | 768 | 4608 | 331776 |
| Crystals | 16 | 384 | 2304 | 165888 |
| ASICs | 1 | 24 | 144 | 10368 |
| Modules | - | 24 | 144 | 10368 |
| Readout units (RU) | - | - | 6 | 432 |
| Trays | - | - | - | 72 |



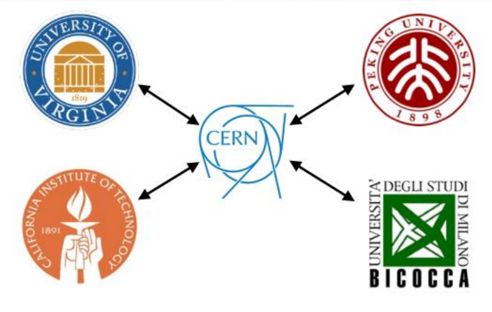

At Assembly Center

At CERN

# BTL模块生产与组装

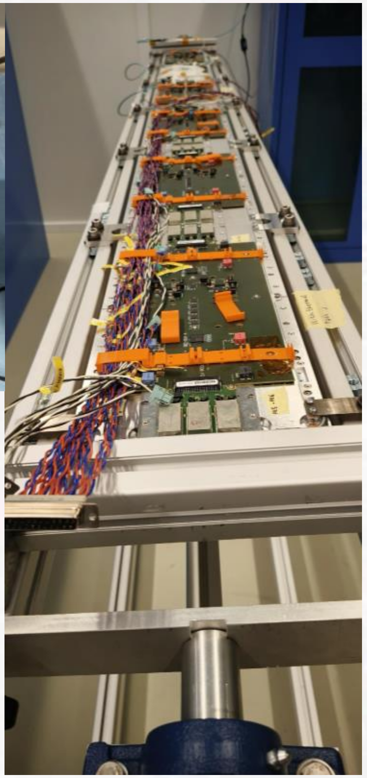
## ◆ 四个BTL装配中心

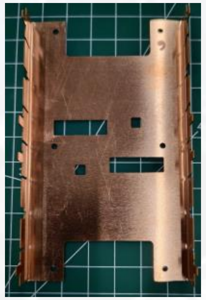
- BTL模块生产由四个BTL Assembly Centers（BACs）共同承担：
- 各装配中心采用统一的装配工具、操作流程和QA/QC标准，以保证不同中心生产模块的一致性。




## ◆ 模块装配流程

- Sensor Module（SM）
  - ➢ 将LYSO晶体与SiPM阵列精确对准并完成胶合。
  - ➢ 装配过程中控制环境湿度，保证光学耦合质量并避免污染。
- Detector Module（DM）
  - ➢ 将Sensor Modules与前端板连接。
  - ➢ 将模块集成到铜壳和支撑、热学结构中。
- BTL Tray
  - ➢ 完成测试的Detector Modules安装到$CO_2$冷却托盘上。



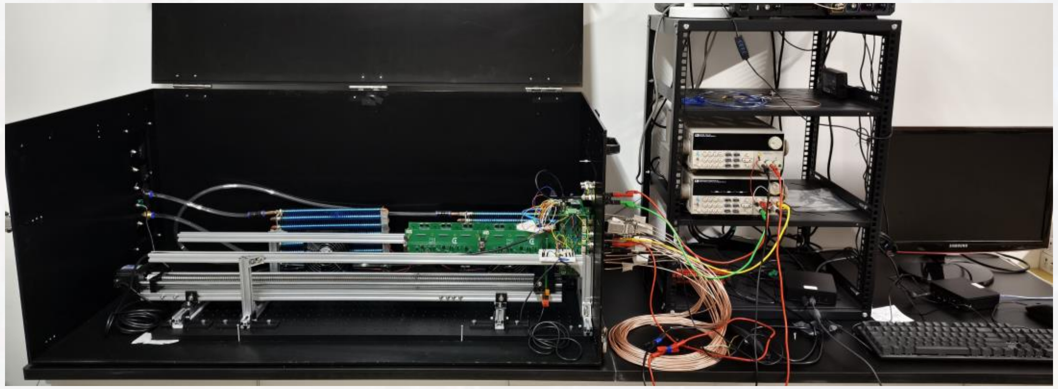


✓ 北航、清华同学参与了模块组装工作与SiPM QAQC工作

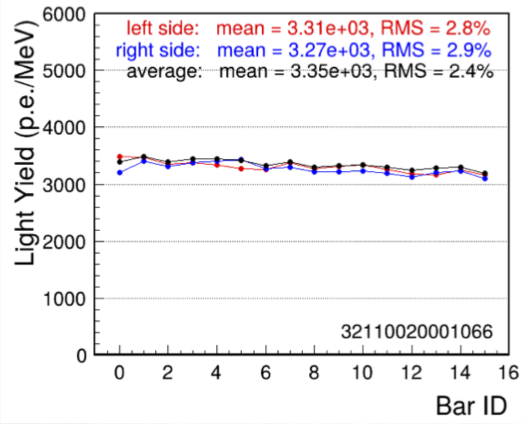
**LYSO和SiPM生产已经完成，模块组装基本完成，Tray装配工作进入收尾阶段。**

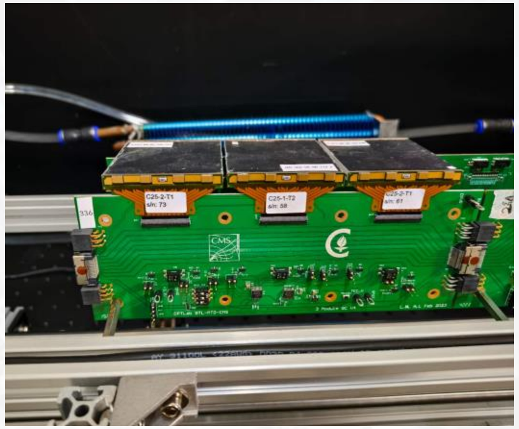
# BTL模块质量控制（QA/QC)

## ◆ QA/QC of Sensor Module

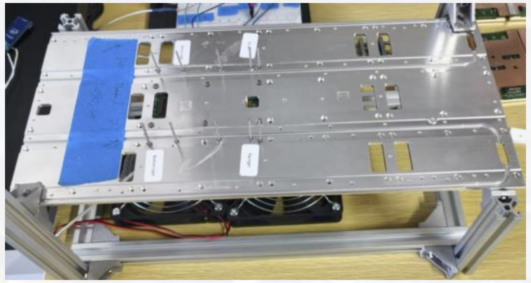


- 利用 $^{22}$Na放射源 逐通道测量光产额。
- 检查LYSO晶体与SiPM之间的光学耦合质量，以及不同通道之间的响应均匀性。
- 组装Sensor Modules的光产额均匀性RMS约为 5%。

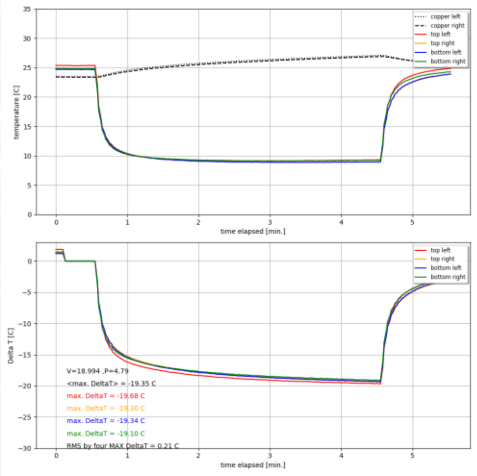


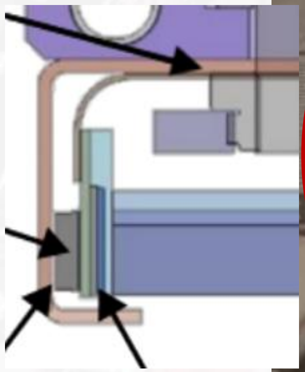



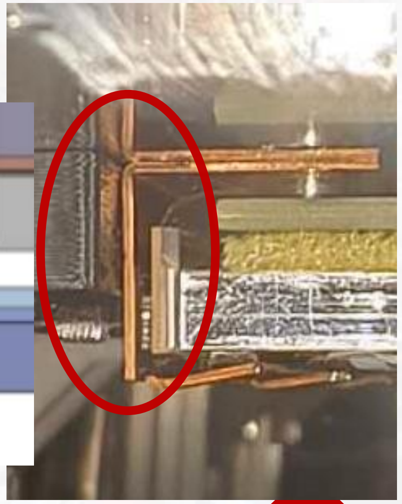
## ◆ QA/QC of Detector Module



- 通过前端板为TEC供电，同时读取安装在SiPM阵列上的温度传感器。
- 测量SiPM阵列相对于冷却板产生的温差 ΔT。
- 验证TEC的连接、极性和制冷能力，以及模块内部的完整热传导路径。



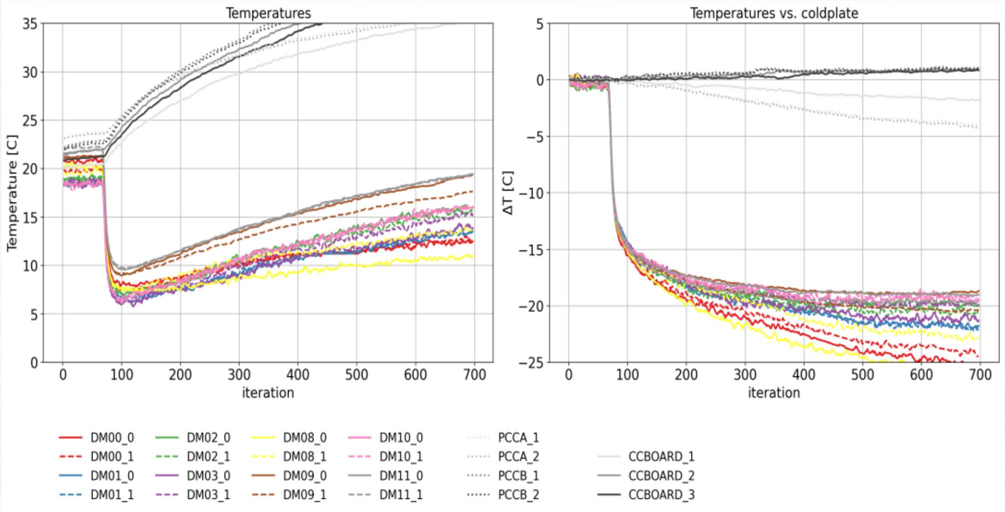




# BTL Tray QA/QC

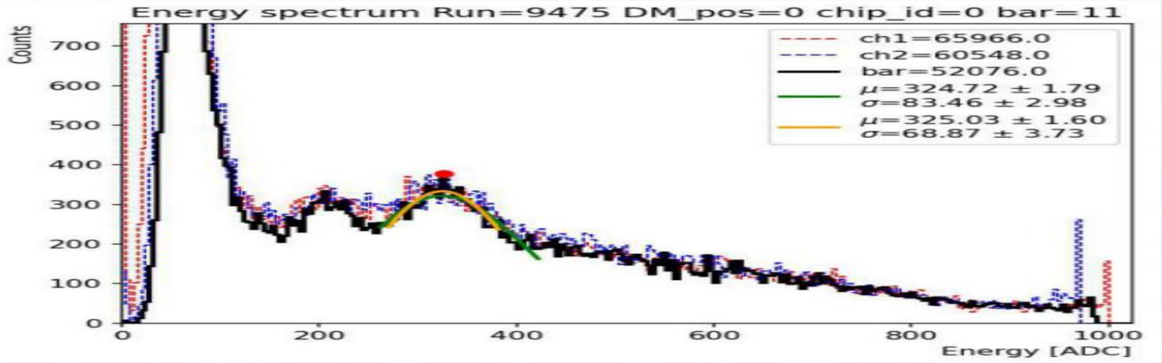
## ◆ TEC功能测试

- 监测温度变化 并 检查TEC工作是否正常



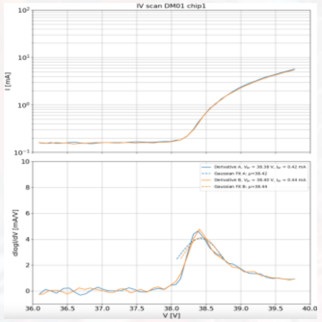

## ◆ LYSO本征放射性测试

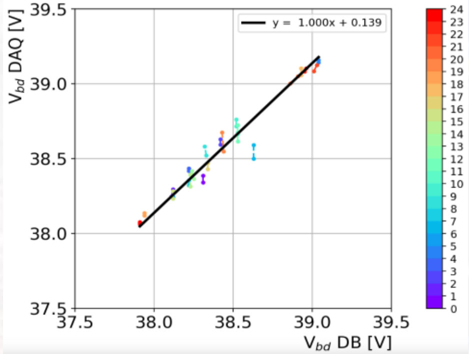
- 利用LYSO本征放射性测量 307 keV γ峰
- 检查通道连通性，确认各通道正常工作
- 测量通道响应，确认光输出良好保持




## ◆ 对每个SiPM阵列进行I–V扫描

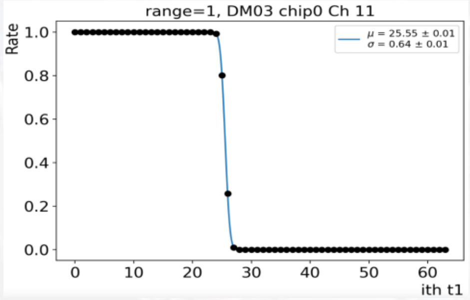
- 与数据库中的参考结果进行比较，确认SiPM未受损且ALDO工作正常

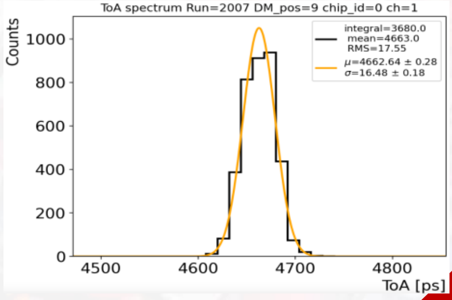



## ◆ 利用数字测试脉冲进行触发，并测量信号到达时间

- 检查通道连通性，确认所有通道均正常工作
- 测量TDC时间分辨率



# PKU BAC：装配进展

- 北大、清华及北航师生共同完成了所承担的全部 18个BTL Trays 的模块装配、Tray组装和组装中心 QA/QC。
- 在PKU组装的Sensor Modules中， 良品率超过 96% 。
- 在PKU组装的Detector Modules中， 良品率超过 99% ，满足BTL验收要求。
- 所有完成的托盘均通过 QA/QC，并已运往CERN进行后续工作。

| | Tray | | | | | |
|---|---|---|---|---|---|---|
| | CIT | MIB | PKU | UVA | Total | Fraction |
| Assembled at BAC | 15 | 17 | 18 | 17 | 67 | 93.06% |
| QA/QC passed @ BAC | 14 | 17 | 18 | 16 | 65 | 90.28% |
| Shipped | 2 | 12 | 18 | 0 | 32 | 44.44% |
| Arrived @ CERN | 2 | 12 | 18 | 0 | 32 | 44.44% |
| Tested @ CERN | 0 | 3 | 5 | 0 | 8 | 11.11% |
| QA/QC passed @ CERN | 0 | 2 | 1 | 0 | 3 | 4.17% |

*Our final tray within the crate*


*At CERN Now!*

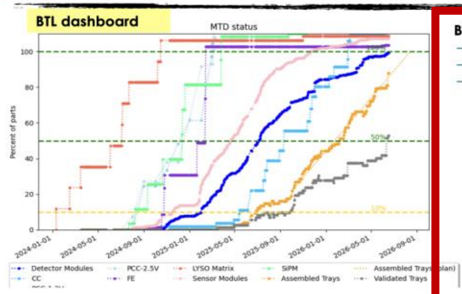
**Hot topic 2b - tray shipping**

*Andrea's slides from MTD Days*

- Shipment of cold trays to BACs almost completed [cfr. Guillermo's presentation for further details]
- The **first, fully-dressed tray** shipped from a BAC (Peking University, China) was **received at CERN** last Friday
  - now with the CERN Radiation Protection Group for radiation measurements before it can be released and delivered at TIF
  - based on a visual inspection, the tray is fine
    - even though one of the vertical boards on the outside of the wooden crate was ripped off
  - detailed QA/QC will happen as soon as we have the tray in TIF

## BTL: 1-Slide Status

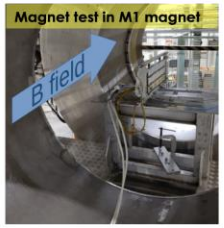
**BTL dashboard**




**BTL production towards completion**
- tray production >90%
- Reaching ~50% of trays at CERN
- Preparing final documents to summarise SM, DM, tray assembly QA/QC


More details in Maria's talk

**Magnet test in M1 magnet**




**BTL integration:**
- Test of repaired BTST concluded successfully at the end of May
- Resumed BTST preparation for BTL integration. Insertion testing in July, procurements ongoing for last components for integration (see also BTL integration readiness review)
- Magnet test:
  - readout instability > 2.7T observed due to magnetic pins in MT-MT optical fiber connectors. Main showstopper towards integration
  - Studying optical connection in magnetic field in PT7 magnet. No loss observed up to 2.5 T, would like to repeat test with pins with increased magnet sensitivity
  - Playing with VRTX parameters, towards a 2nd test end of July in M1 magnet

*Paolo's slides from 41st MTD IB meeting*

Paolo Meridiani 3

# PKU BAC：装配进展

- 北大、清华及北航师生共同完成了所承担的全部 18个BTL Trays 的模块装配、Tray组装和组装中心 QA/QC。
- 在PKU组装的Sensor Modules中， 良品率超过 96% 。
- 在PKU组装的Detector Modules中， 良品率超过 99% ，满足BTL验收要求。
- 所有完成的托盘均通过 QA/QC，并已运往CERN进行后续工作。

| Tray | CIT | MIB | PKU | UVA | Total | Fraction |
|---|---|---|---|---|---|---|
| Assembled at BAC | 15 | 17 | 18 | 17 | 67 | 93.06% |
| QA/QC passed @ BAC | 14 | 17 | 18 | 16 | 65 | 90.28% |
| Shipped | 2 | 12 | 18 | 0 | 32 | 44.44% |
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Hot topic 2b - tray shipping

*Andrea's slides from MTD Days*

- Shipment of cold trays to BACs almost completed [cfr. Guillermo's presentation for further details]
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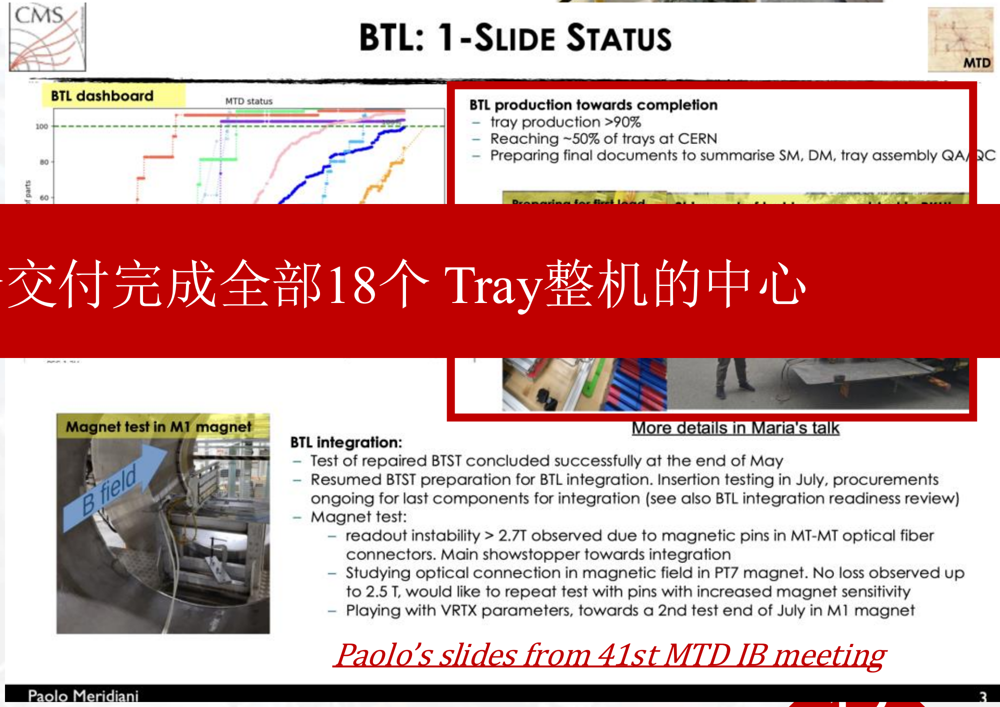



*Paolo's slides from 41st MTD IB meeting*

**PKU是首个成功将BTL Tray运抵CERN的BAC，也是第一个交付完成全部18个 Tray整机的中心**


*Our final tray within the crate*

*At CERN Now!*

# BTL生产时间线

- **2023年**
  - 装配工具开发，确定统一的模块装配和QA/QC流程。
- **2024年秋**
  - Sensor Module、Detector Module和BTL Tray进入批量生产阶段。
- **2025年秋**
  - CERN开始对各BAC发运的完整托盘进行测试。
- **2026年夏**
  - 各装配中心完成剩余托盘生产与发运，BTL分布式生产进入收尾阶段。
- **2026年秋起**
  - 完整托盘将在CERN安装到BTL Tracker Support Tube（BTST）上，开始系统集成。
- **2027年**
  - BTL随CMS开展系统级commissioning，为HL-LHC运行做准备。

# 总结

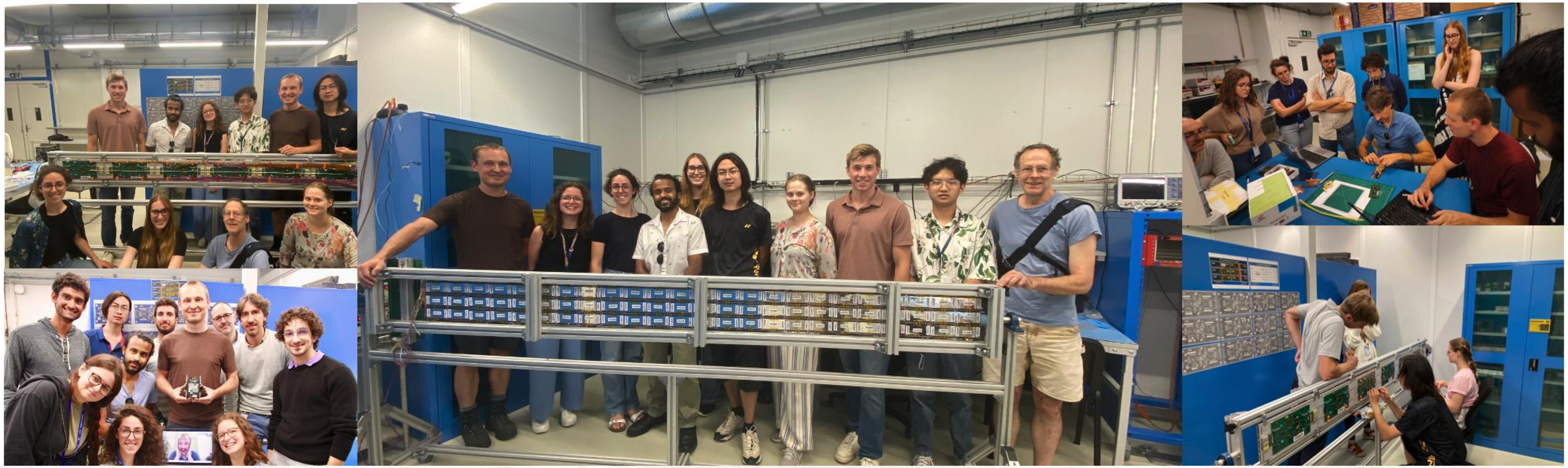
◆ BTL采用 LYSO晶体、SiPM双端读出和TOFHIR2电子学，在有限空间内实现高精度时间测量。

◆ 束流与辐照测试证明，BTL可以在整个运行周期内保持 30–60 ps 的时间分辨率。

◆ 各BAC的模块装配与QA/QC均已开始收尾，项目重心正转向CERN的托盘调试和整体集成。

◆ BTL将为HL-LHC高堆积环境提供关键的单径迹时间信息，维持CMS的粒子重建和物理研究能力。

谢谢！



北京大學
PEKING UNIVERSITY

# BACK UP

# Performance Validation

- **Time Resolution Uncertainty Sources**

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

- **Typical Contributions (from beam test + irradiation studies)**

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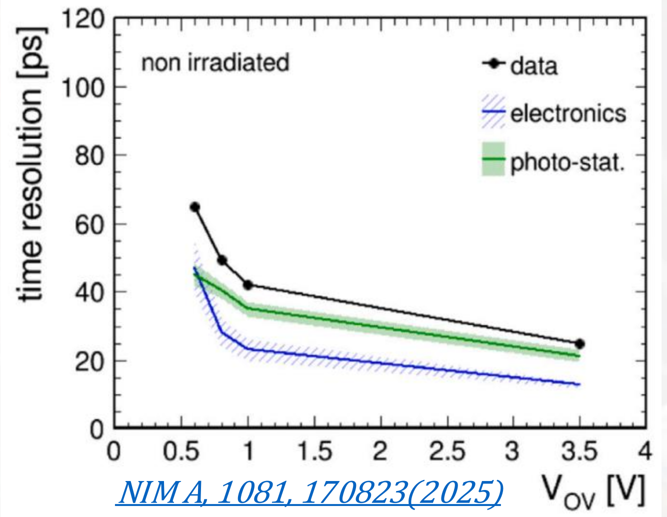


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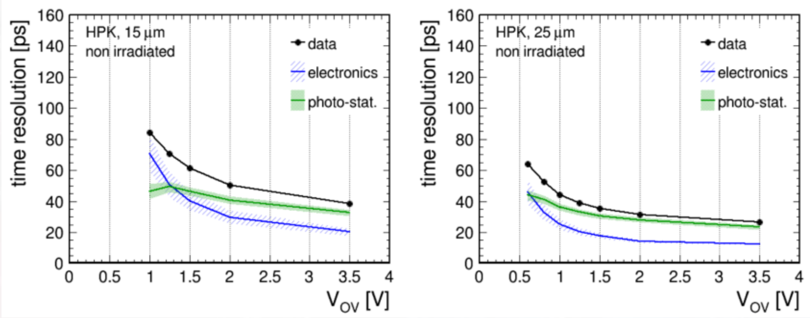
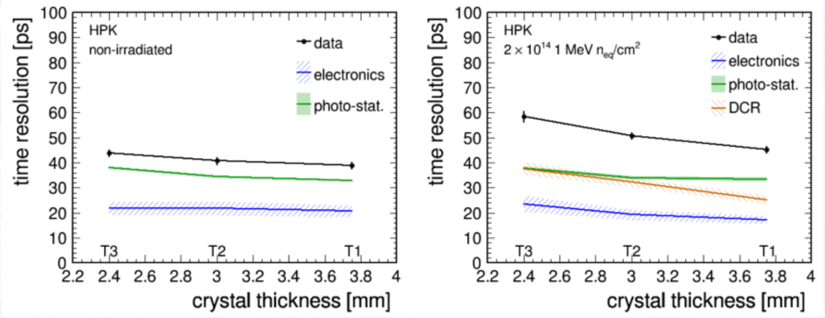
✓ $\sigma_t^{ele} = \frac{\sigma_{noise}}{dI/dt} \oplus \sigma_t^{TDC}$ : **electronic noise & TDC jitter**

**~15–20 ps at 15 µm SiPMs cell-size, reduced to ~10 ps with 25 µm**




✓ $\sigma_t^{phot} \propto \frac{1}{N_{pe}^{\alpha}}$ $(with\ \alpha \approx 0.5)$: **photo-statistics fluctuations**

**~40–30 ps depending on LYSO crystal thickness (2.4–3.75 mm)**




✓ $\sigma_t^{DCR} \propto \frac{DCR^{\beta}}{N_{pe}}$ $(with\ \beta \approx 0.5)$: **radiation-induced dark count rate**

- **TECs and dual-phase $CO_2$ cooling: operate at –45 °C with periodic 60 °C annealing to minimize DCR and heal radiation damage**

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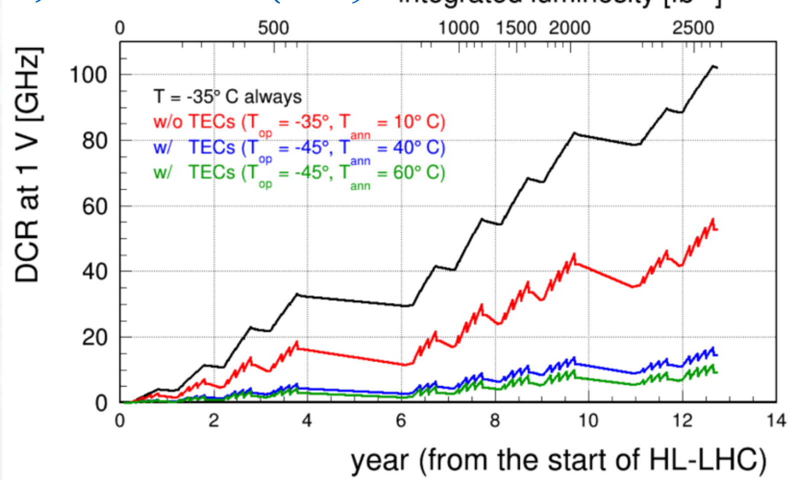


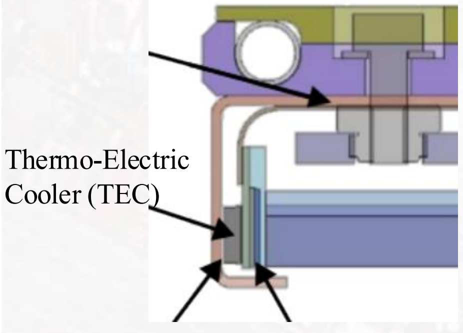


✓ $\sigma_t^{clock}$ : **clock distribution instabilities (< 10 ps, negligible)**