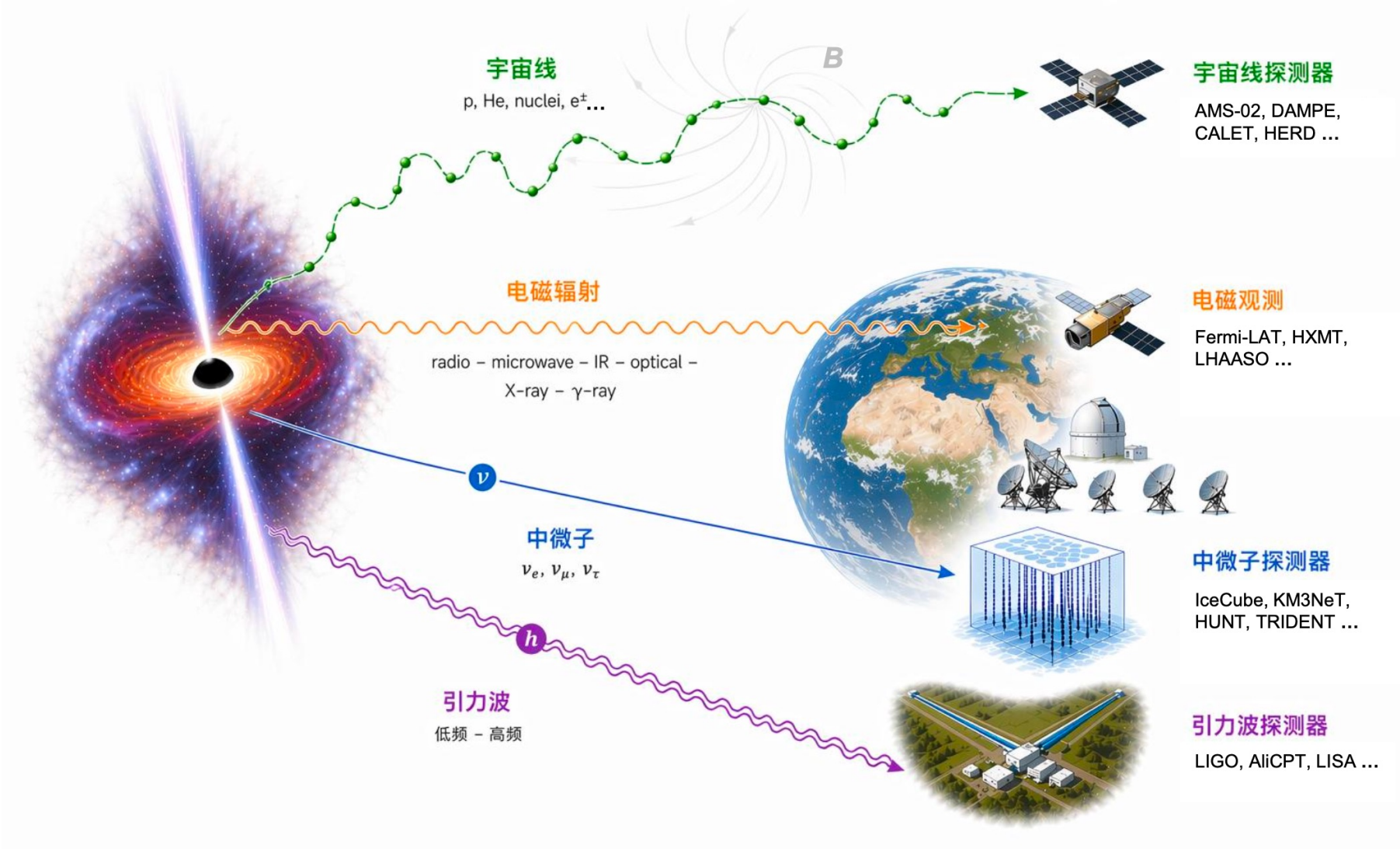
物院青年教师线上论坛（第37期）

AMS实验L0探测器研制

袁煦昊 （高能所）

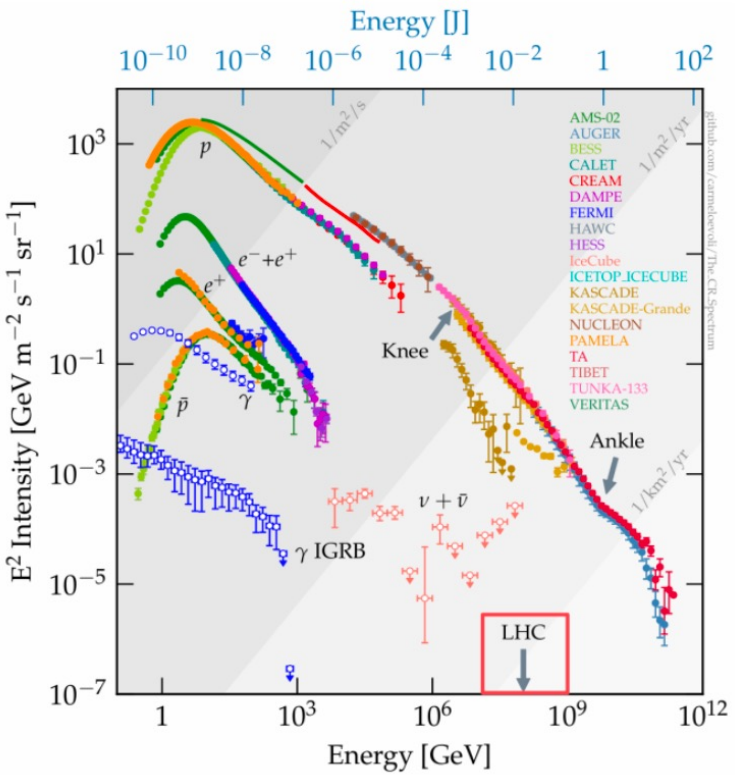
2026-06-28

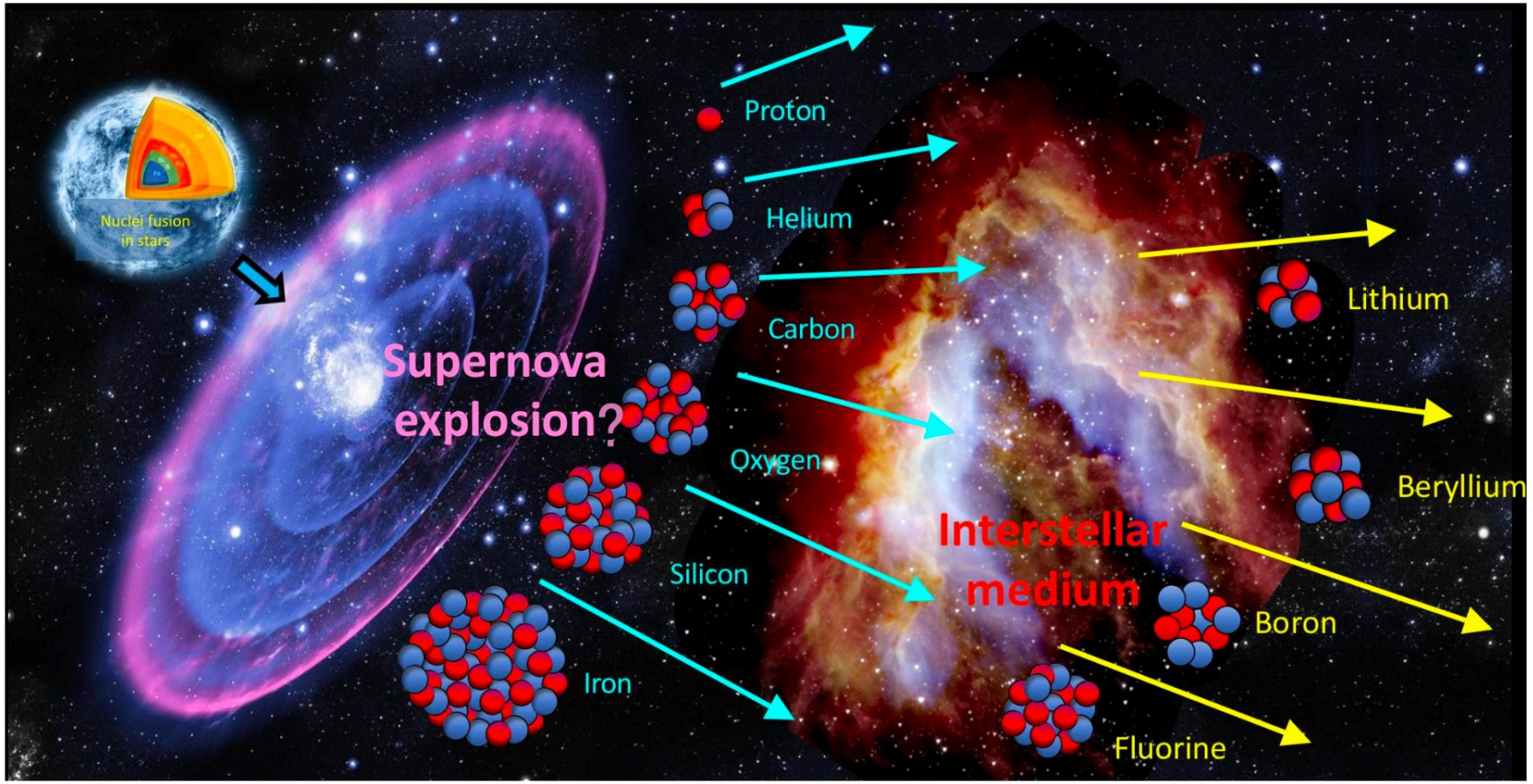
宇宙线研究



- 揭示高能天体物理过程
- 研究银河系传播环境
- 探测暗物质于新物理
- 推动探测技术发展

宇宙线研究

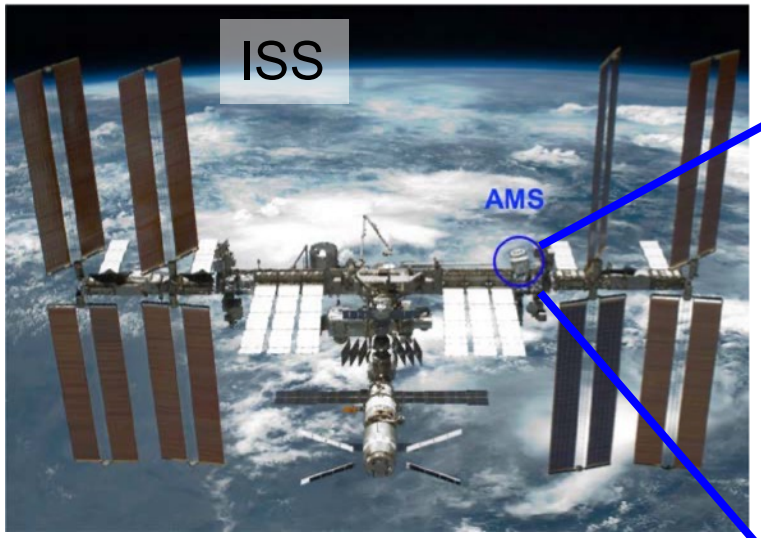


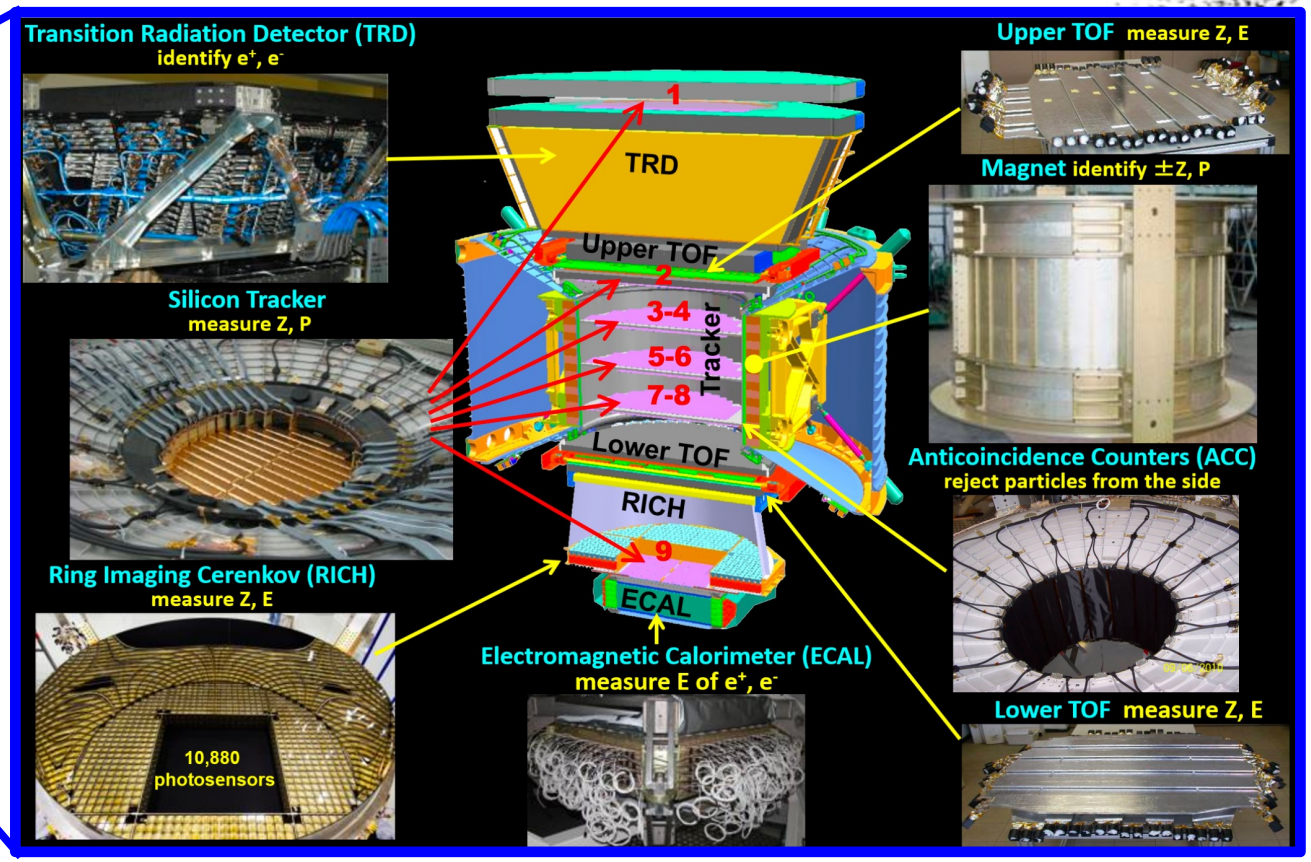


宇宙线中包含高能量粒子：人类迄今为止观测到能量最高的带电粒子

- 高能宇宙线起源与加速机制；银河系传播环境
- 反物质与暗物质的寻找

AMS-02实验





AMS实验：丁肇中教授领导大型国际合作项目，人类目前唯一运行空间中的磁谱仪

- 2011/05/19开始稳定运行
- 研究目标：暗物质、反物质和宇宙线起源等

AMS-02实验中国团队贡献

04 要闻 人民日报

寄哀思 表敬意 促振兴

——各地群众开展多种形式祭奠活动

民政部在冀东烈士陵园公祭烈士

公祭轩辕黄帝典礼举行

确保烈士妥善安葬新规出台

近5年2204名民警因公牺牲

邮轮旅游实验区获批

整顿"一日游"秩序

北齐壁画再现"年轻美颜"

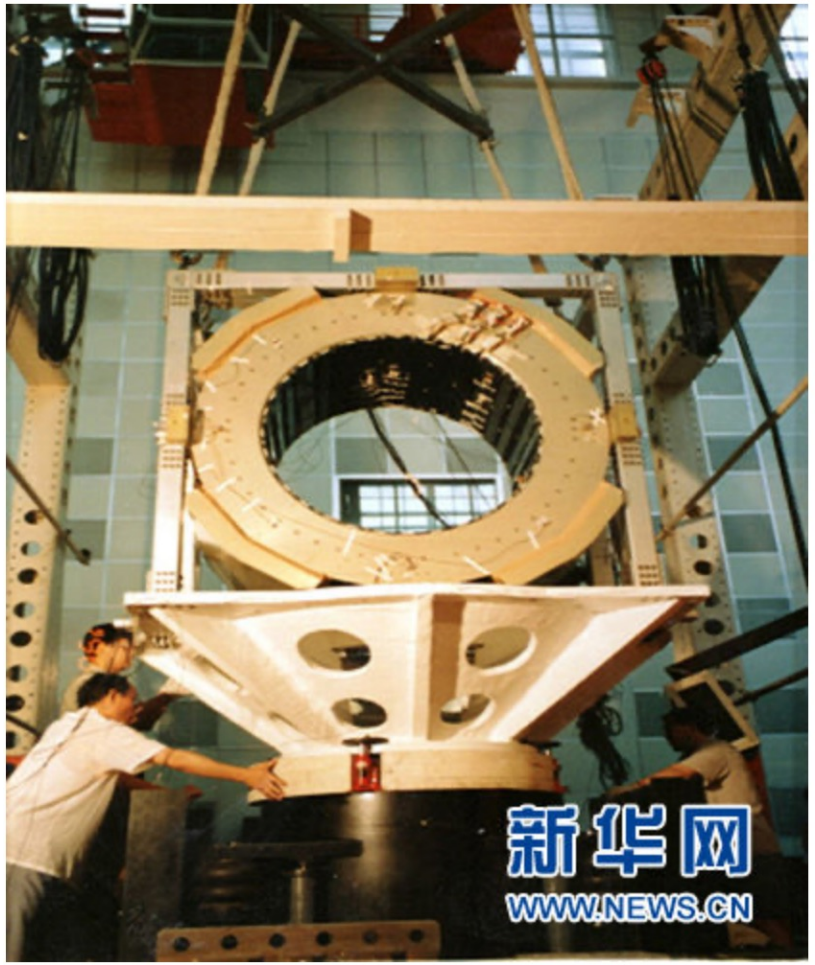
新疆吐鲁番旅游渐热

垃圾短信治理行动将开展

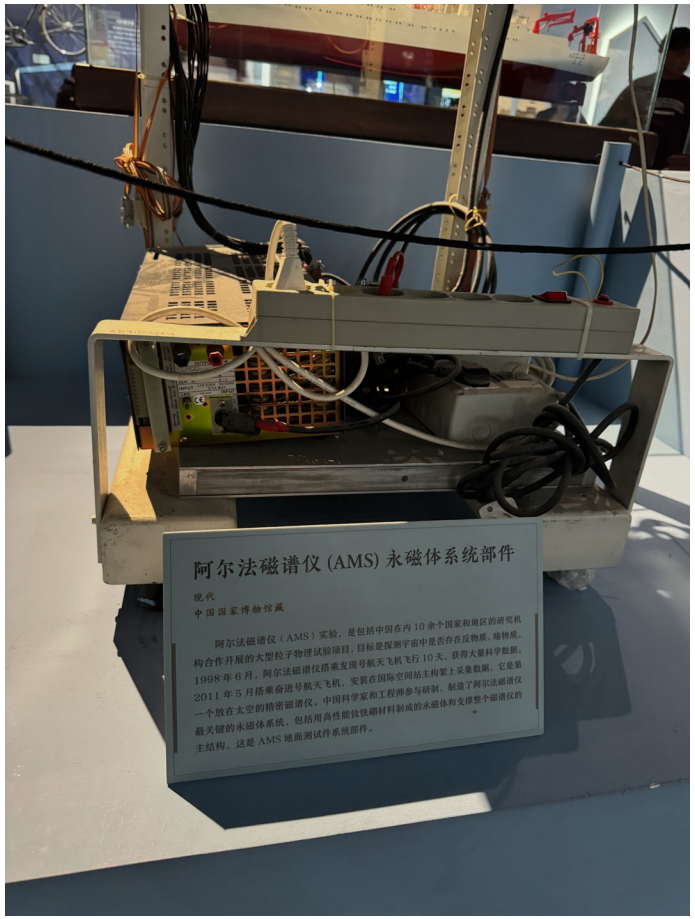
"书博大施车"环岛行

寻找暗物质有了新线索

《人民日报海外版》2013年4月5日

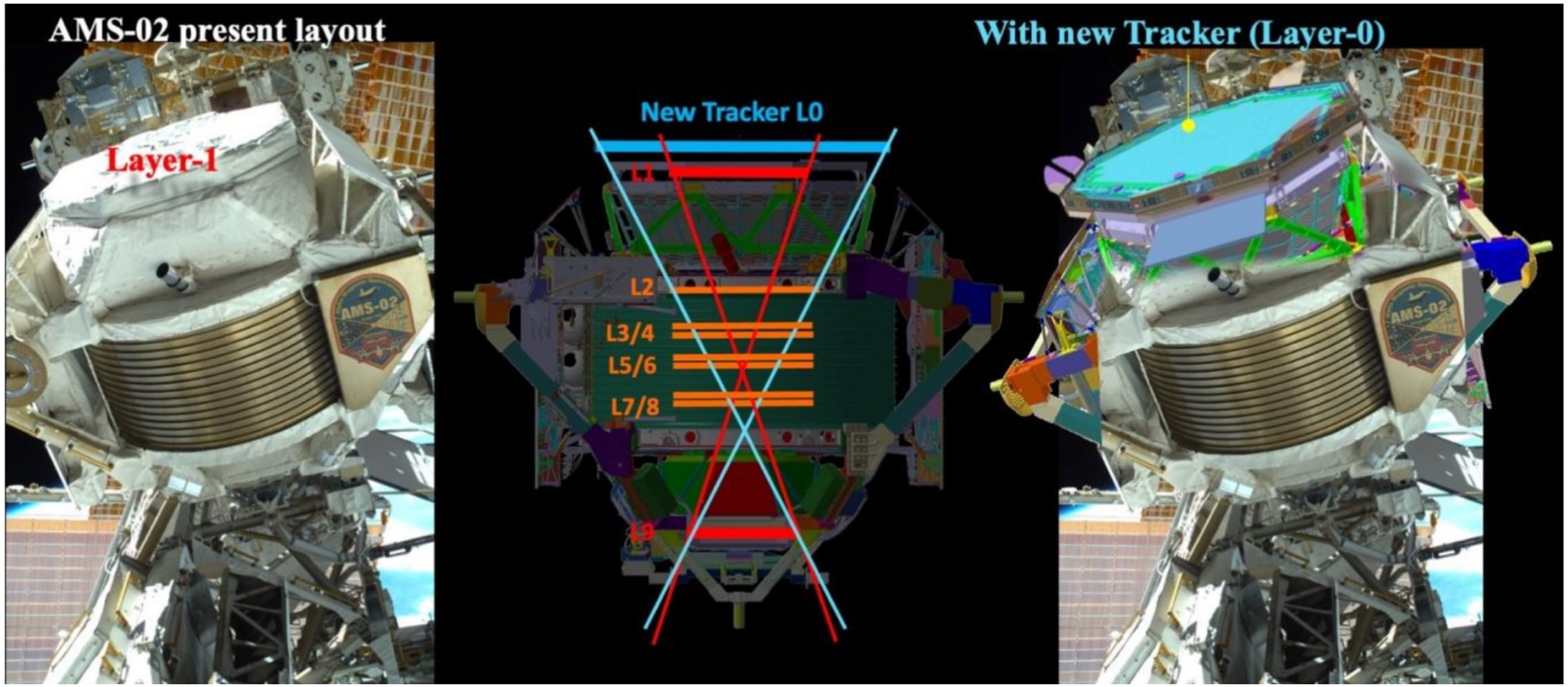


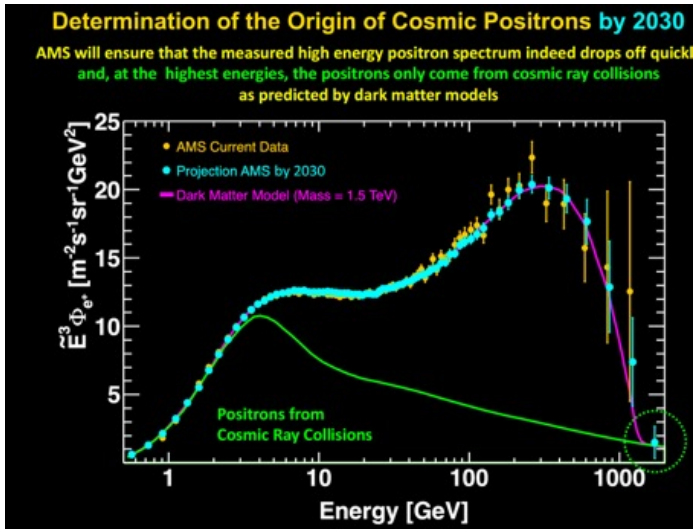
中国永磁体再次"出征"大宇宙（新华社）
2011年5月16日



国家博物馆展品，
2023年底拍摄

AMS-02 Layer0 (L0) tracker





G. Ambrosi, AMS-L0: upgrade status and prospects @ ASAPP 2023

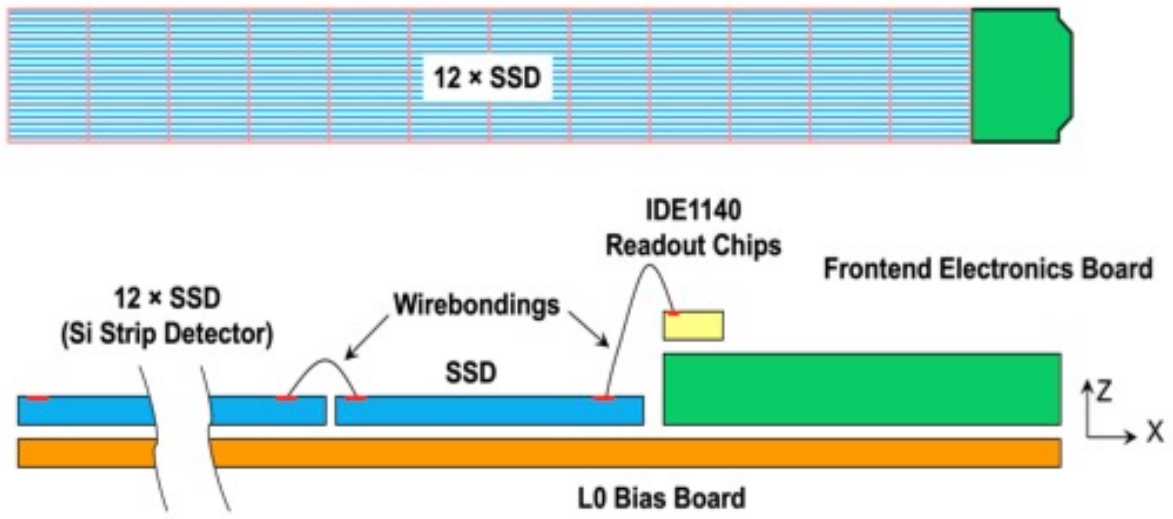
A new tracker (L0) on the top of AMS-02

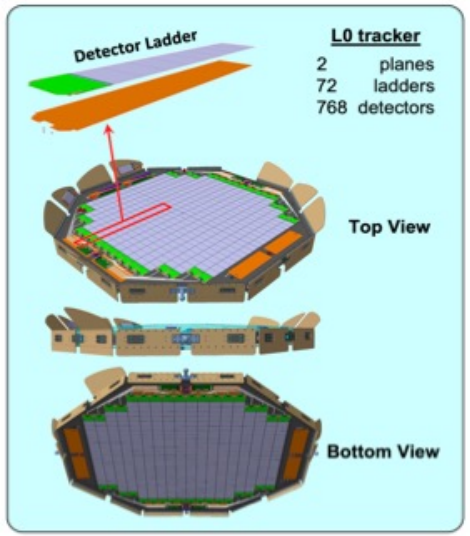
- Decision on Dec. 2021, ready for flight ~ 2027
- Larger sensitive area (~ 7 m^2) ⇒ acceptance to 300% (L1+L2+..+L9 ~ 6 m^2)
- Better charge measurement for cosmic ray nuclei

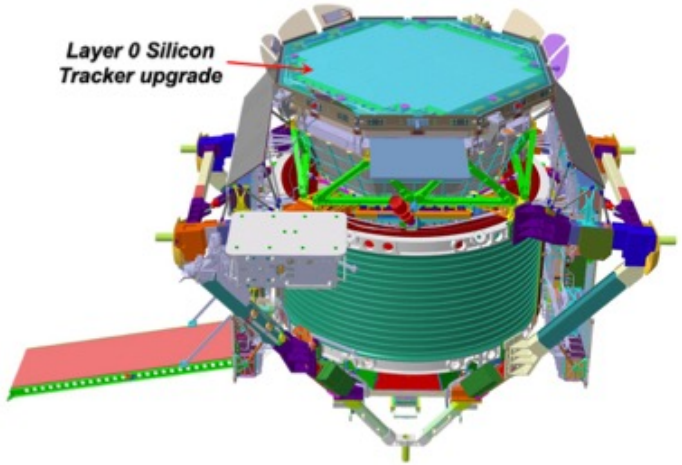
arXiv:2511.22246

AMS L0 探测器

AMS L0探测器探测模块







AMS L0探测器基于硅微条传感器技术

- 利用多片硅微条传感器"串行"实现世界最长（96 厘米）硅微条传感器

由中国科学院高能物理研究所和山东高等技术研究院共同完成

研究内容：传感器设计、探测器模块研制和测试，以及探测器集成与实验

核心技术指标：
1. 完成半导体探测器模块研制，模块总面积~**8 m²**
2. 位置分辨率**<10 微米**
3. 优良通道比**>95 %**

高精度空间半导体径迹探测器研制经验积累，为未来由中国主导的深空探测实验做技术支持

项目人员安排

IHEP-EPD (10)		
Jianchun Wang	王建春	Professor
Gang Chen	陈刚	Professor
Mingyi Dong	董明义	Professor
Jing Dong	董静	Senior engineer (R)
Shanzhen Chen	陈缮真	Associate professor
Zijun Xu	徐子骏	Associate professor
Xuhao Yuan	袁煦昊	Associate professor
Feng Wang	王峰	Research scientist
Xiyuan Zhang	张希媛	Engineer (R)
Congcong Wang	王聪聪	Engineer (R)

IHEP-PAD (10)		
Zuhao Li	李祖豪	Professor
Wenxi Peng	彭文溪	Professor
Zhicheng Tang	唐志成	Associate professor
Cheng Zhang	张诚	Associate professor
Rui Qiao	乔锐	Associate professor
Xingzhu Cui	崔兴柱	Associate professor
Yaqing Liu	刘雅清	Associate professor
Sheng Yang	杨生	Senior engineer (M)
Ke Gong	龚轲	Senior engineer (E)
Dongya Guo	郭东亚	Research scientist

Graduate Students (18)	
Dexing Miao	缪德星
Tiange Li	李天歌
Chenglong JinLiang	金梁程龙
Shengjie Jin	金胜杰
Yuhang You	尤宇航
Haotian Yang	杨昊天
Qinze Li	李沁泽
Ji Peng	彭吉
Shuqi Sheng	盛书琪
Xiaojie Jiang	姜啸捷
Mingjie Feng	冯铭婕
Hao Chen	陈昊
Hengyi Cai	蔡恒逸
Zixuan Yan	闫子轩
Yuan Yuan	袁源
Yisheng Fu	傅逸昇
Shuaiyi Liu	刘帅毅
Zibing Wu	吴子兵

College Students (14)	
Shengbo Cao	曹胜博
Changcheng Liu	刘长城
Hanbing Liu	刘涵兵
Lusen Zhang	张鲁森
Yuman Cai	蔡雨漫
Tianyu Shi	史天宇
Zhijie Wang	王智颉
Yaohui Yang	杨耀晖
Yutong Li	李雨彤
Ming Dai	代铭
Yang Liu	刘洋
Danyan Huang	黄丹艳
Jiaru Wang	王佳如
Jingbo Liu	刘京博

SDIAT (6)		
Weiwei Xu	许伟伟	Professor
Huiling Li	李慧玲	Principal scientist
Suyu Xiao	肖素玉	Research scientist
Pingcheng Liu	刘平成	Research scientist
Cong Liu	刘聪	Engineer (M)
Hongbo Wang	王泓博	Engineer (E)

Postdocs (6)		
Baaska Batsukh	Baaska	IHEP-EPD
Daojin Hong	洪道金	SDIAT
Zetong Sun	孙泽同	IHEP-PAD
Fengze Zhang	张丰泽	IHEP-PAD
Zhiyu Xiang	项治宇	IHEP-EPD
Mengke Cai	蔡孟珂	IHEP-EPD

The IHEP+SDIAT team

26 staff members
6 postdocs
18 graduate students
14 college students

The professional title represents the date the member joined the team

参与人员涵盖高能所内部多部门和山东高研院，

- 近30名职工
- 多名博士后
- 超过20名学生（含研究生以及本科生）

项目进展主要节点

- 2022.07.09 前端电子学读出芯片IDE1140于CIAE完成辐照研究
- 2022.07.22 首条硅模块由佩鲁贾大学、高能所和山东高研院共同完成
- **2022.11.04 10条测试用模块由中方寄往意大利**
- **2023.05.16 首条全尺寸硅模块样板机在高能所完成组装**
- 2023.05.18-19 AMS TIM会议在高能所召开
- 2023.06.18 7条测试模块寄往意大利
- 2023.07.11-27 于高能所完成低能电子束流测试
- 2023.08.17-23 于CERN完成质子和缪子束流测试
- 2023.08.31 7条电装硅模块寄出
- 2023.10.24-30 与CERN完成离子束流测试
- 2023.12.07 最后一批测试模块寄出
- 2024.01.11-25 于高能所完成低能电子束流测试
- 2024.01.17 L0模块正式生产启动
- 2024.01.22 AMS TIM在高能所召开
- 2024.05.08-29 于CERN完成缪子束流测试
- 2024.05.14 首批正式生产模块寄出
- 2024.09.06 生产结束

2023年05月16日首条样板机生产完成

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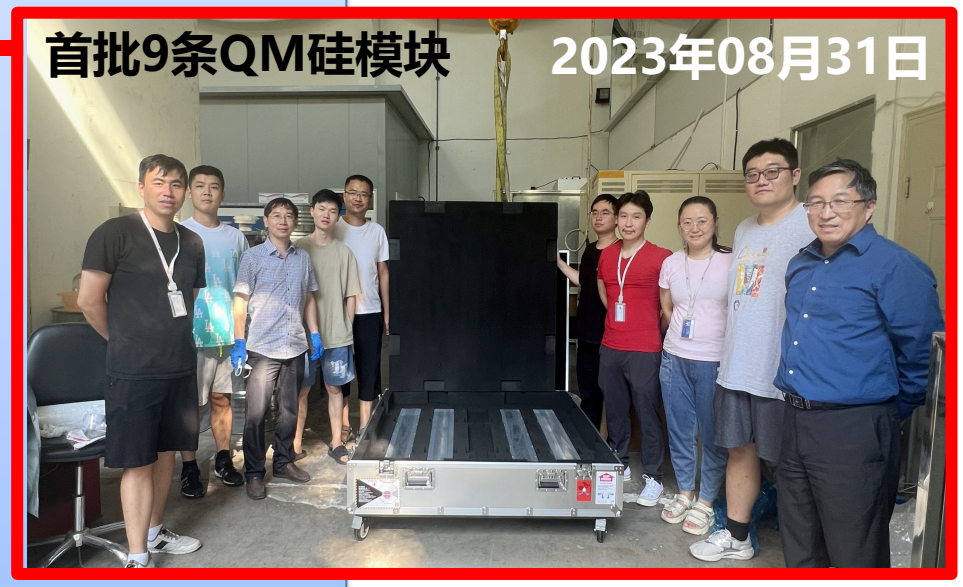

项目进展主要节点

- 2022.07.09
- 2022.07.22
- 2022.11.04
- 2023.05.16
- 2023.05.18-19
- 2023.06.18
- 2023.07.11-27
- 2023.08.17-23
- 2023.08.31
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- **2024.05.14 首批正式生产模块寄出**
- **2024.09.06 生产结束**

2024年5月首批正式生产模块完成装配并寄出

2024年9月完成全部正式模块生产

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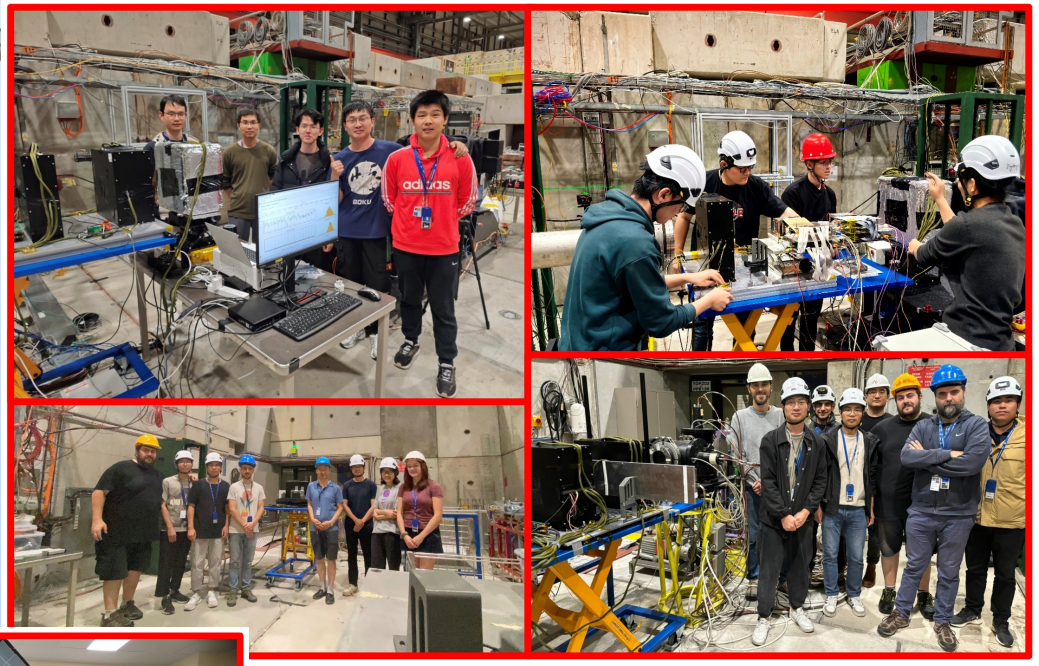
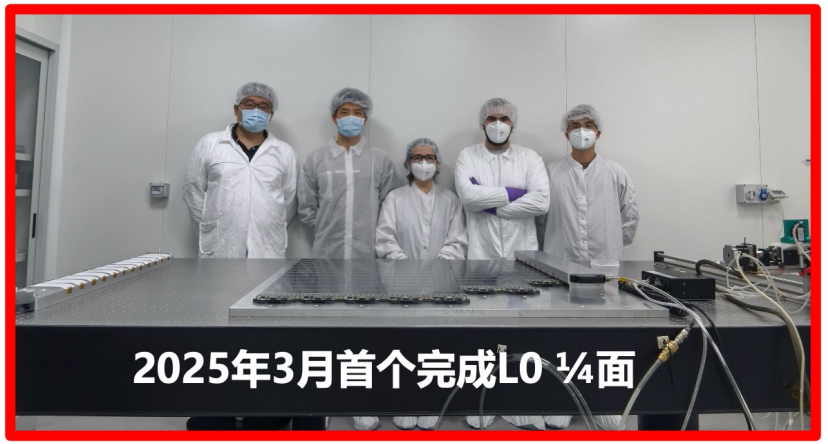


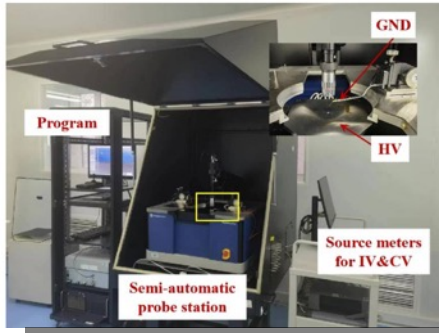


硅模块组装实验室

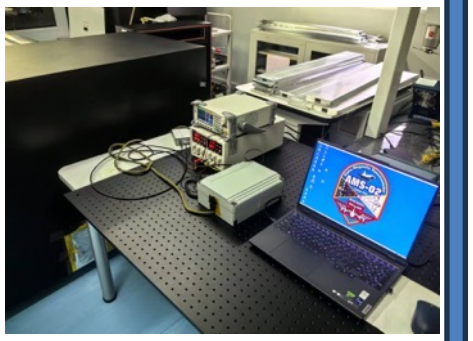
高能所三号厅千级洁净间示意图

地心科技 Gantry

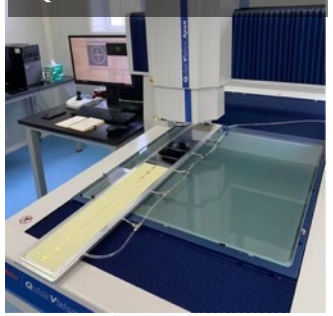
BondJet BJ850



Cascade Microtech的PA200 BlueRay半自动探针台


电子学测试平台

日本三丰
QUCIK VISION Apex
QV-X606

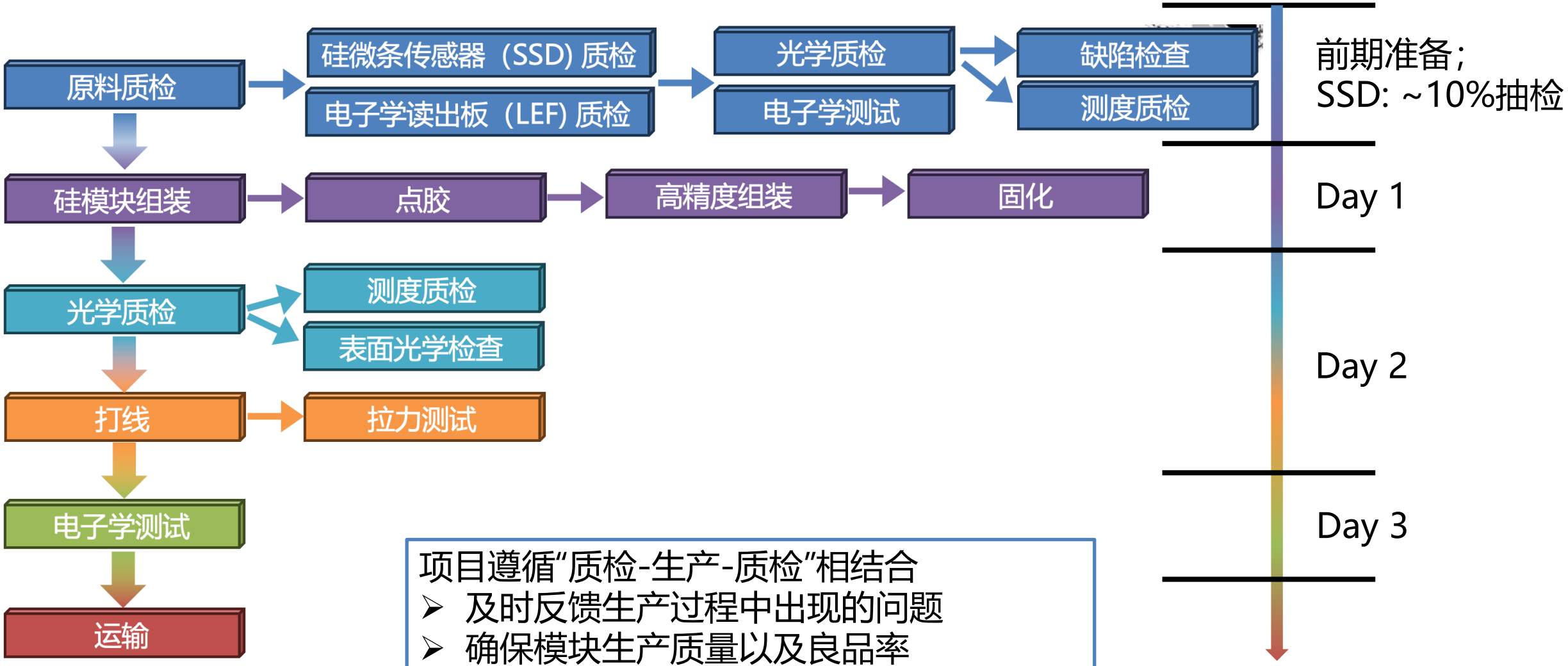


芯片存储干燥柜

风淋室

换衣区

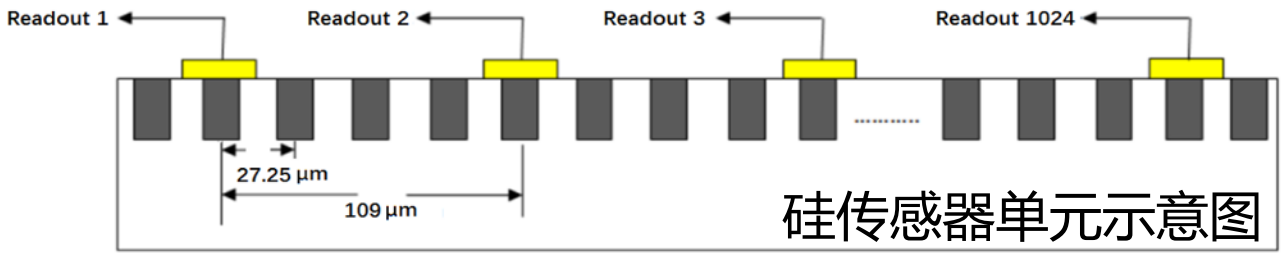
L0硅模块生产流程



项目遵循“质检-生产-质检”相结合

- 及时反馈生产过程中出现的问题
- 确保模块生产质量以及良品率

硅微条传感器芯片研发



硅传感器单元示意图

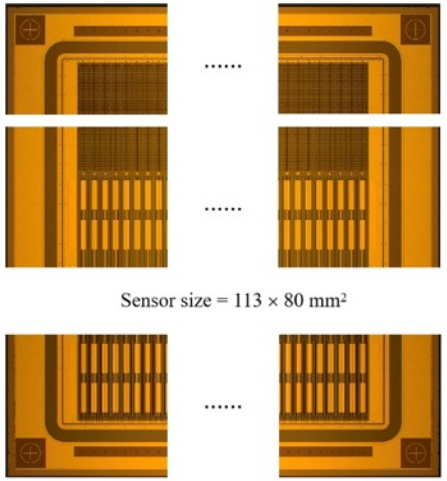
中方参与并完成完成硅微条传感器（SSD）设计：

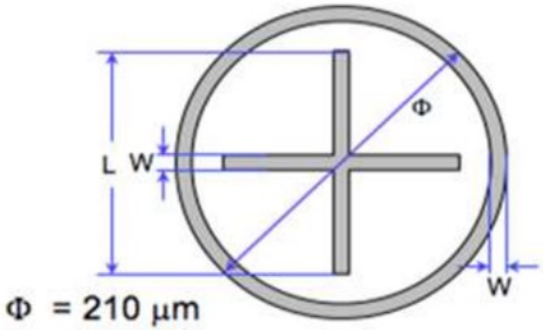
- N型硅单面AC耦合读出
- 读出条间距109微米，4条注入条间距27.25微米
- 耗尽电压~50伏

定位识别点：

- 芯片识别以及精确定位
- 实现模块高精度组装

硅微条传感器外观图与识别点



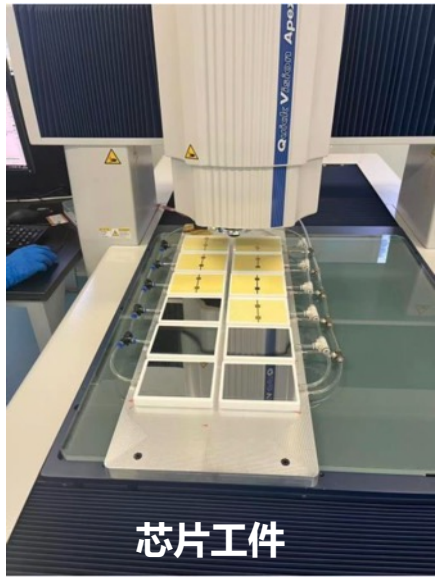


HPK SSD Deliveries		
Delivery on	Number	To Perugia
06/27/2022	30	(10)
12/05/2022	15	(3)
02/06/2023	181	(21)
03/13/2023	436	
04/10/2023	360	
05/15/2023	108	
08/28/2024	61	
Total	**1191**	**(34)**

共计1191块硅微条传感器，包括30块预生产，1100块正式生产，61块备份，由日本滨松生产

784块测试用硅微条传感器，由高能瑞泰生产，用以工艺检验及测试

硅微条传感器芯片测试

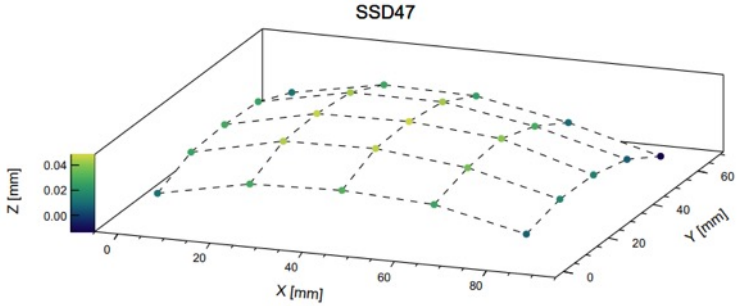


芯片测试包括光学质检和电子学测试 (10%抽检)

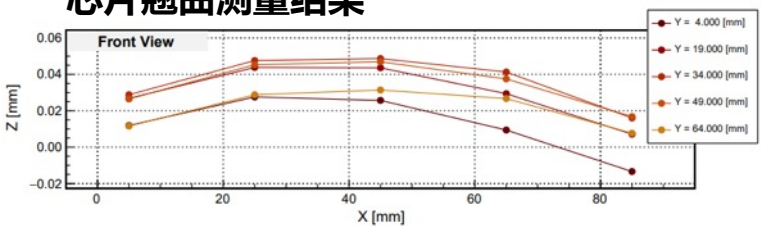
- 光学质检研究芯片外观检查，包括芯片测度以及划痕、污损检查

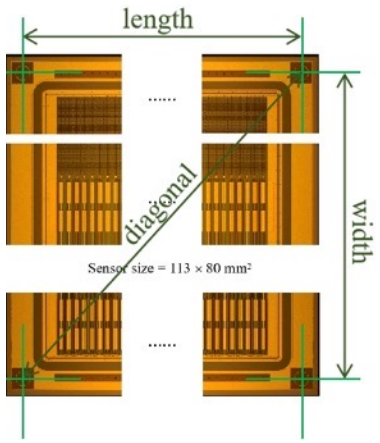
芯片测度质检

- 自然状态芯片翘曲程度在60微米以内
- 芯片识别点间距、半径
  - 与设计指标相一致

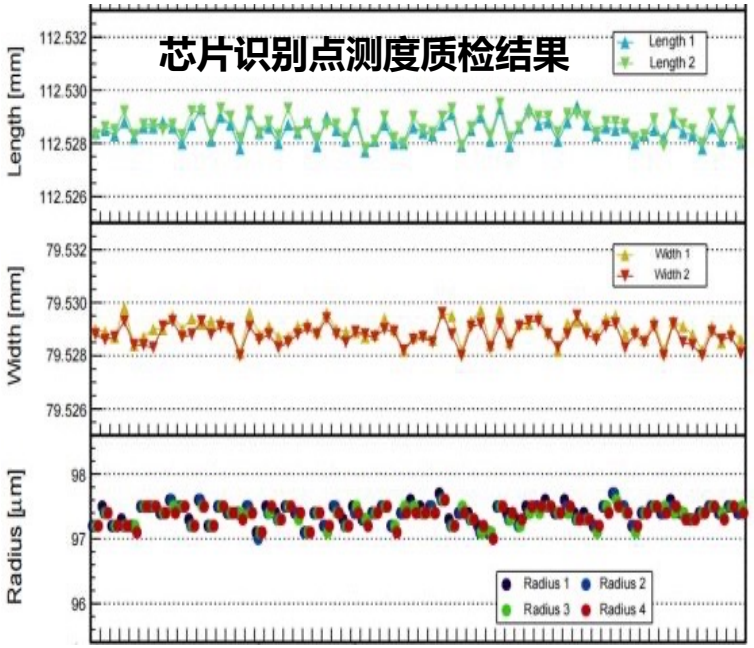


芯片翘曲测量结果

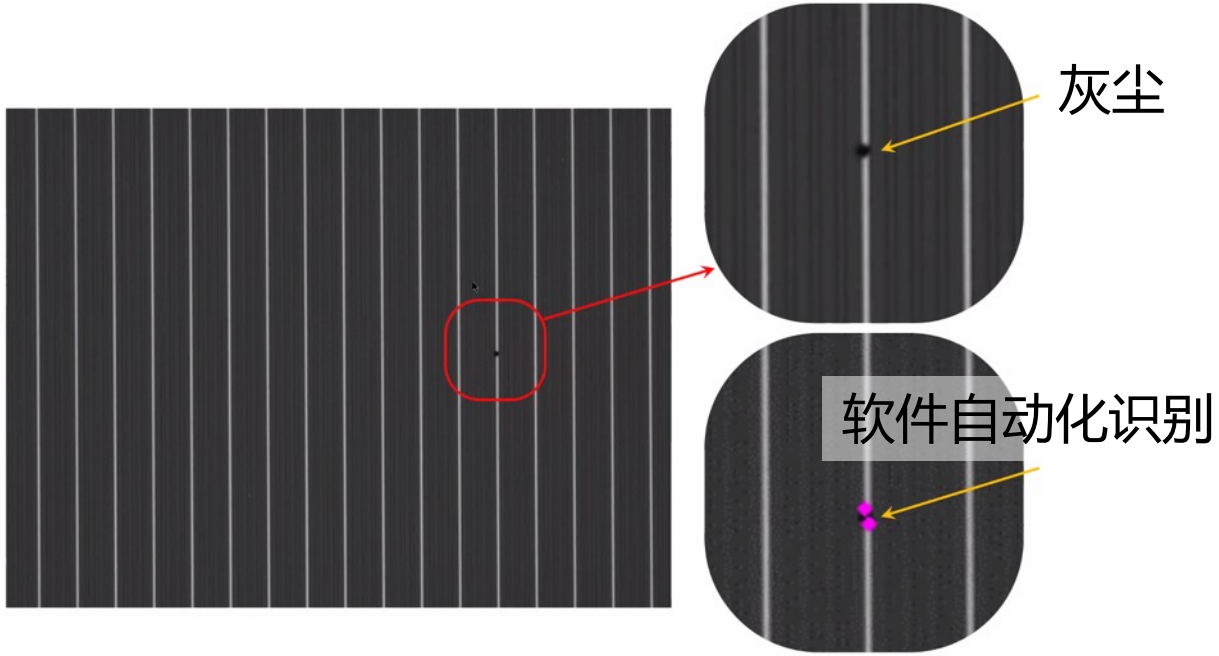


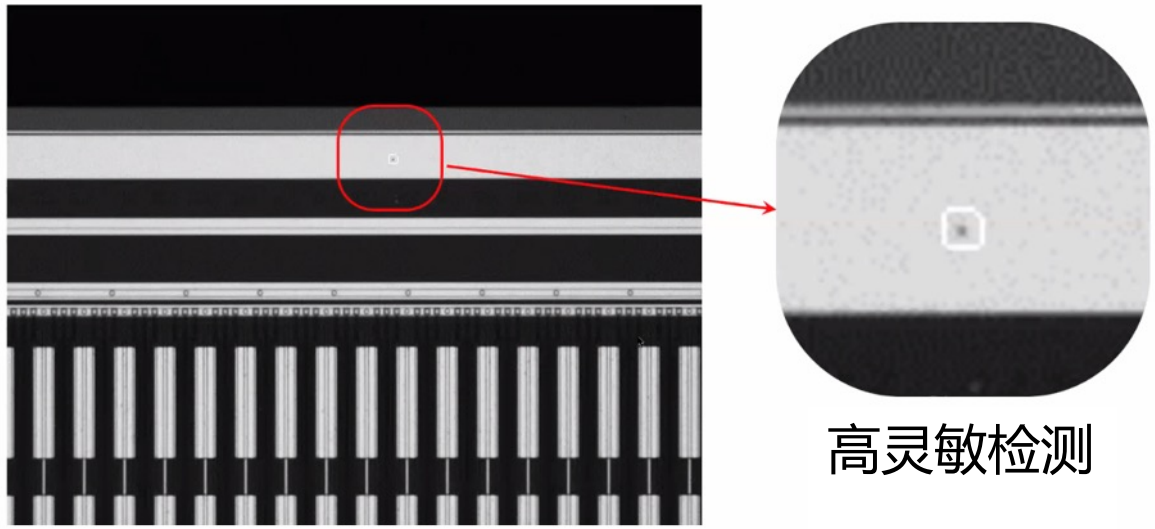


芯片识别点测度质检结果



硅微条传感器芯片划痕、污损自动化检验



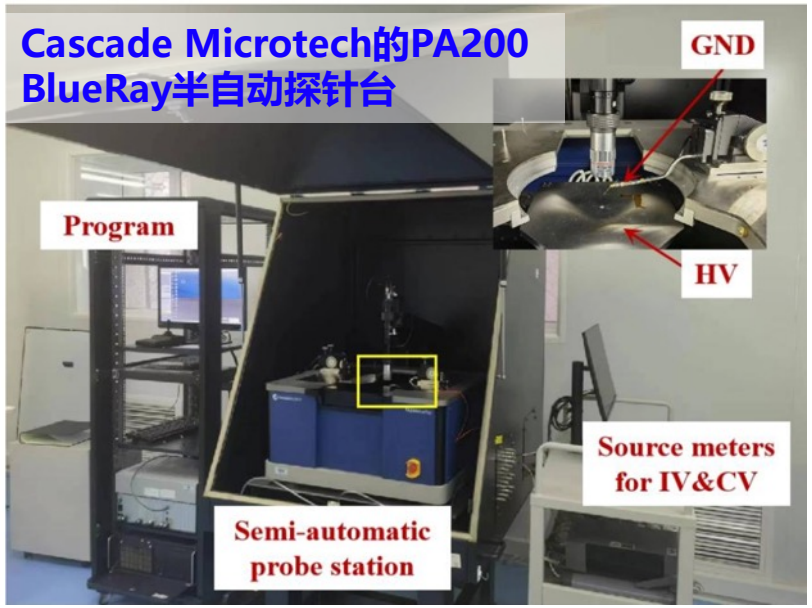


图片样本数量
~5000张显微图片/芯片
取照时间：1小时/芯片

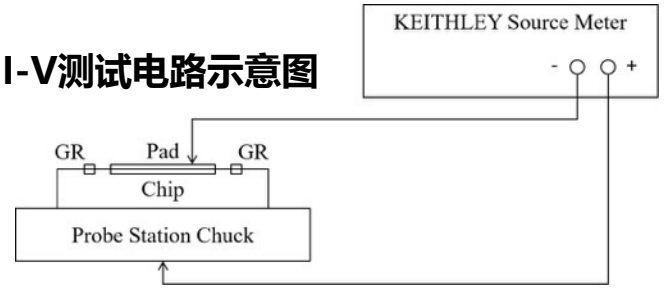
针对该项目开发图像识别技术，实现自动化检验

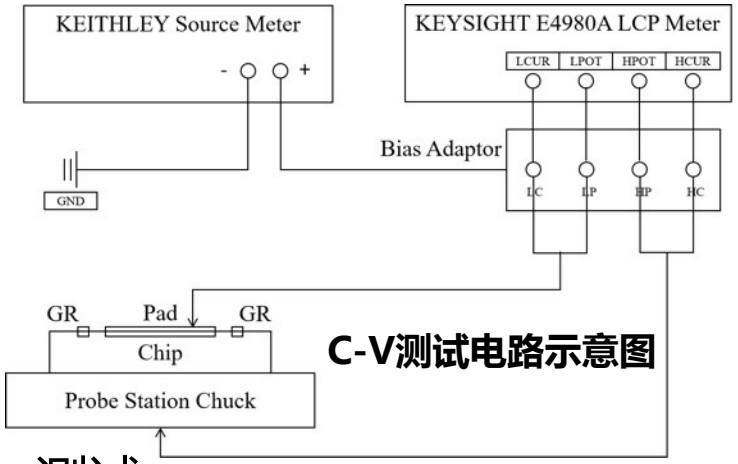
- 后续引入机器学习算法，自动化质检方法拓展到其他多种工艺，如电子学键合连线
- 通用型软件包，将普遍适用于半导体探测器的建造

硅微条传感器芯片电子学检测



I-V测试电路示意图





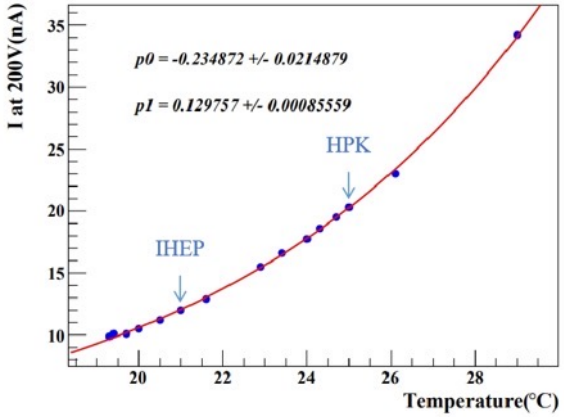
C-V测试电路示意图

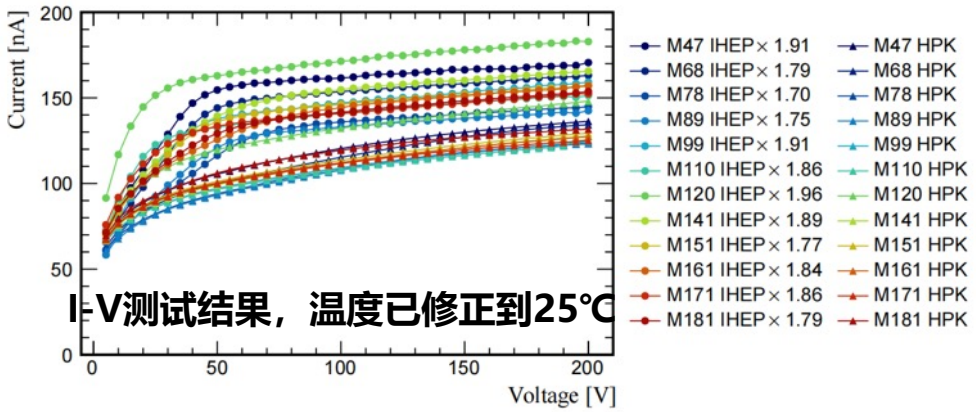
I-V（电流-电压）和C-V（电容-电压）测试

- 电压200伏未见提前击穿现象，60伏以上暗电流呈现稳定状态
- 耗尽电压~50伏

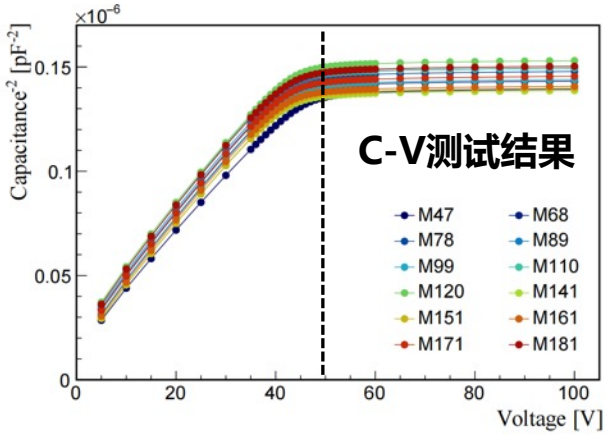
与设计指标相一致

暗电流随温度的变化曲线





I-V测试结果，温度已修正到25℃

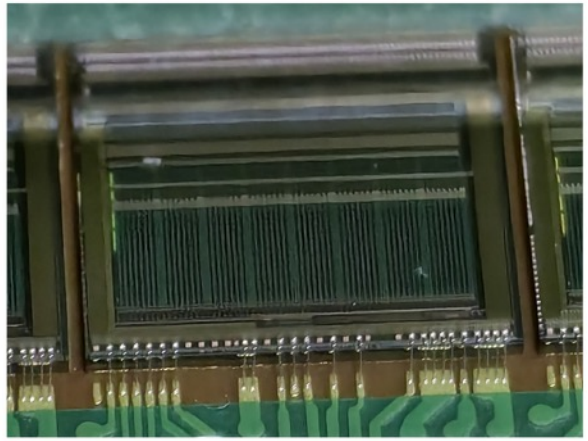


C-V测试结果

读出电路板测试

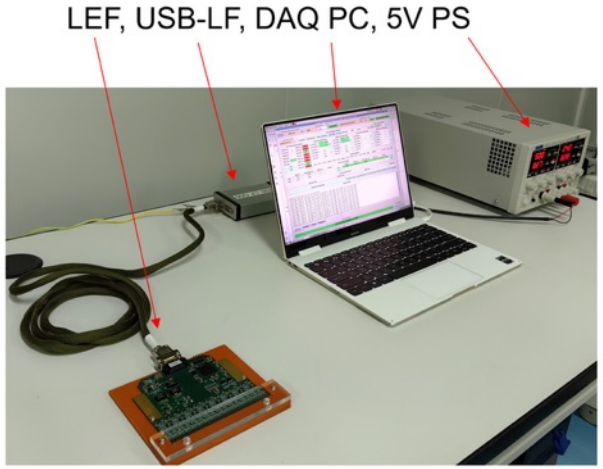
读出电路板由AMS合作组其他单位生产

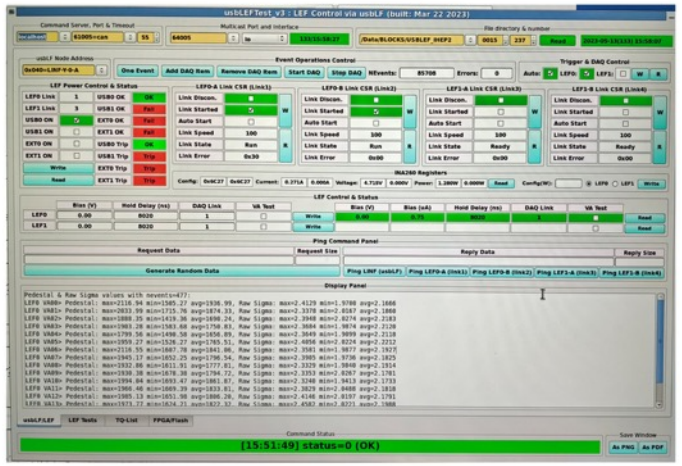
- 质检包括视觉检验和电子学检验



读出电路板视觉检查

视觉检查排除读出电路板运输过程中的意外损坏

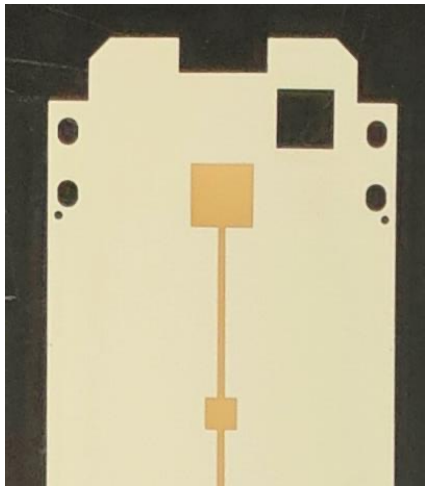




电子学检验

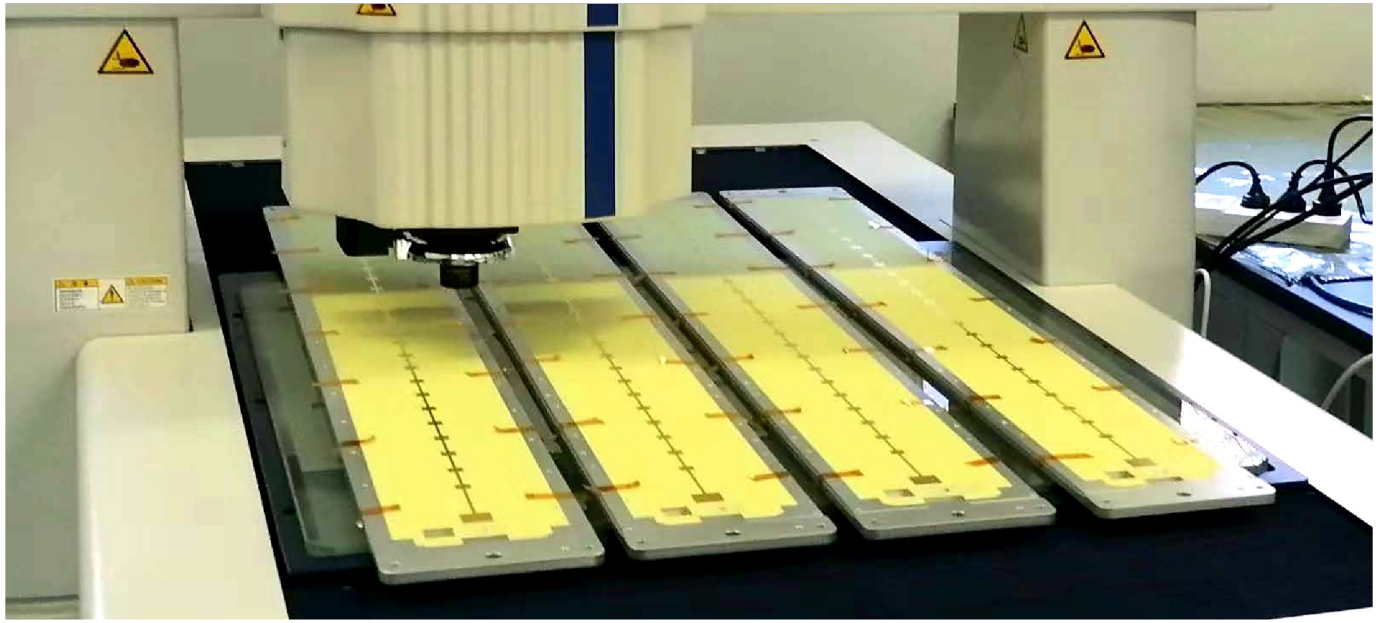
- 读出电路板电流应稳定在0.5毫安培
- 单通道噪声（2.0,2.4）ADC单位
  - 坏道数量低于10/1024

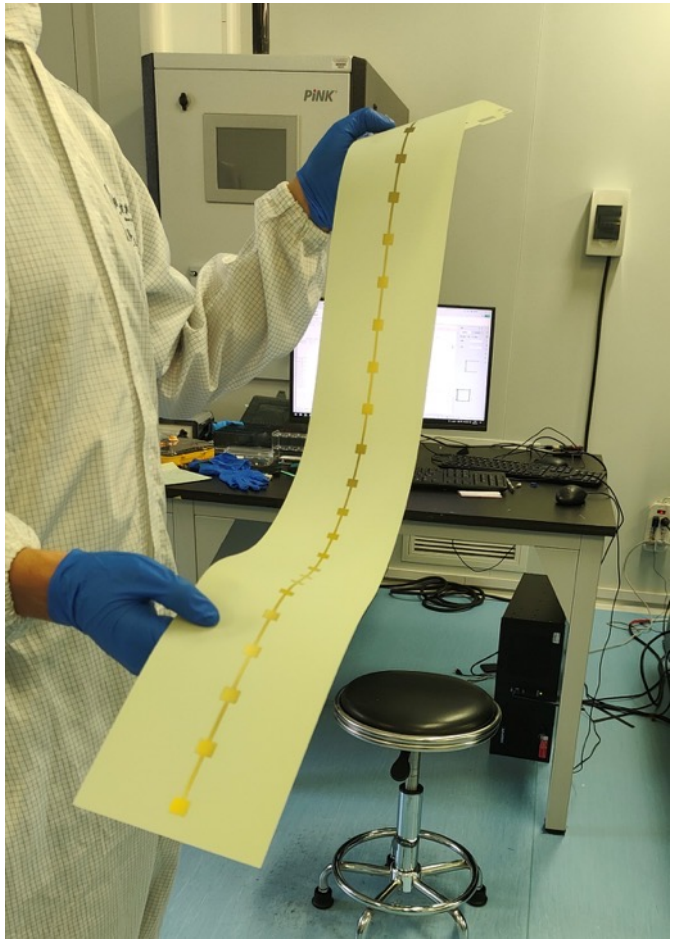
L0偏压板（LBB）



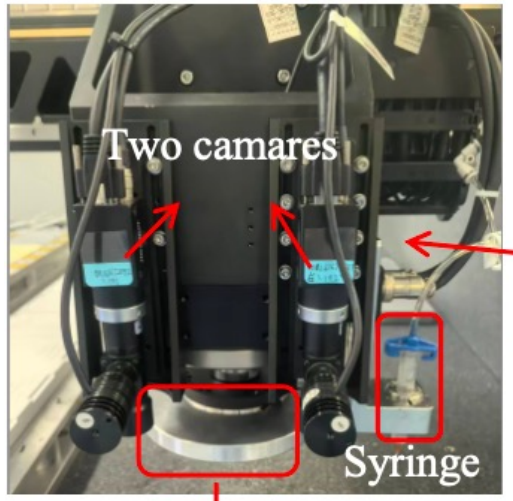
L0偏压板(LBB)由裕维电子生产

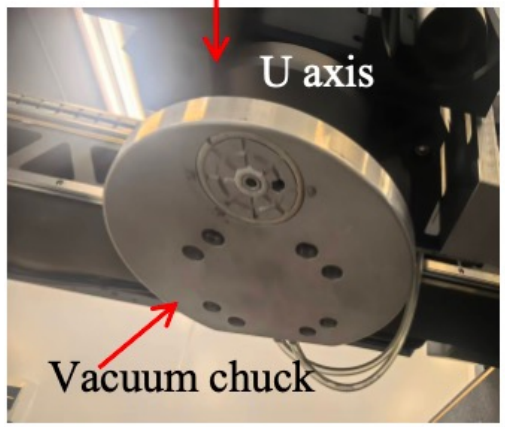
- 共计220张
- 厚度为150 微米

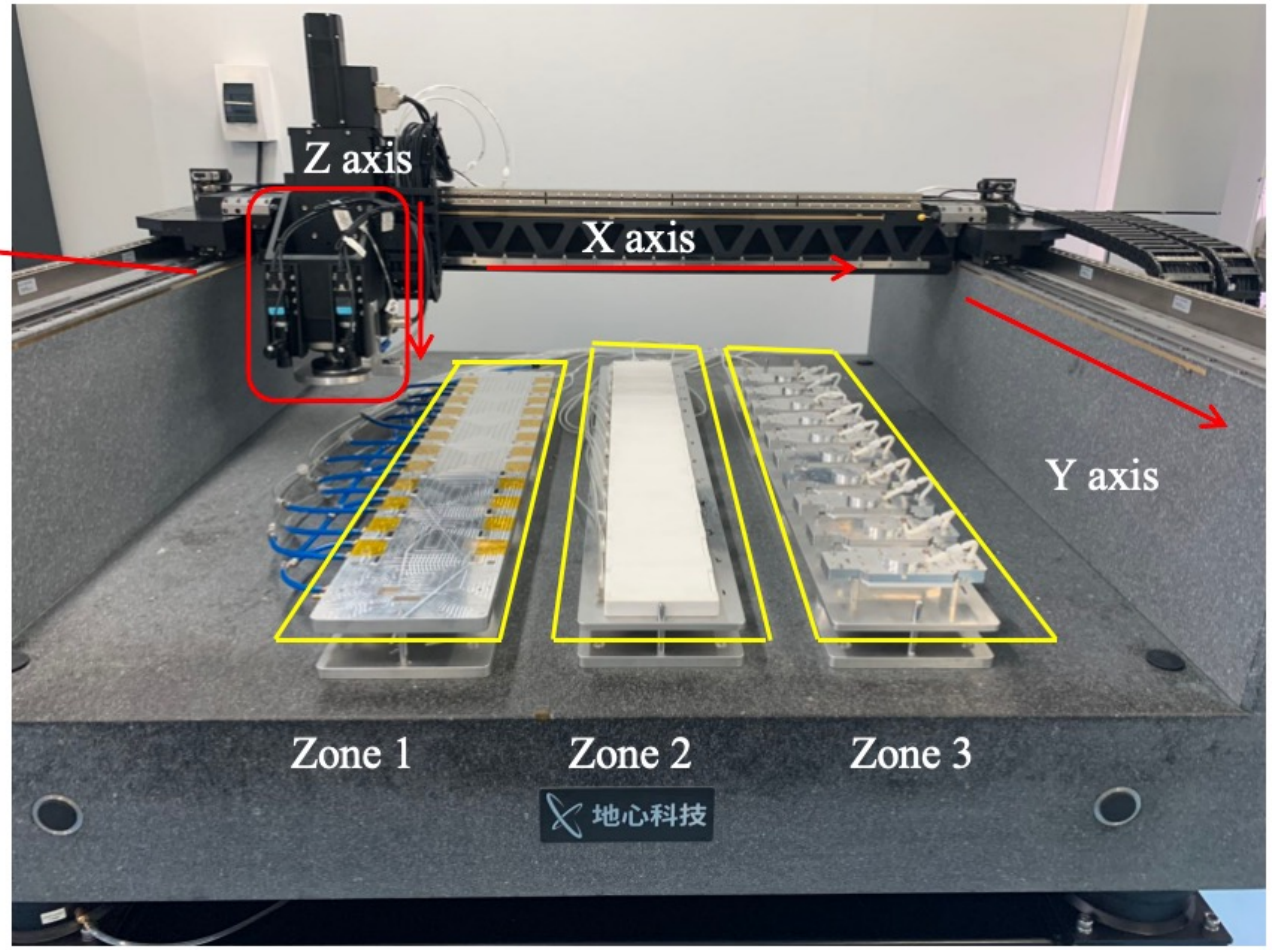


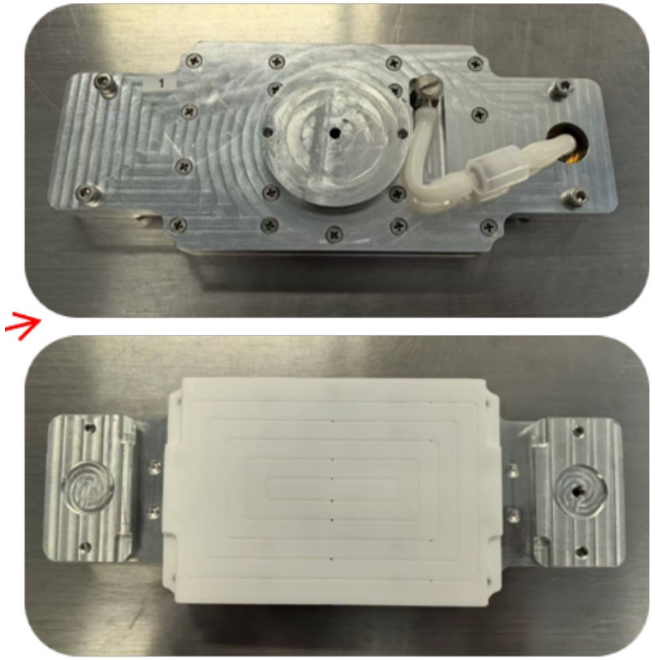


Gantry system for L0 ladders









Custom-designed gantry dedicated to AMS L0 assembly

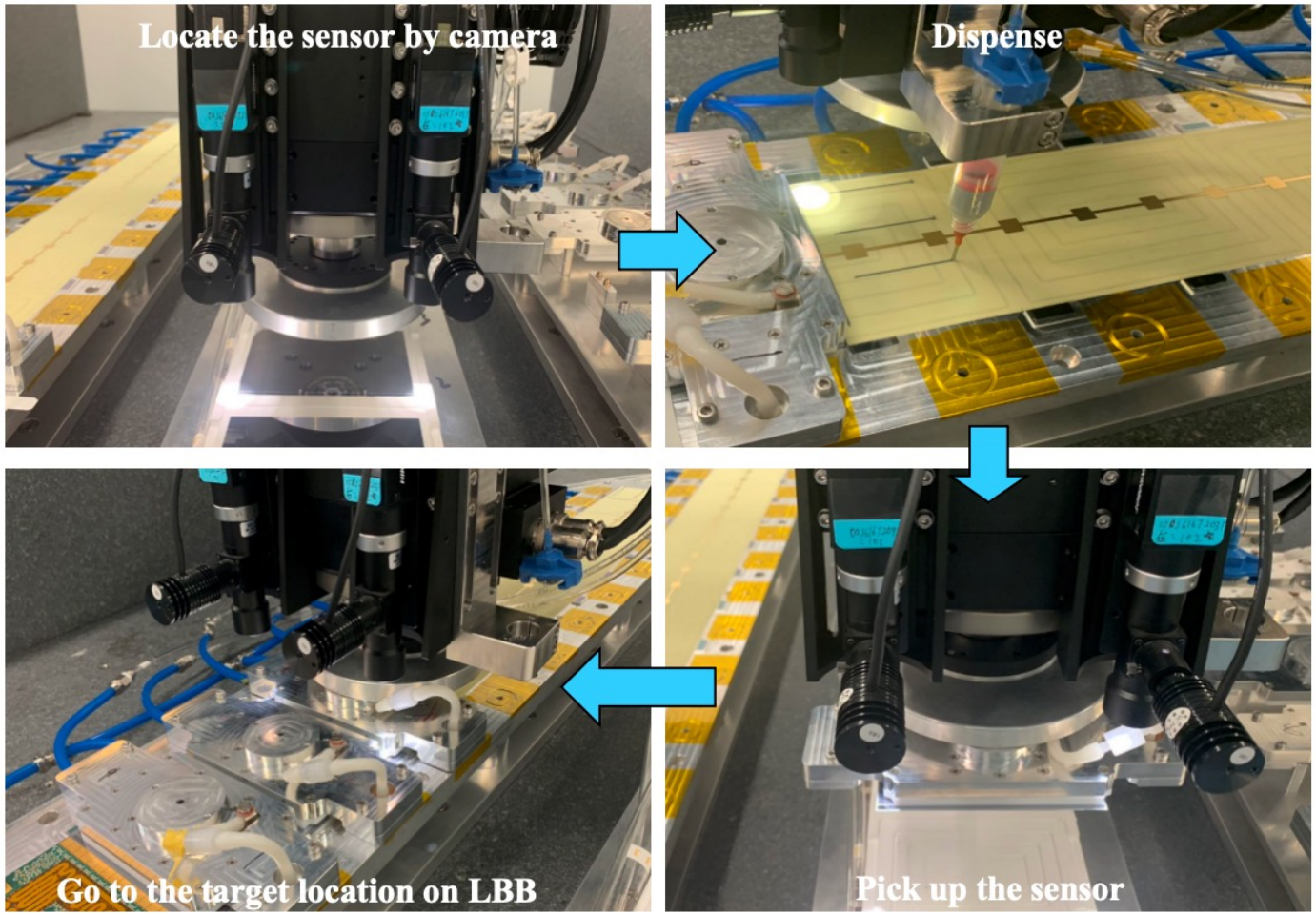
- Glue dispensing; alignment mark recognize; picking up/positioning

JINST 21 C01003

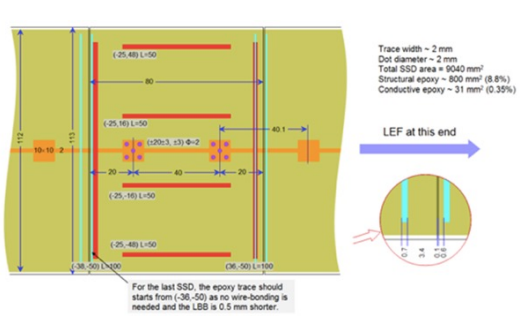
arXiv:2509.24564

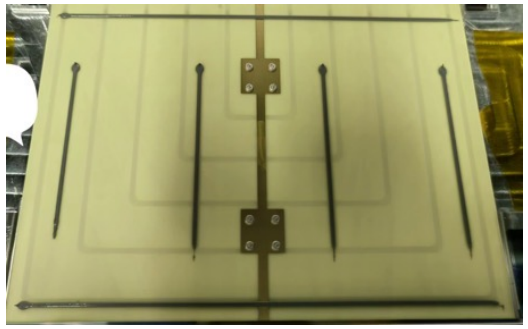
L0 ladder assembly

4-step for SSDs assembly

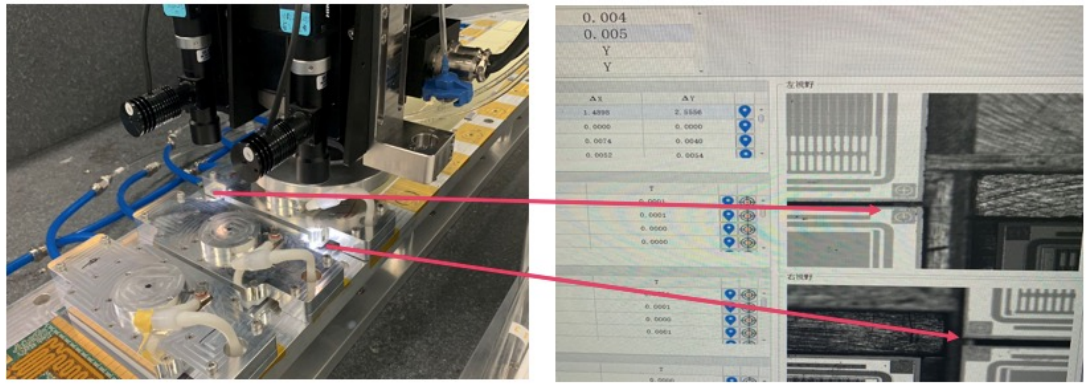


Glue pattern optimization

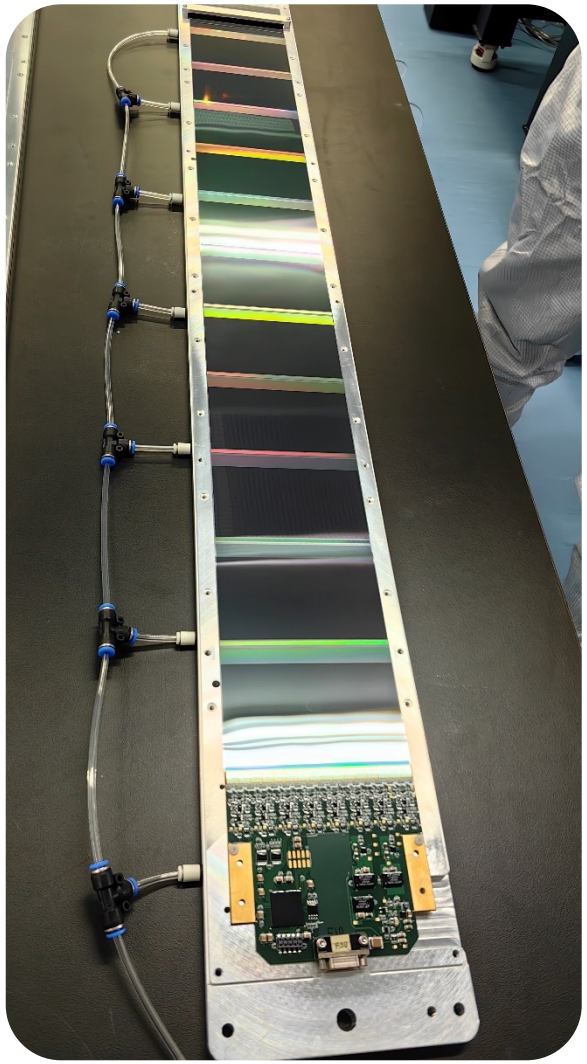




Real-time measuring/correcting SSD location



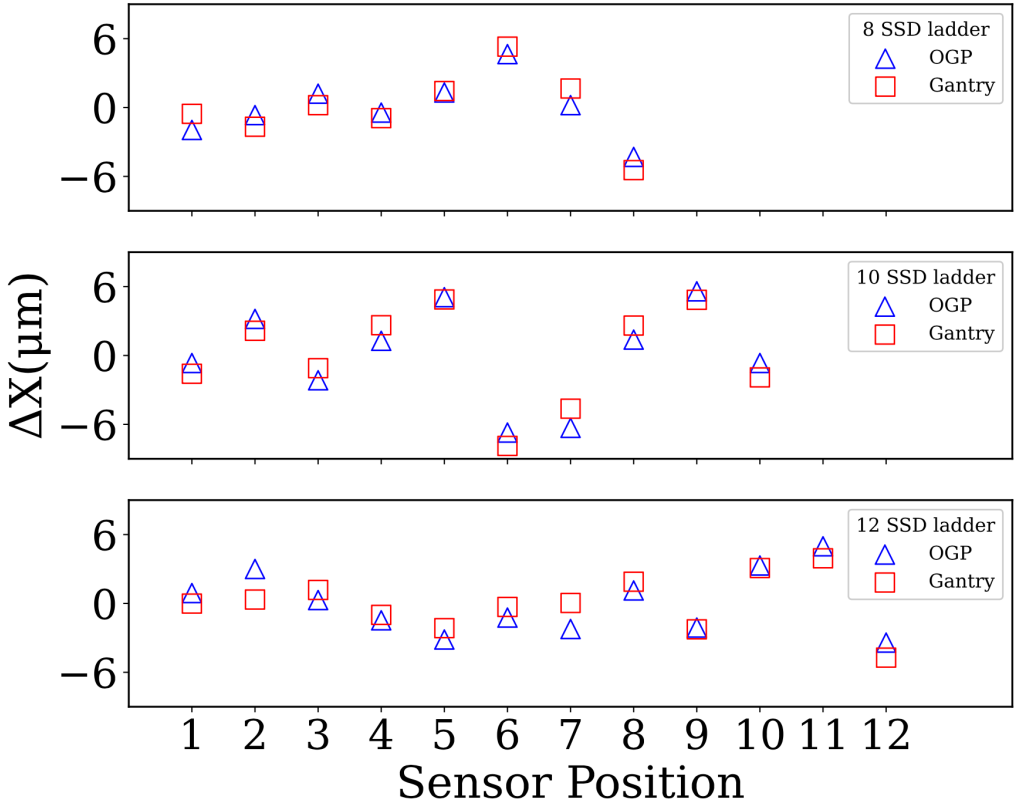
L0 ladder assembly



After curing, a large-size pickup tool used to move the L0 ladder from gantry to transportation plate

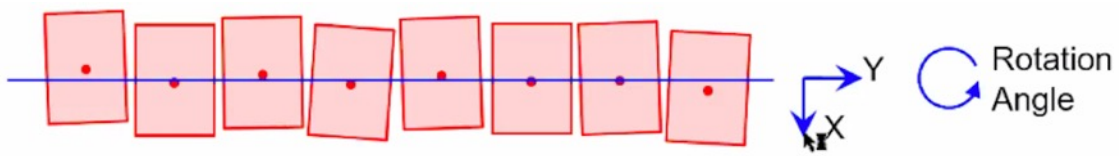
Metrology QC

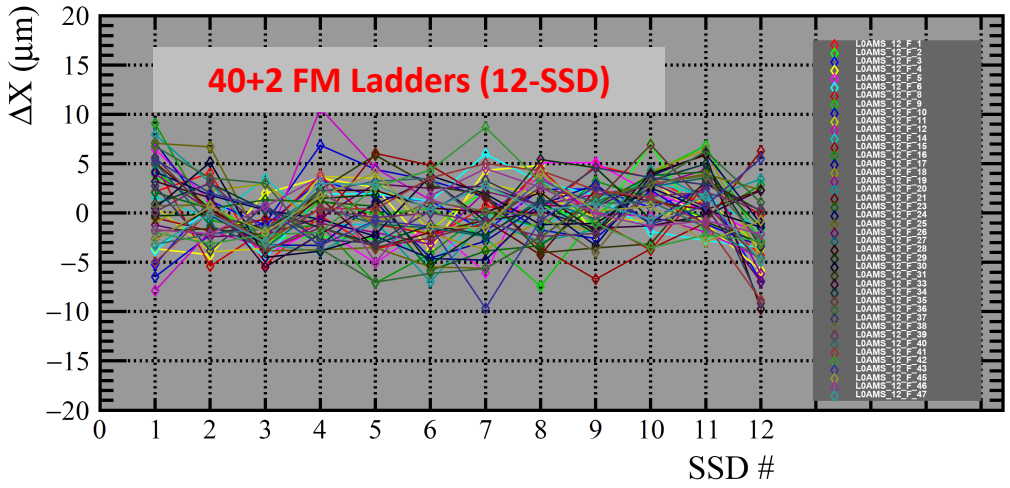
Comparison with SSDs location measured by gantry and OGP

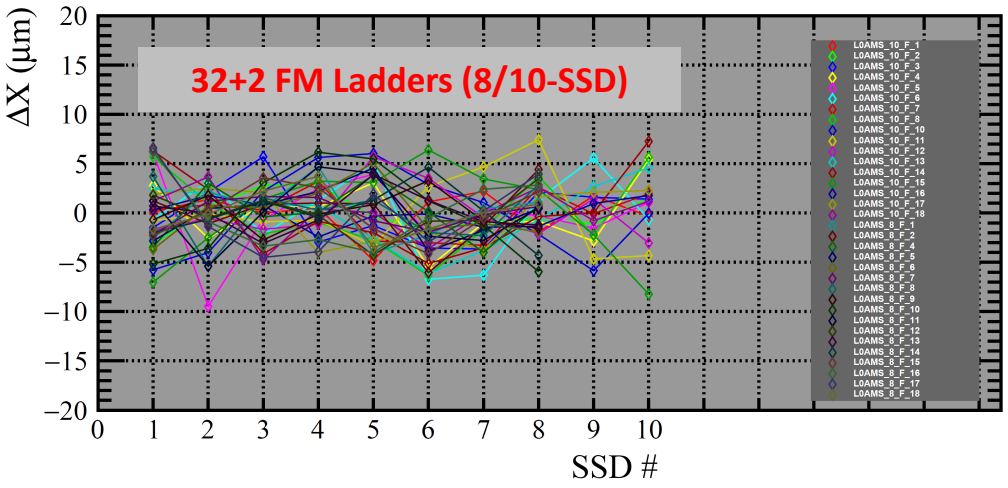


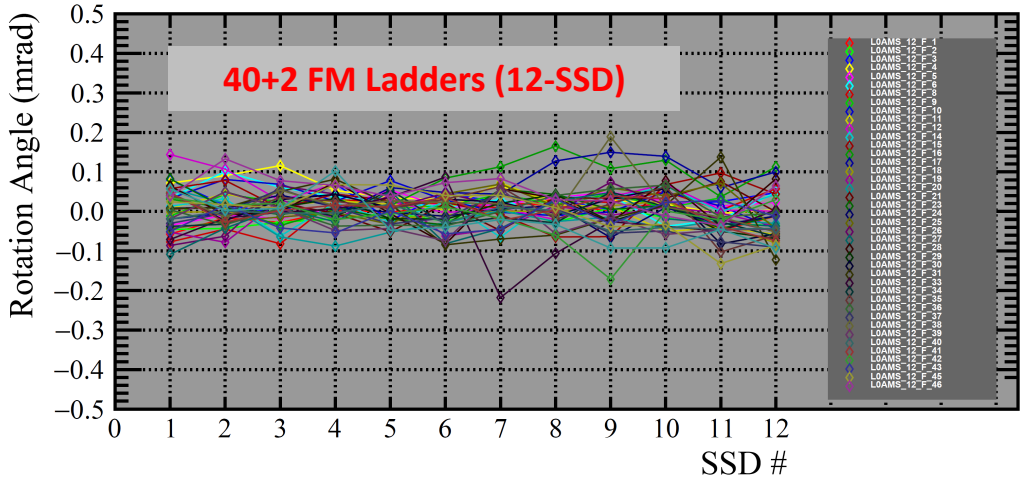
Relative positions of all SSDs are precisely measured by OGP

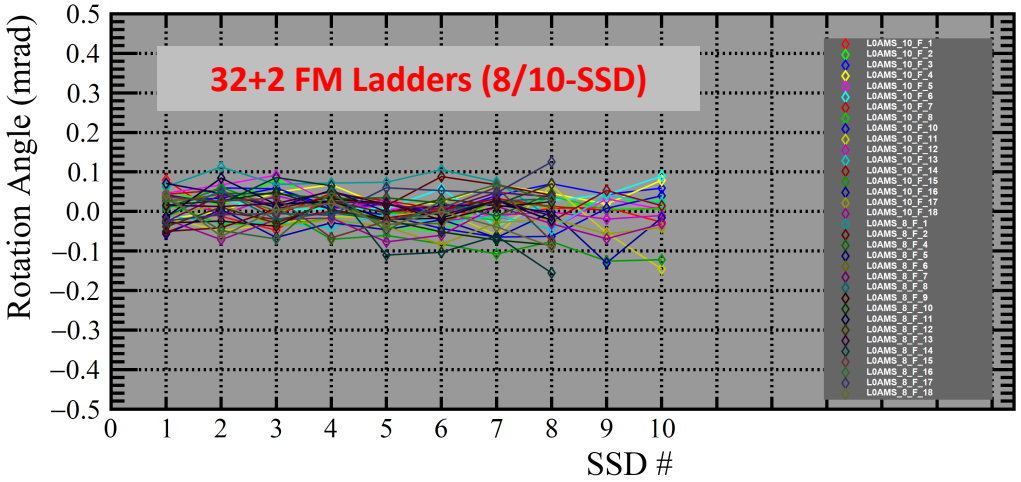
硅微条传感器组装精度


Y
X
Rotation
Angle

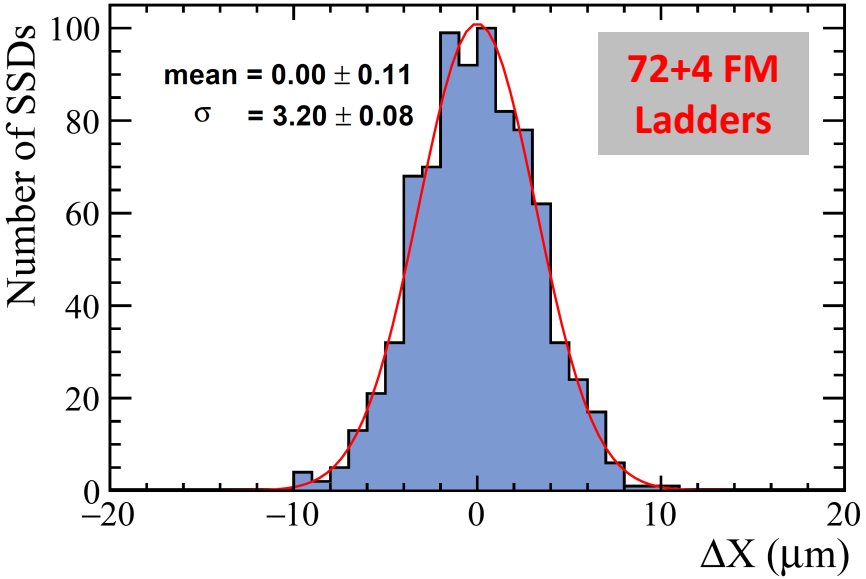

40+2 FM Ladders (12-SSD)
ΔX (μm)
SSD #

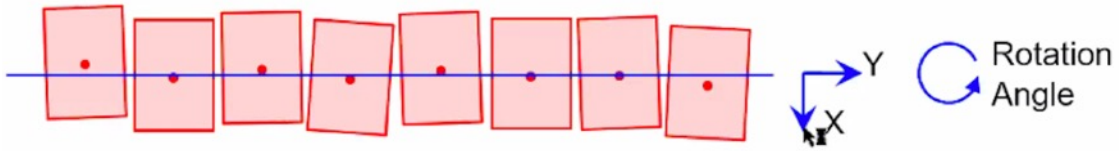

32+2 FM Ladders (8/10-SSD)
ΔX (μm)
SSD #

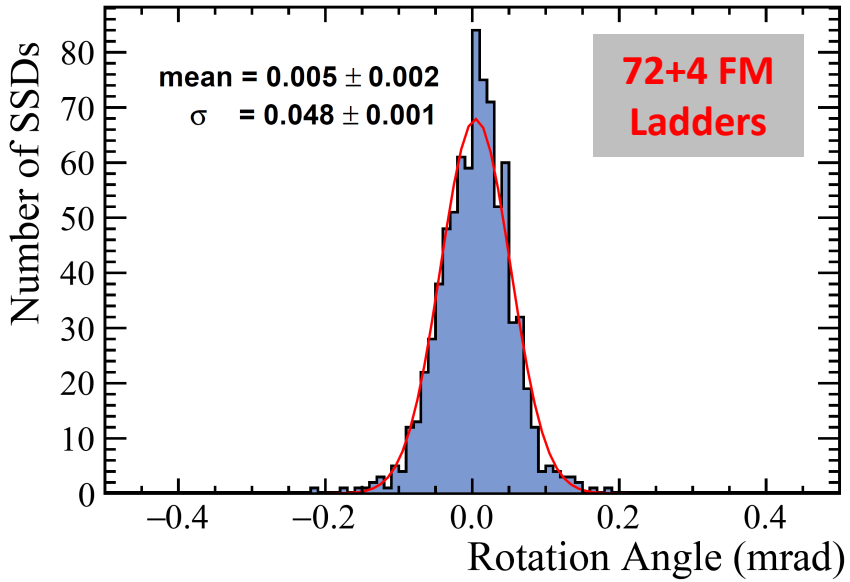

40+2 FM Ladders (12-SSD)
Rotation Angle (mrad)
SSD #

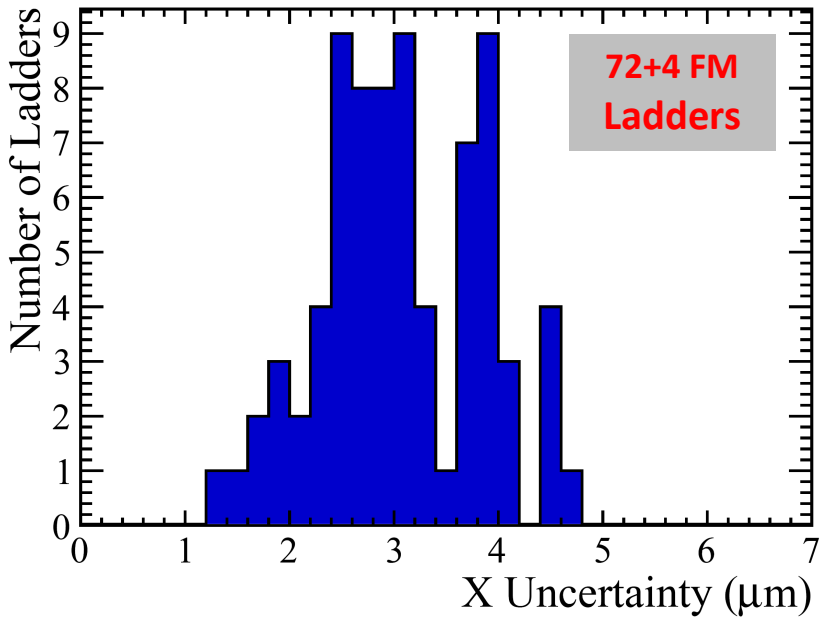

32+2 FM Ladders (8/10-SSD)
Rotation Angle (mrad)
SSD #

硅微条传感器组装精度



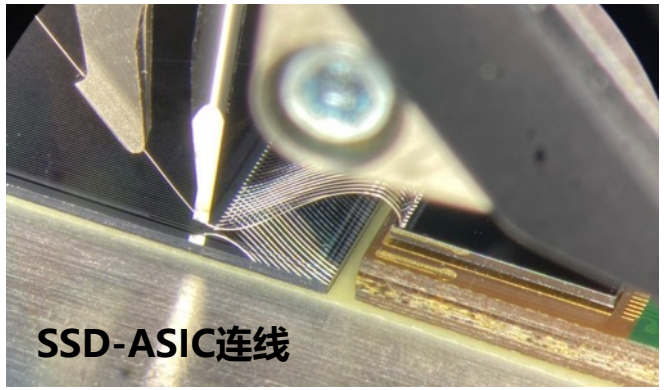






考虑到硅微条横向偏移⊕角度影响，
硅微条组装精度（横向）为**3.4** 微米，
远高于项目要求（**10** 微米）

电子学键合连线工艺设计

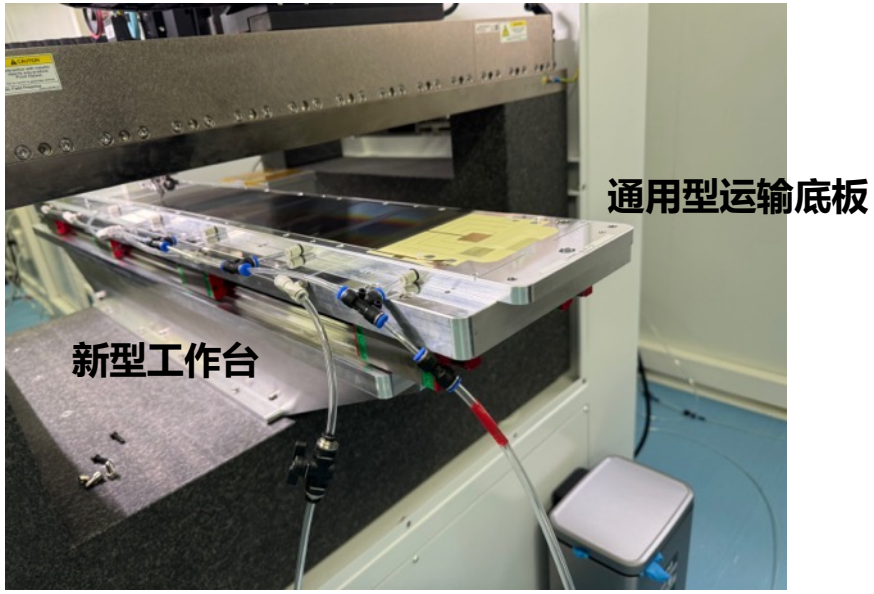


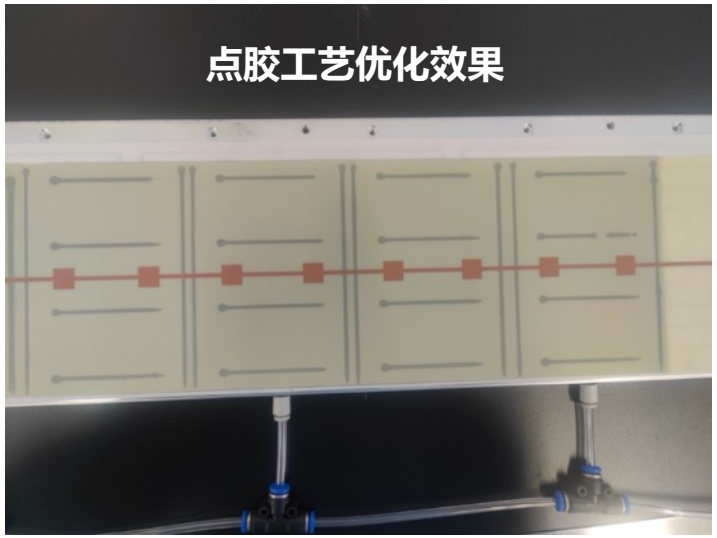
共计需要百万量级电子学键合连线

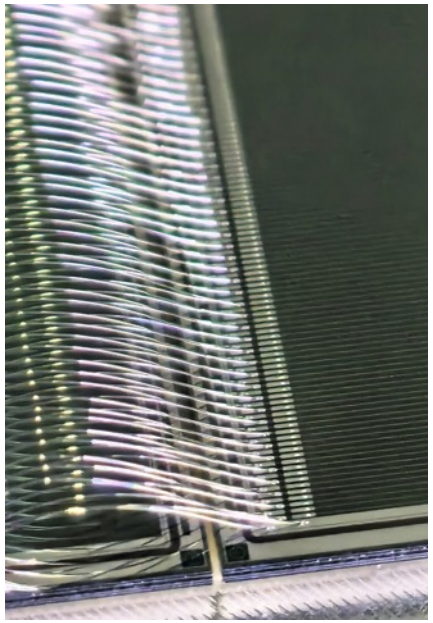
- 发射环境对该工艺提出极高要求
- 设计要求：焊线拉力强度超过7克

工艺改进包括

- 新型工作台以及运输底板
- 优化点胶工艺
- 优化设备参数

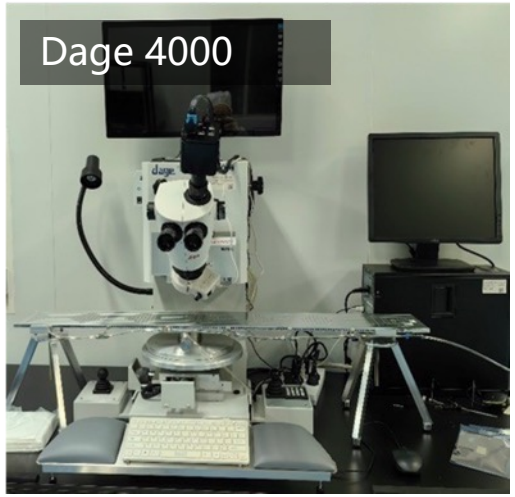




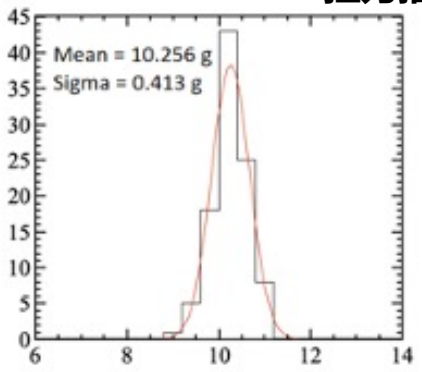


SSD-SSD连线

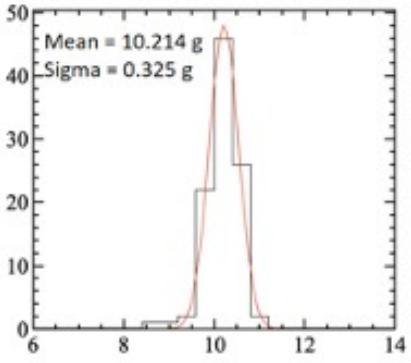
电子学键合连线质检和品控



拉力抽检结果



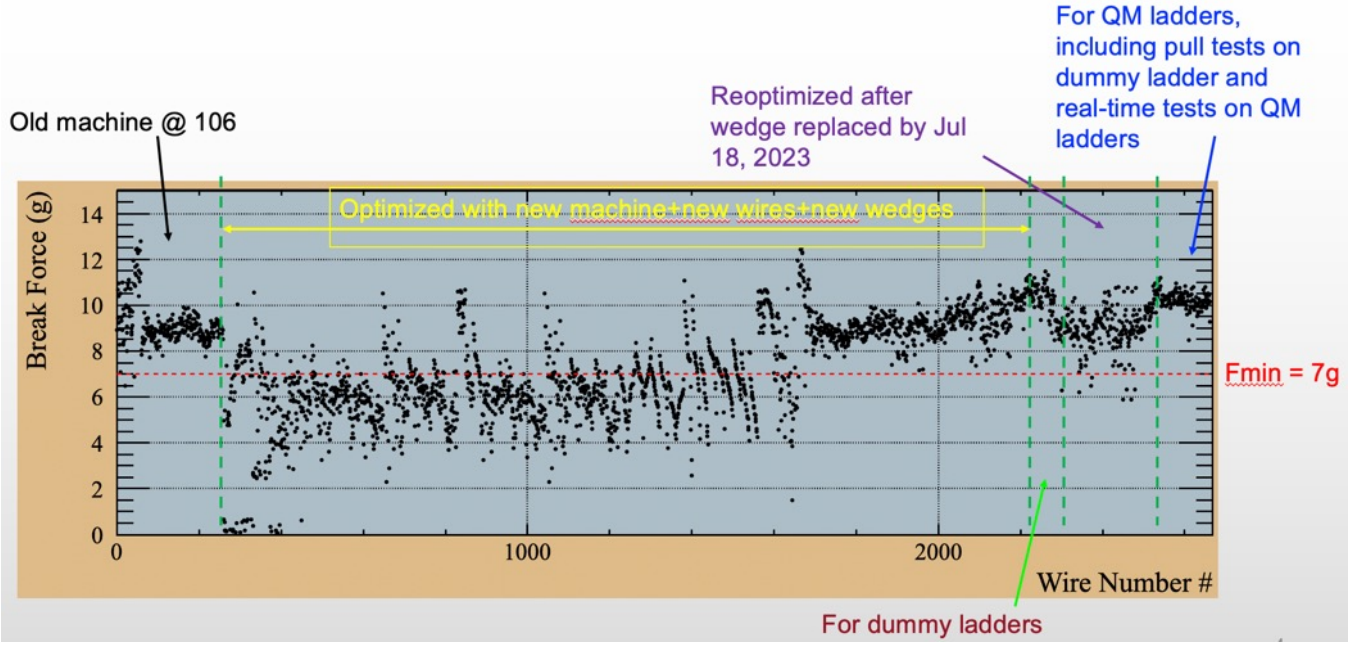
Latest pull tests on dummy SSD-SSD with 60 wires pulled

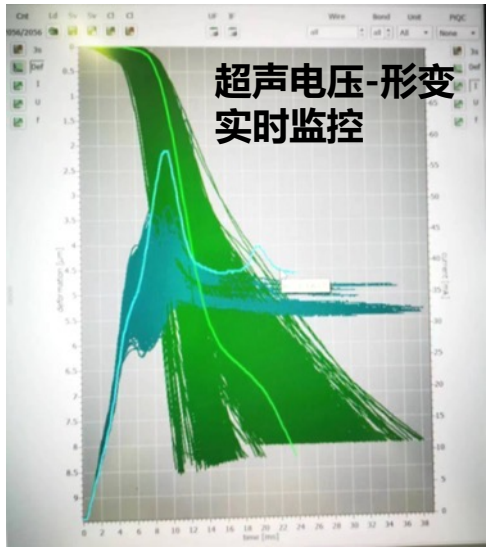


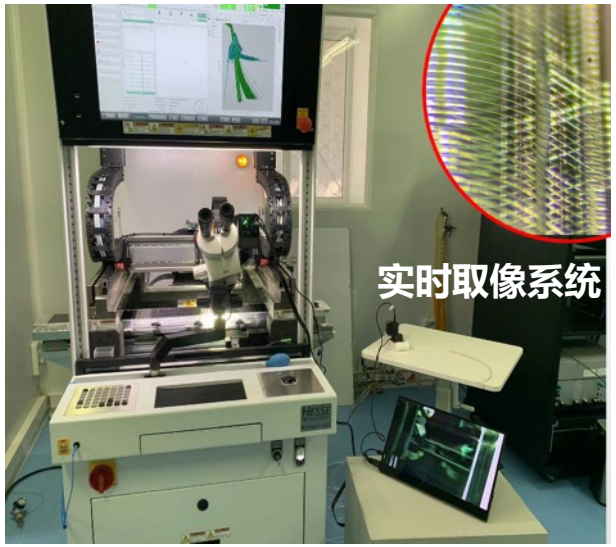
Latest pull tests on real SSD-SSD with 60 wires pulled, so-called real-time pull tests during production of the QM ladder

品控
- 通过拉力测量优化设备参数
- 超声电压与焊线形变实时监测
- 引入取像系统

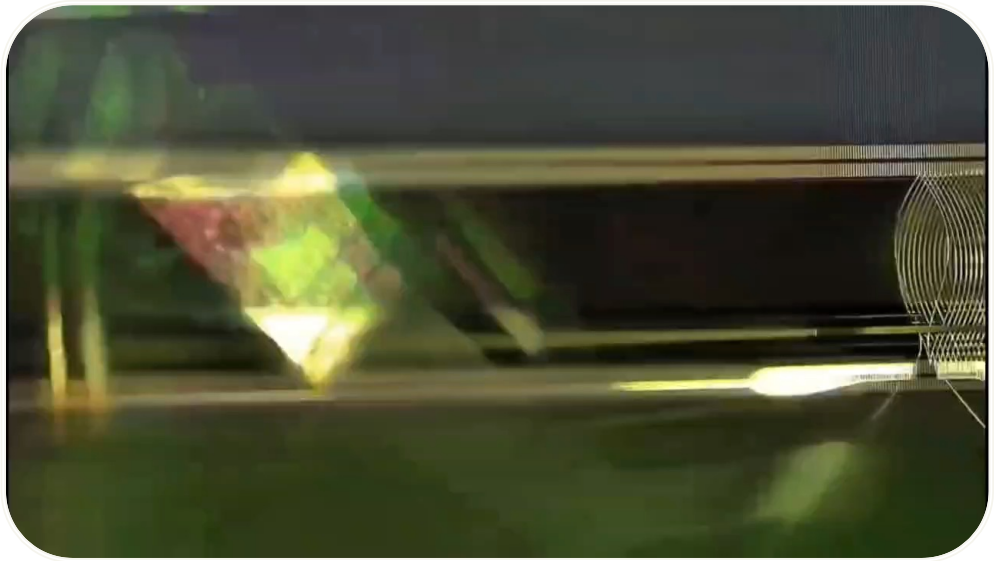
质检
- 拉力抽检
- 2023年底通过振动测试







电子学键合连线

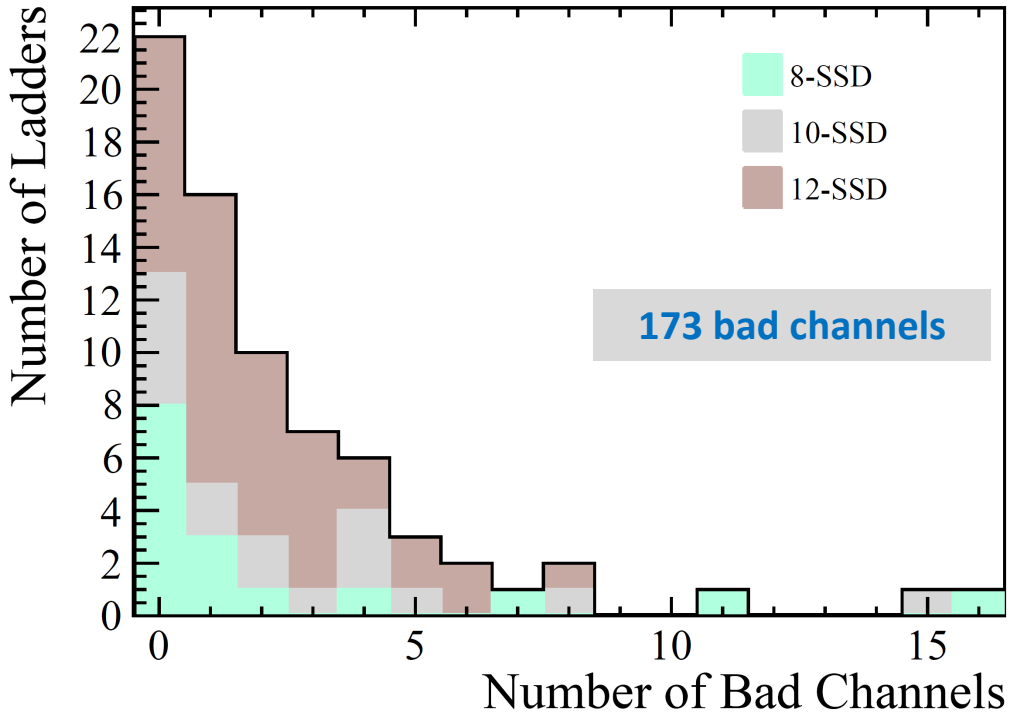


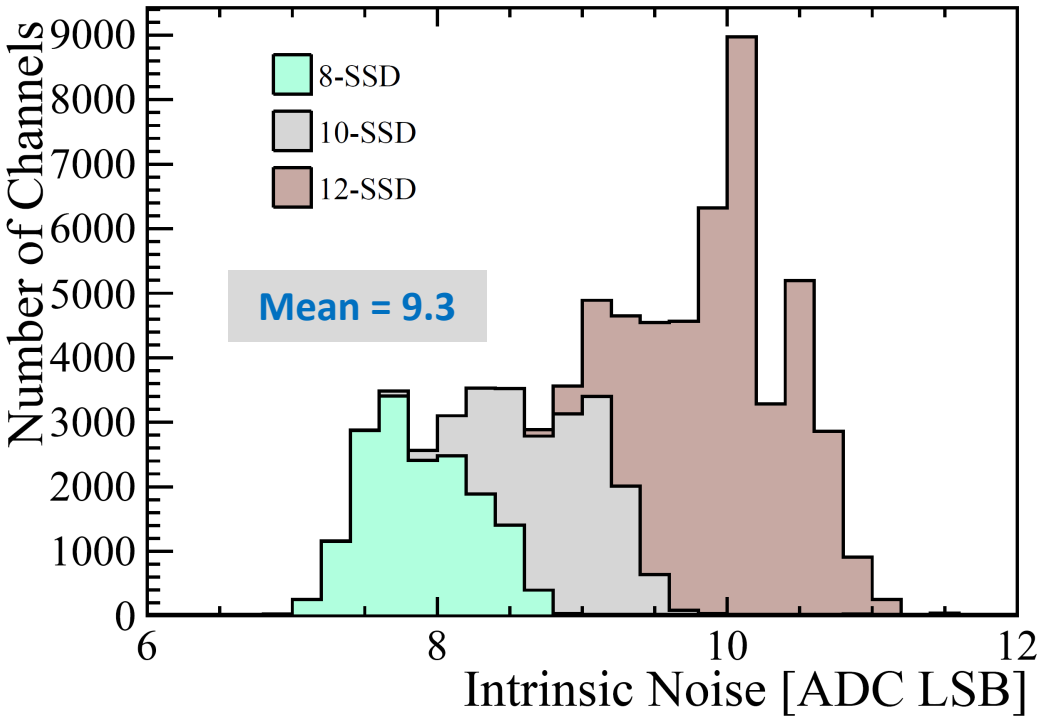
电子学检测

电子学检测

- 暗电流
- 噪声水平
- 通道良品率
- …

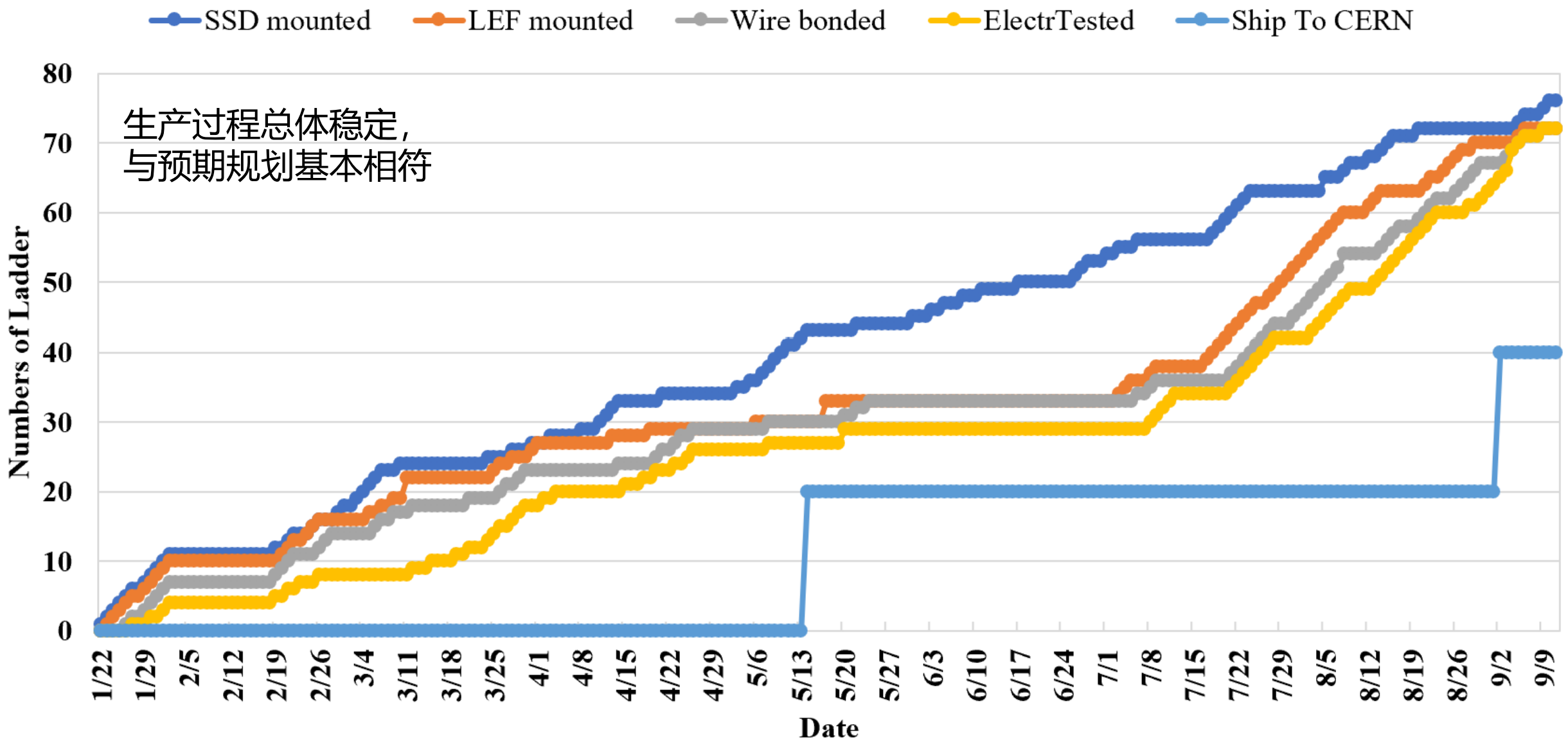
探测器模块电子学性能





- 全部72块模块暗电流低于2 微安
- 平均CMS噪声水平为9.3 ADC LSBs，对比信号水平~60 ADC LSBs
- 坏道总数为173，占探测器全部通道数0.23 %，远高于项目设计指标（良道率>95%)

项目进展监控

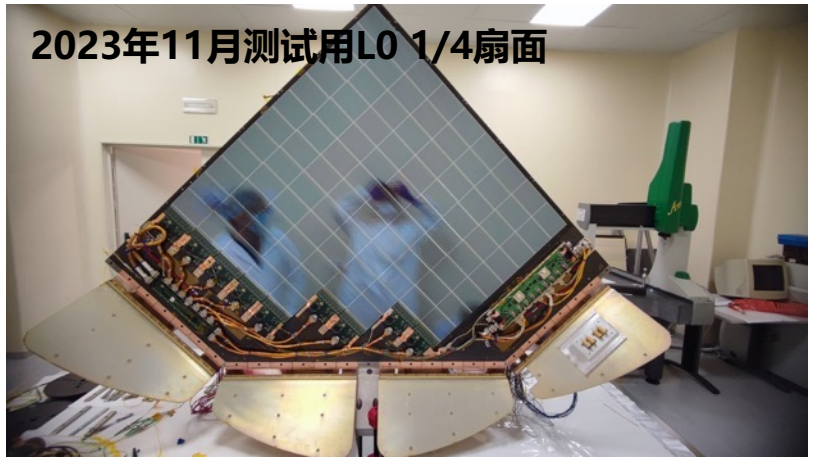

SSD mounted
LEF mounted
Wire bonded
ElectrTested
Ship To CERN
生产过程总体稳定，
与预期规划基本相符
Numbers of Ladder
0
10
20
30
40
50
60
70
80
1/22
1/29
2/5
2/12
2/19
2/26
3/4
3/11
3/18
3/25
4/1
4/8
4/15
4/22
4/29
5/6
5/13
5/20
5/27
6/3
6/10
6/17
6/24
7/1
7/8
7/15
7/22
7/29
8/5
8/12
8/19
8/26
9/2
9/9
Date

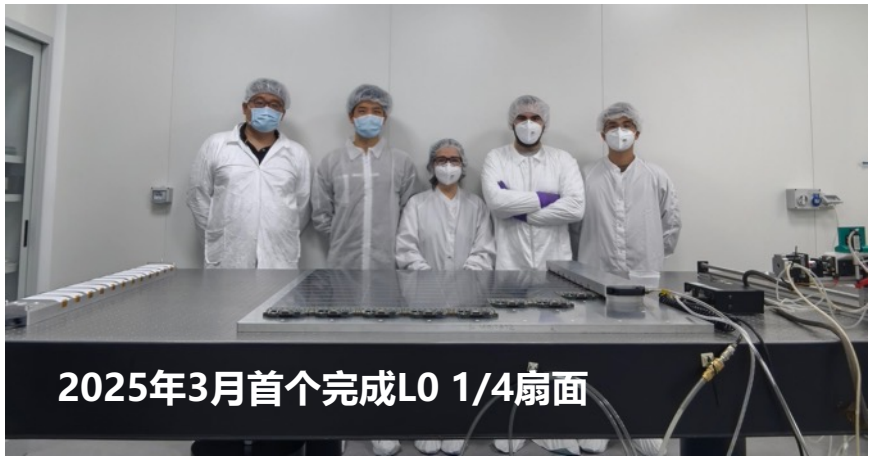
L0探测器组装

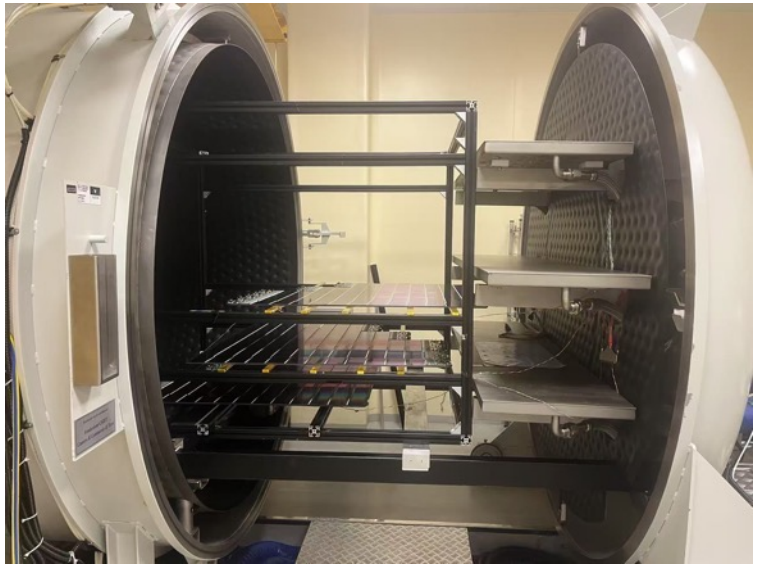
探测器模块于意大利完成“扇面”组装，最终在CERN完成整体组装

- “扇面”组装于2025年3月开始，已经结束
- 中方深度参与组装工作

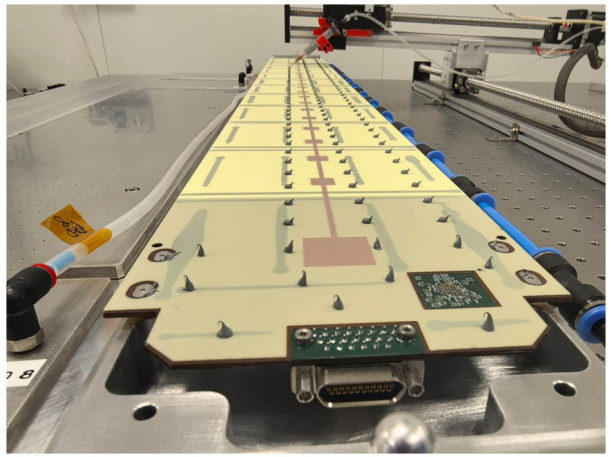
人员	单位	职位
刘平成	山东高能技术研究院	职工
缪德星	中国科学院高能物理研究所	研究生
李沁泽	中国科学院高能物理研究所	研究生
Baaska Batsukh	中国科学院高能物理研究所	博士后

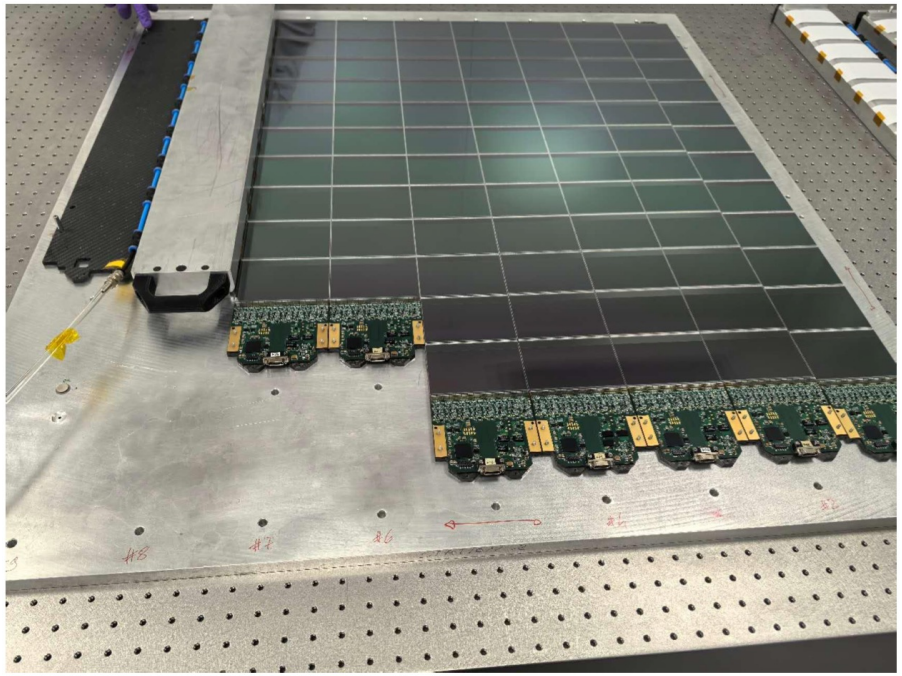


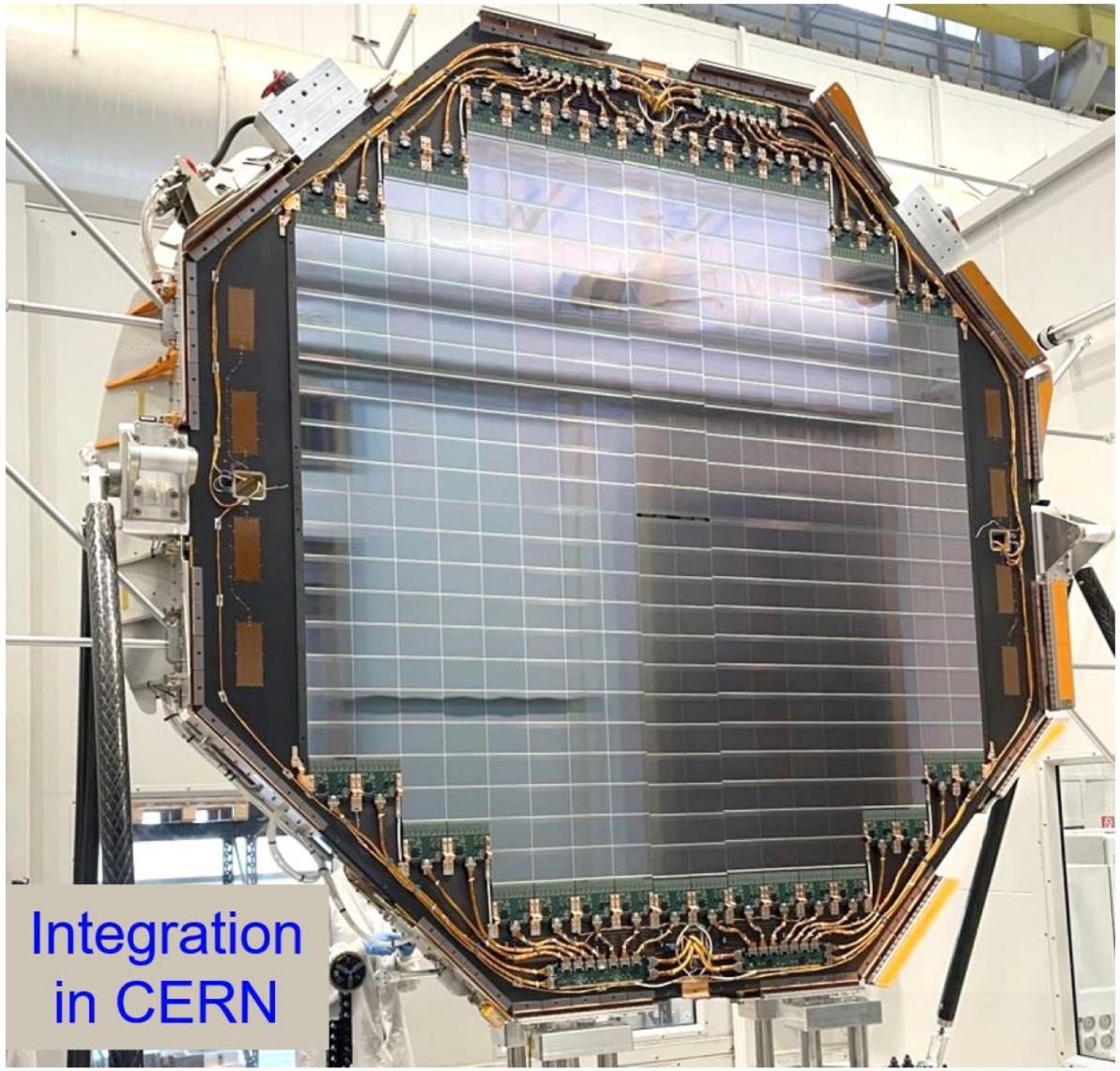




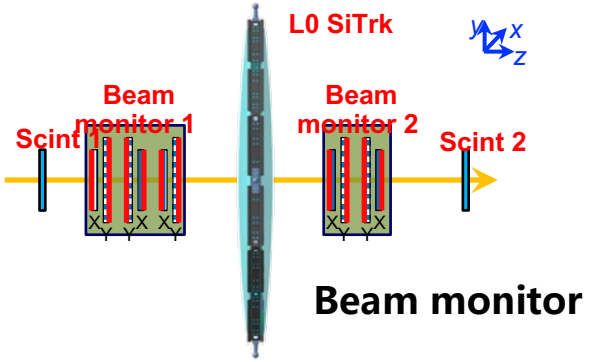
探测器整装

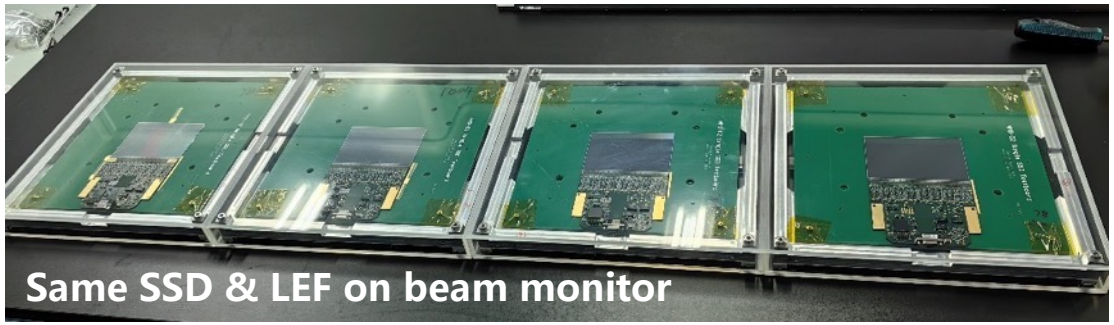


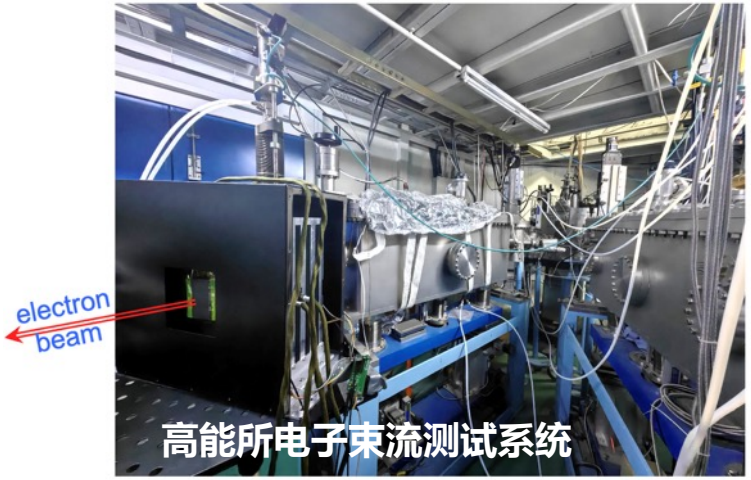


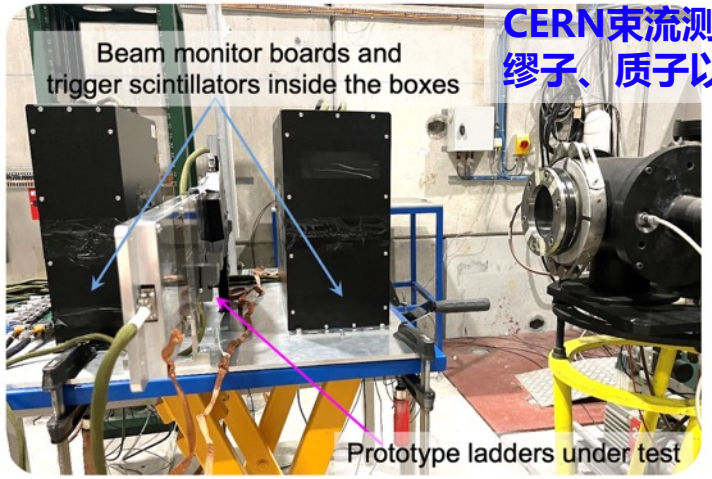


束流测试





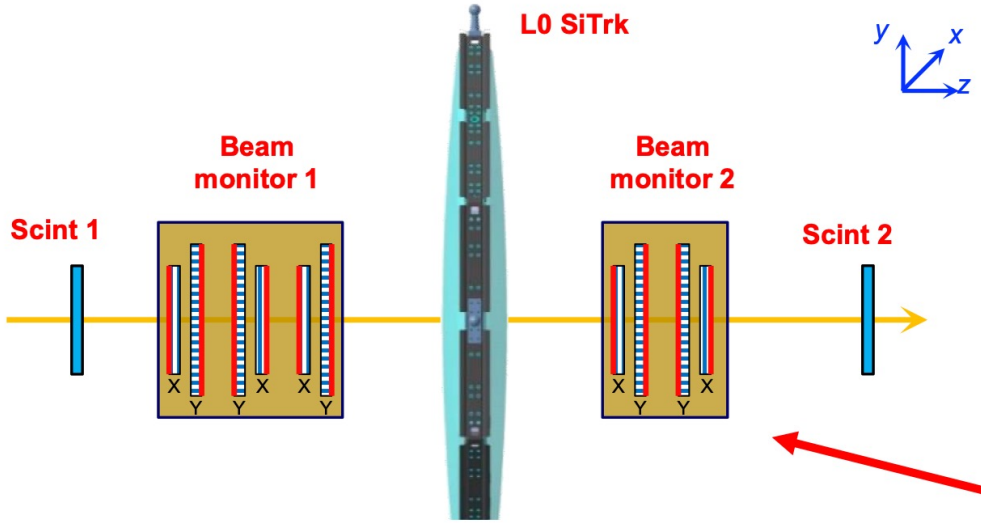


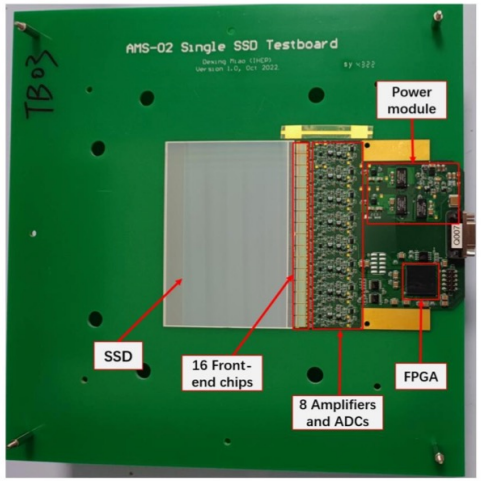


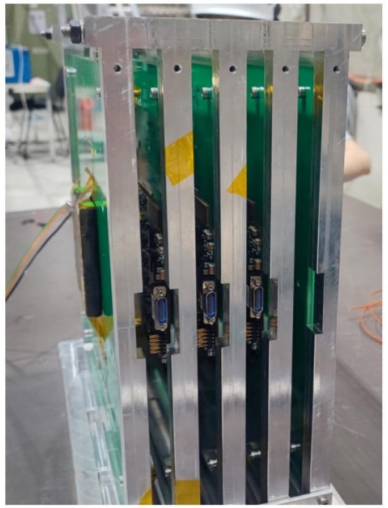
CERN束流测试系统,测试涵盖缪子、质子以及重离子束流

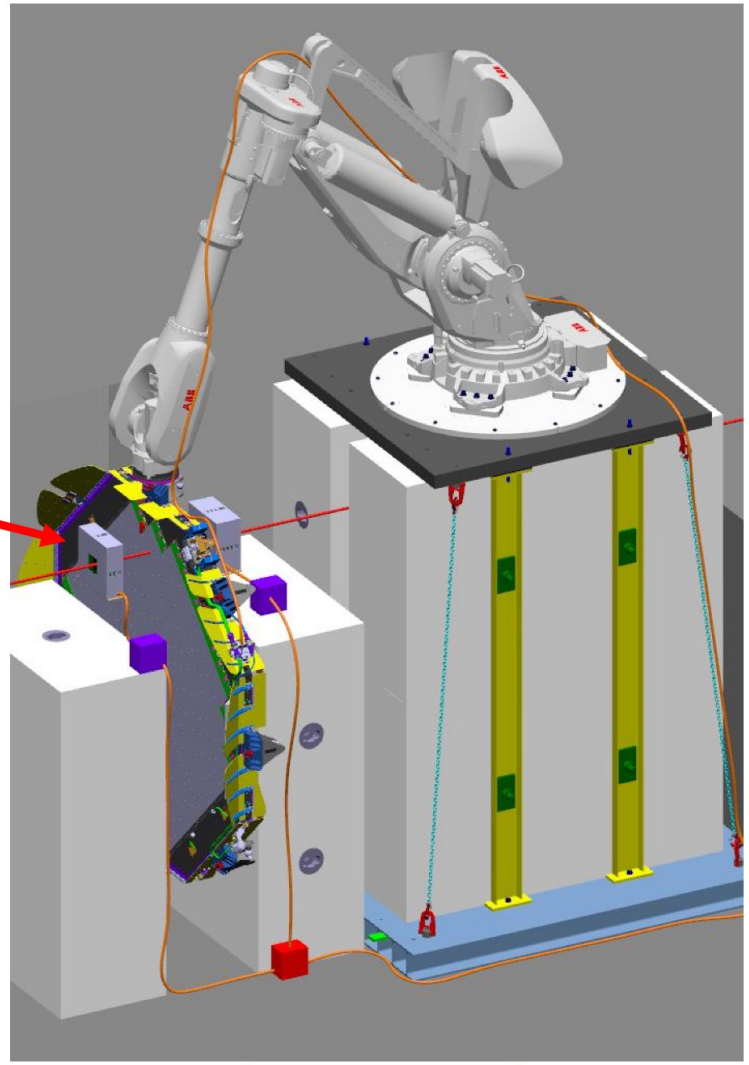
正在开展束流测试数据分析工作

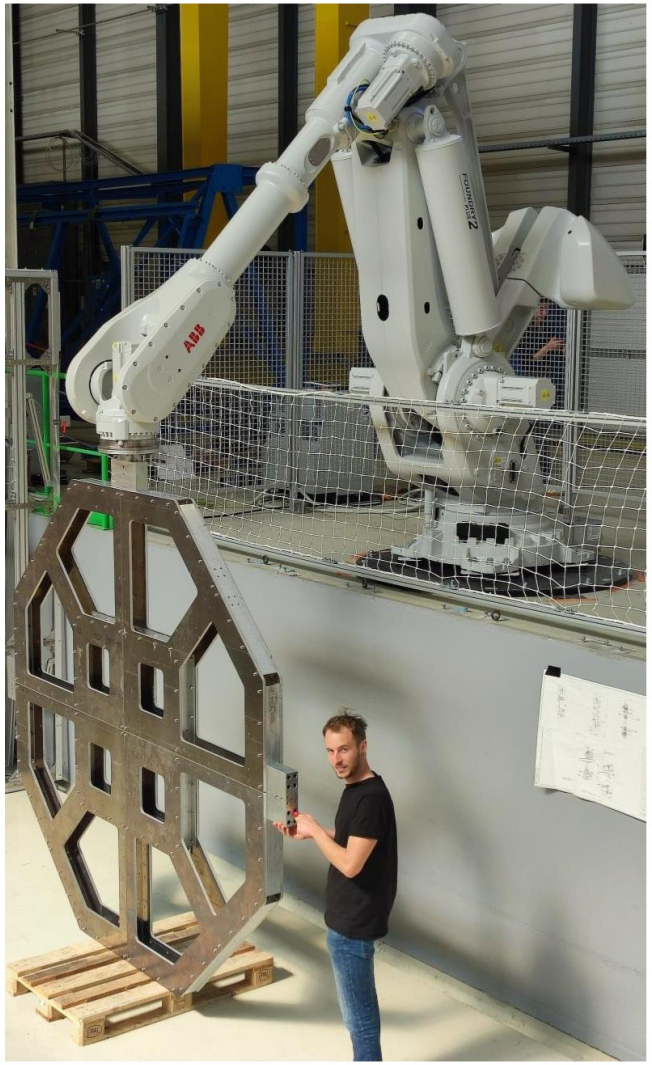
探测器束流实验









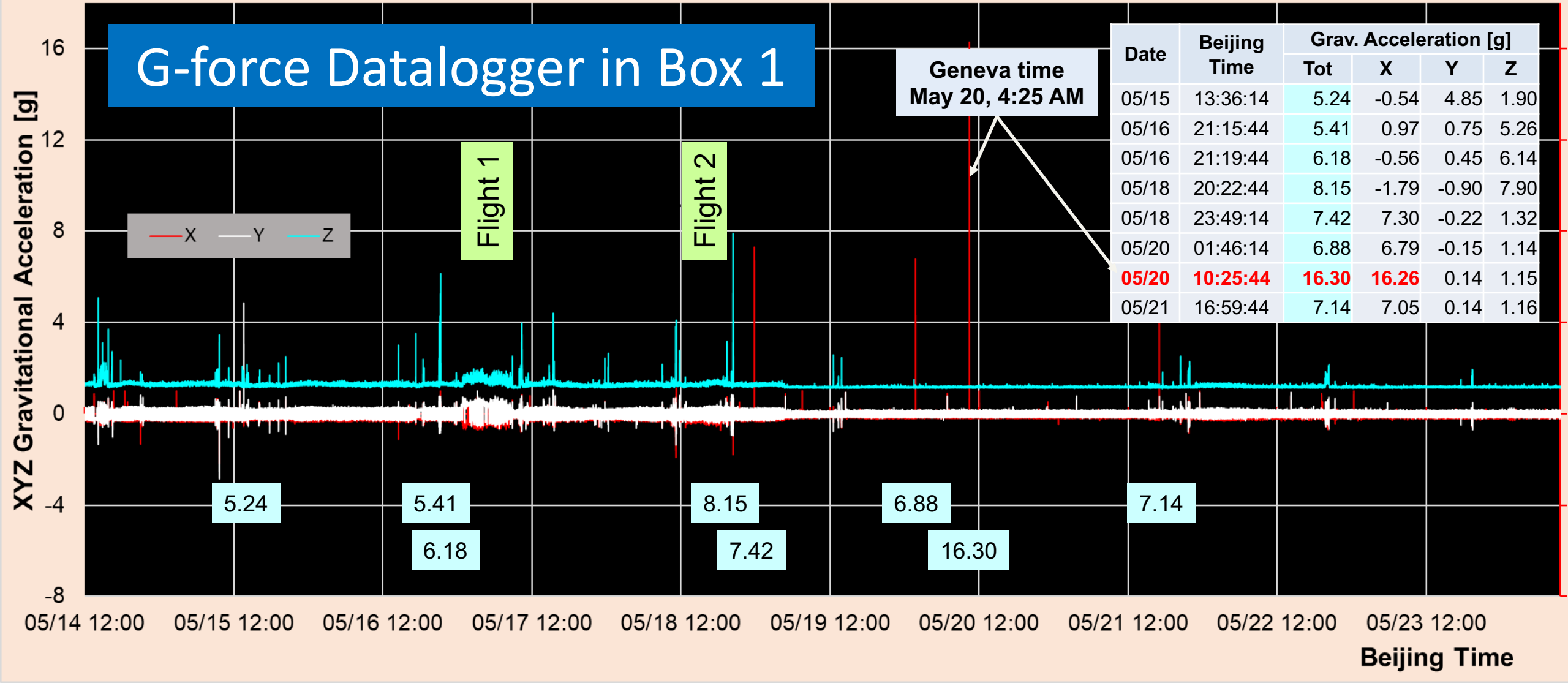


2026年7月

The Shock Indicator Issue

- Joe Burger was informed by the CERN Shipping Management office that the “shock indicators” were deliberately ripped off.
- Mike Capell confirmed that all 8 shock indicators were removed. However, the 8 tilt indicators remained and looked fine.
- We are concerned that it might suggest real accidents and decide to track back with information provided by the shipping agency and CERN.
- Fortunately G-force dataloggers were placed inside the boxes. The data might help us uncover the truth.

G-force Datalogger in Box 1



Date	Beijing Time	Grav. Acceleration [g]			
		Tot	X	Y	Z
05/15	13:36:14	5.24	-0.54	4.85	1.90
05/16	21:15:44	5.41	0.97	0.75	5.26
05/16	21:19:44	6.18	-0.56	0.45	6.14
05/18	20:22:44	8.15	-1.79	-0.90	7.90
05/18	23:49:14	7.42	7.30	-0.22	1.32
05/20	01:46:14	6.88	6.79	-0.15	1.14
05/20	**10:25:44**	**16.30**	**16.26**	0.14	1.15
05/21	16:59:44	7.14	7.05	0.14	1.16

Flights in Beijing Time

Flight 1: May 17, 00:35 – 08:40
Flight 2: May 18, 12:22 – 19:30

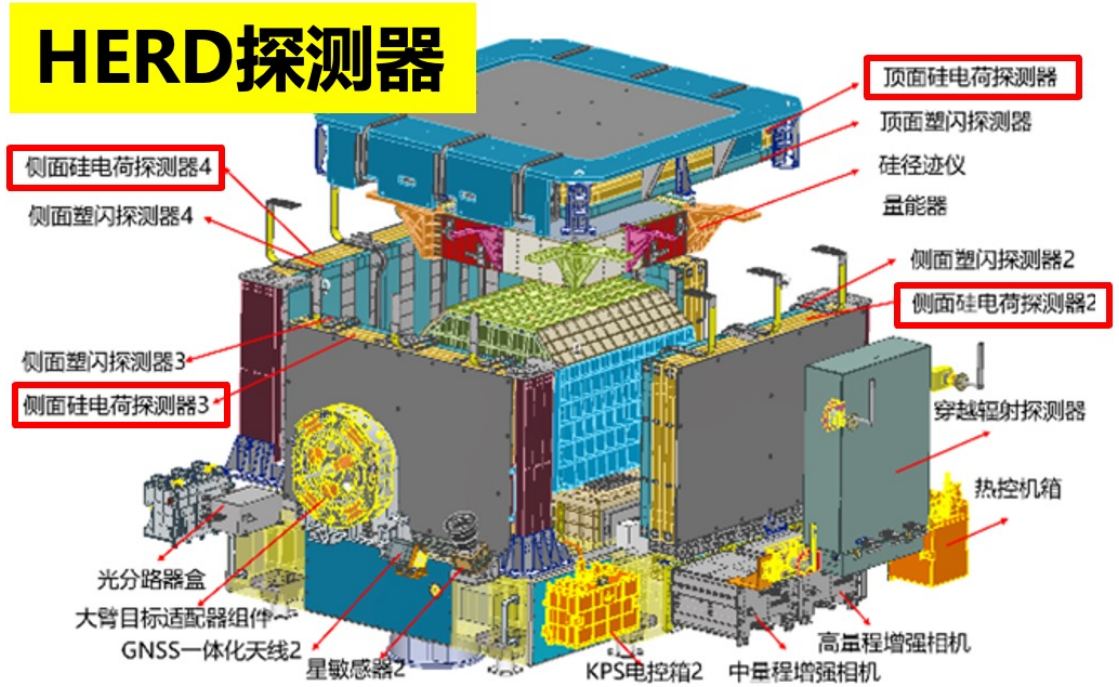
X-direction of the datalogger in Box 1 is the same as the typical forklift moving direction

Incidences that the total gravitational acceleration > 5 are marked

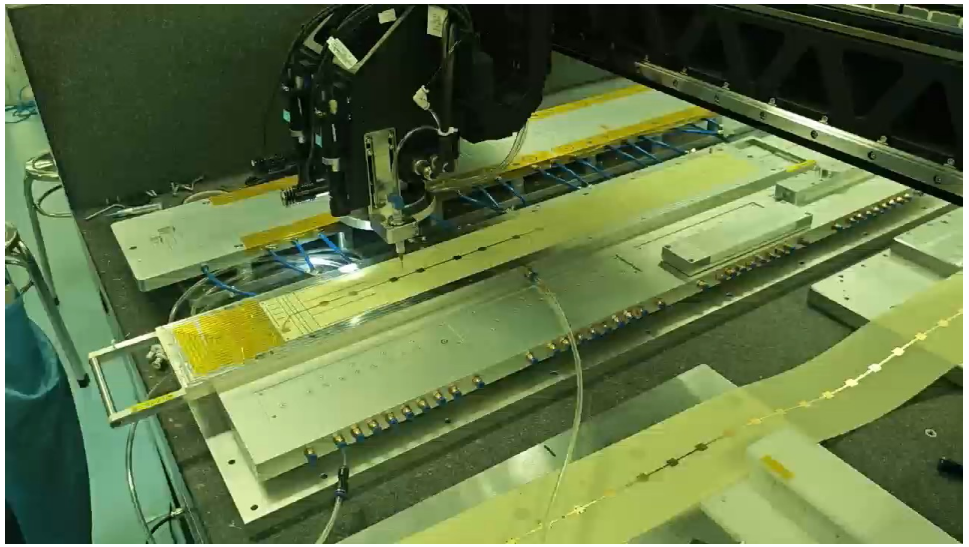
中国空间实验项目：HERD

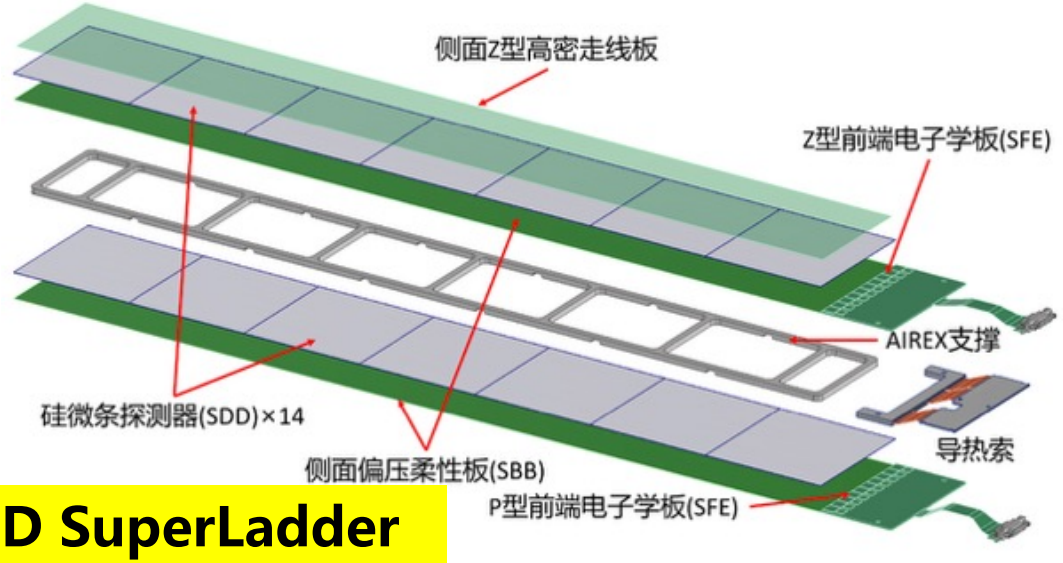
高能宇宙辐射探测设施HERD是中国空间站标志性的旗舰级重大科学装置

- 三维位置分辨、五面灵敏的创新设计，核心科学能力将长时间保持大幅度国际领先
- 核心科学目标：宇宙线性质研究、暗物质信号寻找以及大视场高能伽马射线全天候观测等



HERD SCD/STK探测器





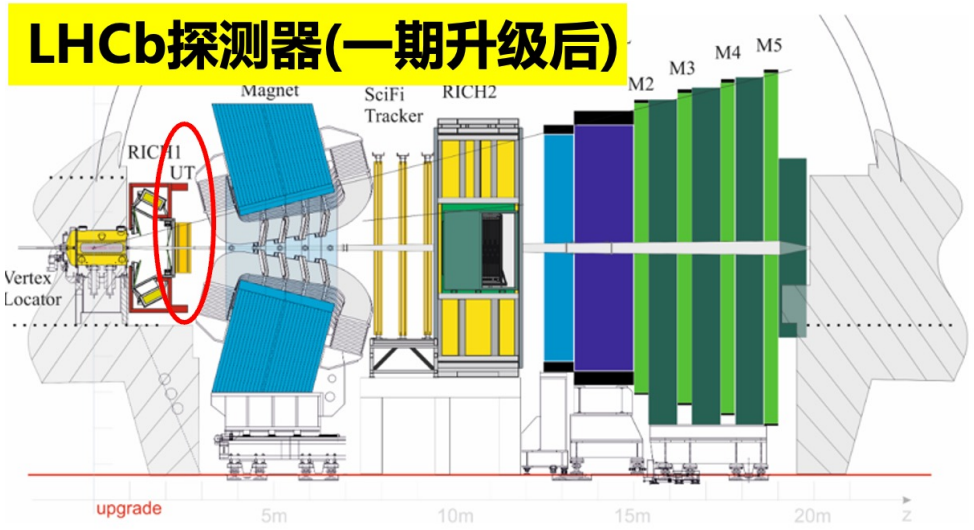
侧面SCD SuperLadder

2026年1月完成Z型ladder力学件组装

2026年2月首个Z型ladder测试件组装

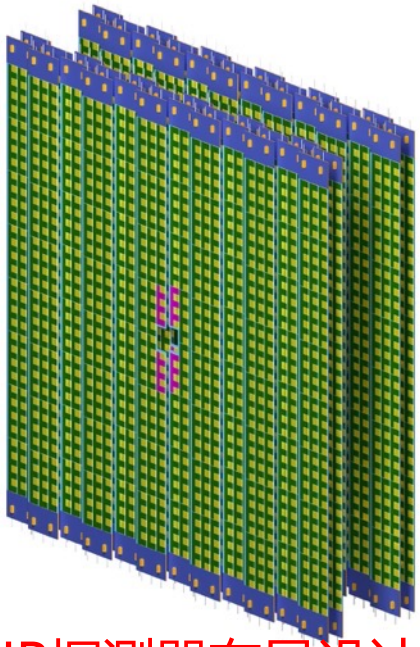
2026年4月完成首个Super Ladder力学件，流程确定

LHCb磁场上游径迹探测器

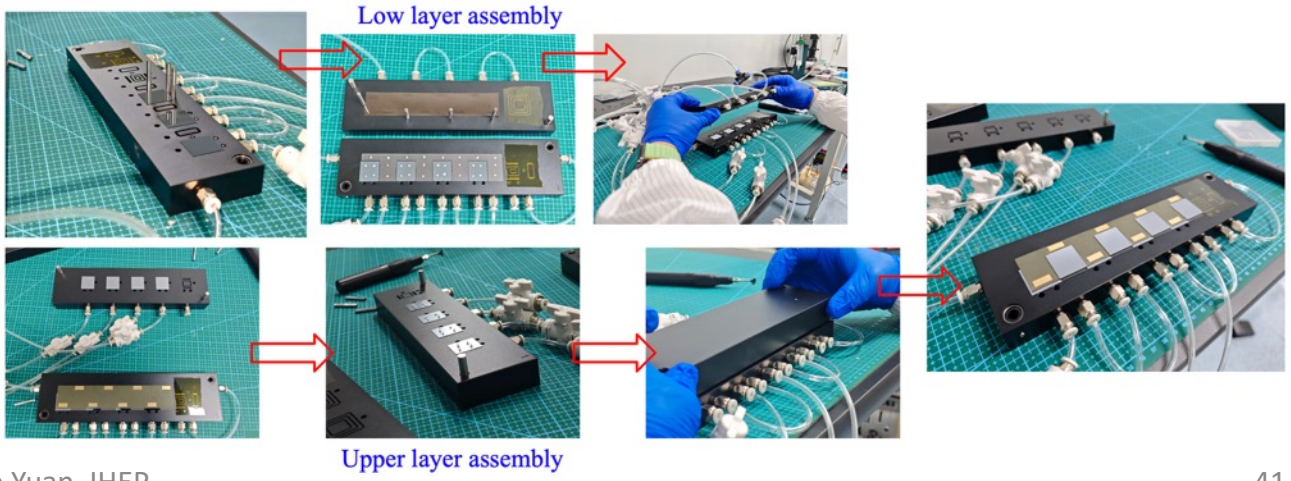


LHCb实验是精度前沿检验标准模型，开展重味物理研究的重要平台

- UT探测器是一期升级全新硅微条径迹探测器，位于LHCb磁场前端，对径迹重建速度、径迹误重建的控制、动量分辨率以及长寿命粒子的重建具有重要意义
- UP探测器是二期升级硅像素径迹探测器，由高能物理研究所领导研发



UP探测器布局设计



总结

AMS L0探测器升级研究项目

- **全部探测器模块组装集成 (已完成)**
- 探测器模块束流测试
- 探测器整体组装

关键技术问题

- 实现超长（96厘米）硅微条探测器模块传感器芯片组装精度~**3.4** 微米
- 探测器通道良品率高于**99** %
- 探测器面积 双层共计**8** 平方米

为未来AMS实验在宇宙学领域的探索奠定重要基础

大面积、高精度半导体探测器组装技术积累，为我国相关探测器研发奠定基础

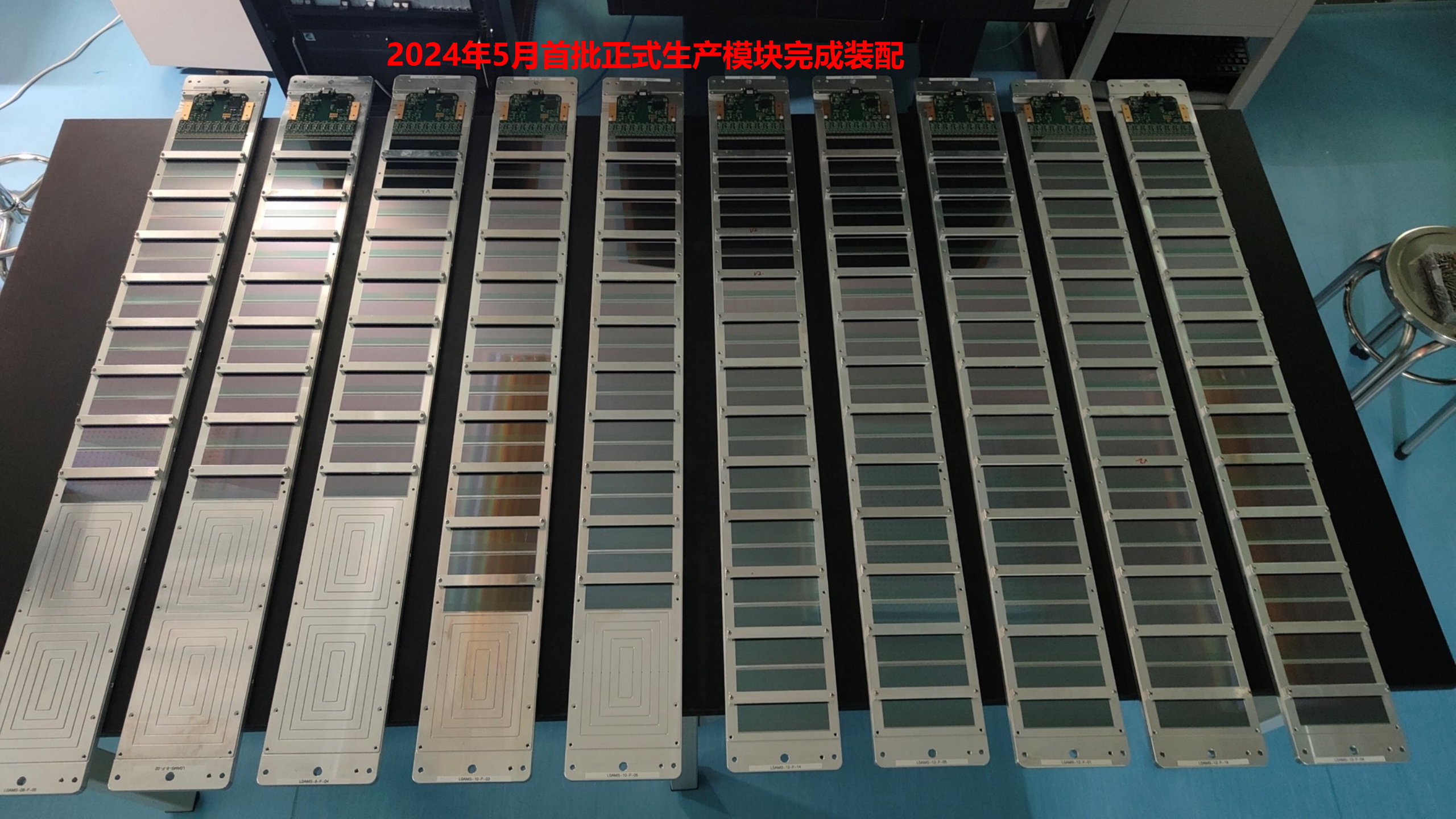
- 我国首个完成的大面积半导体探测器模块
- 与国内厂商深度合作，具有重要的社会意义

中国在半导体探测器的发展，进展迅速

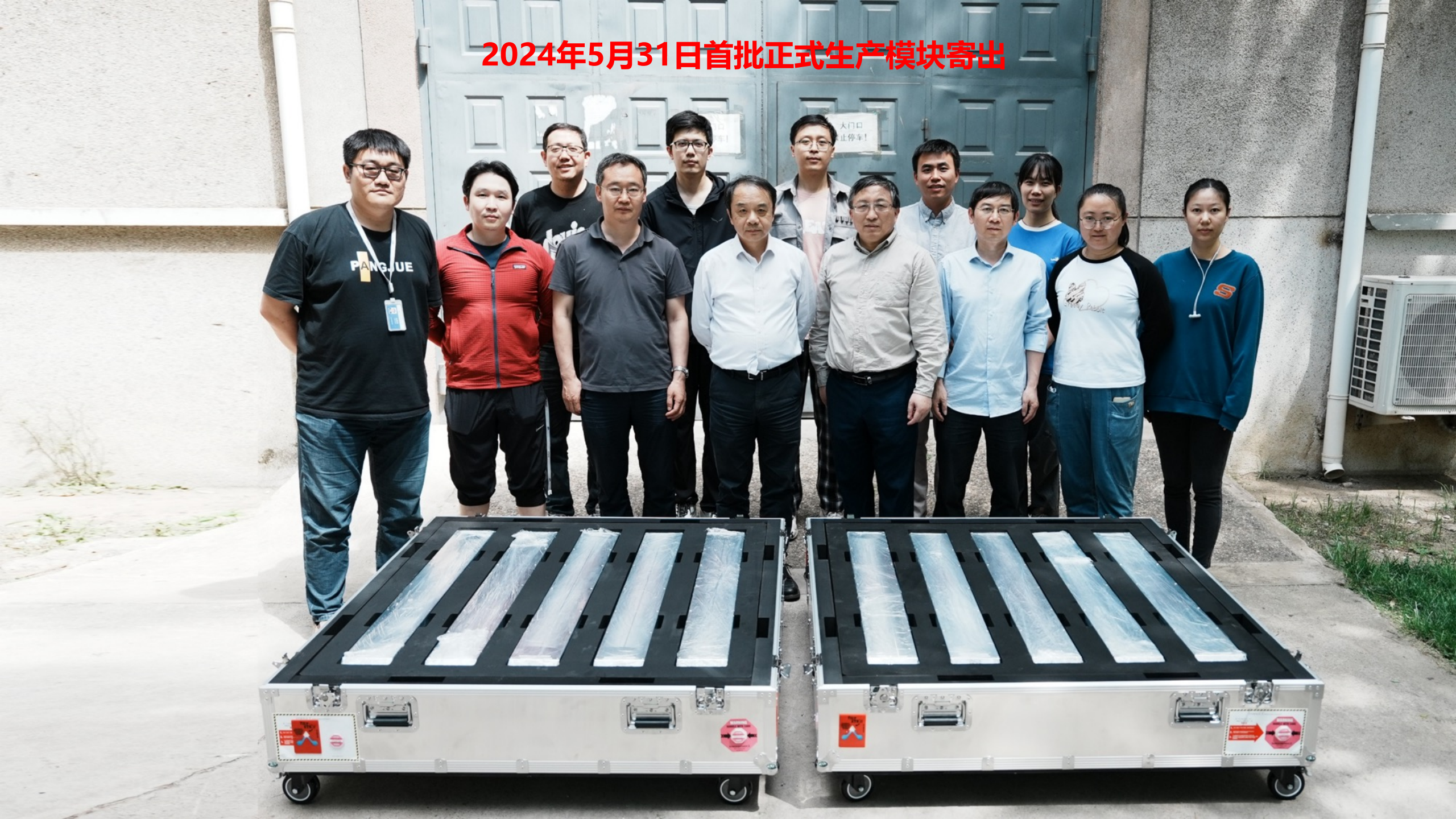
- HERD, CEPC，STCF实验等中国主导探测器研发
- 国际合作领域，LHCb UT/UP，ATLAS ITK/HGTD，CMS HGCal …

补充材料

2023年8月预生产测试模块生产完毕，寄往意大利

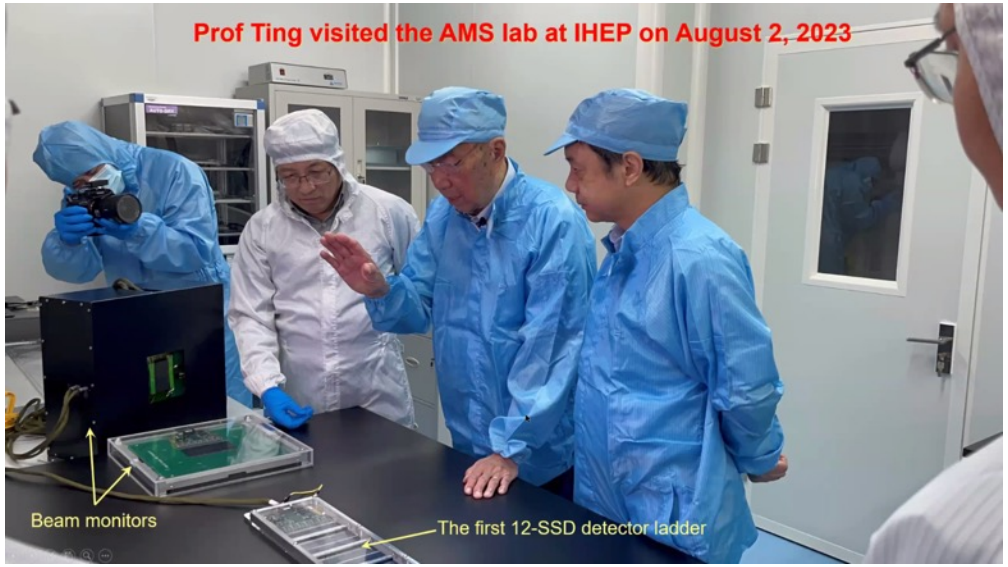

2024年5月首批正式生产模块完成装配

2024年5月31日首批正式生产模块寄出



AMS L0 Upgrade Module Production
Successfully completed
2024年9月完成全部正式生产模块

国际合作与交流

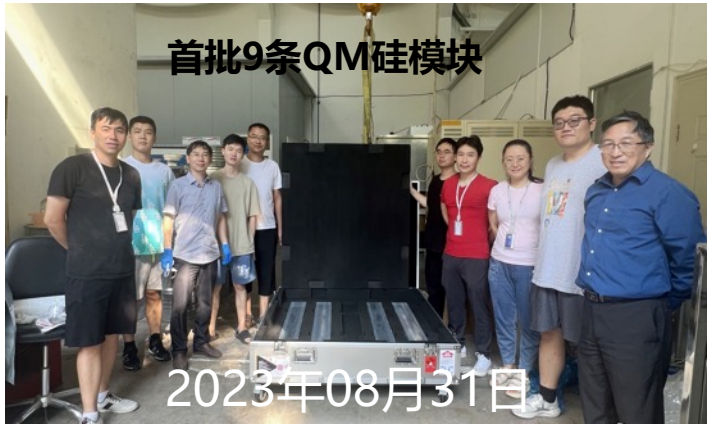


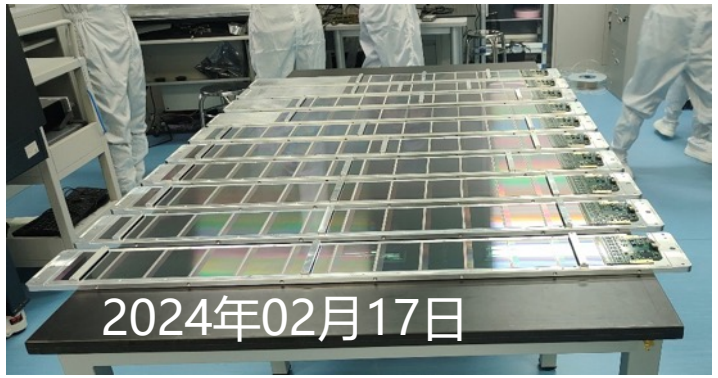
AMS TIM会议

- 2023年5月18日-19日和2024年1月7日

数次接待国内外专家参观访问

AMS L0模块生产进展

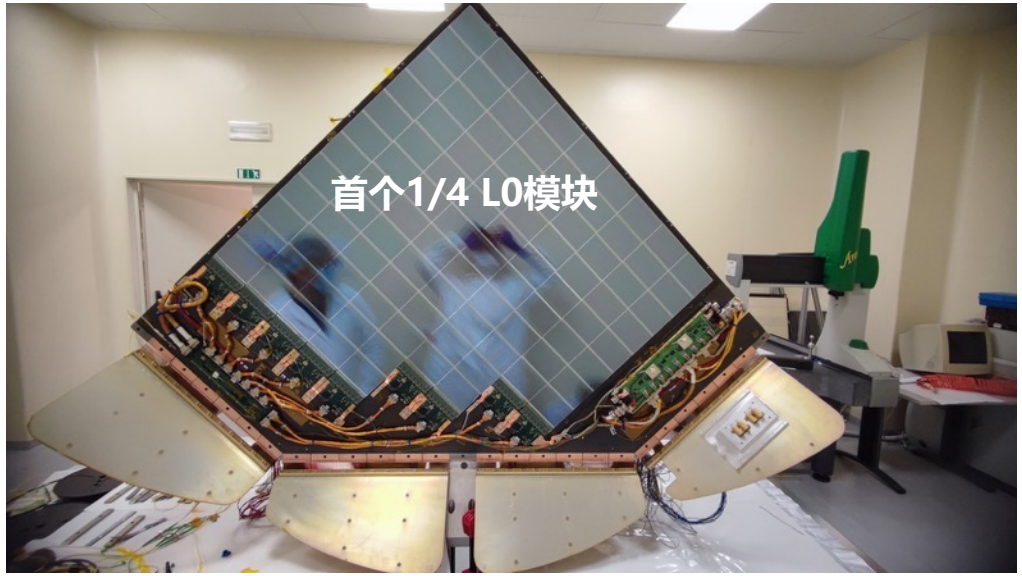




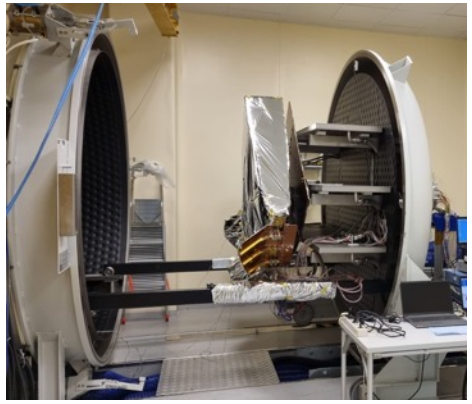
首批正式生产硅模块（9条）

首批正式生产硅模块交付

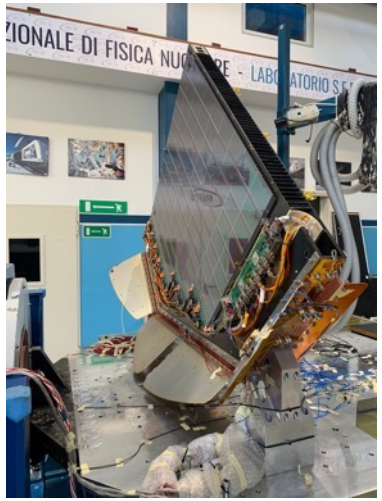
1/4 L0模块测试



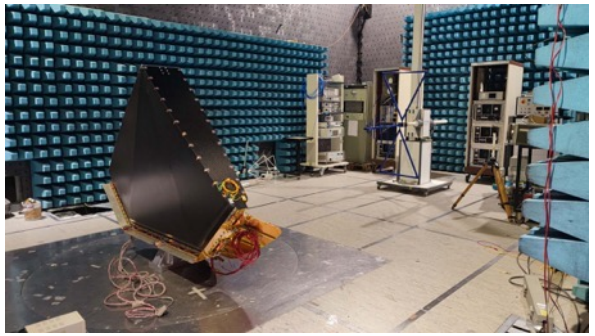
热真空测试



振动测试



EMI测试



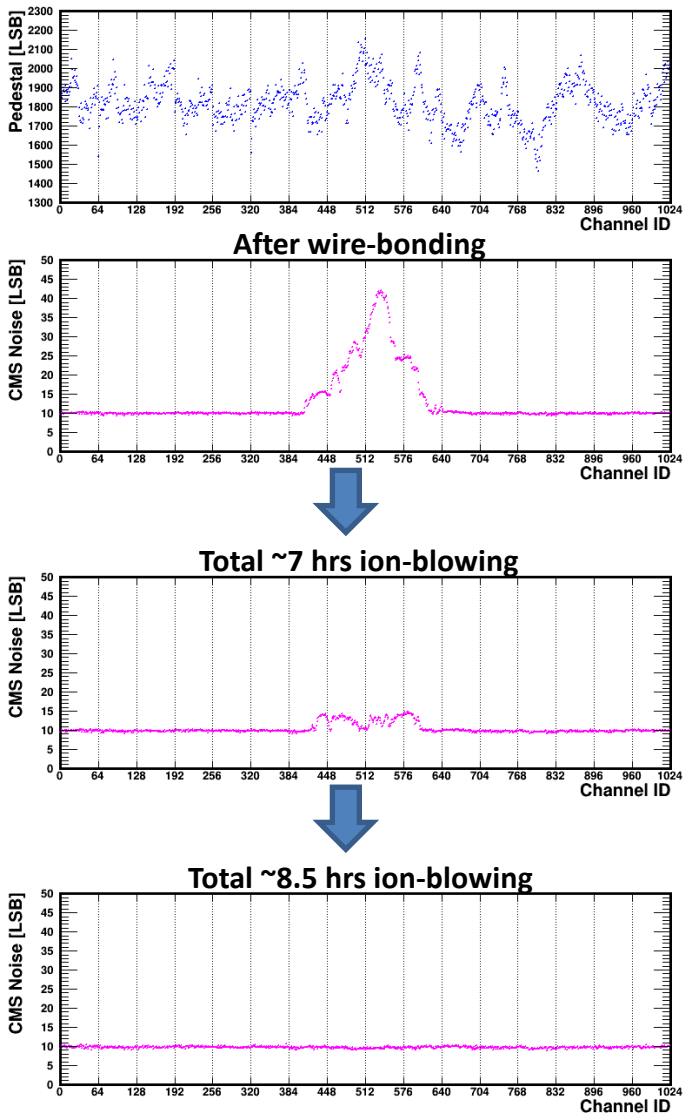
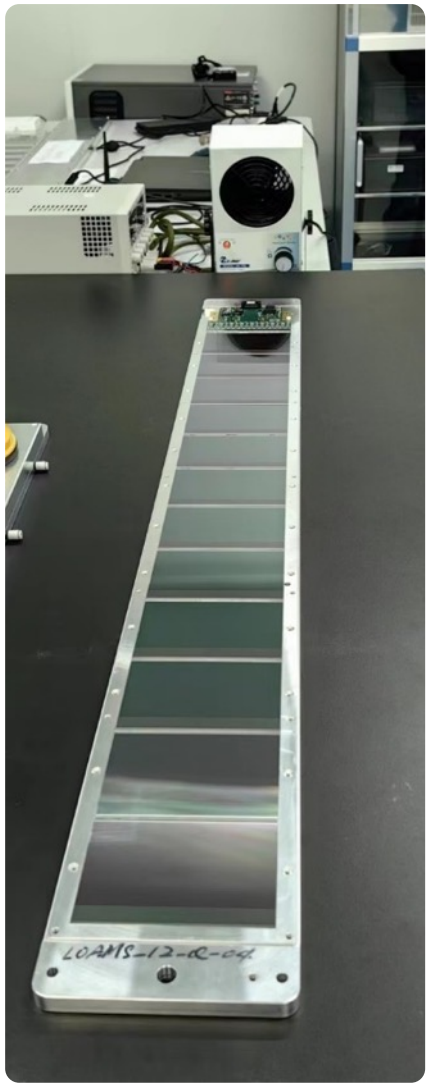
2023年11月完成首个1/4 L0模块组装

- 模块通过热真空、振动测试
- 后续进行EMI测试以及束流测试

硅模块质检

质检包括视觉检验和电子学检验

- 低压控制电路检测
- 高压控制电路检测
  - 12-SSD模块：1.75微安培，50伏
  - 8-SSD模块：1.75微安培，50伏
- 电子学噪声测试
  - 12-SSD模块：10 ADC单位
  - 8-SSD模块：8 ADC单位

数值降低：电子学键合连线失败
数值偏高：硅传感器内部破坏导致

静电效应
- 噪声影响
- 电离风扇消除 ~$\mathcal{O}$(10)小时