CMS 高粒度量能器升级

高能所，清华大学

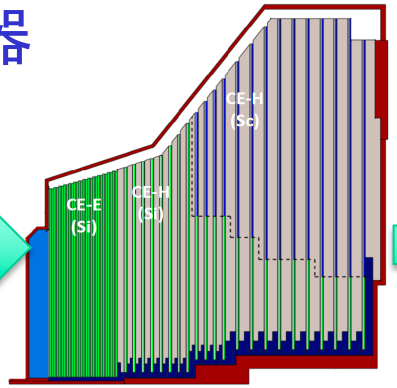
张华桥，高能物理研究所

科技部国家重点研发计划
《大型强子对撞机上CMS和ALICE探测器升级》年会
2024年7月13号

CMS 高粒度量能器：基于硅传感器的真五维量能器

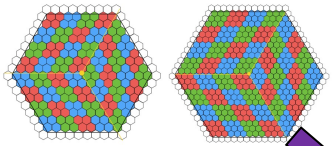
- 基于硅的高粒度量能器

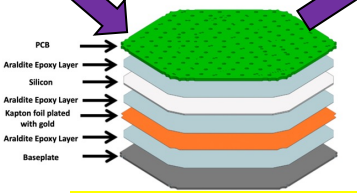
法国/葡萄牙/日本/英国
~20年的研发，未正式建造



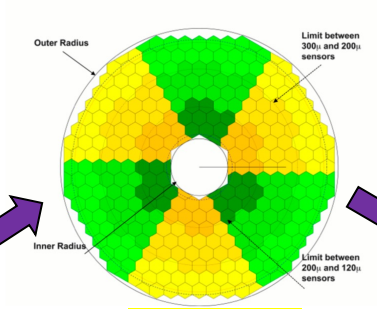
CMS 高粒度量能器（建造中）

其他未来高能物理实验，空间项目等



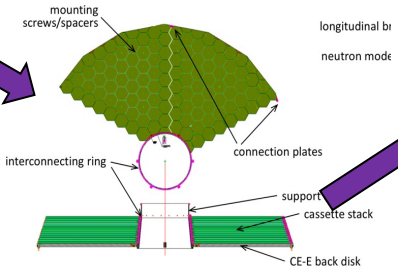


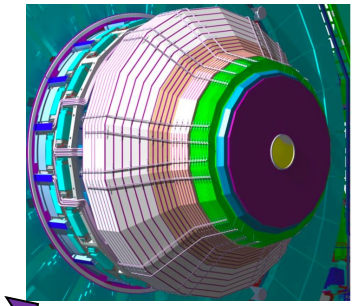
Module Assembly



Tiling

Stacking

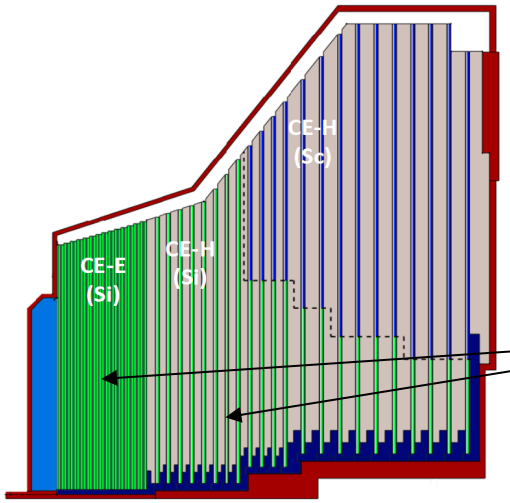


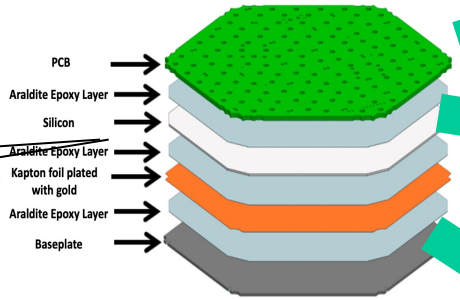


5D量能器：能量，三维位置，时间；
抗辐照性能好：10^{16} MeV 中子/厘米^2

中国CMS高粒度量能器项目

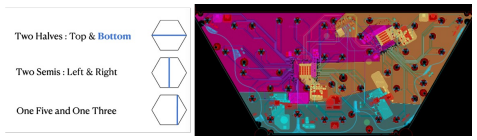
高能所是最早参与的10个单位之一，承担一个硅模块中心等任务



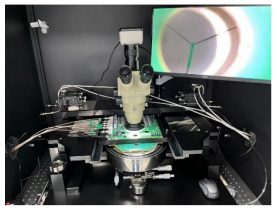


拿到2次为期一年的硅模块材料免税许可

PCB：完成底部硅模块电路板设计
2023/10月通过review（浙江大学）



硅传感器：建立了测试中心，将为高能所硅模块所需所有传感器抽样测试（高能所）

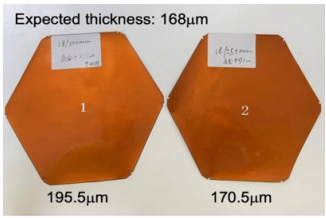


共~26000 硅模块（620平米硅传感器）

中国组核心任务：～1/5硅模块的生产

在高能所建立了硅模块中心，首批通过合作组审核，率先试制成功8寸硅模块，近一年为CERN
电子学系统评估，机械性能测试
提供了>30块新模块

钨铜合金底板：已经生产了75块，将为高能所硅模块中心提供所需钨铜合金底板，正在进行辐照测试



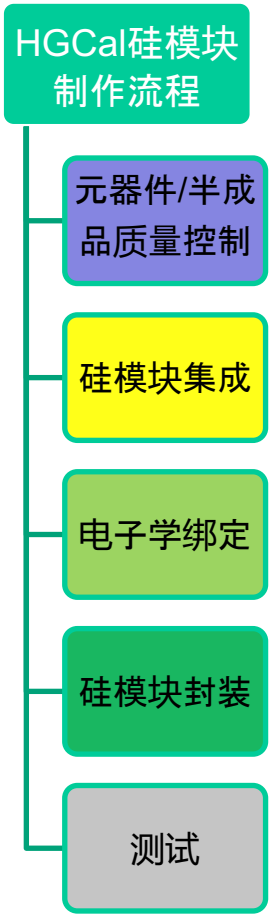
国内参与单位：
- 高能所
- 清华大学
- 浙江大学
- 复旦大学
- 南京师范大学

硅模块集成技术方案

CMS高粒度量能器已经在上期科技部重点研发项目支持下完成了物理设计指标：

- 能量分辨率：25%/ sqrt(E)⊕1% ；时间分辨：50ps；抗辐照性能1×10^{16} neq/cm^2

本项目：百平米量级硅模块的集成，解决硅模块从1到1000的问题，实现5D量能器从0到1



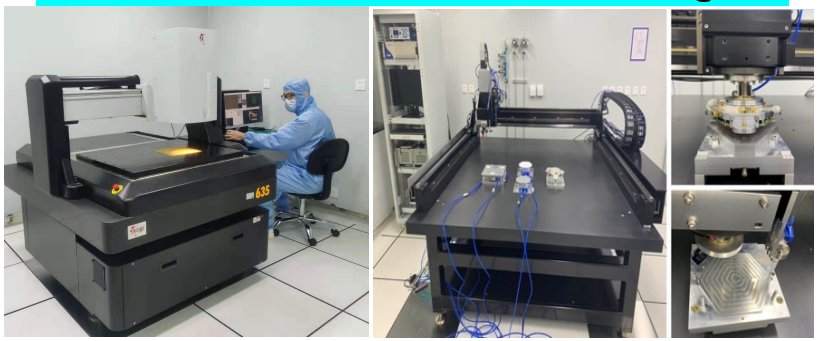
- 发展完善硅模块生产工艺
  - 关键技术：高精度贴片（10微米量级），大面积硅传感器的键合，封装，测试等
- 建立完善的质控流程
  - 元器件表面测量及筛选
  - 硅传感器测试
  - 硅模块电子学测试，噪声控制等
  - 硅模块温度循环测试
- 建立数据库系统对硅模块建造进行全程跟踪，分析，提高硅模块建造成功率

- 高能所高粒度量能器硅模块中心
  - 将承担平均~5000 模块, >100 m^2的硅传感器;
  - 2021 首批通过了cms高粒度量能器硅模块中心站点认证;
  - 近一年内生产了~30块 能获取数据的模块，用于各类R&D
  - 目前已有~30 学生,~10 博士后 在中心进行了相关的工作

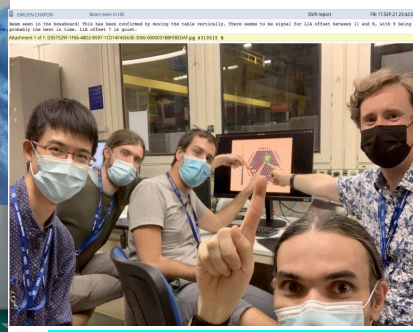
HGCal Module Assembly

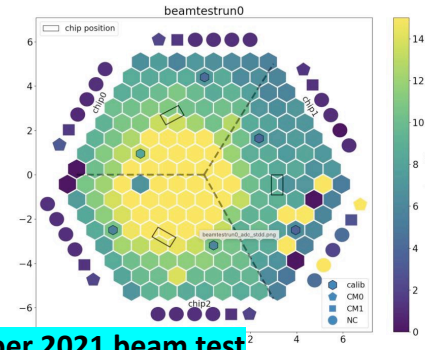
- Components test
- Assembly
- Wire bonding
- Encapsulation
- Module testing
- QA/QC

Dedicated lab established from scratch for HGCal @ IHEP



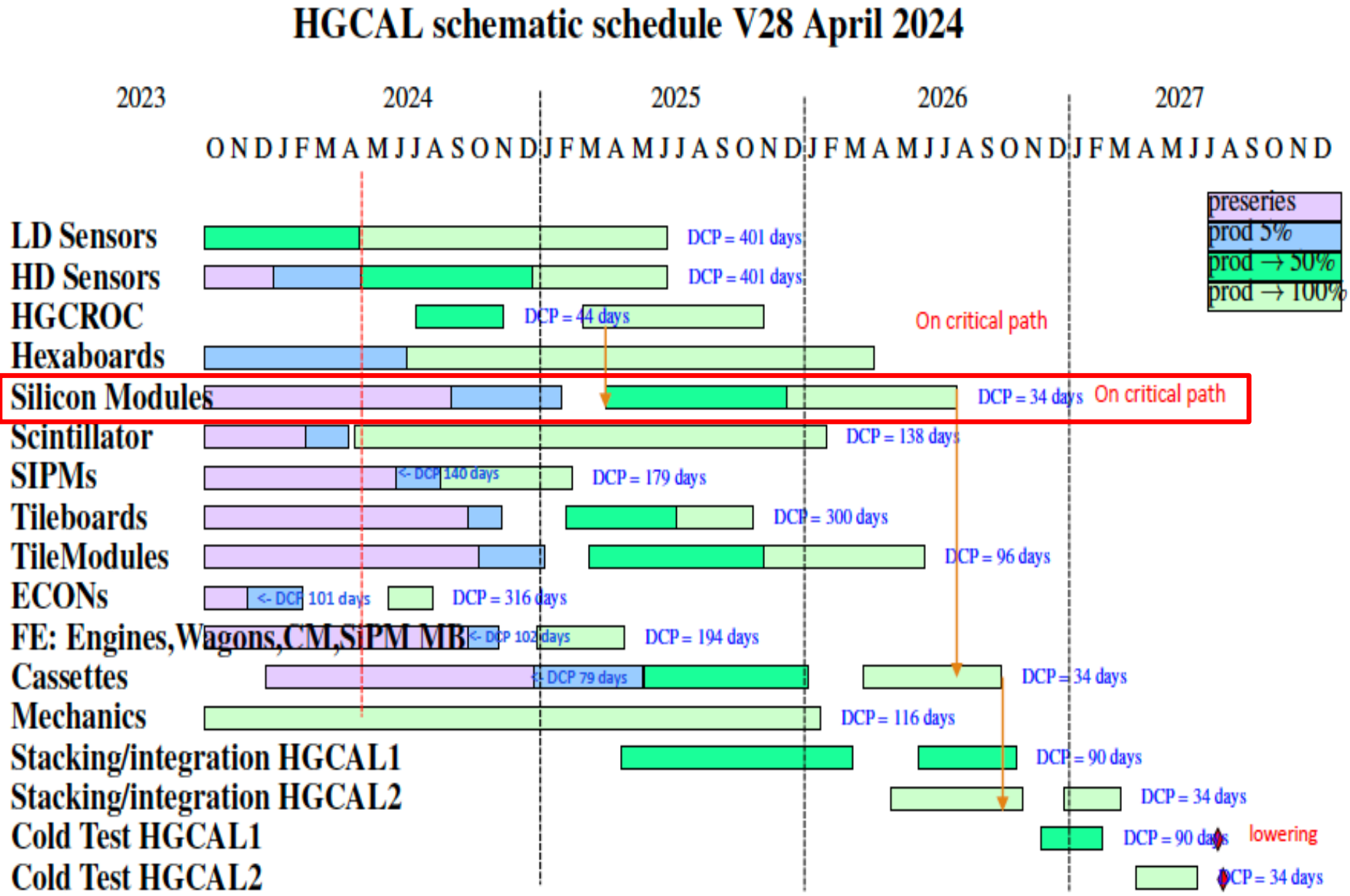
Part of IHEP HGCal team





IHEP LD Module in September 2021 beam test

高粒度量能器项目时间表



高粒度量能器模块生产计划

2023年9月电子学系统评审（4块模块）

2024年2月 pre-series（10块模块）

2024年5月：HGCROC3B 改装测试（9块）

2024年7月：pre-production最终验证（7块）

2024年8月：pre-series 10块

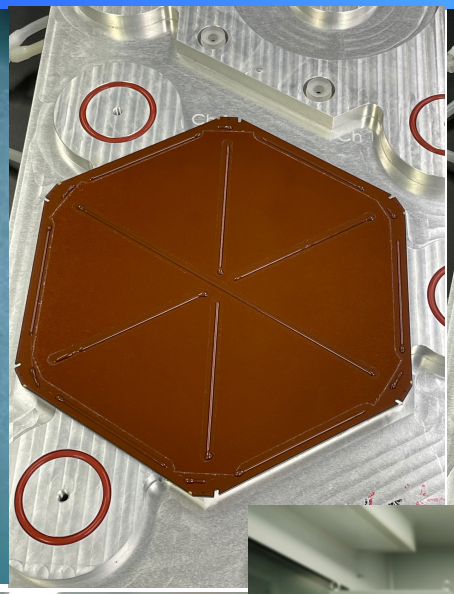
2024年9月-2025年3月：pre-production

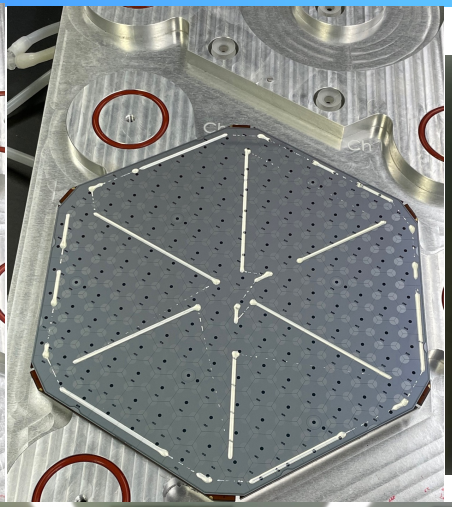
2025年4月-2026年9月：production

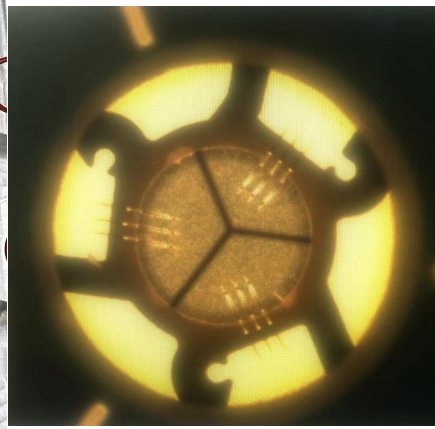
Calendar	July 2024	August 2024	September 2024	October 2024	November 2024	December 2024	January 2025	February 2025	March 2025
CMU			10	20		40	57	0	0
TTU			10	20		40	58	0	0
IHEP			10	20		40	57	0	0
TIFR			10	20		40	58	0	0
NTU			10	20		36	52		
UCSB			10	20		36	53		
LD full modules made this month			40	80	0	160	230	0	
LD full running total (up to 510)			40	120	120	280	510	510	
HD and partial moduls made this month			20	40	0	72	105	0	
HD and partial module running total (up to 132 and 105)			20	60	60	132	237	237	
Notes	Develop second tray! Develop as many partials as possible! Purchase tooling for 2 x assembly trays on gantry!		2 per day(one tray) x 1 week this month	4 per day (on 2 trays) x 1 week this month	Buffer month Multi-module test stand? Hiring/training new workers? Holidays in Dec+Jan?	8 per day (on 2 trays) x 1 week this month	12 per day x 1 week (a couple of modules short on final day)	Perhaps Dec and January plan will need to stretch into later months if new chips cause delays past April 2025	
						UCSB and NTU are out of HD fulls	LD full MACs are out of modules		
							NTU and UCSB work on runs of partials		

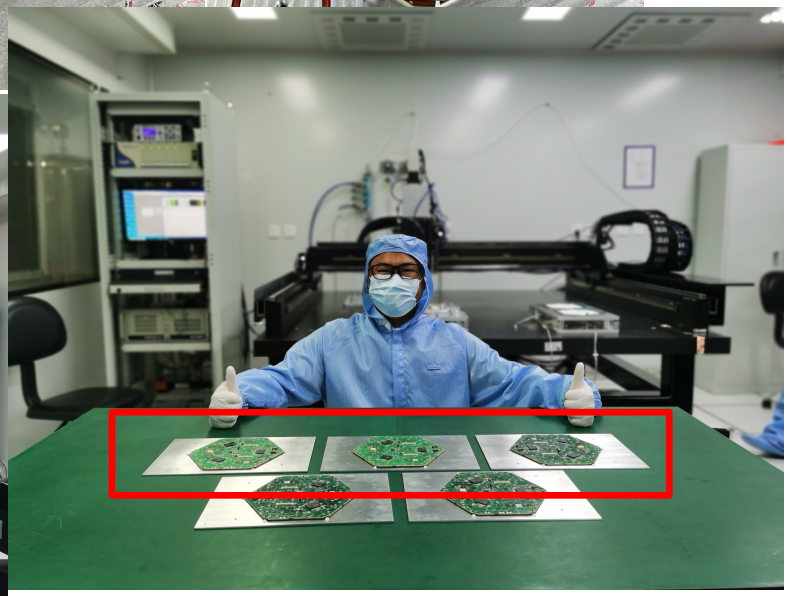
生产从1块/天提升到16块/天

CMS首批7块pre-production模块：可安装上探测器取数







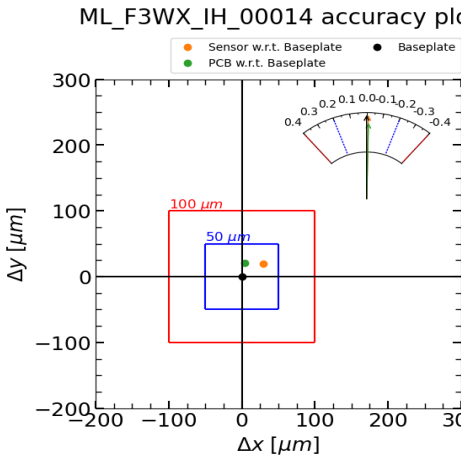


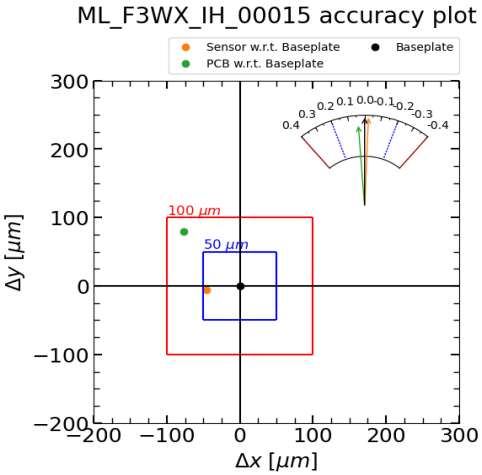
应紧急请求：这三块已经发送到CERN

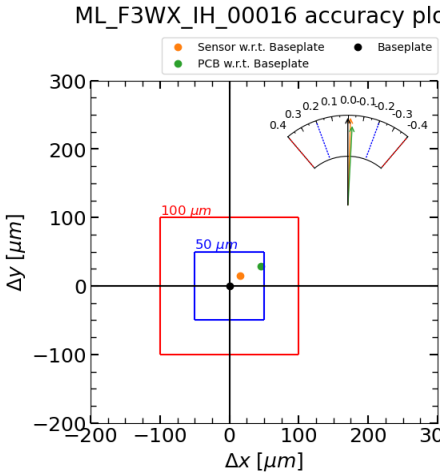
详细的生产可以参考王峰下午的技术报告

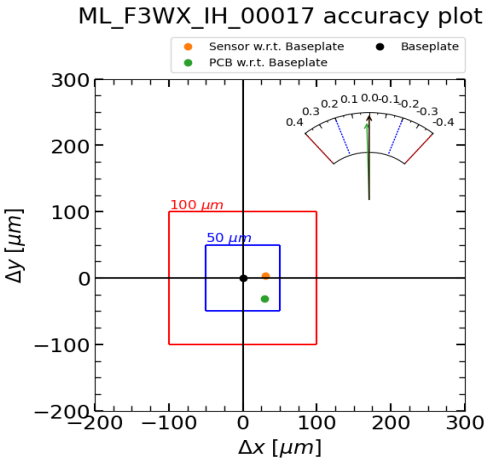
模块集成精度

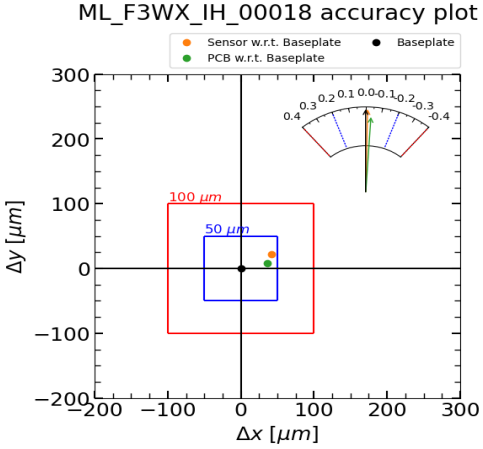
精度考核目标：好于100微米

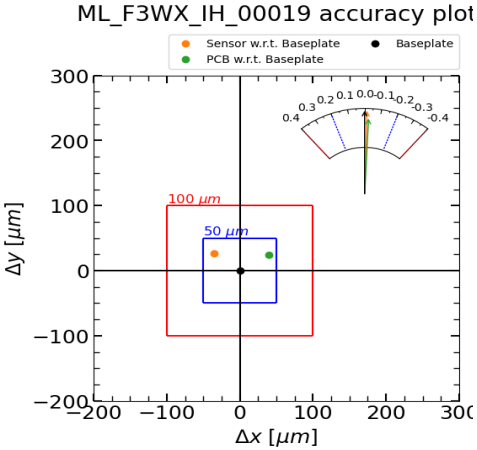


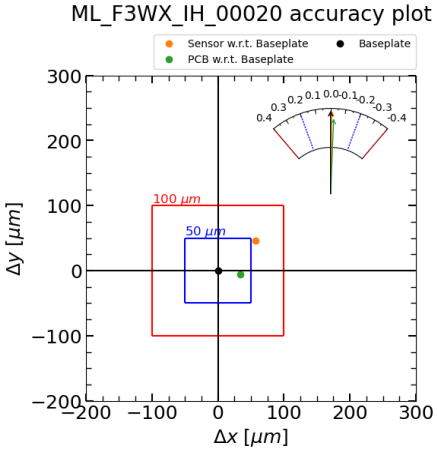






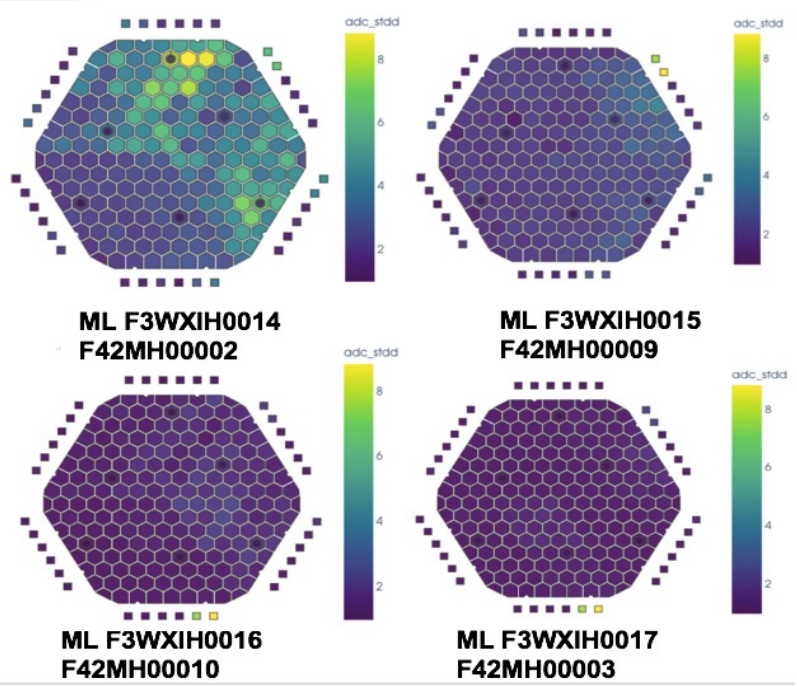


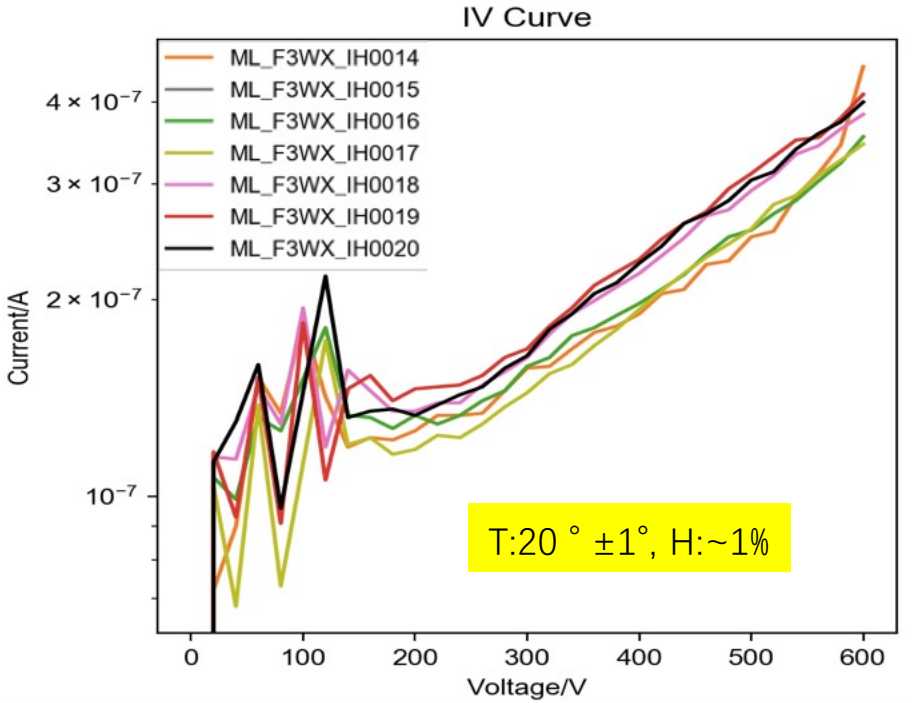


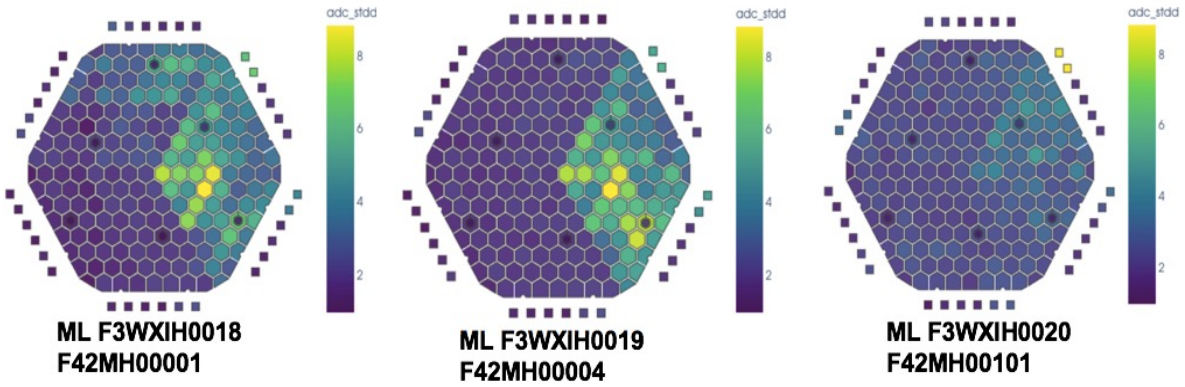


- All modules alignment preforms good (the worst case is 77μm)

模块噪声和I-V测试结果

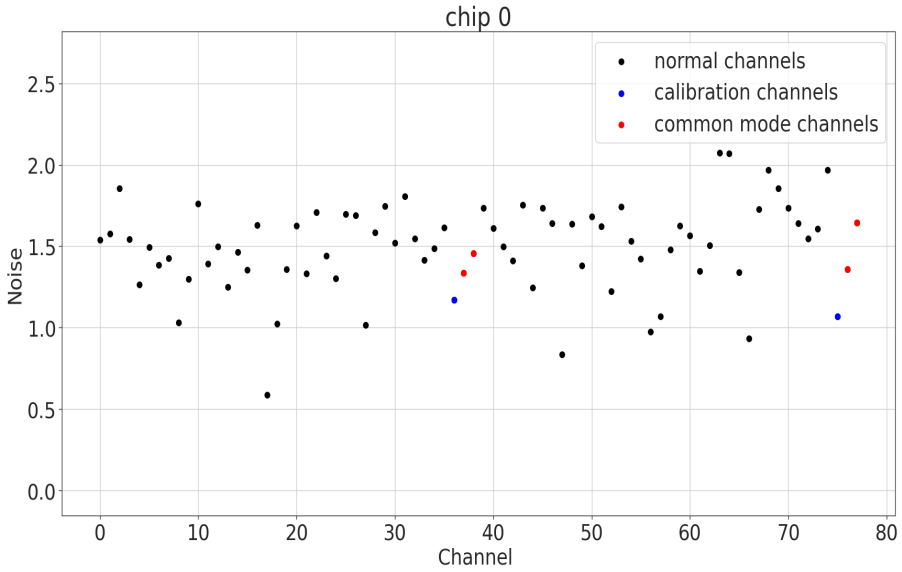


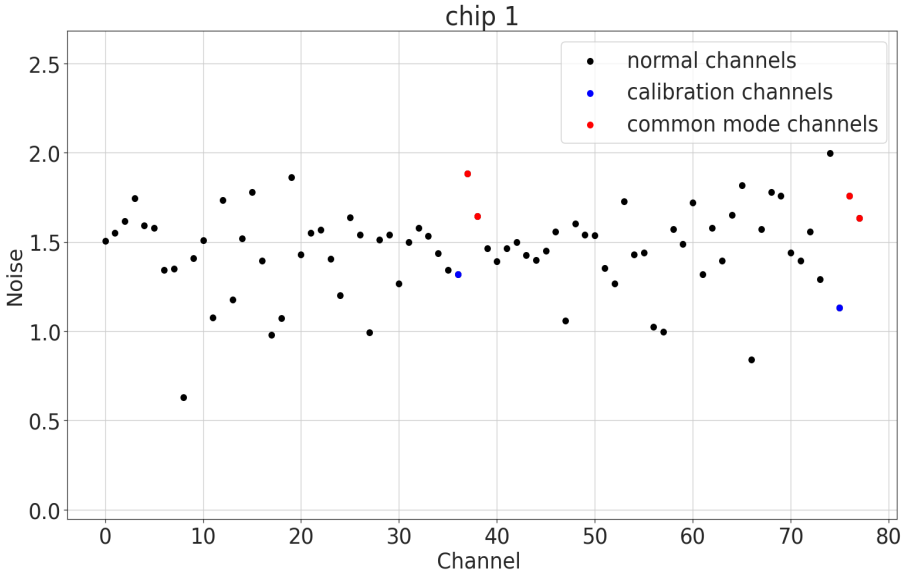


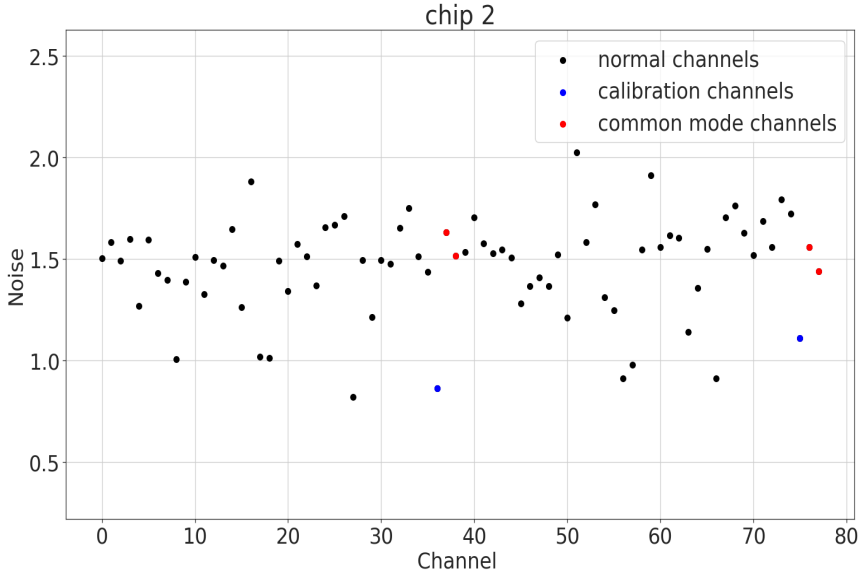


CERN新制作的测试板，新update的测试软件，测试系统未完全优化

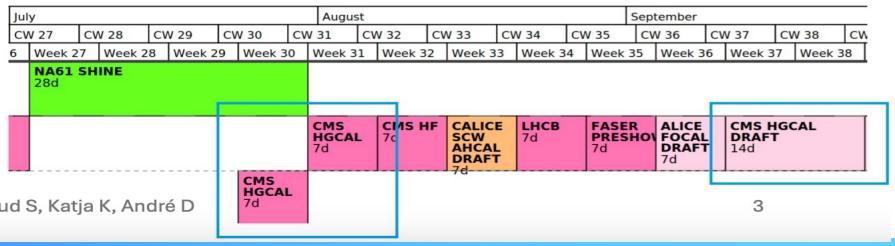
CERN测试IHEP模块的结果（周五晚10点30发给我）







- 非常小的噪声：~1.5ADC
  - Hexaboard：~1 ADC
- 怀疑是发给我们用的测试板DC-DC有问题
  - 马上给我们补发
- 7月底-8月初有HGCal束流



MAC模块生产情况汇总

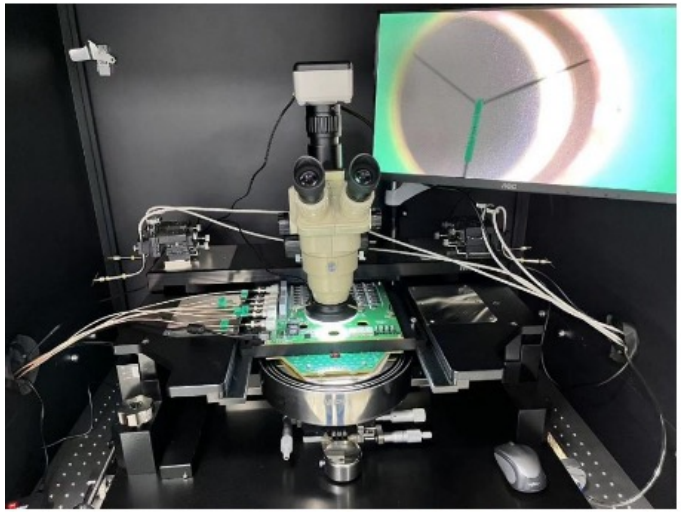
- 高能所硅模块中心模块A级品率和已生产数量均处于领先位置

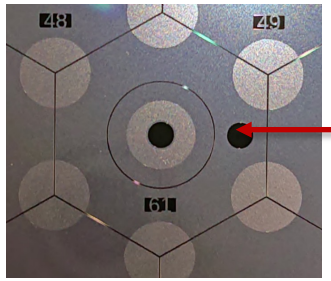
	Module produced	Type	Grade A	Not Grade A		
				Bad IV	Bad Readout	Bad placement
CMU	10	LD FULL	5	1		4
IHEP	30	LD FULL	25	3	3	0
NTU	21	HD FULL LD LEFT	16	5	2	
TIFR	0	LD FULL				
TTU	11	LD FULL	7	3	1	
UCSB	30	LD FULL HD FULL LD RIGHT	18	6	4	2

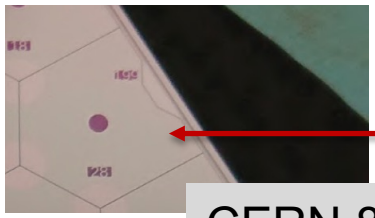
- 部分Bad IV 有可能通过长时间放在干燥环境恢复
- 高能所的3块bad readout都是在hexaboard集成之前已经损坏，其中一块bad IV

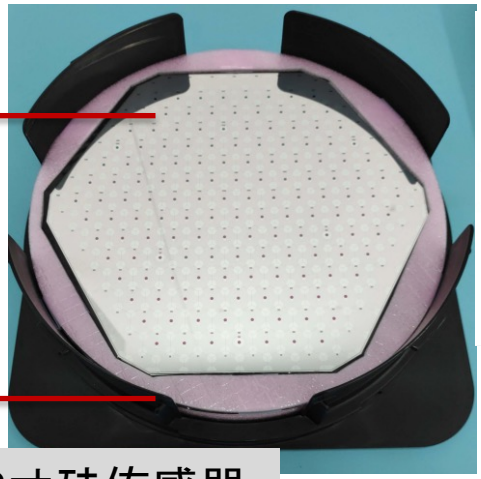
高能所硅传感器测试站点SQC

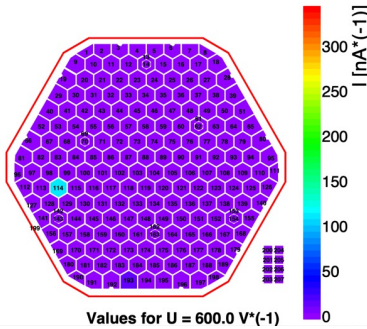
- 目标:为高能所硅模块中心提供抽样测试后的硅传感器
  - 2023年10月份发送了75块production sensor
  - 预计2024年8月再发送75块production sensor





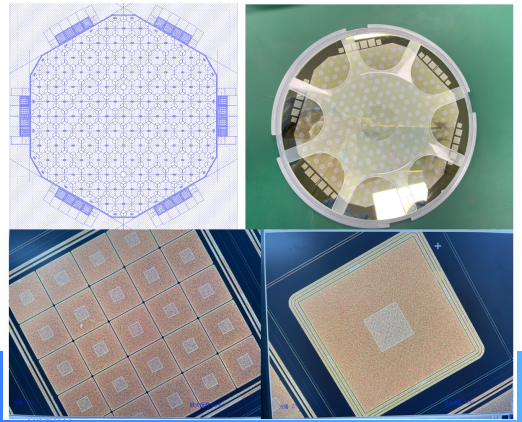


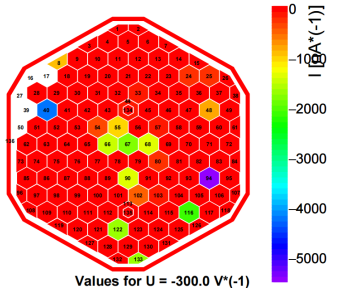




CERN 8寸硅传感器

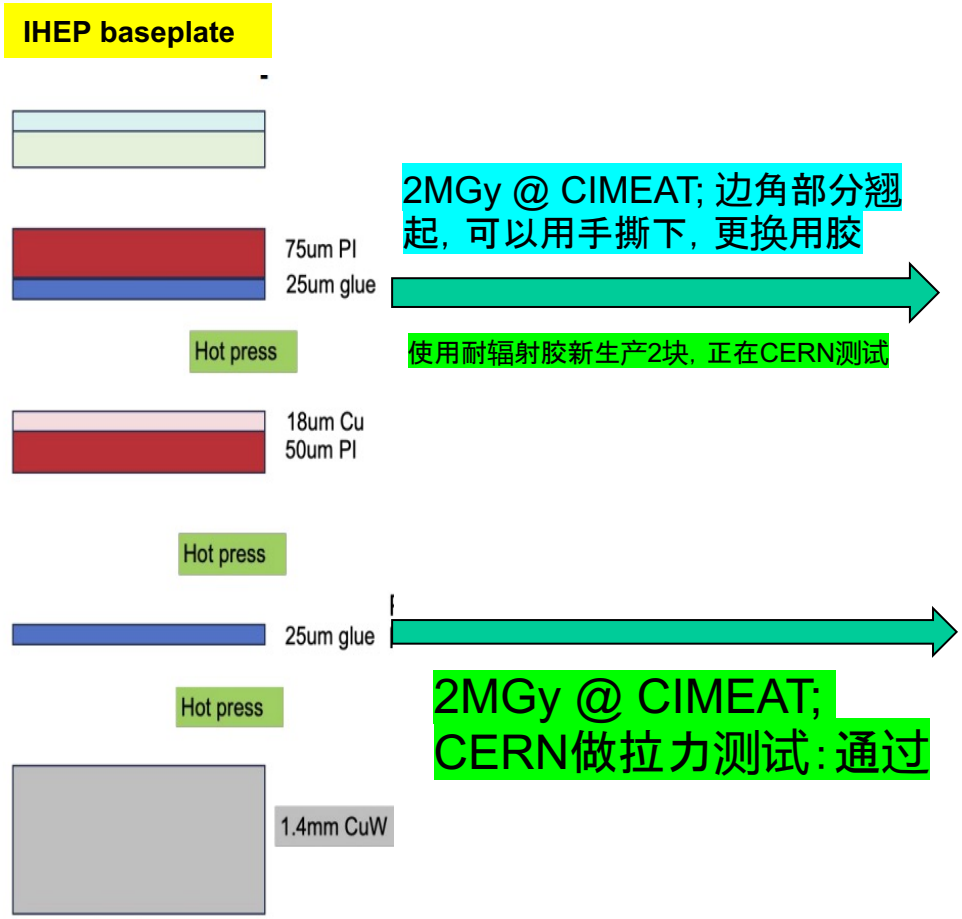
国产6寸硅探测器及测试单元





详细内容可参考刘勇下午的技术报告

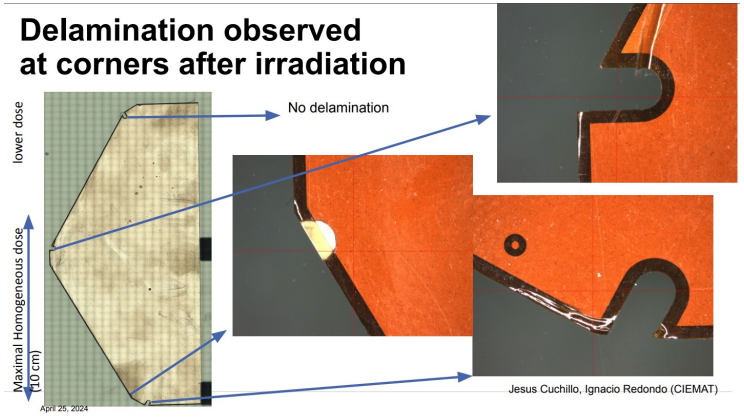
高能所钨铜合金板的辐照测试



2MGy @ CIMEAT; 边角部分翘起，可以用手撕下，更换用胶

使用耐辐射胶新生产2块，正在CERN测试

2MGy @ CIMEAT;
CERN做拉力测试：通过



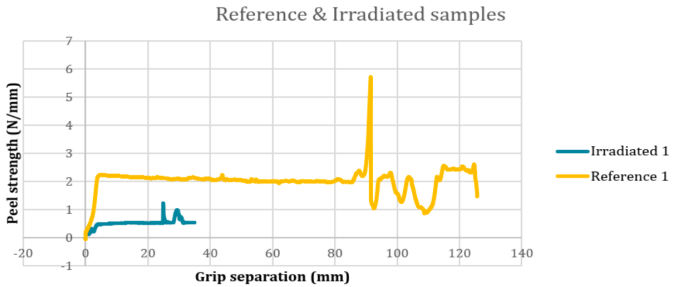


Figure 11- Graph sucessful reference & irradiated results

Table 3- Sucessful reference & irradiated results

	Reference 3	Irradiated 1
Peel strength N/mm	2.06	0.50

Matches the value in the glue specs

目前计划～2/3的 CuW采用我们的设计，CERN和中国一起在国内采购：k-contract

剩下部分采用双面胶+结构胶的设计，由德国，印度，西班牙负责采购生产

文章，专利

- HGCal文章（HGCal合作组文章，参与模块制作、数据获取、分析）
  - Timing Performance of the CMS High Granularity Calorimeter Prototype. JINST, 2024-04, Vol.19 (4), p.P04015
  - Performance of CMS High Granularity Calorimeter prototype to charged pion beams of 20-300 GeV/c, JINST 2023_18_P08014
  - Neutron Irradiation and Electrical Characterization on the First 8” Silicon Pad Sensor Prototypes for the CMS Endcap Calorimeter Upgrade, JINST 2023_18_P08024

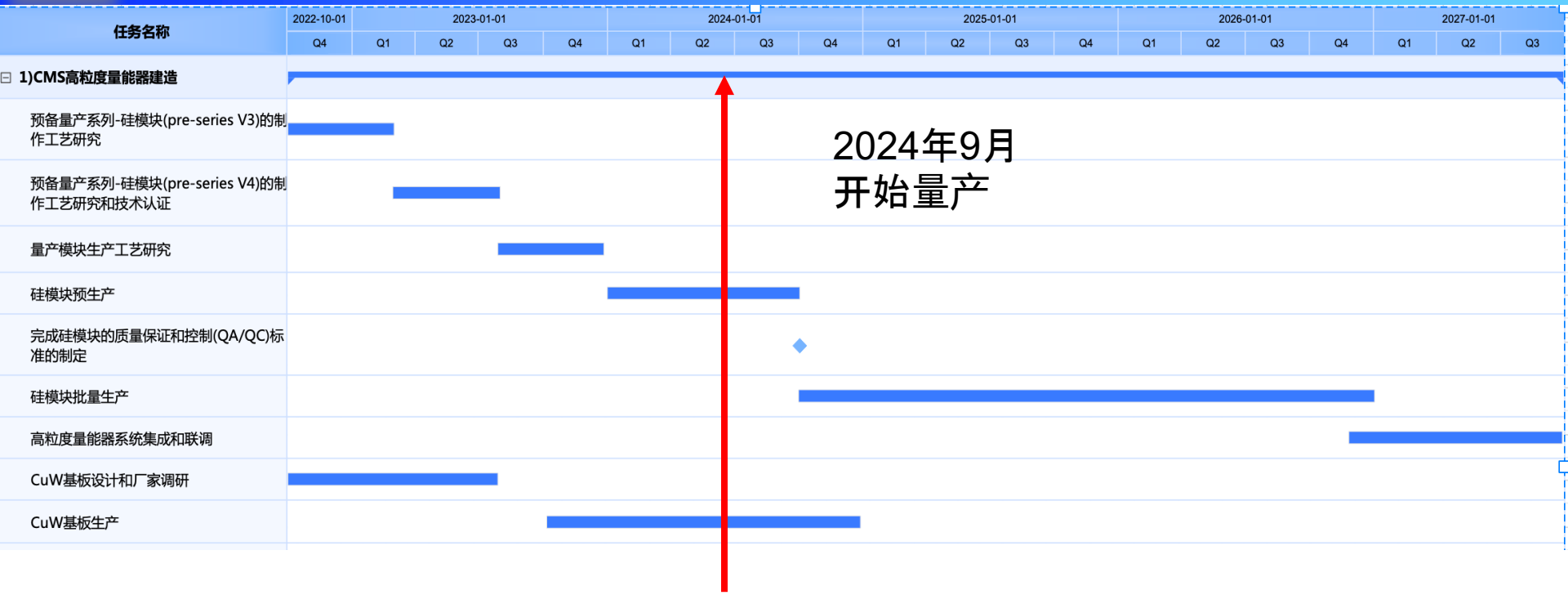
- 实用新型专利三项：
  - 一种大尺寸全自动硅片贴片机的视觉识别点胶装置, 2023-11-14, 中国, 202320302788 6 (专利)；王峰
  - 一种大尺寸全自动硅片贴片机的真空吸取装配装置, 2023-6-23, 中国, 202320352789 1 (专利)；王峰，杨生
  - 一种大尺寸全自动硅片贴片机,2023-3-22,中国, 202320357333 4(专利)，王峰，张华桥，王建春

总结(1)

- CMS高粒度量能器项目正在量产前夕
  - 元器件，生产工艺的最终验证正在有序进行
- 高能所硅模块研制走在各个MAC前列
  - 生产总数，grade A比例高
  - 承担特别紧急重要生产任务
- 高能所硅测试站点已经设立，并开始为高能所提供硅传感器
- 高能所CuW底板正在辐照测试中，预期能满足HGCal需求
  - ～2/3左右使用IHEP设计，在中国生产，CERN出一半的费用
  - 正在敲定和CERN的K-contract细节内容

- 量产准备工作
  - 元器件免税：2023年10和2024年7月分别拿到了2次为期一年的免税许可
  - 从1-16/天 的自动化准备，工艺优化，各种器件的抗辐照测试正在进行
  - 正在准备人力进行量产

总结(2)



- 目前硅模块量产安装计划进行，预期会按时完成模块集成数量
- CuW底板量产推迟，早期采用KIT生产的CuW底板至2025年4月
  - 更换工艺 + 辐照测试 + K-contract(CERN参与采购)；不影响模块量产
- 模块精度(7块)达到好于100微米，达到项目考核指标

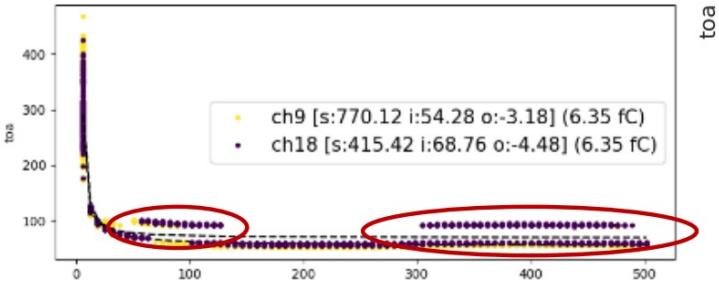
backup

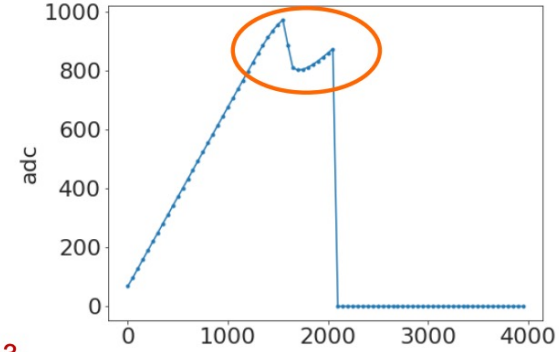
Unexpected TOT effect: sampling_scan

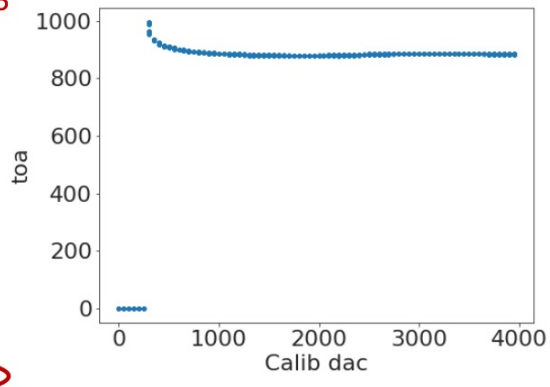
- During a sampling scan, injecting a charge triggering a TOT, data appear only on some phases but not all

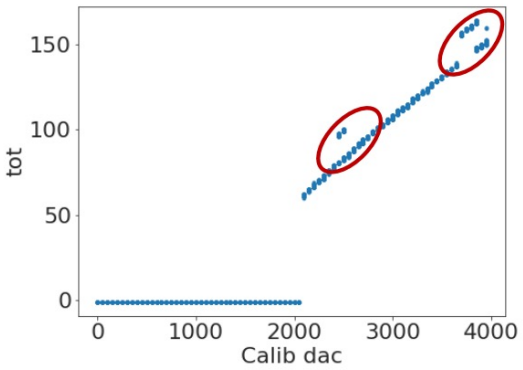
- ToT gap
  - For short ToT, TDC converts but provide 0
  - Mistigate with Cdet as larger ToT

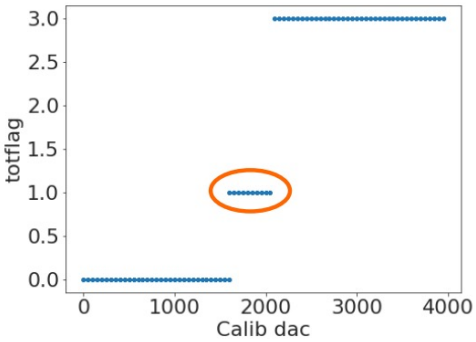
- ToA and ToT outliers
  - Positive outliers on the coarse TDC (+8, +16, +3
  - ToA and ToT





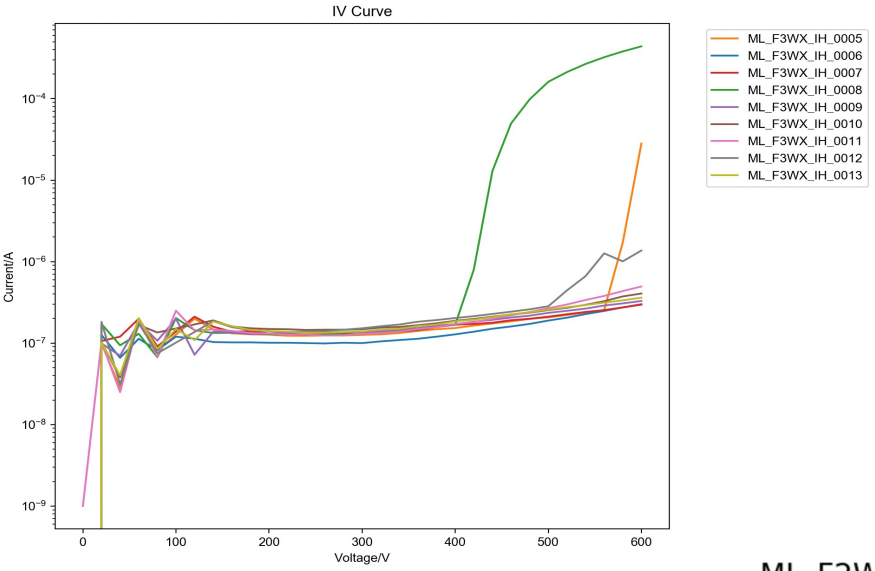


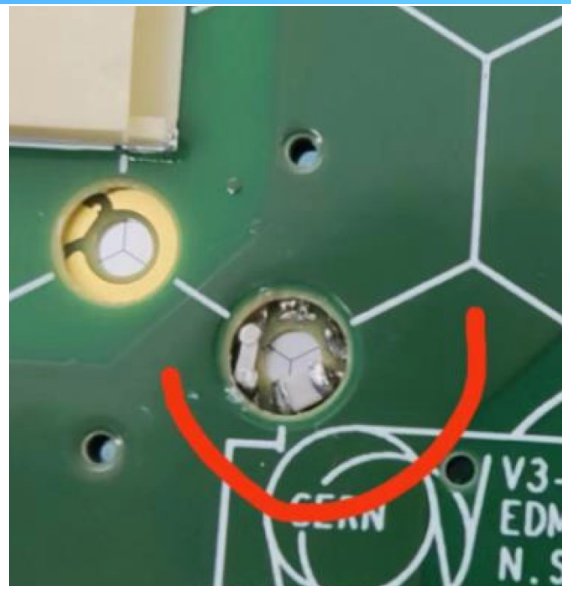


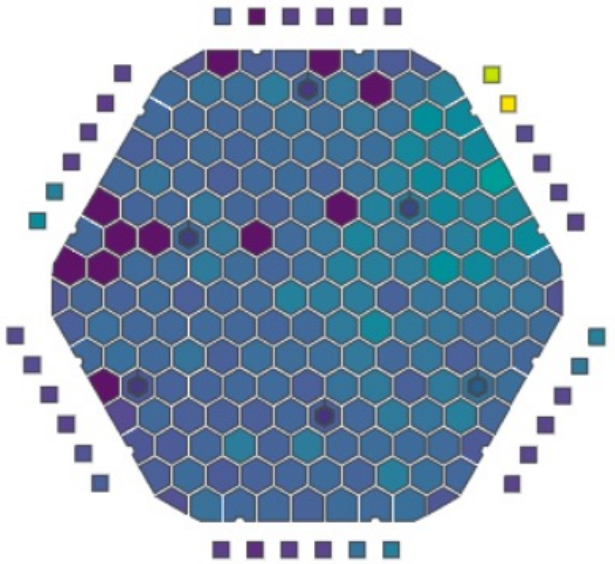


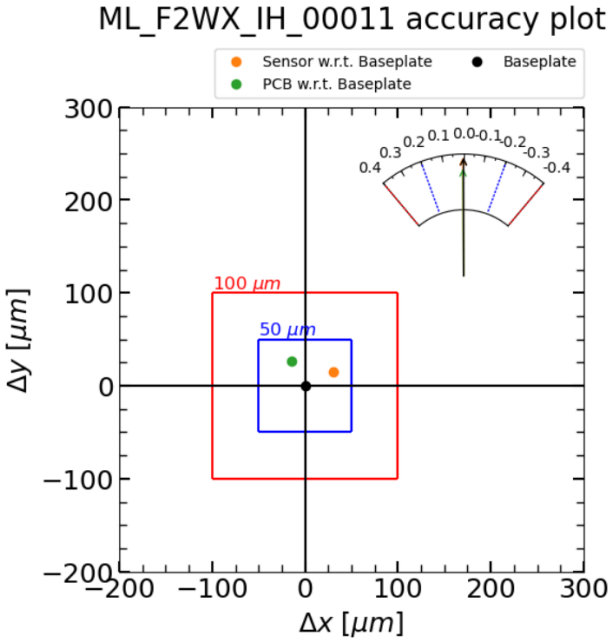
Verification module production

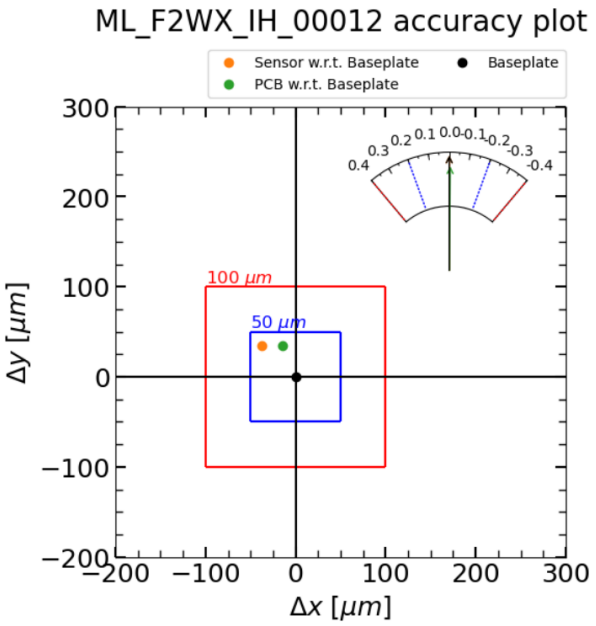
- IHEP produced all 9 verification modules







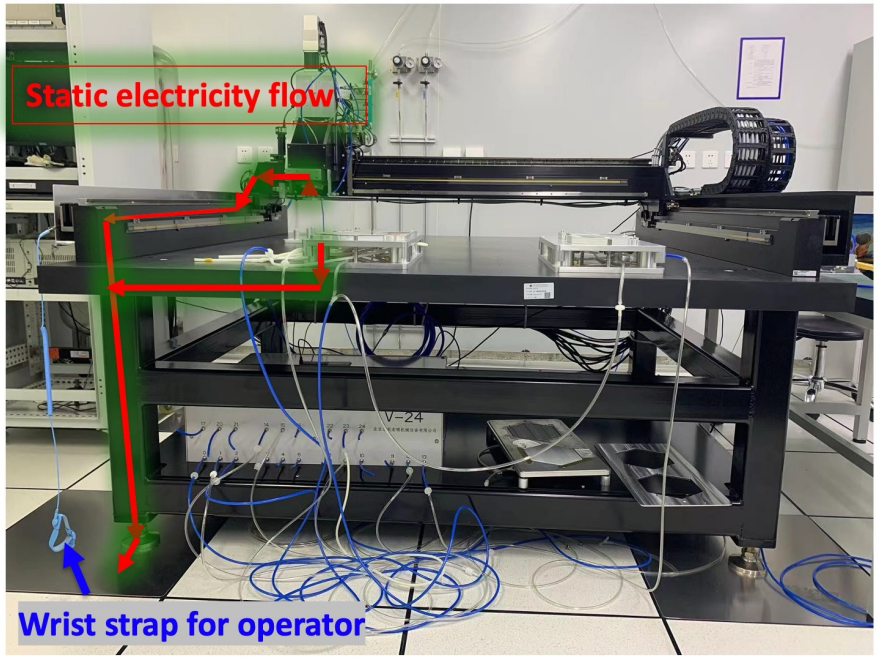


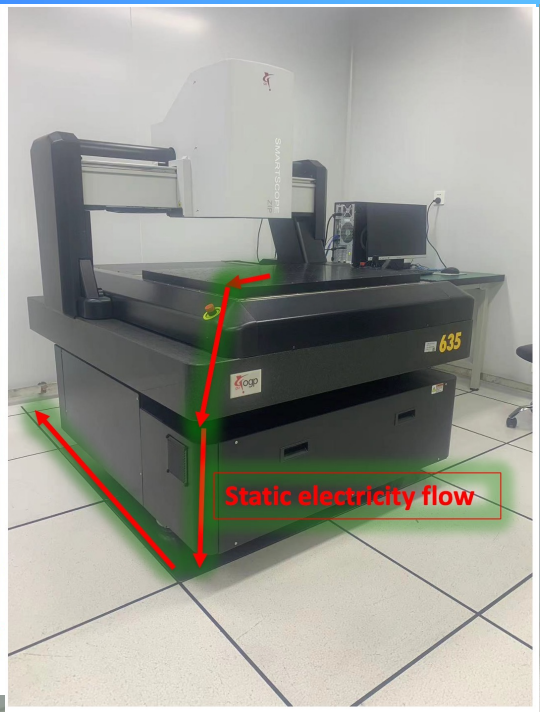


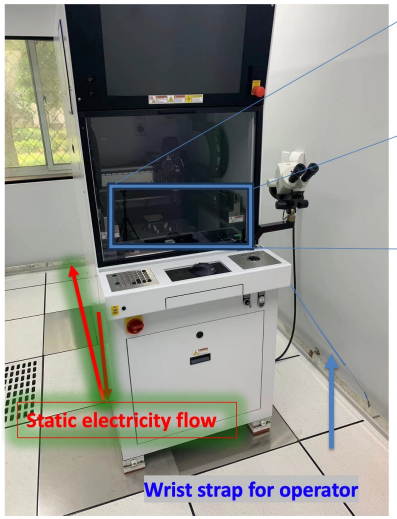
ESD 问题

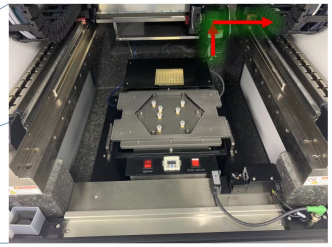
- 首先是高能所最先报道
  - 2023年12月份，6/10块hexaboard在贴双面胶的时候，有chip1或者chip2的36道同时噪声变为0，即读出数值不再改变，其他步骤和其他时间未看到
  - 返回到CERN测试后发现，对应chip的common mode channel被击穿
- 高能所改进了空气湿度，加强了接地，并增加了离子风扇
  - 后续生产了19块，没有击穿，直到上周三，最后一块pre-production的hexaboard在贴双面胶之后的切胶步骤后发现被击穿，怀疑是测试时击穿
- 目前所有的MAC都报道了ESD击穿（hexaboard测试site无击穿）
  - 特定情况～50%的击穿概率
  - 均未完全解决，也没有找到明确的对应原因（在各个步骤都有发现）
- 本周HGCal week，高能所专门汇报了我们的ESD研究
  - 人，设备均完好接地，易产生静电材料材料的处理等，但是还有一个击穿
  - 准备了制作过程的视频，供大家分析
- 会上决定临时增加关于ESD的brain storm讨论（周二）
  - 计划在电子学层面增加可能的防护，同时研究有双面胶易击穿原因

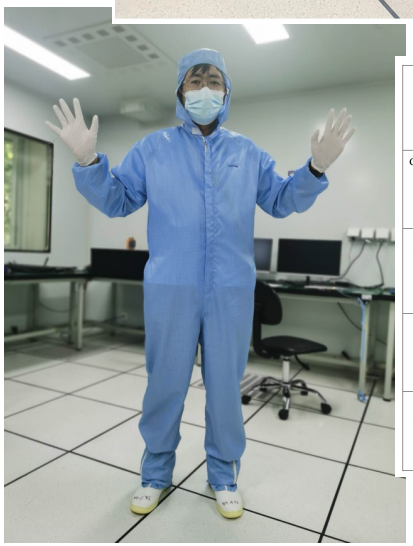
ESD 防护







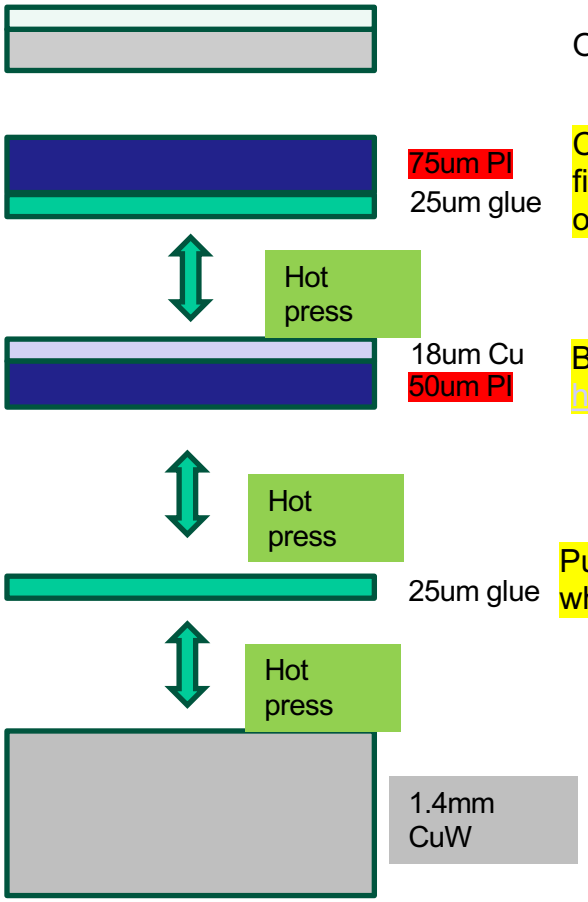




Name	Photo	Voltage level before rubbing (keV)	Voltage level after rubbing (keV)	5s ion blow	Another 10s ion blow	Resistance (Ω)
CD Case		0.05-0.2	~0.8	0.2	Centre 0 Edge 0.2	10^{12} +
Plastic bag for ESD control strap		0.3-0.5	3.6+	~0.3	<0.1	10^{12} +
ABF		0.15	4.6+	Centre 3.5+	Centre 2.1	10^{12} +
Plastic bag for wrist strap		0.5	5.6	2.2	1.5	10^{12} +

Name	Photo	Voltage level before rubbing (keV)	Voltage level after rubbing (keV)	5s ion blow	Another 10s ion blow	Resistance (Ω)
Anti static cleaning cloth (multi-layer)		0	0.4-0.8 (decline gradually)	0	/	// 10 ⊥ 10
Testing modulus		0	0.3	0	/	
2 localization rod		0	0.2	0	/	10^{1}
PVC flexible tube		0	0.05-0.2	0	/	10^{1}
syringe		0.2	0.8 (decline quickly)	0	/	10^{1}
Silicon release liner		0	0.4 (local)	0	/	10^{1}
		0.1	0.3	0	/	10^{1}

Process of bonding Kapton and CuW



Optional: 50 um 3M transfertape + protection paper for hybrid sensor gluing

Coverply: Taihong MHK3025 (100um= 75um PI + 25um glue), made of a polyimide film, one side or both sides of which is coated with a prescribed adhesive and then overlaid with polyimide film

Bottom layer: Panasonic R-F777 (18 um Cu+50 um PI)
https://www.x-pcb.com/wp-content/uploads/R-F777-performance_www.x-pcb.com_.pdf

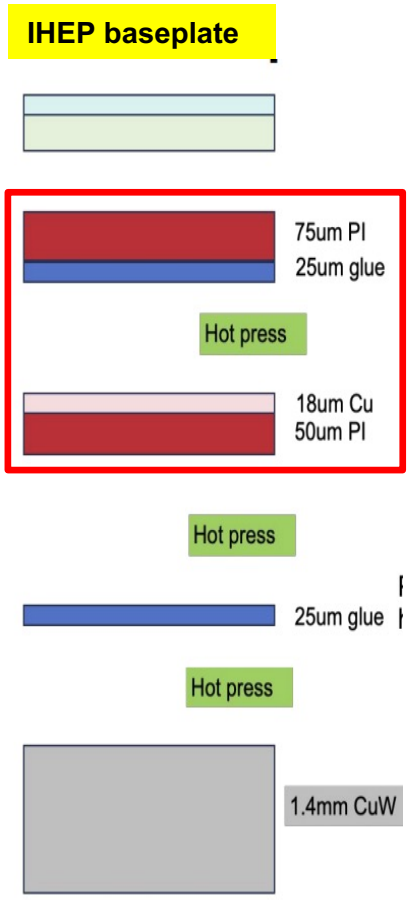
Pure adhesive: HaynerTaiXing Electronics HC25 (25um), epoxy adhesive, melts when heated.

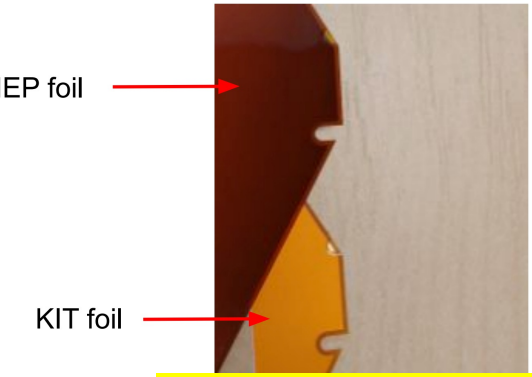
Kapton and CuW are bonded together through a hot pressing process at a temperature of approximately 180℃.

We have produced 2 baseplates which use the epoxy adhesive（Hayner TaiXing Electronics HC25）for each layer of kapton and CuW baseplate lamination in hot press.

高能所/KIT的kapton膜辐照测试

- 高能所钨铜合金底板：已经生产了75块，用在了UCSB，NTU，IHEP硅模块中心pre-series的模块生产，辐照测试等各方面

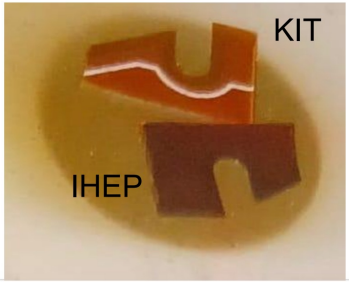




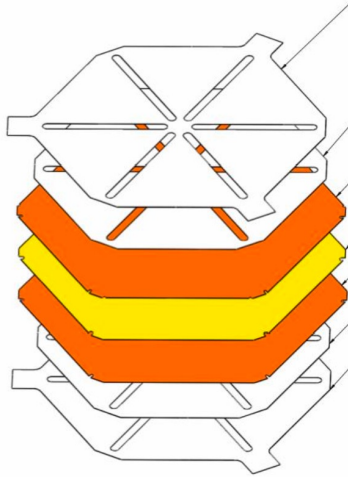
IHEP/KIT foil radiate at 0.5 and 1 MGy: OK
~90% modules < 1MGy

Kapton irradiation

- 1 each "KIT" and "IHEP" type Kapton corner v
- "IHEP" type Kapton is not hot pressed
- Irradiated 2 kapton foil pieces to 1 MGy using
  - Cut-off energy 60 keV
- Further irradiation to 2 MGy ongoing
- Humidity <5%



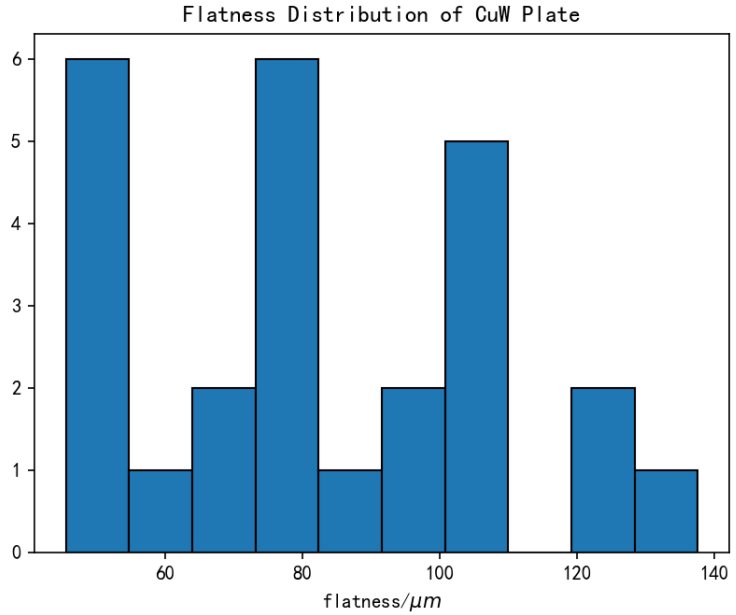
KIT baseplate



- Backing paper (not in final sandwich)
- 50 um 3M tape with gaps for epoxy
- 100 um Kapton (75 um PI + 25 um adhesive) – electrical isolation
- 18 um Copper – shielding of the sensor
- 50 um Kapton – electrical isolation
- 50 um 3M tape with gaps for epoxy
- Backing paper (not in final sandwich)

IHEP and KIT kapton foil 都通过了KIT在温度湿度控制情况下的2MGy辐照测试

Transfer tape + Kapton + CuW baseplate



- New batch of 30 CuW baseplates
  - Lamination with Kapton foil and transfer tape: done
  - The flatness of them less than 150 μm (unconstrained)
  - 2 baseplates use the epoxy adhesive for each layer of kapton and CuW baseplate lamination in hot press. （sent to CERN in last month for irradiation test）
  - 28 baseplates use the epoxy adhesive only for between kapton and CuW baseplate lamination (for module production)
- Shipment
  - 7 CuW baseplates sent to NTU this week