国家重点研发计划

Outcome of MOST Project: R&D and Verification of Key Technologies for a High Energy Circular Electron-Positron Collider

CEPC Day, June 21, 2023

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

南京大学

任务分解和主要研究: Task Arrangement and Main Research

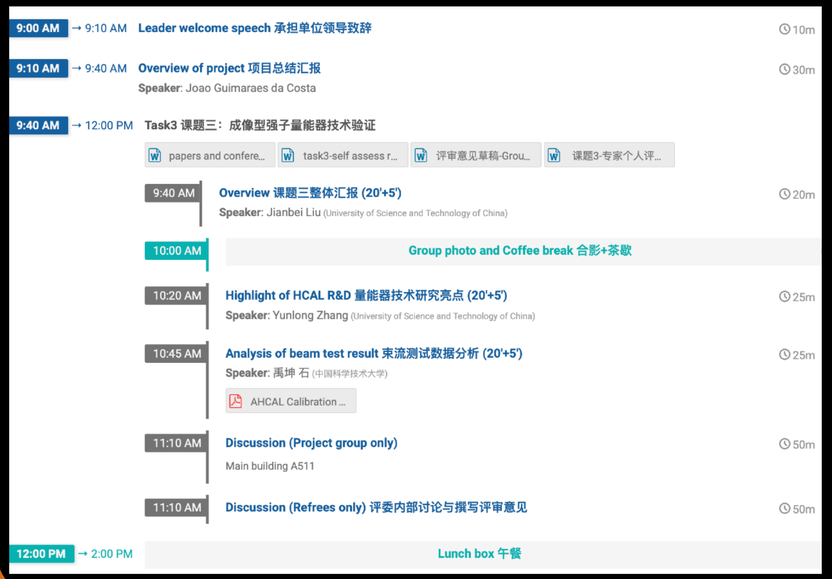
Task	Task Leader Institute	Research Content	Funds
Task 1: Accelerator	Yunlong Chi IHEP	Prototypes: low-field dipole magnet, vacuum pipe, RF shield bellows, HE separator. Beam polarization study	974万
Task 2: Silicon Detector	João Guimarães da Costa IHEP	Prototype: silicon tracker with high-resolution sensor, radiation resistant	1200万
Task 3: Hadronic Calorimeter	Jianbei Liu USTC	Prototype: imaging hadron calorimeter with scintillator + silicon photomultiplier tube (SiPM)	971万

Total funding: 3145 万

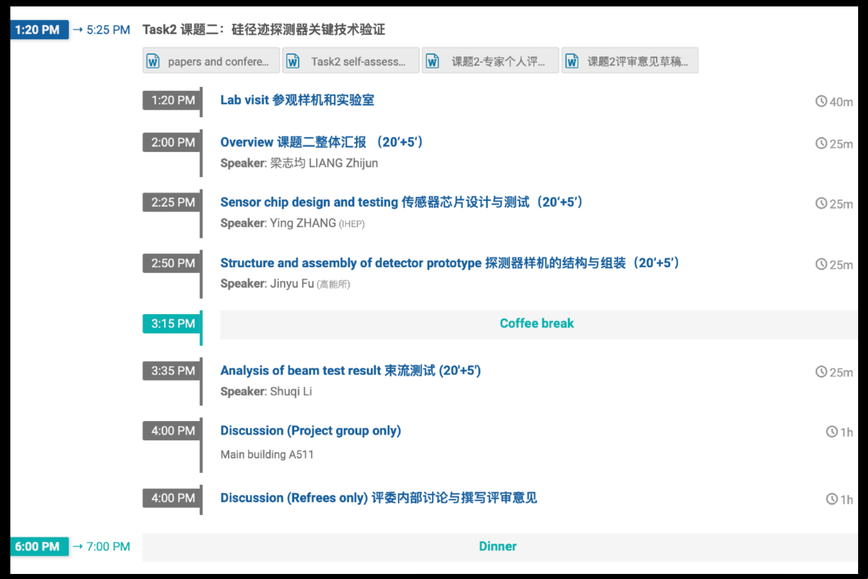
Task final review: June 19-20

Monday, June 19

Task 3: Calorimeter

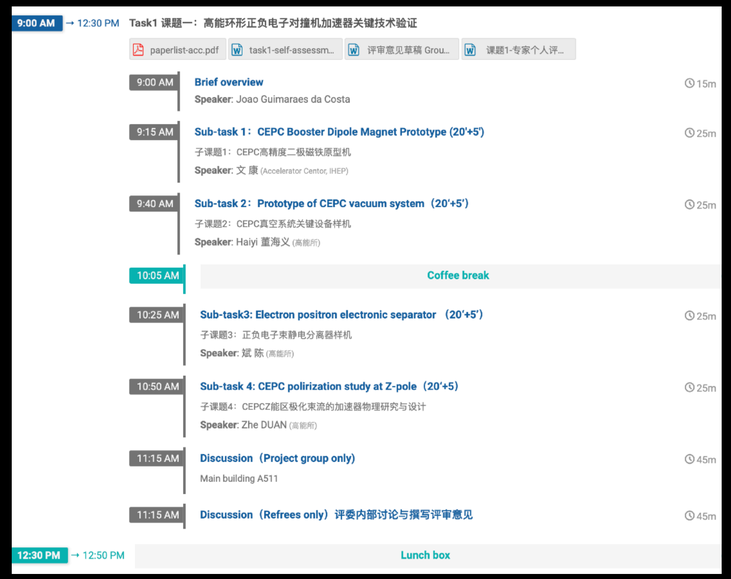


Task 2: Vertex Detector



Tuesday, June 20

Task 1: Accelerator



All three tasks passed the review

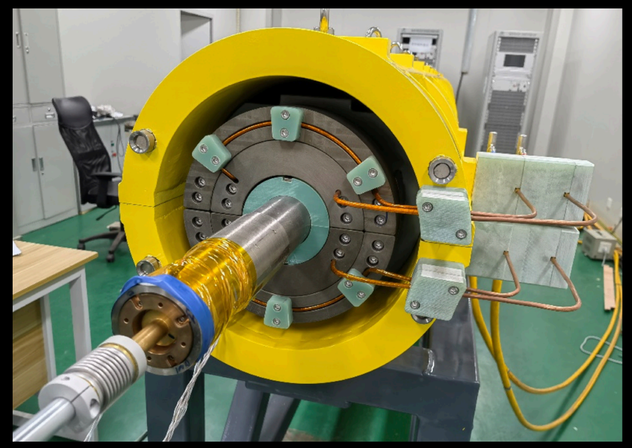
Task 1: Accelerator

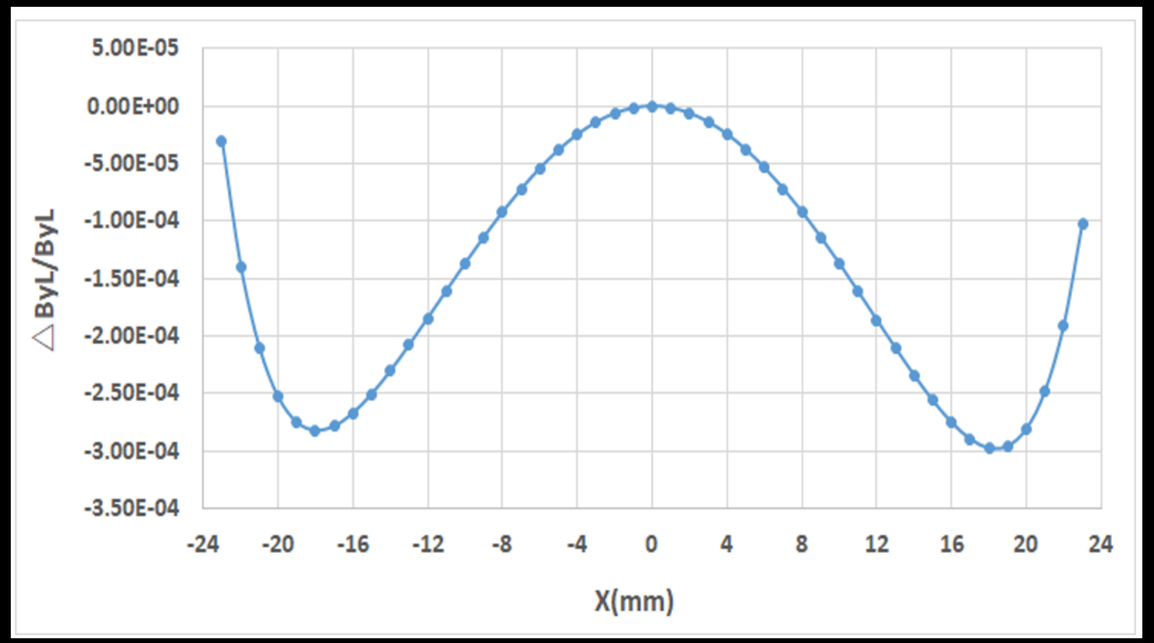
Subtask	Indicator	Requirement	Result	Conclusion	
High precision low-field dipole magnet prototype	Lowest field	<31 Gs	28.5 Gs	✓ Surpassed	World leading
	Field uniformity	<5×10^{-4}	3×10^{-4}	✓ Surpassed	

Very challenging magnet built and measurement done

4.7 m long

World leading



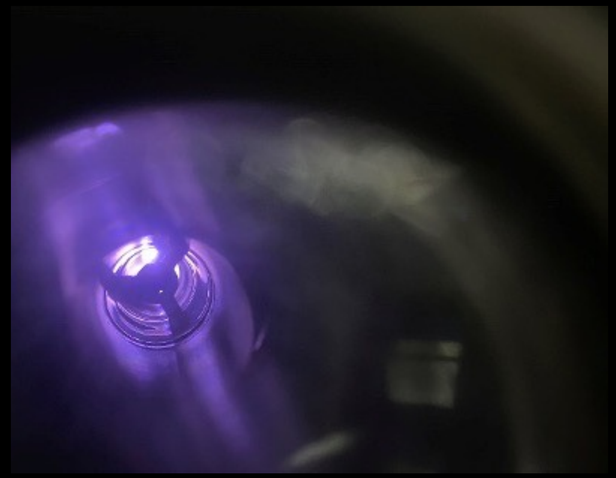


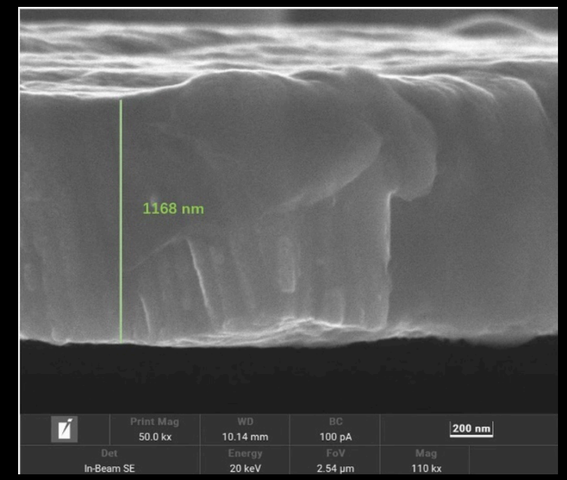
Permanent magnets added at the end to help keep the beam uniformity within the MOST2 requirements

Task 1: Vacuum system and RF shielding bellows prototypes

Prototype 6-m log vacuum chambers for beampipe

Develop technique for NEG coating of the inside of the beampipe (using sputtering technique)

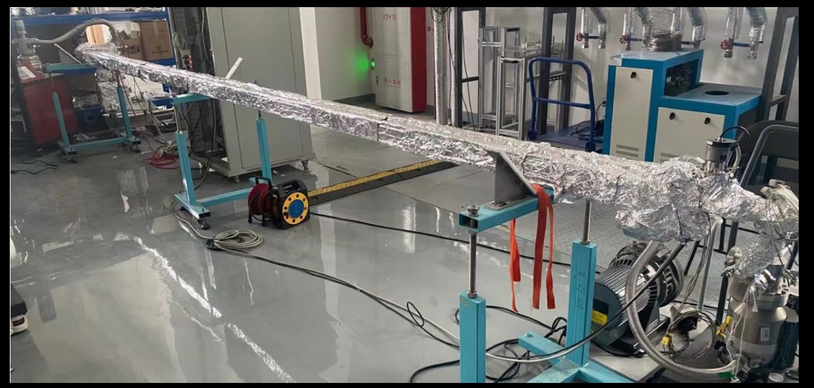




Coating done in sections for 6-m vacuum tube ultimately achieved good enough uniformity

7 patents developed for this work

Subtask	Indicator	Requirement	Result	Conclusion	
High precision low-field dipole magnet prototype	Lowest field	<31 Gs	28.5 Gs	✓ Surpassed	World leading
	Field uniformity	$<5\times10^{-4}$	3×10^{-4}	✓ Surpassed	
Vacuum pipe and RF shielding bellow prototype	Vacuum degree	$< 2\times10^{-10}$ Torr	1.08 - 0.99 x10^{-10} Torr	✓ Surpassed	First in China
	Vacuum leakage	$< 2\times10^{-10}$ Torr.L/s	1×10^{-10} Torr.L/s	✓ Surpassed	
	RF shield bellows contact force	125±25 g/finger	123-135 g/finger	✓ Achieved	

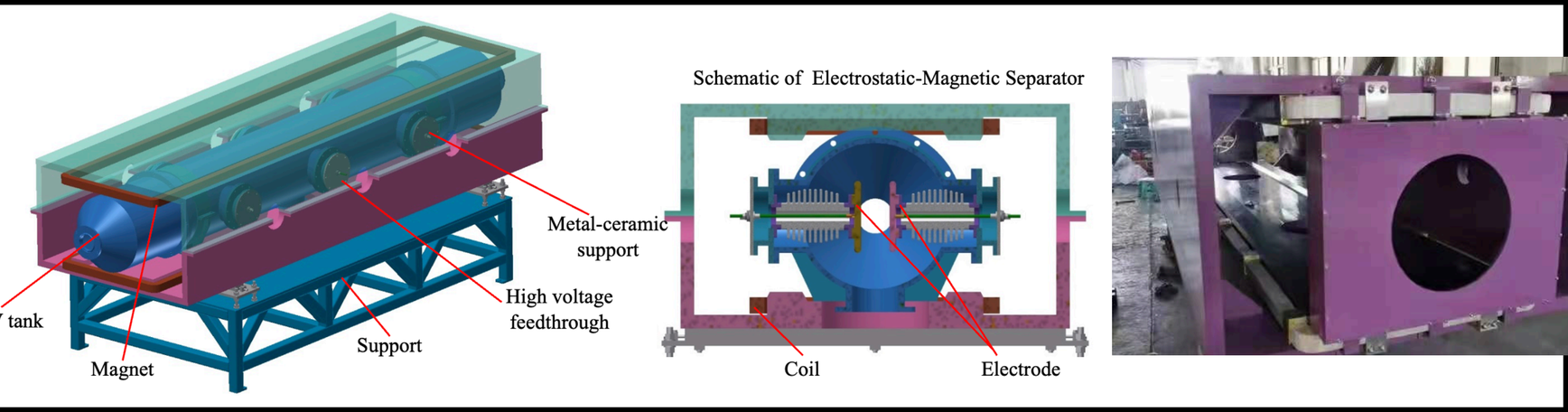


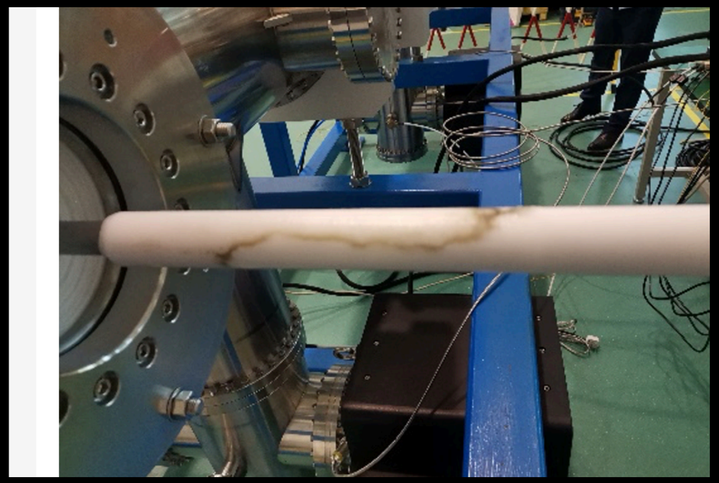
all requirements achieved well within project timescale

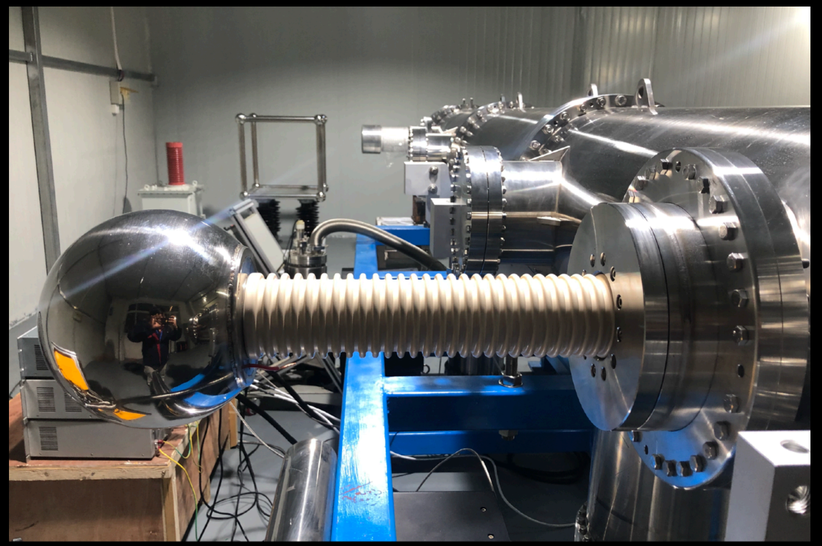
Task 1: Electrostatic separator prototype

Most challenging subtask to pass review

Ultra-High-Vacuum tank and electrostatic components finished — Magnet to be finished







Subtask	Indicator	Requirement	Result	Conclusion	
High precision low-field dipole magnet prototype	Lowest field	<31 Gs	28.5 Gs	✓ Surpassed	**World leading**
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	Vacuum leakage	$< 2\times10^{-10}$ Torr.L/s	1×10^{-10} Torr.L/s	✓ Surpassed	
	RF shield bellows contact force	125±25 g/finger	123-135 g/finger	✓ Achieved	
High energy electrostatic separator prototype	Electric field	>2 MV/m @ ±110 kV	3.09 MV/m @ ±116 kV	✓ Surpassed	**First in China**
	Field uniformity	(1‰)10x10 mm^2	(0.5‰)46x30 mm^2	✓ Surpassed	
	Vacuum	$< 2.7\times10^{-8}$ Pa ($<2\times10^{-10}$ Torr)	$< 2.6\times10^{-8}$ Pa	✓ Achieved	

Referee Report:

课题组完成了120GeV 高能正负电子束静电分离器原型样机的研制，其各项指标均达到或优于任务书要求技术指标。样机的研制完成，攻克了主环高频区正、负电子束团分离关键技术，进一步降低了CEPC工程制造成本。

The research group has completed the development of the prototype of the 120GeV high-energy positron-negative electron beam electrostatic separator, and its various indicators have reached or exceeded the technical indicators required in the mission statement. The development of the prototype machine was completed, and the key technology of positive and negative electron bunch separation in the high frequency area of the main ring was overcome, which further reduced the CEPC engineering manufacturing cost

Subtask	Indicator	Requirement	Result	Conclusion	
High precision low-field dipole magnet prototype	Lowest field	<31 Gs	28.5 Gs ✓	Surpassed	**World leading**
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	Field uniformity	(1‰)10x10 mm^2	(0.5‰)46x30 mm^2 ✓	Surpassed	
	Vacuum	$< 2.7\times10^{-8}$ Pa ($<2\times10^{-10}$ Torr)	$< 2.6\times10^{-8}$ Pa ✓	Achieved	
Polarization design	Beam polarization	> 50%	P_{avg} > 70% ✓	Surpassed	**World leading**
	Beam lifetime	> 60 min	> 60 min ✓	Achieved	

Referee Report on Polarization

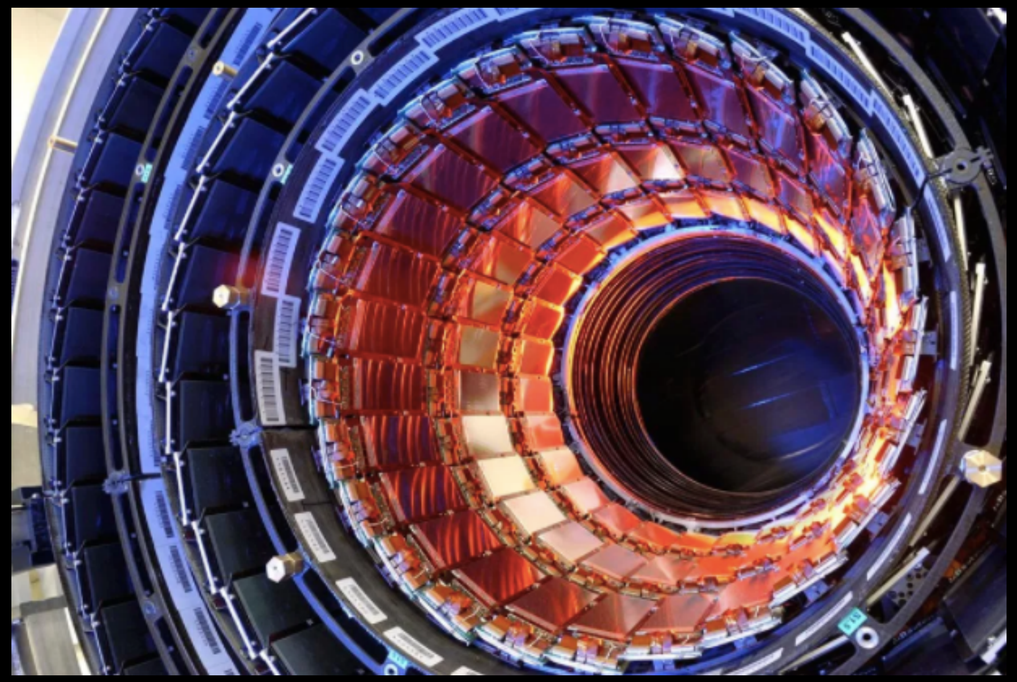
在CEPC Z能区极化束研究方面，课题组提出并研究了极化束流的产生、逐级加速和传输、并实现极化束对撞和共振退极化束流能量测量的初步可行方案。基于CEPC概念设计报告的磁聚焦结构和关键参数，完成了Z能区纵向极化束对撞的完整设计。模拟研究显示，对撞束流时间平均极化度可达到50%以上，在对撞环中加入非对称扭摆磁铁和自旋旋转器对束流寿命没有显著影响，束流寿命大于60分钟，符合考核指标要求。针对高能电子环形加速器，拓展了自旋共振结构的理论模型，首次解释了自旋共振强度增强和削弱的物理机理；模拟验证了辐射退极化效应存在非相干共振穿越区域，首次揭示了现有理论在处理相关问题时存在缺陷。这些研究加深了对自旋退极化物理机理的认识，为在未来对撞机中开展极化束应用提供了重要参考

Task 2: Vertex Detector Prototype

Task 2: Vertex Detector Prototype Research Goal

- **Produce a world class vertex detector prototype**
  - Spatial resolution 3~5 μm (pixel detector)
  - Radiation hard (>1 MRad)

Typical vertex tracker



Typical cost of such detectors: 350-700 MRB

Resolution

ATLAS/CMS upgrade
（10-20 μm）

Alice upgrade
（5~10 μm）

This project（3~5 μm）

World leading

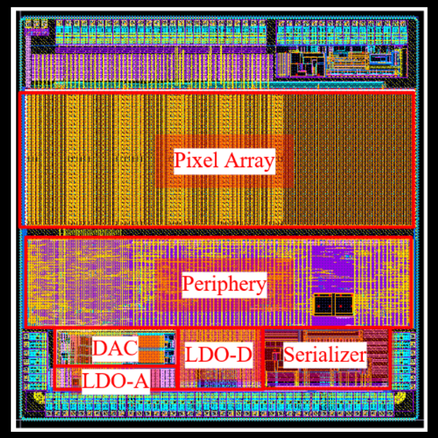
Key ingredient:

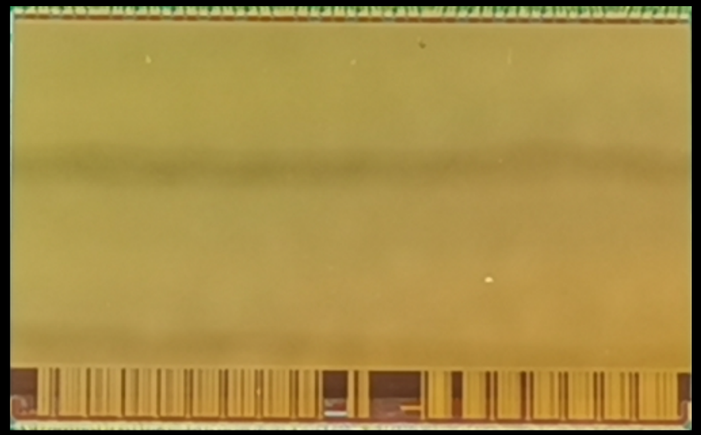
Full size sensor/ASIC (2-4 cm^2)

Major goal: develop the know-how in China to build such advanced detectors

Task 2: Vertex Detector Prototype Development

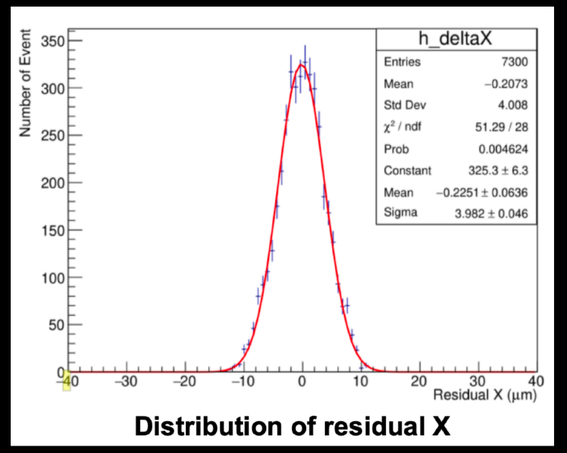
- **Developed first full-size CMOS monolith imaging sensor in China**, adequate for the production of this vertex detector and other silicon-based devices



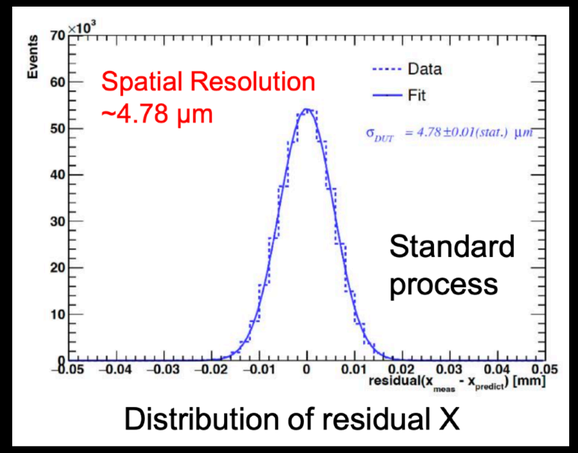


- Full size 1024×512 Pixel array, Chip Size：15.9 × 25.7 mm²
- 25×25μm² pixel size allowing high spatial resolution
- Process: Towerjazz 180 nm
- Fast Periphery digital readout , high-speed data interface

- **Resolution of < 5 μm demonstrated with:**
  - laser tests on bench
  - test beam telescope
  - test beam with full size CEPC vertex prototype



Distribution of residual X

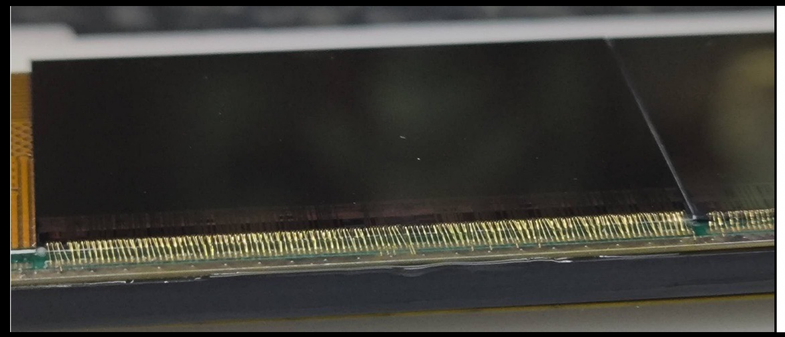


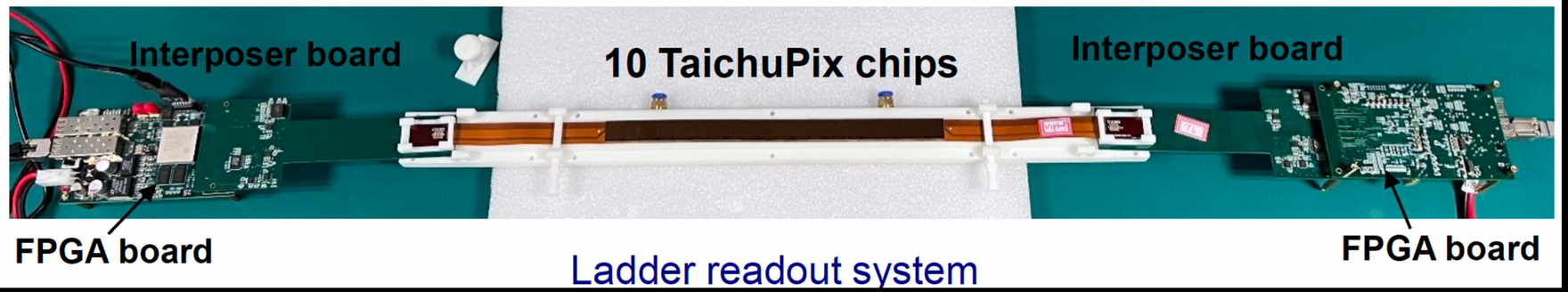
Distribution of residual X

Task 2: Vertex Detector Prototype Development

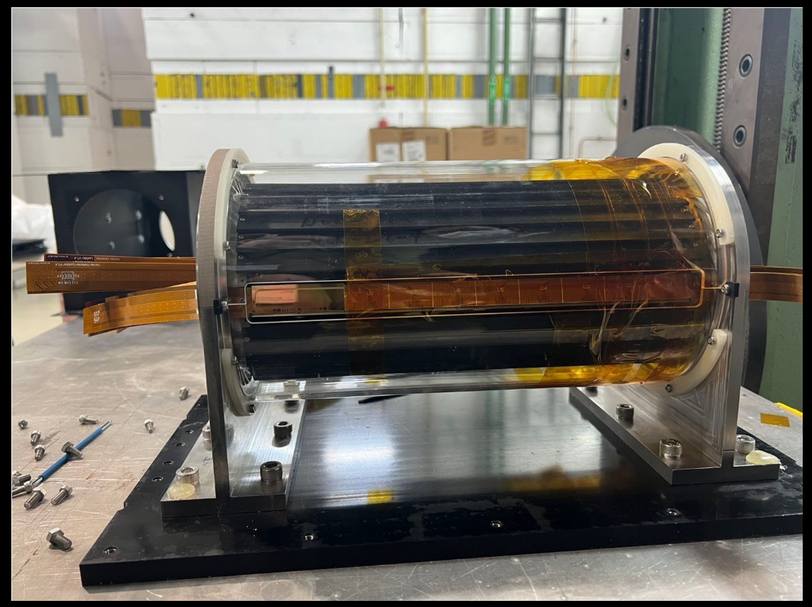
- **First in-depth full scale silicon vertex prototype developed in China** allowing for the studies of mechanical structures, low-mass materials, and cooling procedures

Full scale ladder



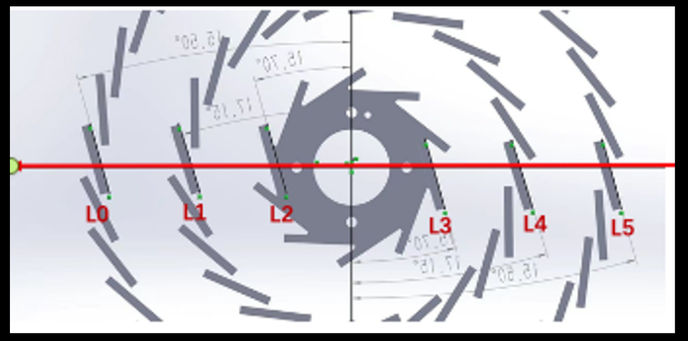


Ladder readout system



Vertex detector configuration for test beam

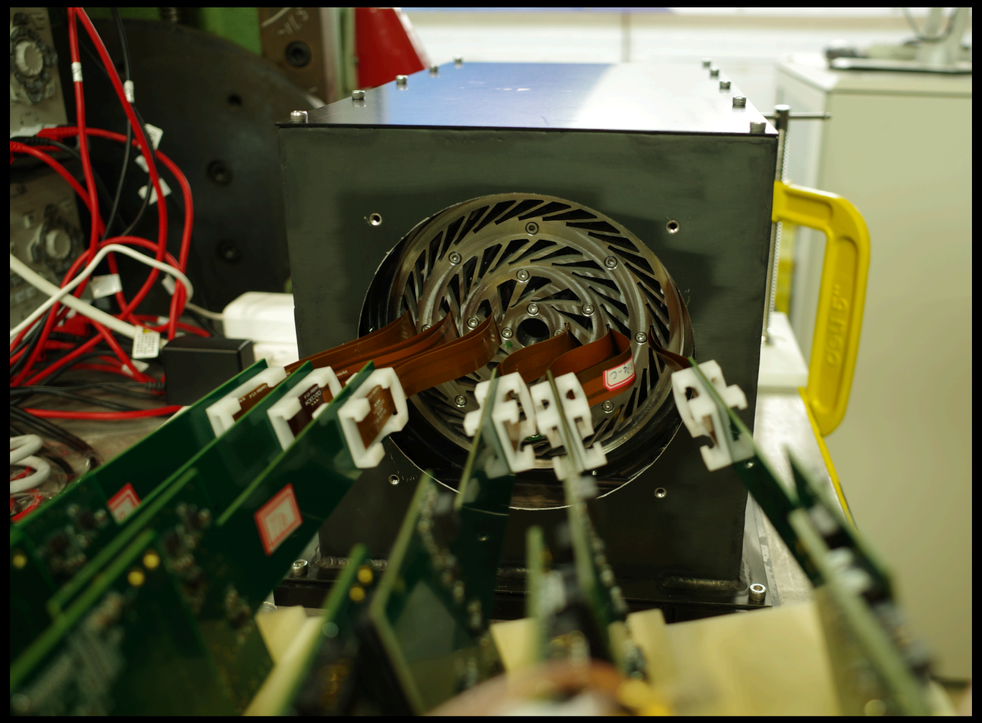
- Three double sided ladders in two sets, for a total of 12 layers
- Twice the layers that a particle would transverse in a real detector



Task 2: Vertex Detector Prototype Test Beam

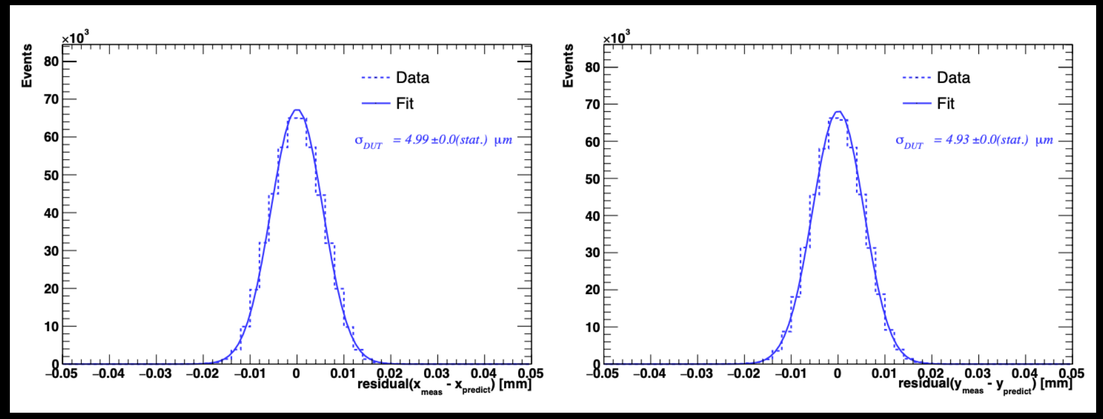
Two test beam events at DESY, Germany:

- **December 2022**
- **April 2023**



Prototype connected with readout electronics
12 layers of sensors visible

Resolution with full-size mechanical prototype



Indicators and review report

Indicator	Requirement	Result	Conclusion	
Spatial resolution	3-5 μm	Laser test: x: 4.0 μm; y: 4.1 μm Beam test: x/y: 4.8-4.9 μm	Achieved	**World leading**
Total ionization dose (TID)	> 1 MRad	> 3 MRad	Surpassed	**First in China**

该课题在高性能硅像素传感器芯片研究方面攻克了高空间分辨、低物质量和抗辐照等一系列关键技术难题，达到了国际先进水平，…… 建议加强束流实验数据的分析处理，为探测器的进一步优化设计提供参考。同时，建议持续开展该技术的研发，以促进国内先进传感器芯片技术的发展

Task 3: Calorimeter Prototype

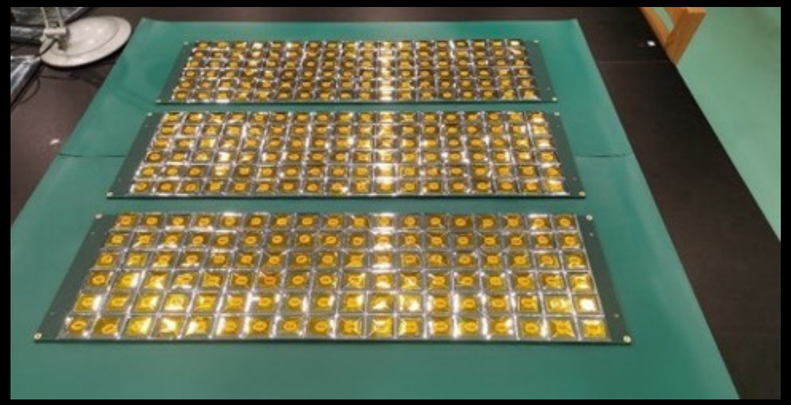
Task 3: HCAL Prototype Research Goals

- **R&D of SiPM based HCAL prototype**
  - **High energy resolution (60%√E/GeV⊕3%)**
  - **High linearity（non-linearity <3%）**
- **Initial prototype design**
  - **0.5×0.5 m² ， 35 layer (4λ)， 3×3cm² module**
  - **SiPM and scintillator coupling**

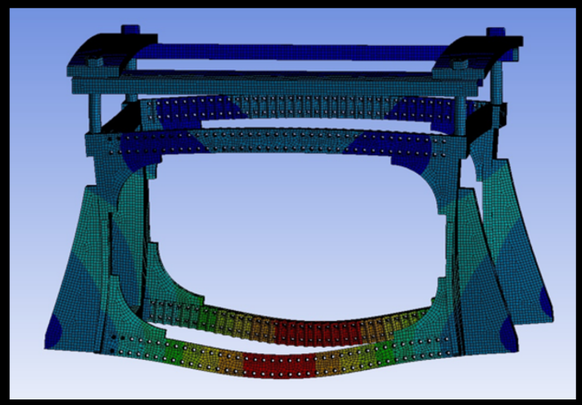
- **Actual prototype built**
  - **0.72×0.72 m² ， 40 layer (4λ)， 4×4cm² module**
  - **Number of total channels: 12,960**

Automatic system developed to cope with the large number of channels

Assembled HCAL Basic Units



Mechanics design

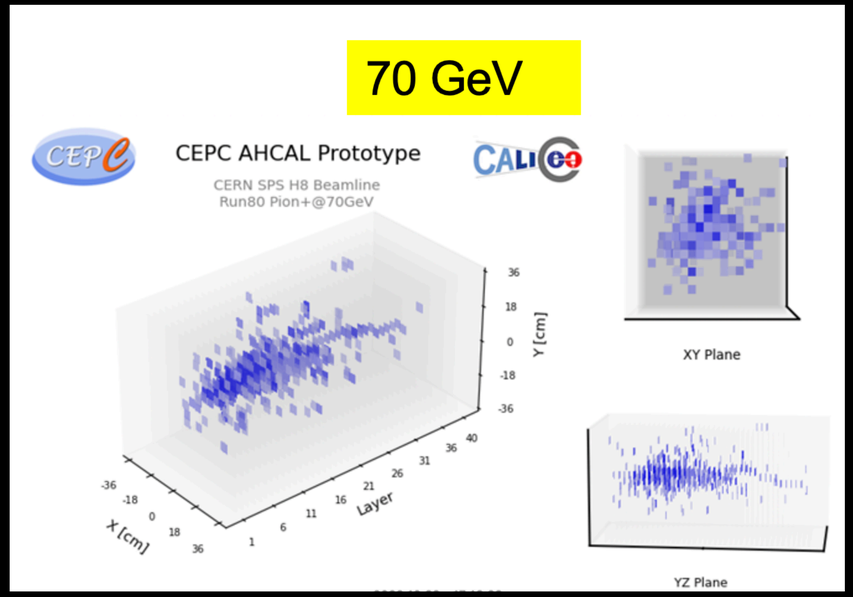


Task 3: HCAL Prototype Testing

Three test beam campaigns at CERN: Oct 2022, April 2023 and May 2023

HCAL prototype

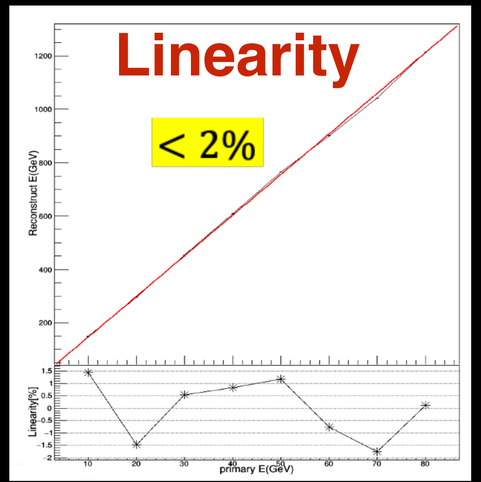
Pion event display

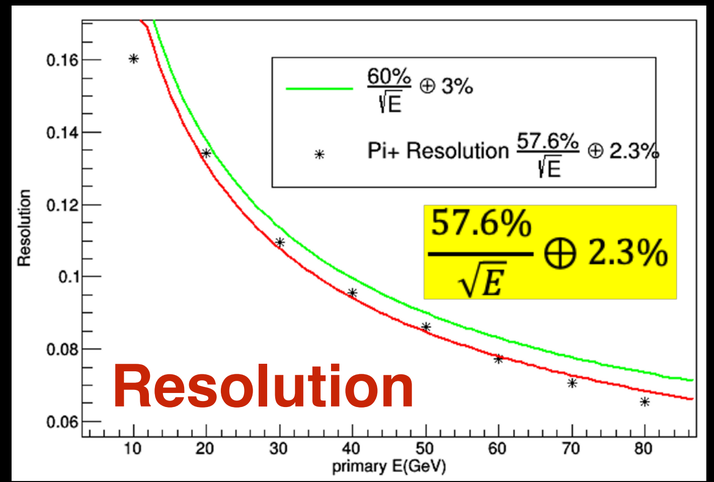


Team at CERN

65 million events collected in total

- **Achieved requirement with second test beam data**
- **ECAL tested in front of HCAL**





Achievements and Assessment Methods

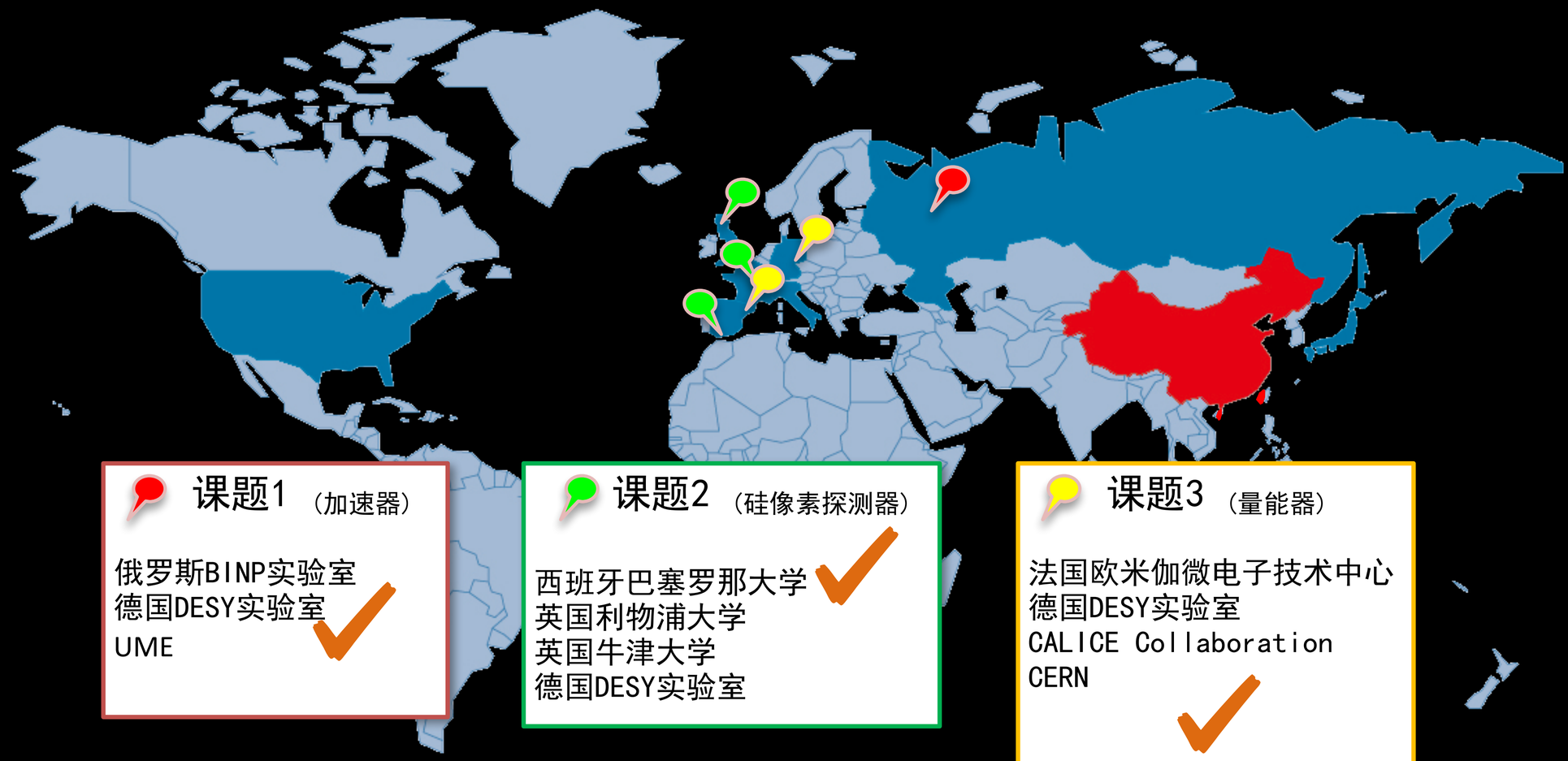
Indicator	Requirement	Result	Conclusion	
Energy resolution	60%/√(E/GeV) ⊕ 3% (10 GeV < E < 80 GeV)	(57.6%)/√E⊕2.3%	Surpassed	First in China
Energy linearity	3% (10 GeV < E < 80 GeV)	<2%	Surpassed	First in China

This project has made a series of innovative achievements in key technologies including mass production, packaging and testing of plastic flash units, large area, high integration, fully embedded readout electronics, large-scale and fast SIPM performance monitoring and calibration based on LED, which plays an important role in the research and development of key technologies of cepc.

Academic Achievements

	Accelerator	Vertex	Calorimeter	Total
Patents	8	12	1	21
Papers	11	5	8	24
Proceedings	2	1		3
Conferences	16	18	28	62
PhD Students	6	8	4	18
Master Students		23	3	26
Postdocs		2	1	3

International Collaboration



The pandemic made international collaboration much complicated, and prevented collaboration with UK and US institutes within the vertex detector project

小结

- **All indicators have been achieved in the project**
  - **Several world-leading and china-first achievements were made**
  - **Long-lasting knowledge was acquired that will help us progress further in the future**

谢谢

The end