# 束流测试线上的粒子探测器研究

史欣

2022年12月28日

质子试验束探测器讨论会

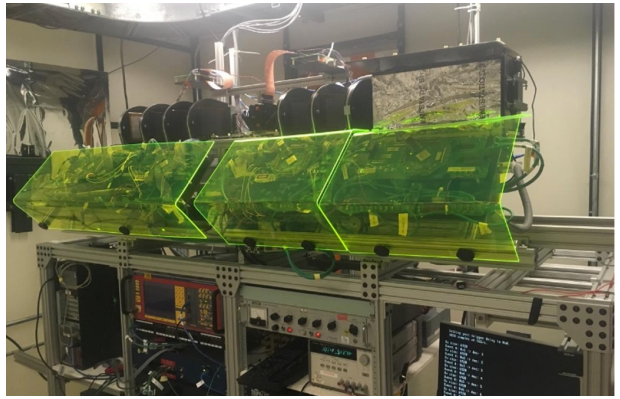
# 内容概要

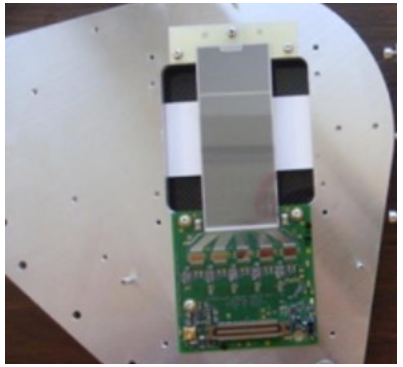
- 探测器研究的种类
  - 位置测量
  - 时间测量
  - 能量测量
  - 辐照测量
- 总结与展望

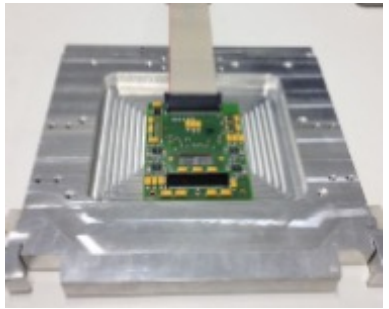
https://indico.cern.ch/event/1058977/
10th Beam Telescopes and Test Beams Workshop

# 探测器位置分辨研究

- 束流望远镜， 用于研究硅微条、硅像素型探测器
- FNAL
  - 空间分辨5 μm
  - 硅微条探测器覆盖 3.8 cm x 3.8 cm
  - 未来升级为像素型探测器
- DESY
  - 6 层像素型传感器（MIMOSA26）
  - 空间分辨率 ~ 2μm
  - 传感器 2cm x 1cm， 厚度50μm
  - 像素尺寸： 18.4μm x 18.4μm
  - DAQ： NI , TLU, EUDAQ

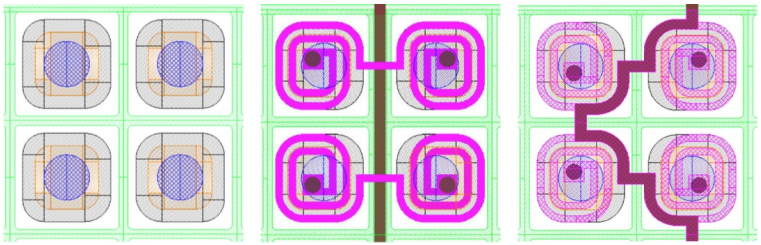


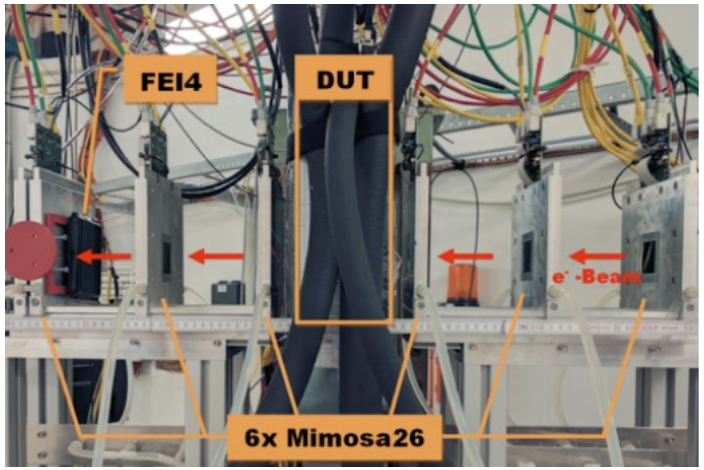


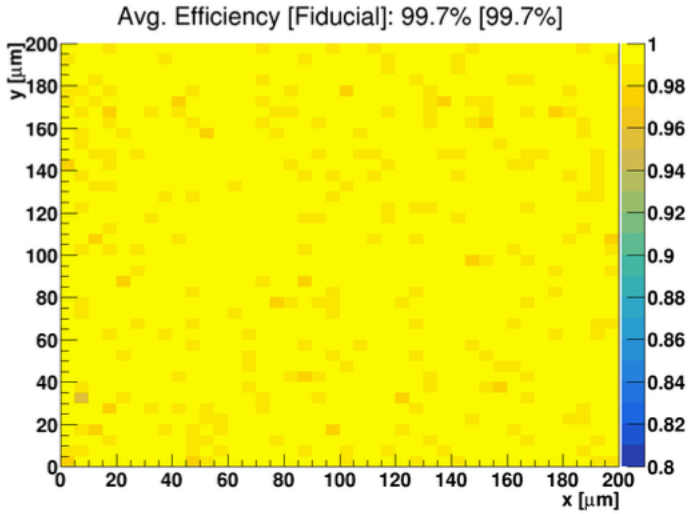


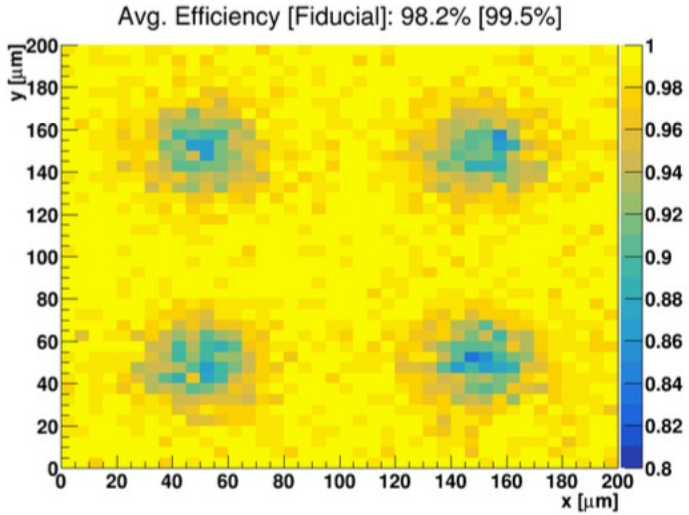
# 位置分辨研究 – ATLAS ITk RD53A

- RD53A bump-bonded to 150μm n-in-p planar sensor, 50x50μm$^2$
- Different punch through bias (PTB)
- Irradiated 3.4x10$^{15}$n$_{eq}$/cm$^2$



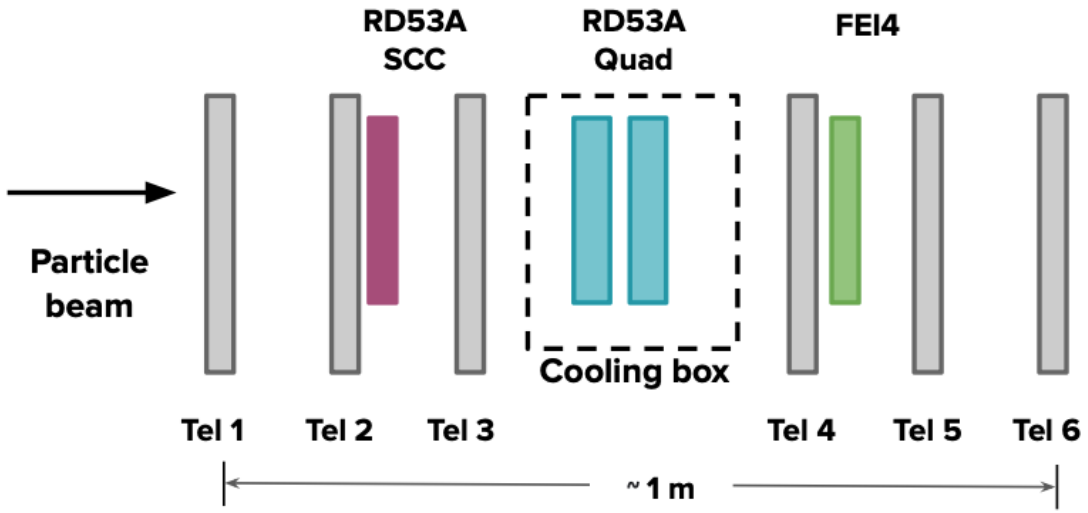



- Modules with and without PTB achieve global efficiency above 97%

# 位置分辨研究 – ATLAS ITk pixel quad module



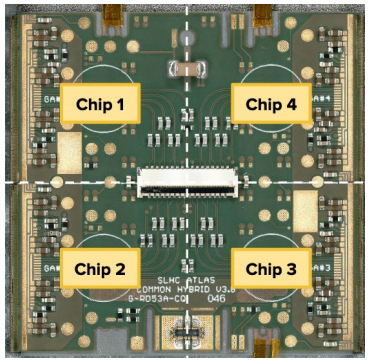

**Beam telescope**

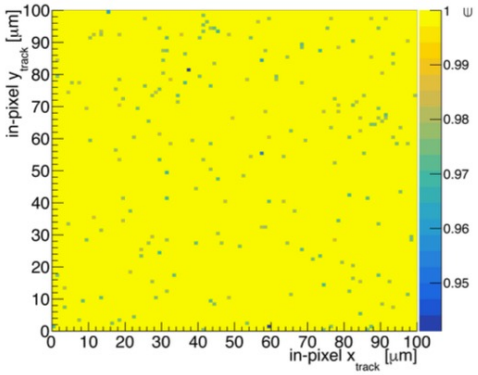
**RD53A single-chip card (SCC)** as a timing reference

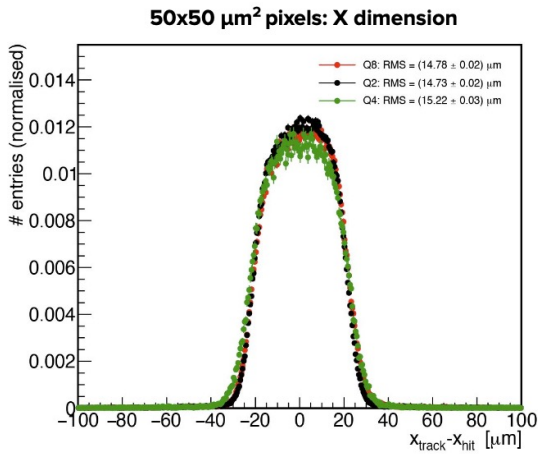
**FEI4 single-chip card**

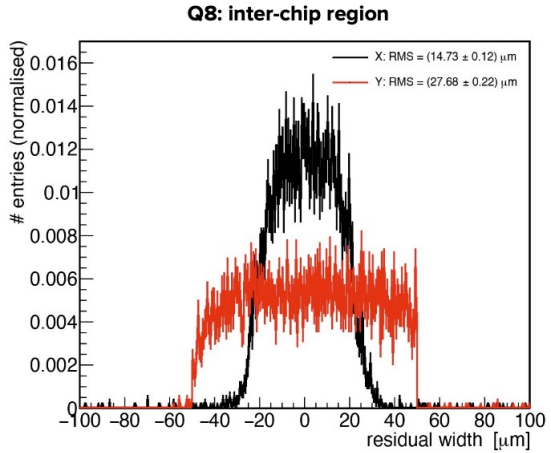
**RD53A quad modules** with n-in-p planar sensors of 150 µm thickness and 50x50 µm$^2$ pixel size:

- non-irradiated Hamamatsu (HPK) Q8
- non-irradiated Micron Q2
  - PT biasing structure
- irradiated HPK Q4
  - Fluence: $\phi_{eq}$ = 5 x 10$^{15}$ $n_{eq}$cm$^{-2}$



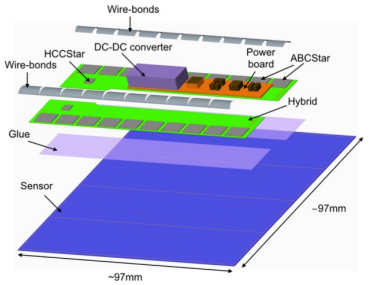



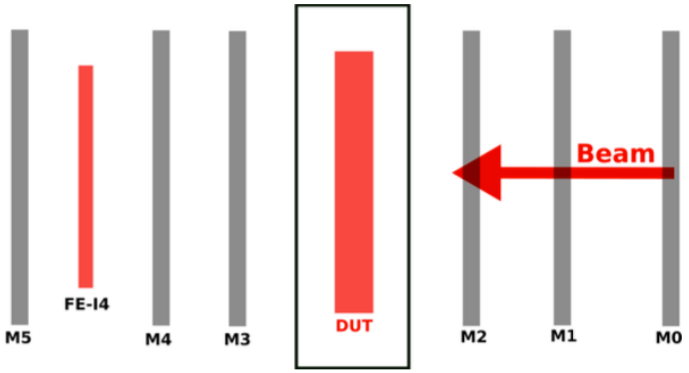




- Hit efficiency > 97% for irradiated modules

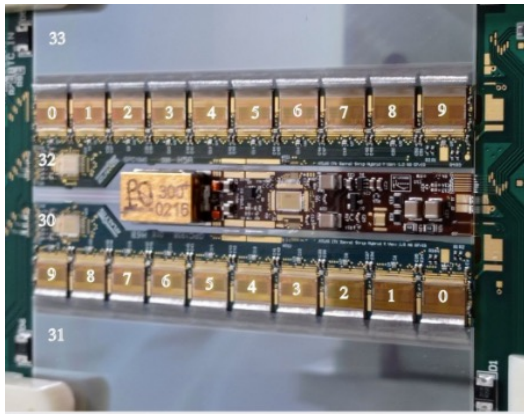
$\sigma_{int}$ (50 µm, 100 µm) = 14.43 µm, 28.87 µm

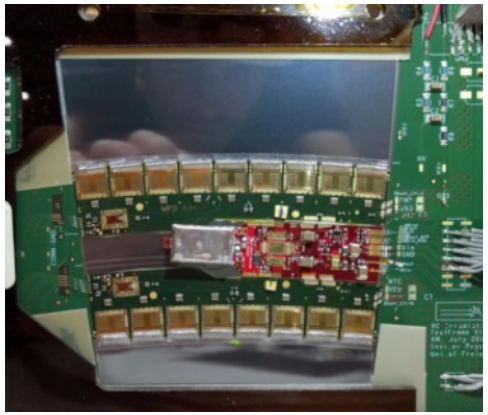
# 位置分辨研究 – ATLAS ITk strip

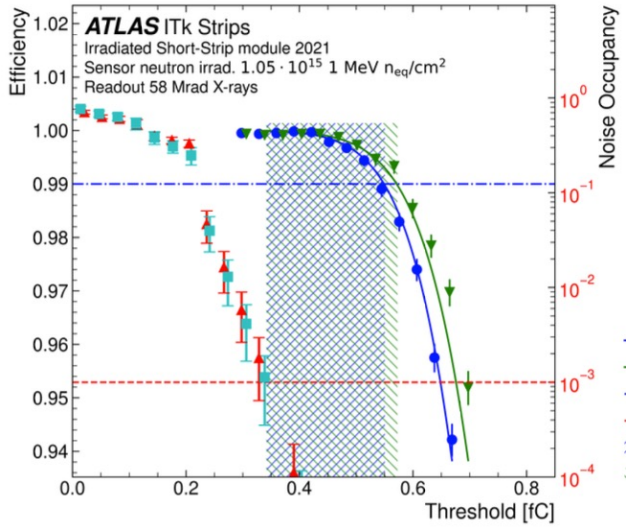


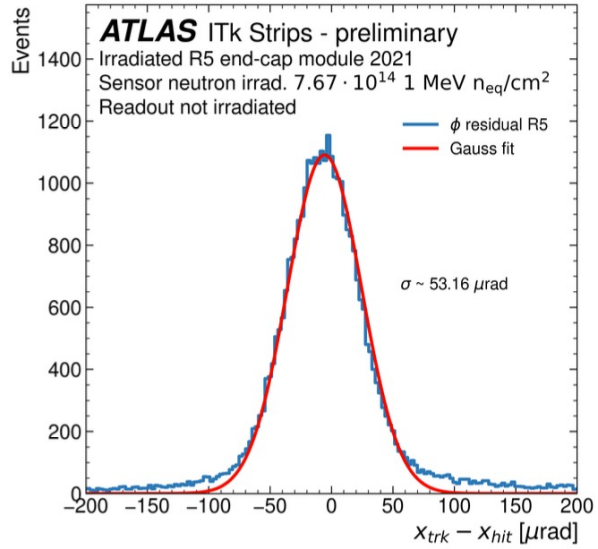




- Six Mimosa26 planes and an additional FE-I4 timing plane (with USBPix read-out).
- EUDAQ2 used for control and read-out of the telescope and the DUT.
- Tracking resolution of 5–10 $\mu$m.
- DUT placed in a cold box and operated at -500V bias voltage.





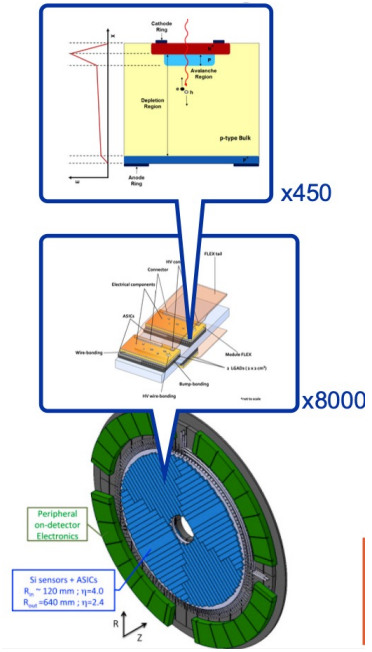



- Short-Strip modules: S/N 16.9 (>10) efficiency > 99%  noise occupancy < 0.1%

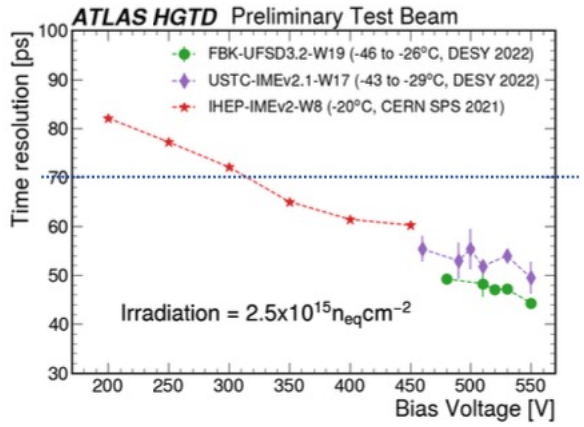
# 时间分辨研究 – ATLAS HGTD LGAD

- Low-Gain Avalanche Detector (LGAD)
  - Radiation-hard + excellent timing resolution
  - 4fC, <70ps, $2.5 \times 10^{15} n_{eq}/cm^2$
  - ALTIROC: ~25ps, 2fC, 225 channels




- Objectives reached over **4 testbeam campaigns** in 2021 and early 2022:
  - SEB studies at DESY in June 2021 and SPS in November 2021 (no telescope)
  - SEB + performance studies at SPS in July-Nov 2021 using MALTA telescope
  - Sensor performance studies at DESY in March 2022 using DATURA telescope

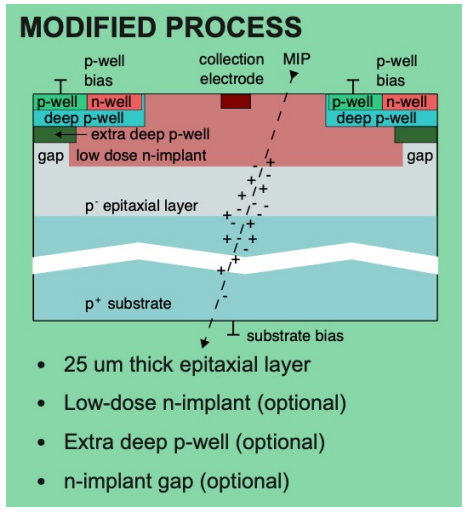
**SEB probability typically below $10^{-5}$**

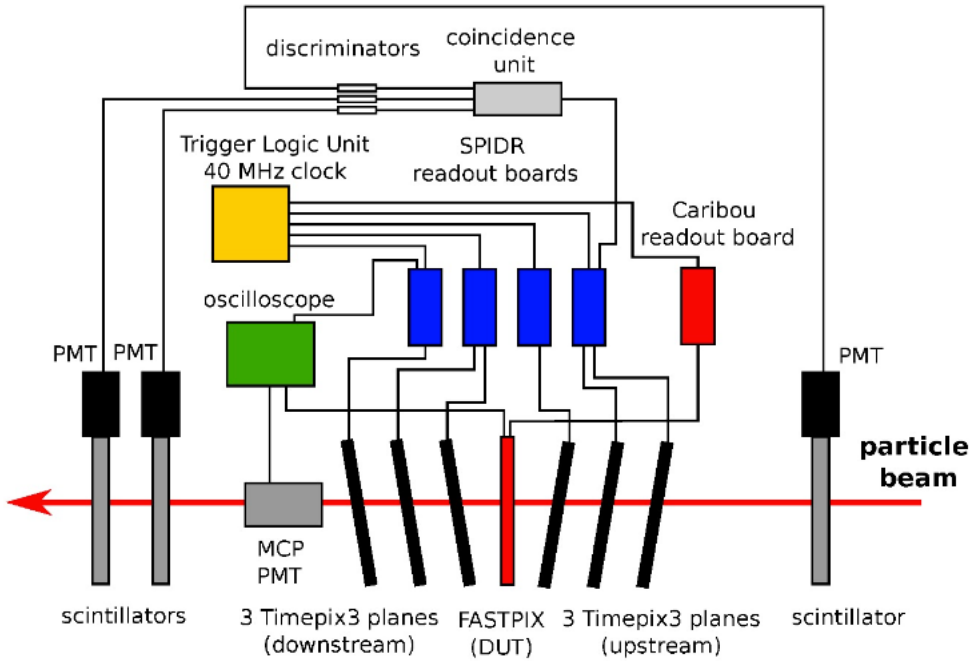


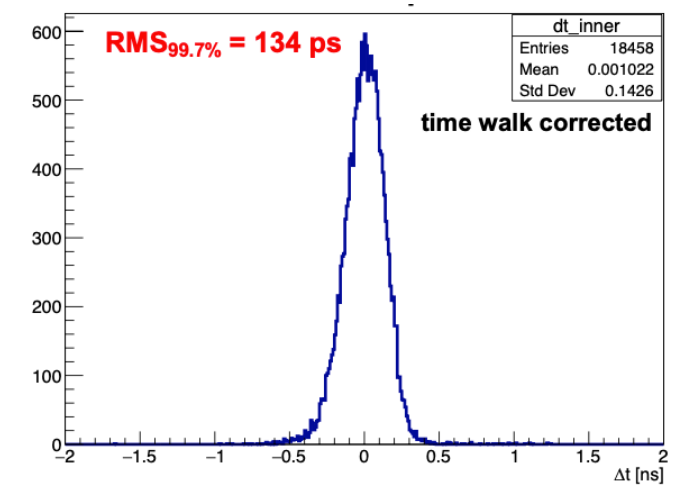

At highest biases, DUTs irradiated up to 2.5E15, have efficiency > 95%, charge > 4 fC and time resolution < 70 ps. **Meet HGTD specifications !**

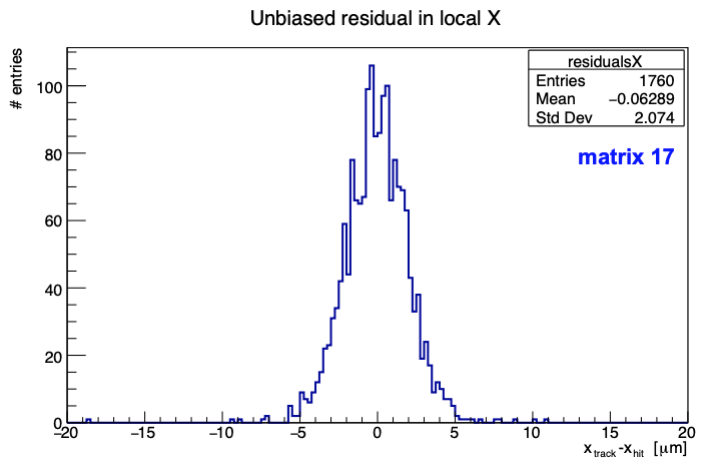
# 时间分辨研究 – FASTPIX

- Monolithic pixel sensor 180nm CMOS imaging process



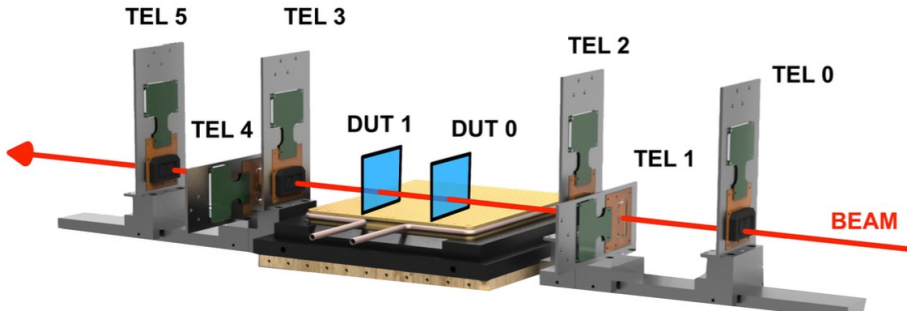



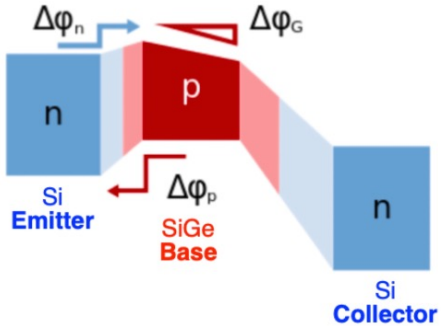

- reaches a timing precision of O(150ps)
- spatial resolution 1.0μm -3.8 μm

# 时间分辨研究 – ATTRACT

- Monolithic SiGe BiCMOS pixel sensor



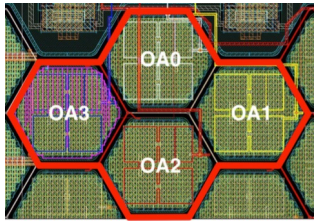

**NPN SiGe HBT**
(depleted regions in light colors)
from wikimedia

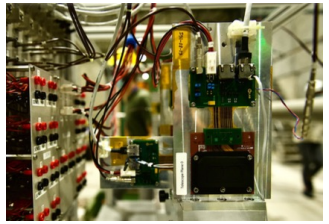


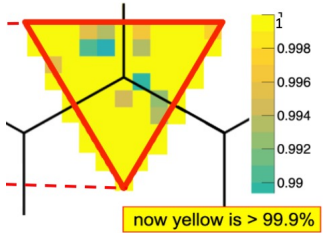

**Reduced base resistance $R_b$**
**Higher current gain $\beta$**
**Charge transport via drift**

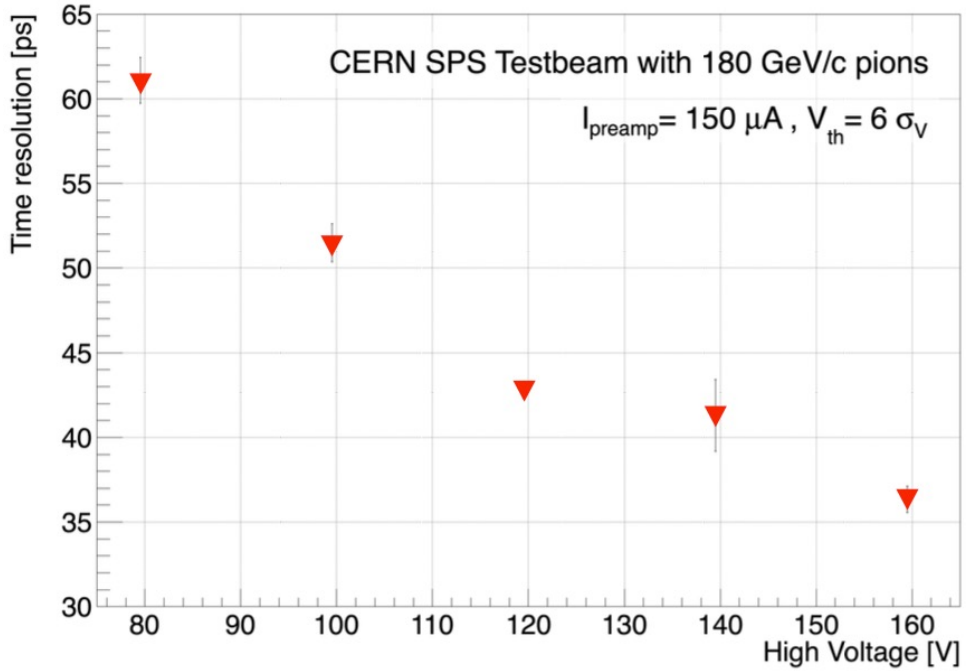
Reduced Equivalent Noise Charge (ENC):

$$ENC_{\,Series\ Noise} \propto \sqrt{k_1 \frac{C_{tot}^2}{\beta} + k_2 R_b C_{tot}^2}$$



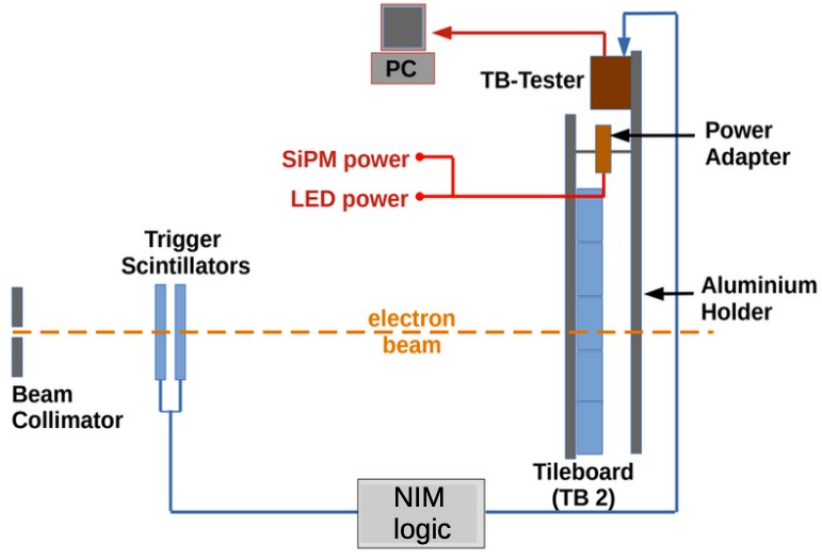


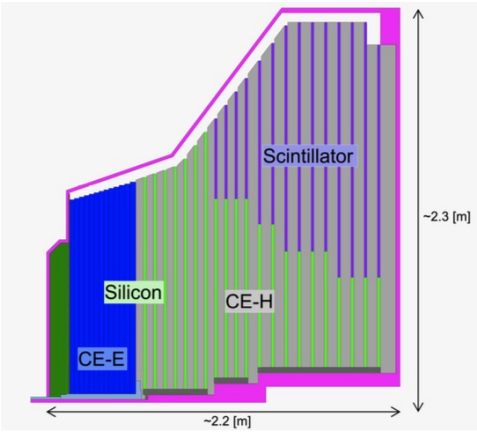



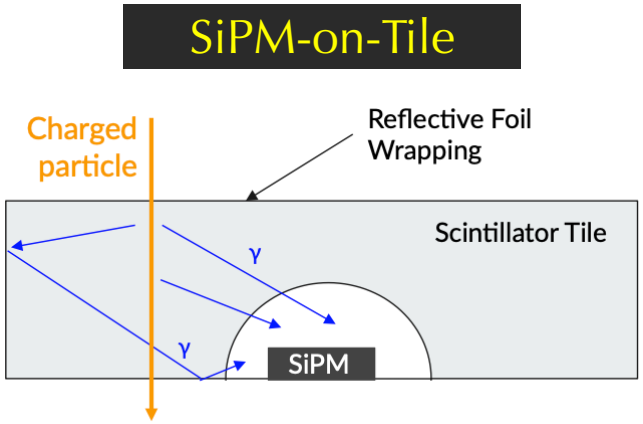

- Power 1.8W /cm$^2$ ,36ps, efficiency 99.9%

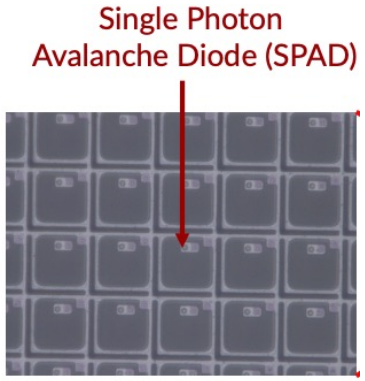
# 量能器研究 – CMS HGCAL

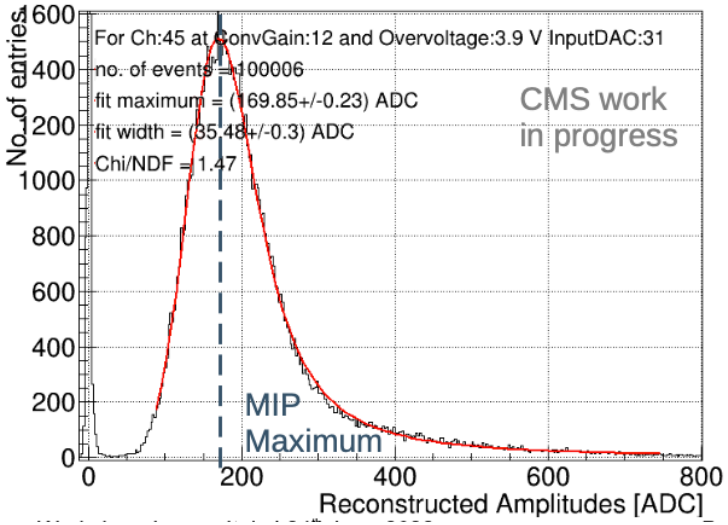
- 5D (imaging) calorimeter using particle flow
  - Silicon and scintillator section



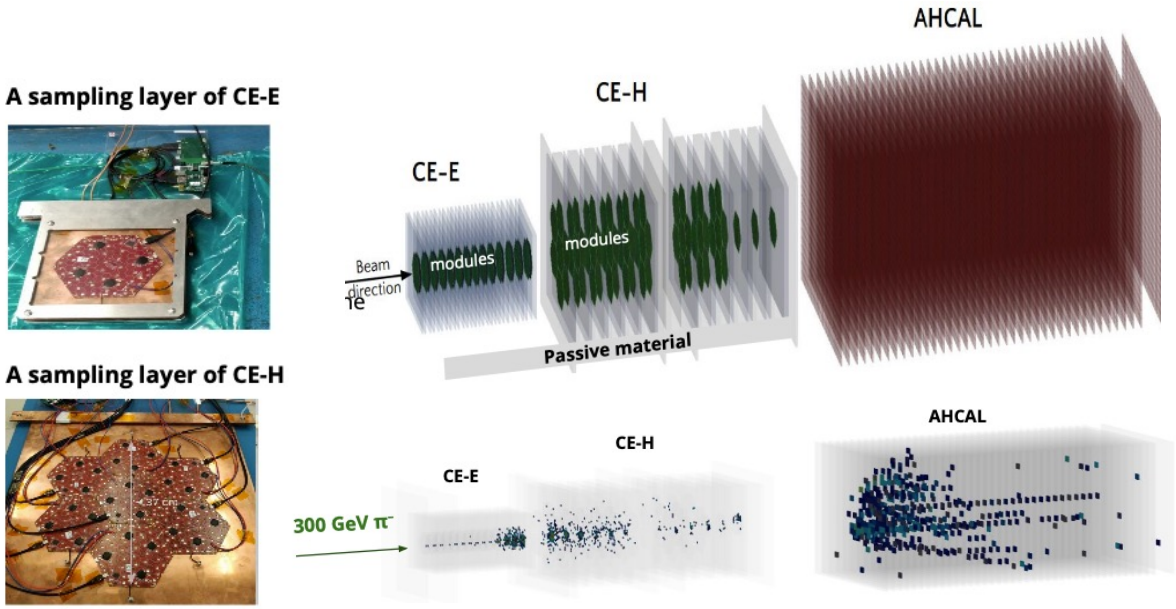



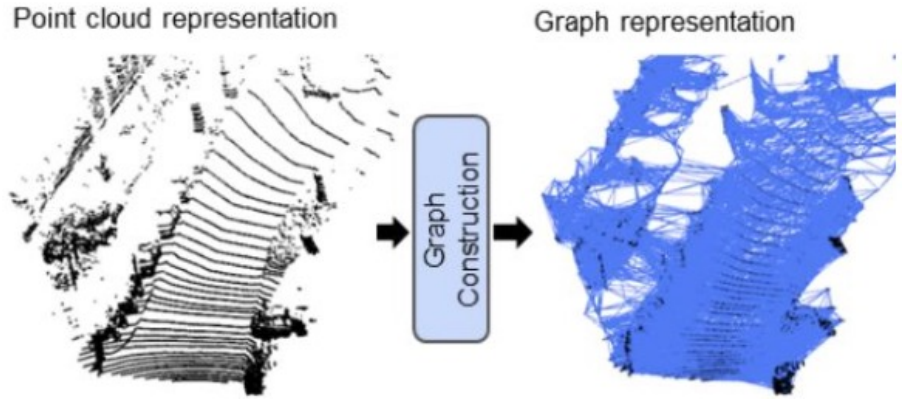




- Measure particle trigger time with ~0.8 ns resolution

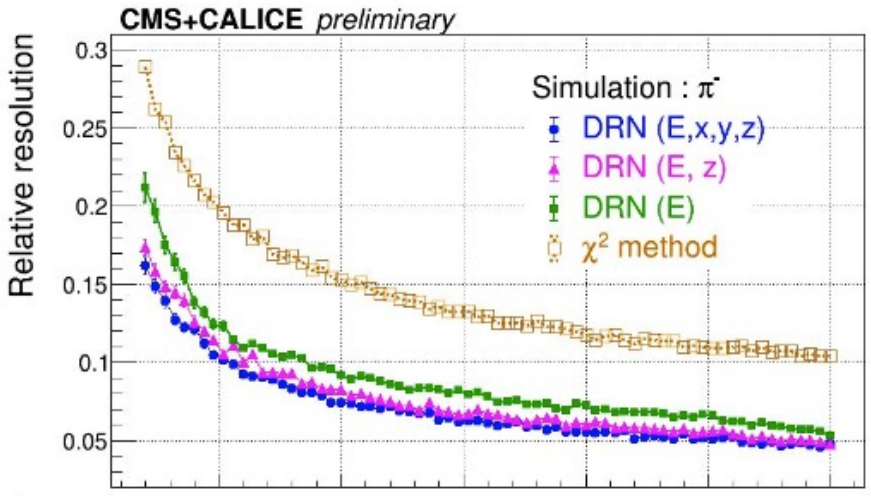
# 量能器研究 – 用GNN对 $\pi$ 进行能量重建

- $\pi$- energy reconstruction in HGCAL using Graph Neural Networks (GNNs)



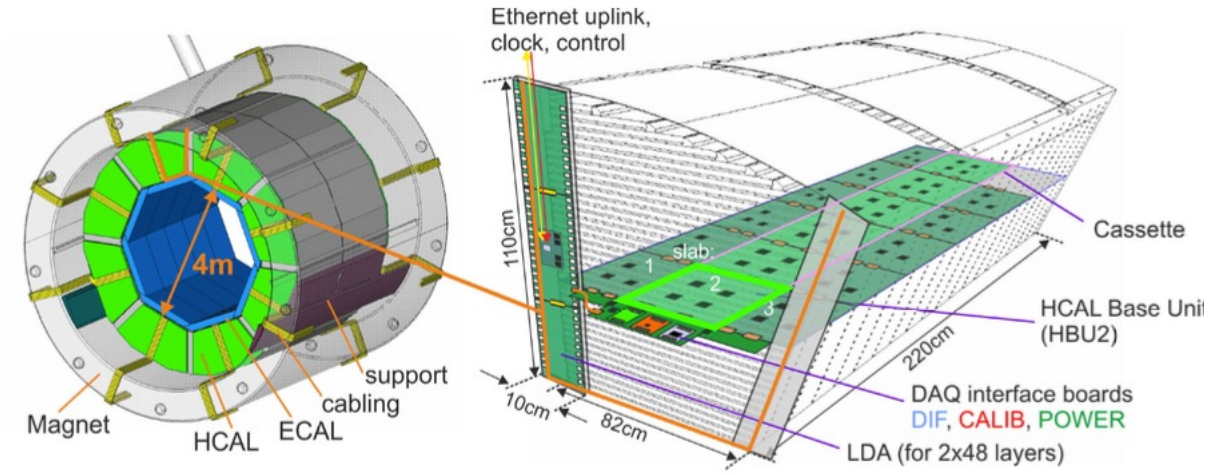



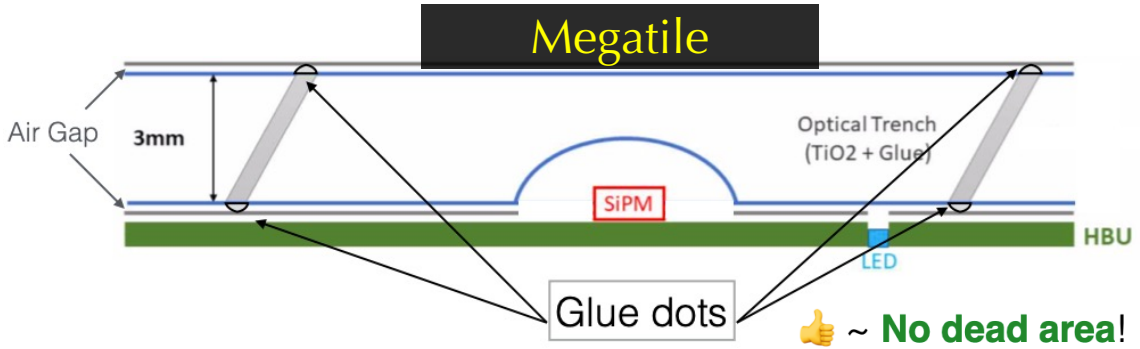

- GNN method substantially improves the energy resolution compared to simple energy reconstruction based on $\chi^2$ method



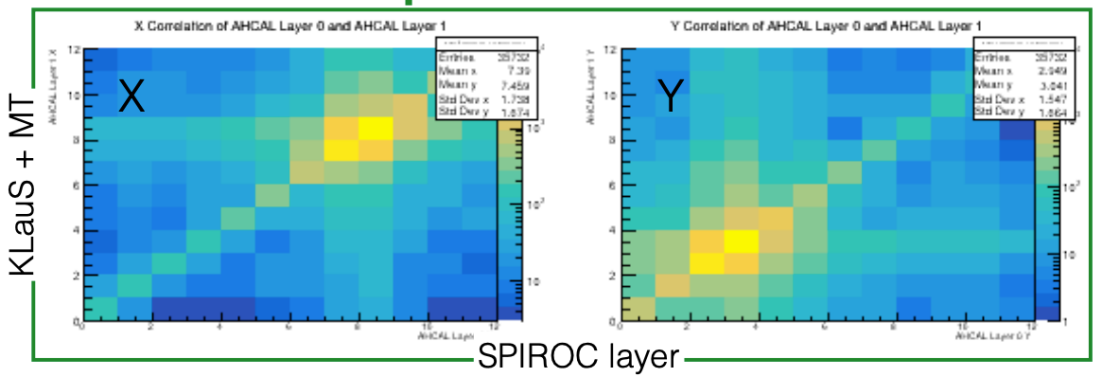
# 量能器研究 – CALICE AHCal test beams

- AHCal: Analogue Hadronic Calorimeter
  - Plastic scintillator tiles, SiPM readout
  - Hadronic calorimetry few % resolution




**Spatial correlations**

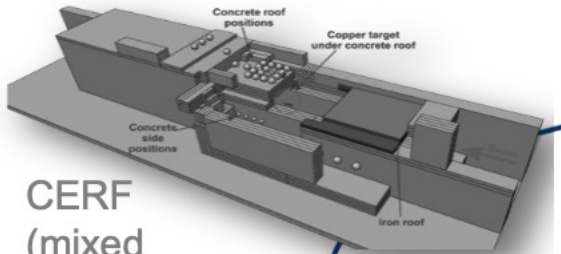



- Good space and time correlations observed.

# Irradiation Facility: Why ?

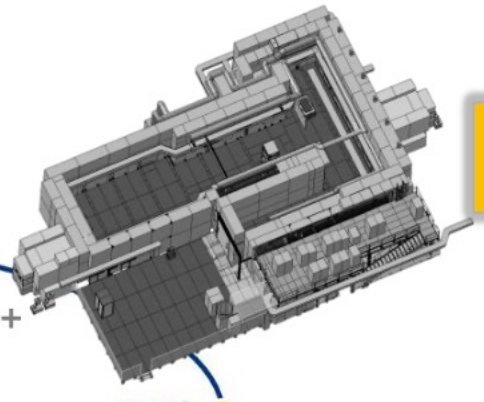
- **Radiation damage studies on:**
  - **materials** used around accelerators/experiments
    - structural material, glues, pipes, insulations, thermal materials, …
  - **electronic components**
    - transistors, memories, COTS, ASIC, …
  - **semiconductor** and **calorimetry** devices
    - silicon diodes, detector structures, scintillating crystals …
    - **equipment sitting in the inner/middle layers of HEP experiments**
- **Test and development of prototypes / final assemblies / electronics equipment before installation:**
  - performance **degradation after long exposure**/ageing (TID, NIEL, …)
  - functional **degradation of electronics** (SEU, latch-up, …)
- **Test and calibration of components:**
  - **dosimeters**, radiation monitoring / measurement devices
  - detector performance in presence of high background

# CERN Irradiation Facilities

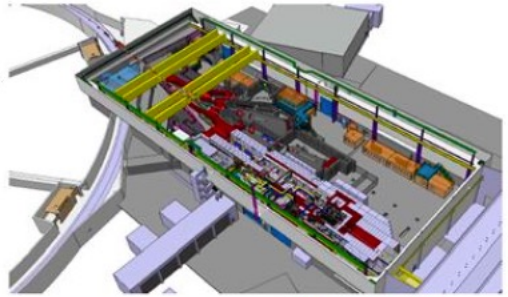


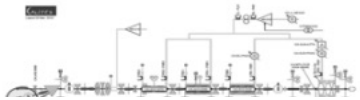

CERF (mixed field)

CALLAB (irradiation sources)

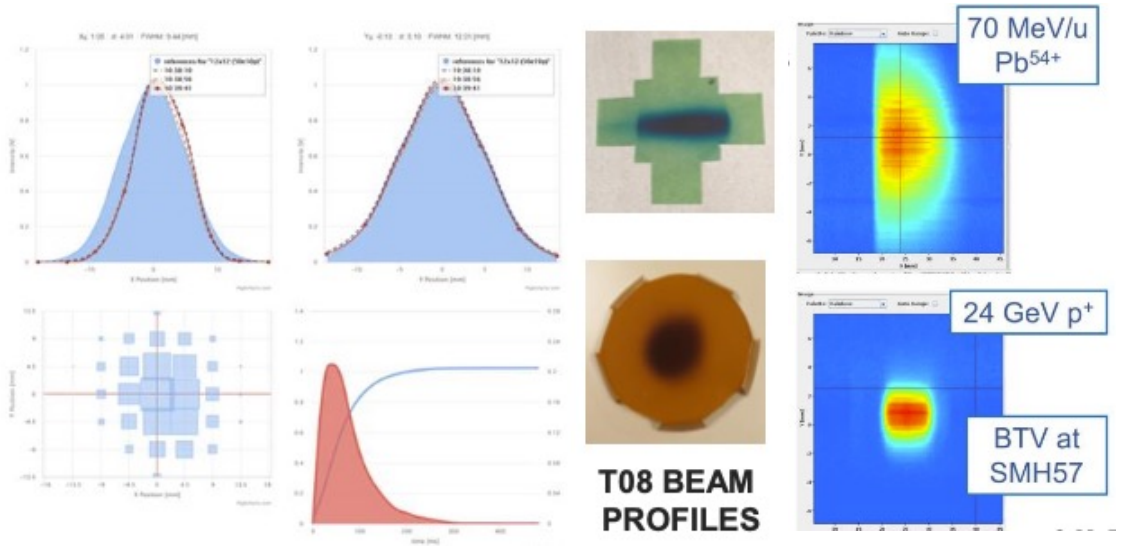


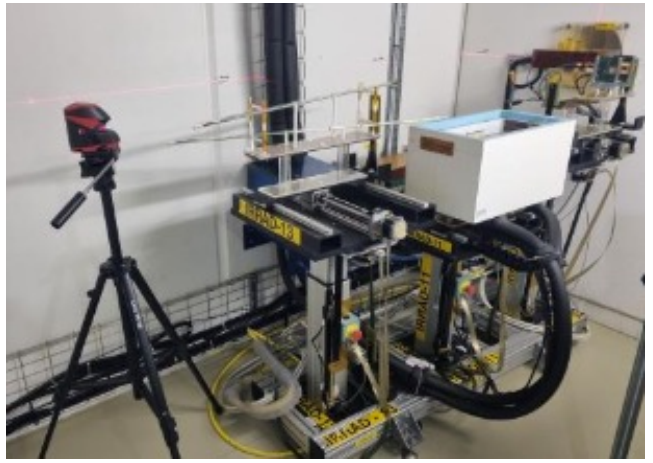
Presentation from M. Jaekel

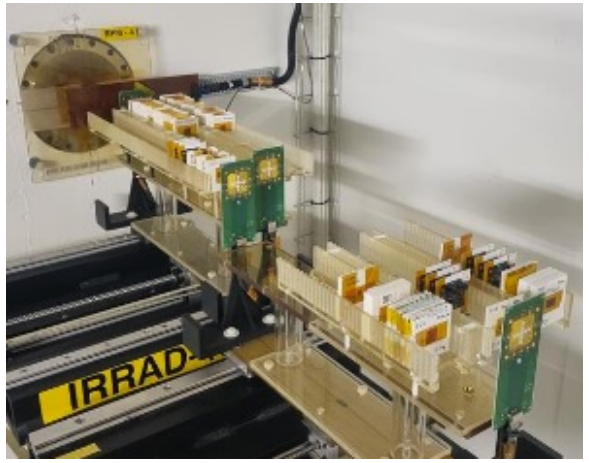




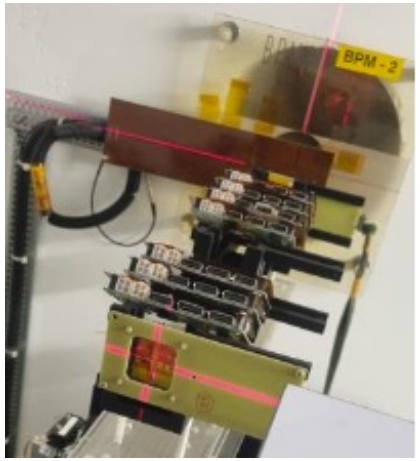
# IRRAD Beam Commissioning and User Run







# 用户需求响应

- 高能物理实验：
  - 位置精度：3 μm
  - 能量精度：<2%
  - 能量范围：最低至100MeV
  - 单质子计数率：1kHz以上
  - 次级计数率：100Hz以上

- 航天器探测器测试需求：
  - 面积：10×10$cm^2$
  - 计数率：1kHz以下

- 测试环境
  - 温度环境： -40℃ ~ 100℃
  - 磁场环境：~1.5T

# 总结与展望

- 束流测试线是开展探测器研究的重要基础设施
  - 质子、电子、π介子、重离子束流等

- 主要开展的探测器研究包括
  - 位置分辨： 微条、像素型
  - 时间分辨： LGAD、3D、CMOS, SiGe BiMOS 等
  - 能量测量： SiPM-on-Tile, 5D, HGCal， AHCal
  - 辐照研究： 材料、电子学、半导体探测器、量能器等

- 未来束流测试平台： 综合位置分辨、时间测量、能量测量、辐照等

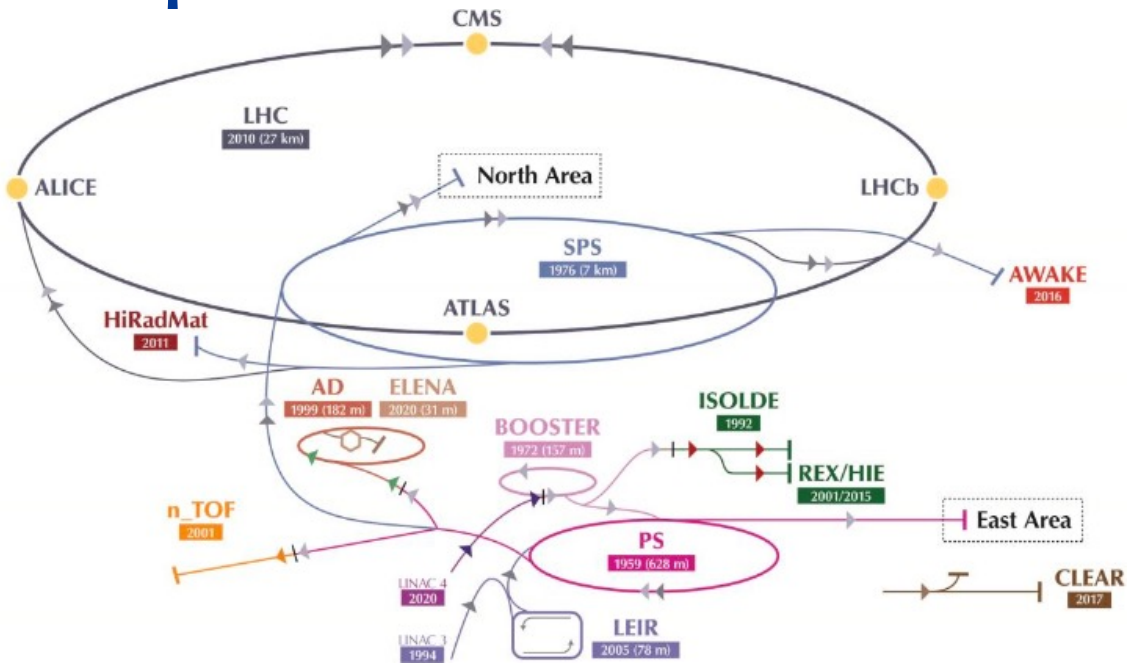
# Backup

# 束流测试线的种类

| 粒子类型 | 束流能量 | 束流强度 | 供数时间 | 所属实验 |
|---|---|---|---|---|
| 质子 | 24 GeV | | | CERN/SPS |
| 质子 | 400 GeV | | | CERN/PS |
| 电子 | 0.45GeV ~ 6.3GeV | 10k | 99% | DESY |
| 质子 | 120 GeV | 1k~900k | 9 m/year | FNAL |
| 质子 | 1~66 GeV | | | FNAL |
| 质子 | 200 MeV | | | FNAL |

# CERN has a test beam complex

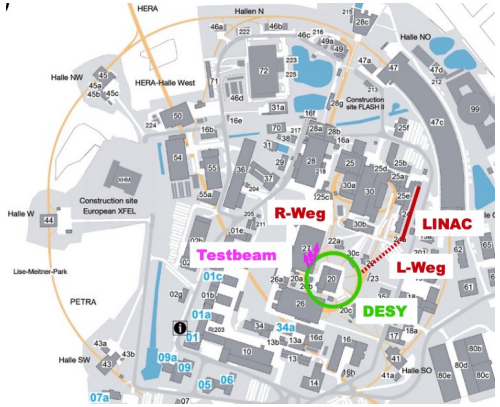
- East Area
  - Momentum : 0.5 GeV/c – 15 GeV/c
- North Area
  - Momentum: 10 GeV/c – 400 GeV/c
- Capable to provide
  - Protons
  - Electrons
  - Hadrons
  - Pure pions
  - Muons
  - Tagged photons
- Diverse instrumentation for various purposes



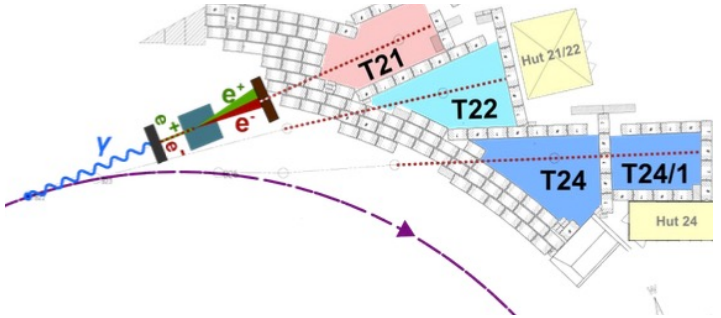

SPS : protons/ions @ 400 GeV/c/Z
PS: protons /ions @ 24 GeV/c/Z

# DESY II Test Beam

- Facility parasitically fed by DESY II synchrotron (PETRA III injector)
  - 1 bunch per fill
  - 1 MHz circulation frequency
  - Energy ramps sinusoidal @ 12.5 Hz, 0.45 ~ 6.3 GeV
  - Very high availability (~99% uptime)



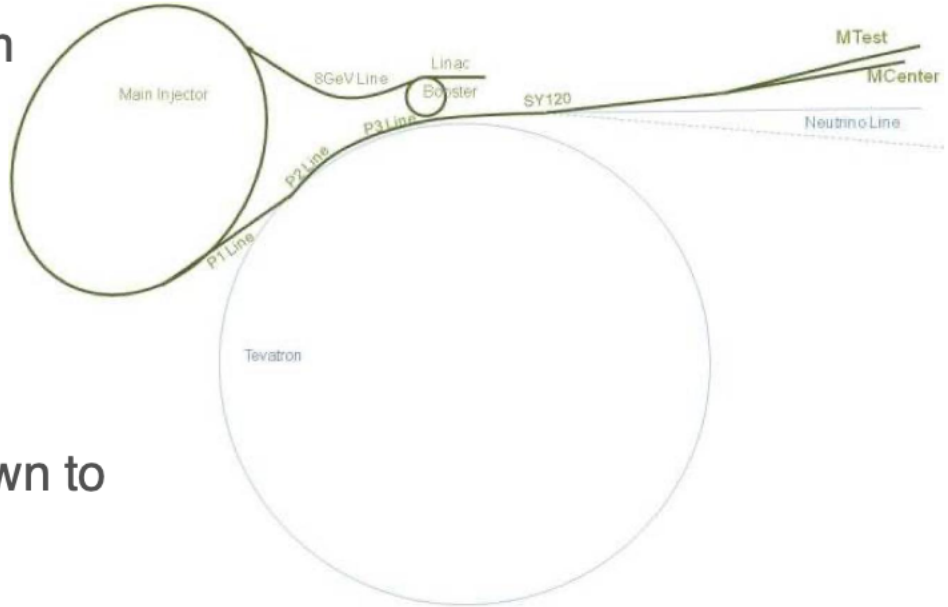

- Test beam generation
  - 3 primary carbon fiber targets generate bremsstrahlung photons
  - Conversion at secondary target to e+/e- up to 6 GeV
  - Energy selected with dipole / collimator



# Beamline Details

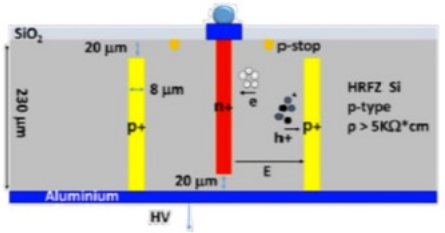
- 4 second beam spill every 60 seconds, available 24/7
- ~1000 to 900,000 particles per spill
- MTest
  - 120 GeV primary protons
  - 1-66 GeV secondary beam
  - ~2cm spot size
  - 1-4 week runs
- MCenter
  - Secondary beam
  - Two tertiary beamlines down to 200 MeV
  - longer term experiments

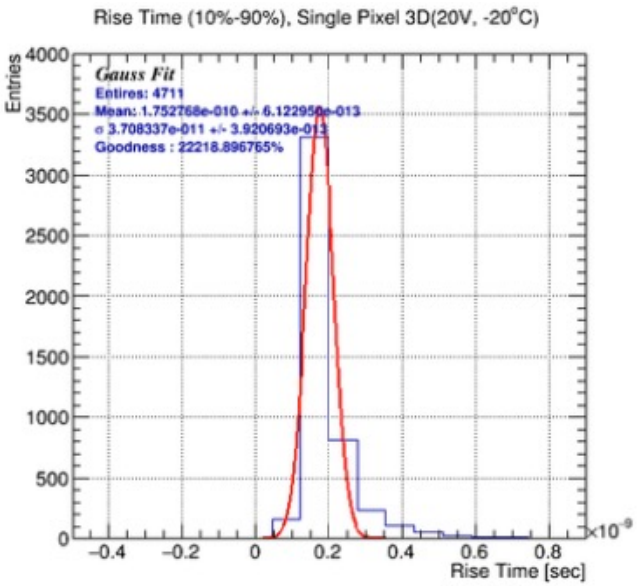
- Fermilab Test Beam Facility (FTBF) – Supports a wide program of research and detector R&D
  - 2 Beamlines (MTest and MCenter) – can provide particles from 120 GeV protons to secondaries of ~200 MeV

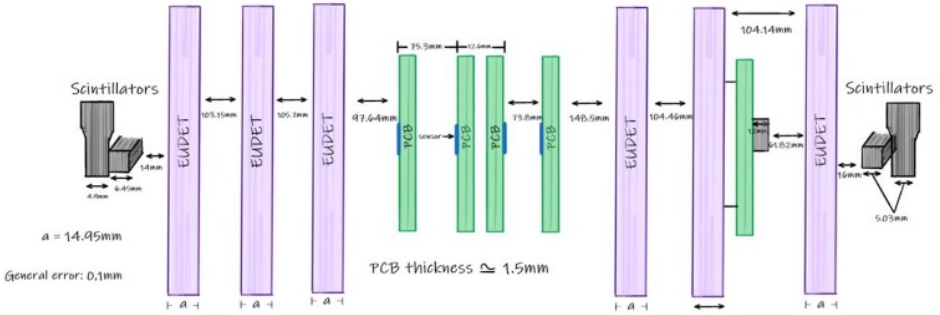


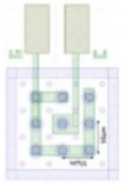

# 时间分辨研究 – 3D

- 小间距3D传感器
  - 解耦电荷产生与漂移体积
  - 抗辐照能力强 ~$10^{16} n_{eq}/cm^2$
  - 漂移距离短，上升时间快
  - 能量沉积扰动小
  - 电场不均匀、造价高、单元电容大



ATLAS IBL Type

- ✓ Double sided n-on-p process
- ✓ Pixel Size 55 × 55 µm²
- ✓ Active thickness 230 µm
- ✓ High Resistivity (> 2 kΩm × cm) Fz silicon

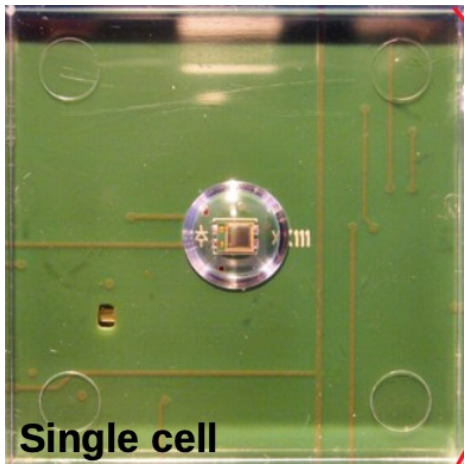
$$\sigma_{tot}^2 = \underbrace{\sigma_{timewalk}^2}_{\sigma_{Dist.}^2 + \sigma_{Landau}^2} + \underbrace{\sigma_{jitter}^2}_{\left(\frac{t_{rise}}{S/N}\right)^2} + \underbrace{\sigma_{conversion}^2}_{\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2} + \underbrace{\sigma_{Clock}^2}_{\text{Fixed Term}\ \sim 5\text{-}7\ psec}$$

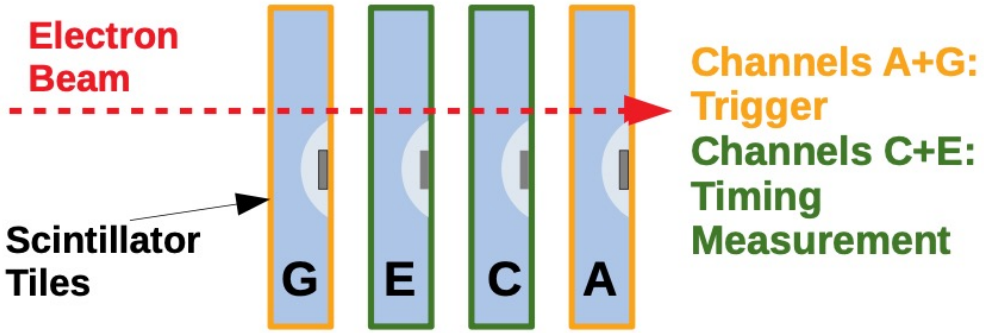
- **Extremely fast rising edge (< 180 psec)**
- **Linear stable behavior with CFD, good SNR control**

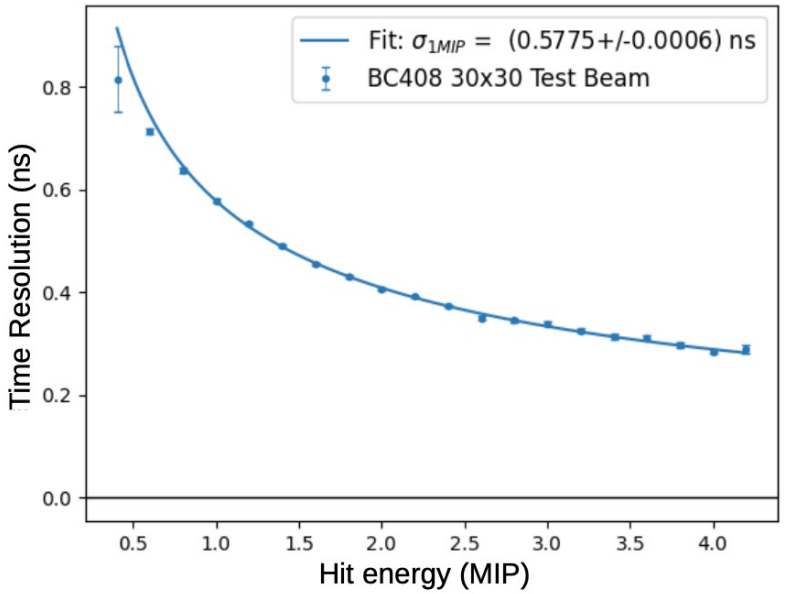
$$(\sigma_{\mathrm{Dut}})_{CFD_{ij}} = \sqrt{(\sigma_{\mathrm{Tot}}^2)_{CFD_{ij}} - (\sigma_{\mathrm{Ref}}^2)_{CFD_i}}$$

# 量能器研究 – CALICE SiPM-on-Tile

- Scintillator telescope with two coincidence triggers (Ch A+G)
- Two additional scintillator tiles (Ch C+E ) to determine time resolution

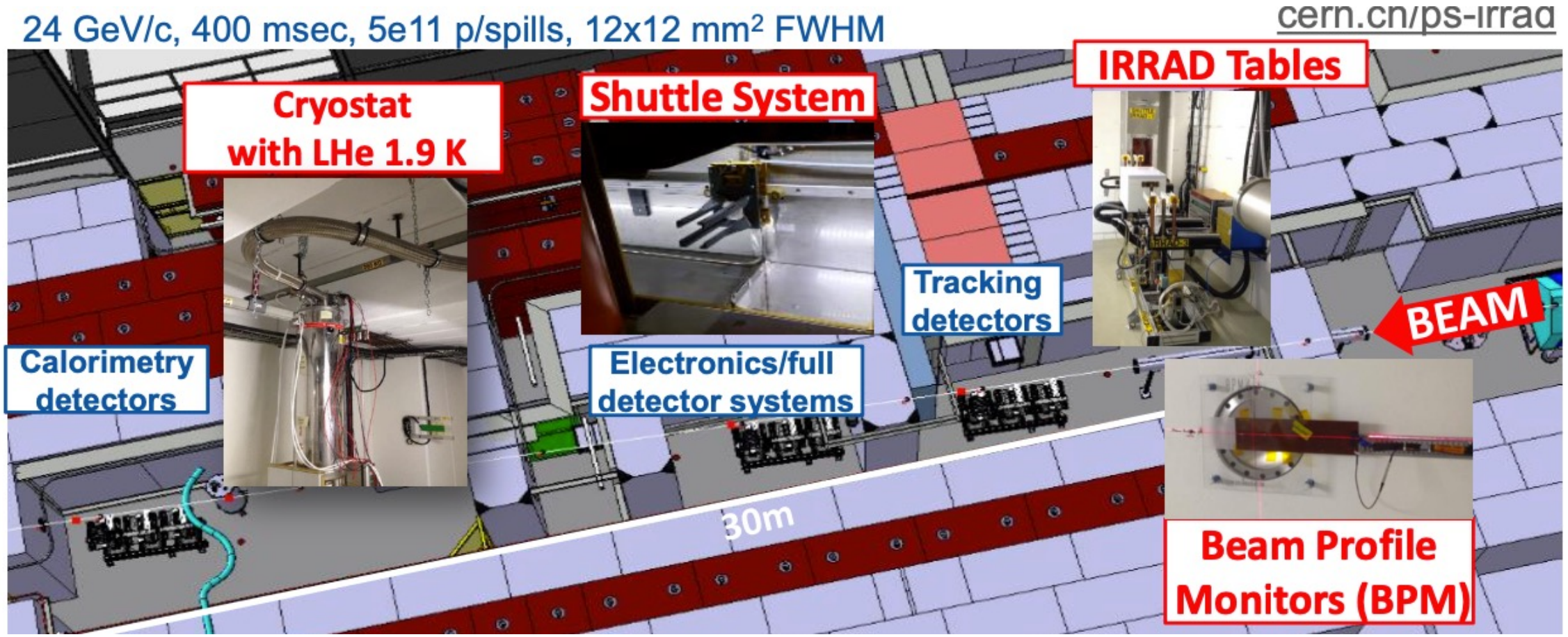


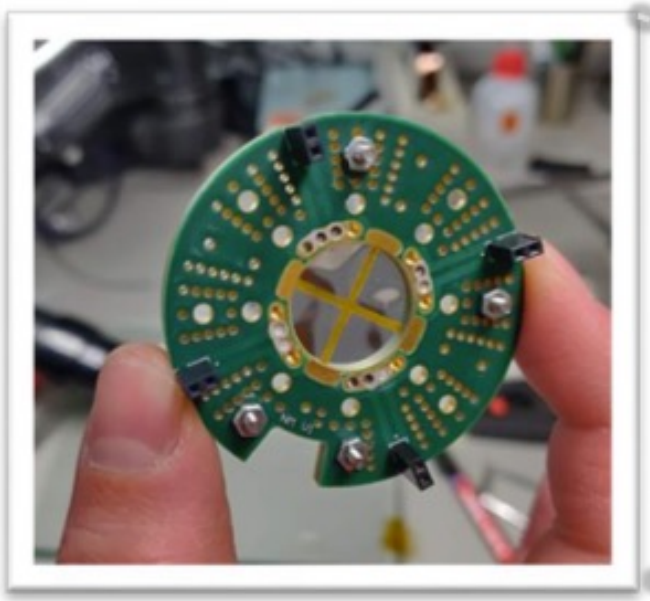

- Tile size 20x20 with time resolution ~380ps

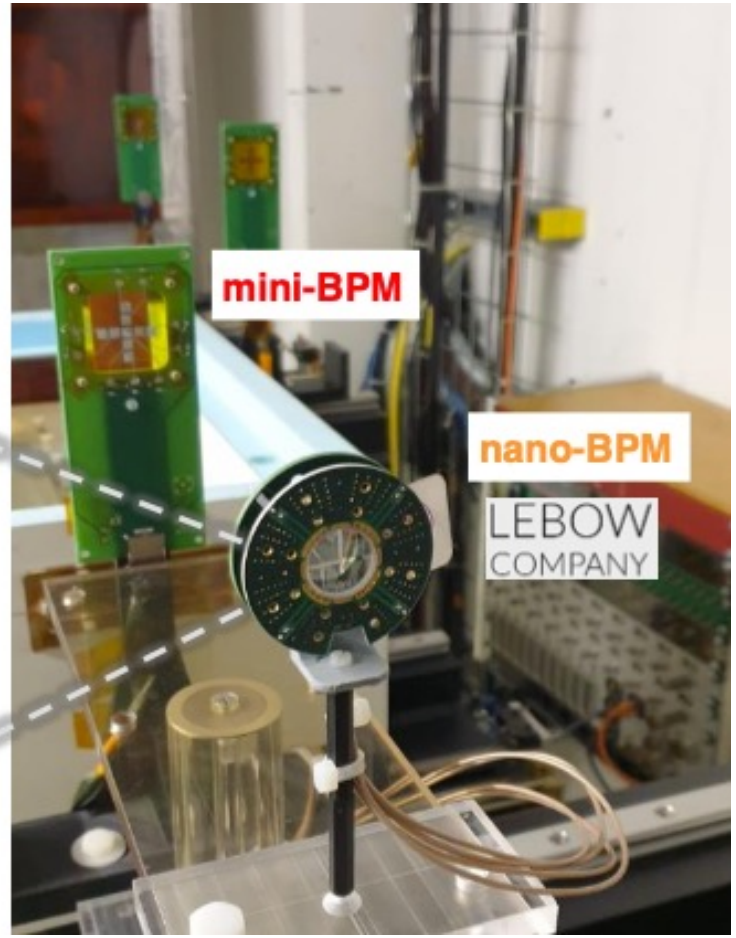
# CERN Proton Irradiation Facility (IRRAD)



# Ultra Thin Beam Position Monitors

Support the development of **nano-BPM** for AD **Al/Parylene** (**10/100nm**) for keV range

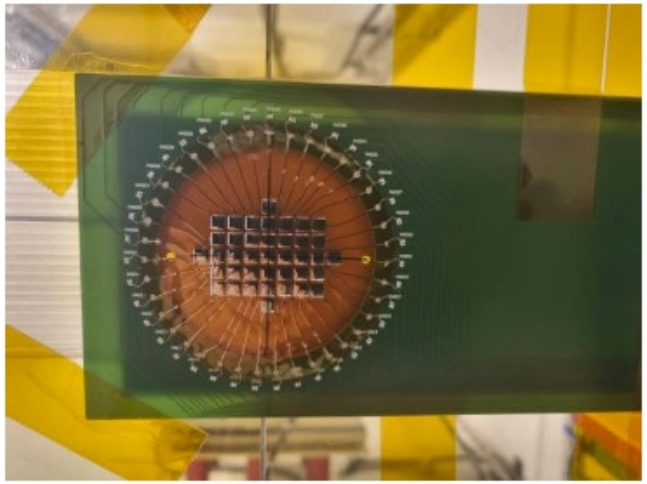




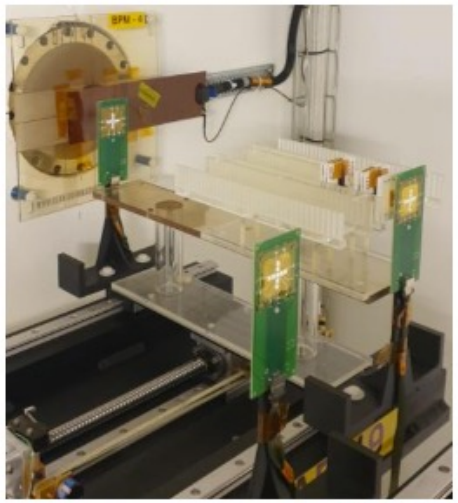
# IRRAD Beam Profile Monitors

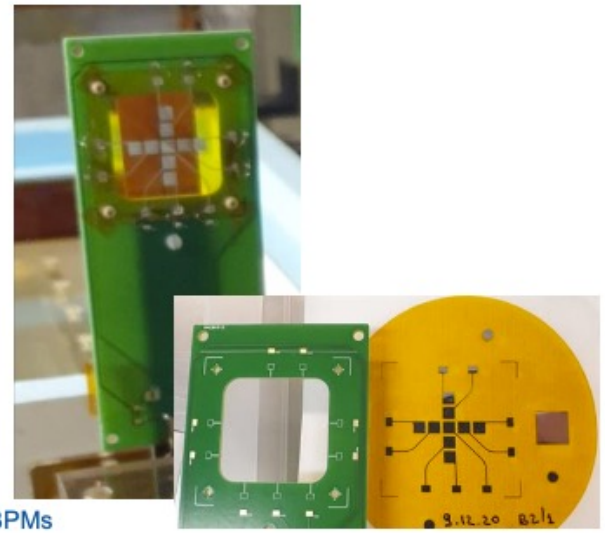
## Innovative Beam Profile Monitors:

- new **mini-BPM Al/Kapton (0.3/25μm)** produced, tested in IRRAD, now operational
- large pattern **micro-BPM Al/Kapton (0.2/25μm):** first prototype tested, new production ongoing



40channel micro-BPM device





New mini-BPMs