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

Vertex detector

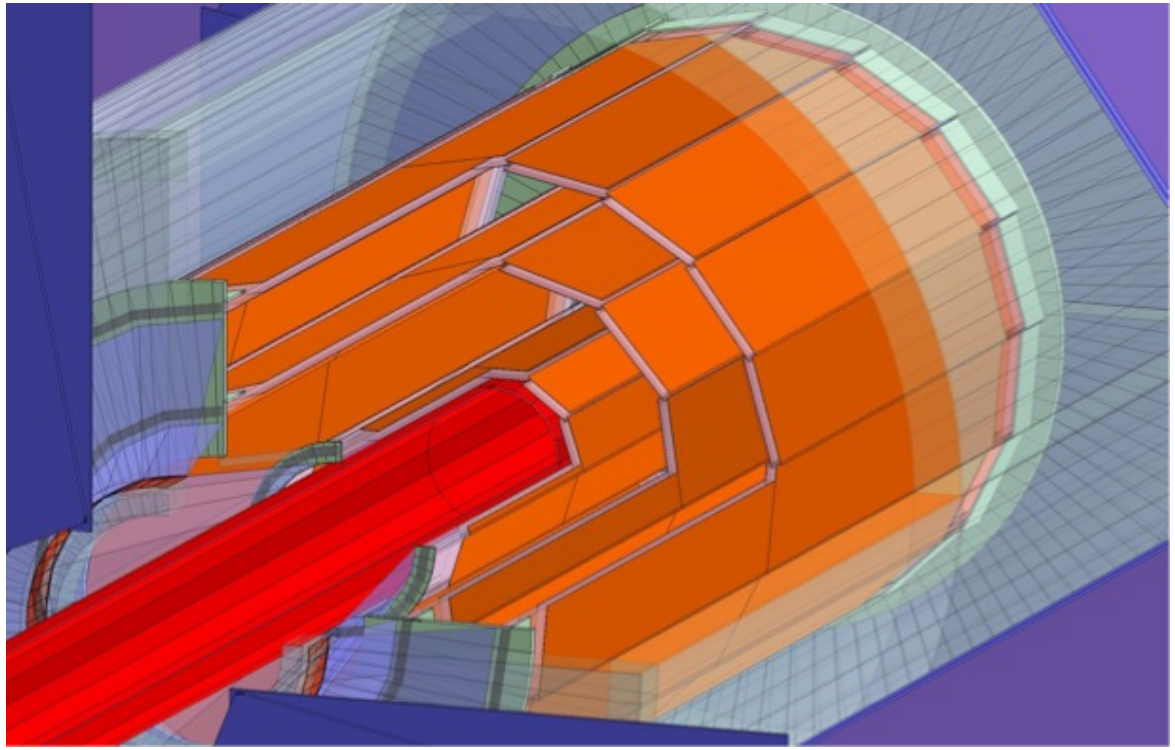
Zhijun Liang

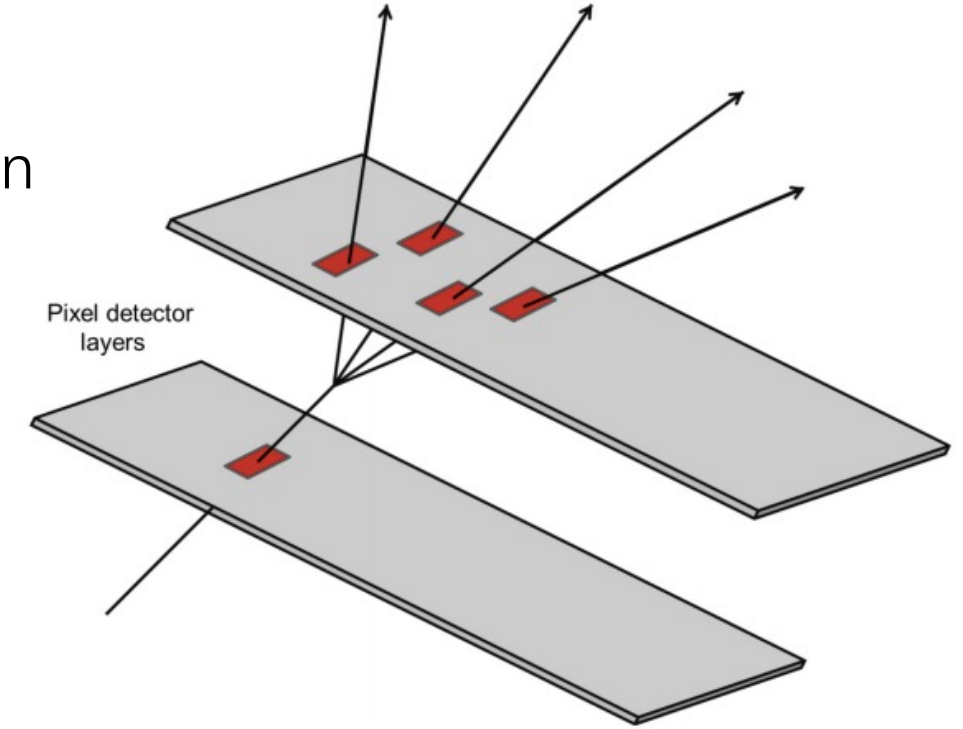
on behalf of CEPC vertex detector group

CEPC
Circular Electron Positron Collider

Physics goal for vertex detector

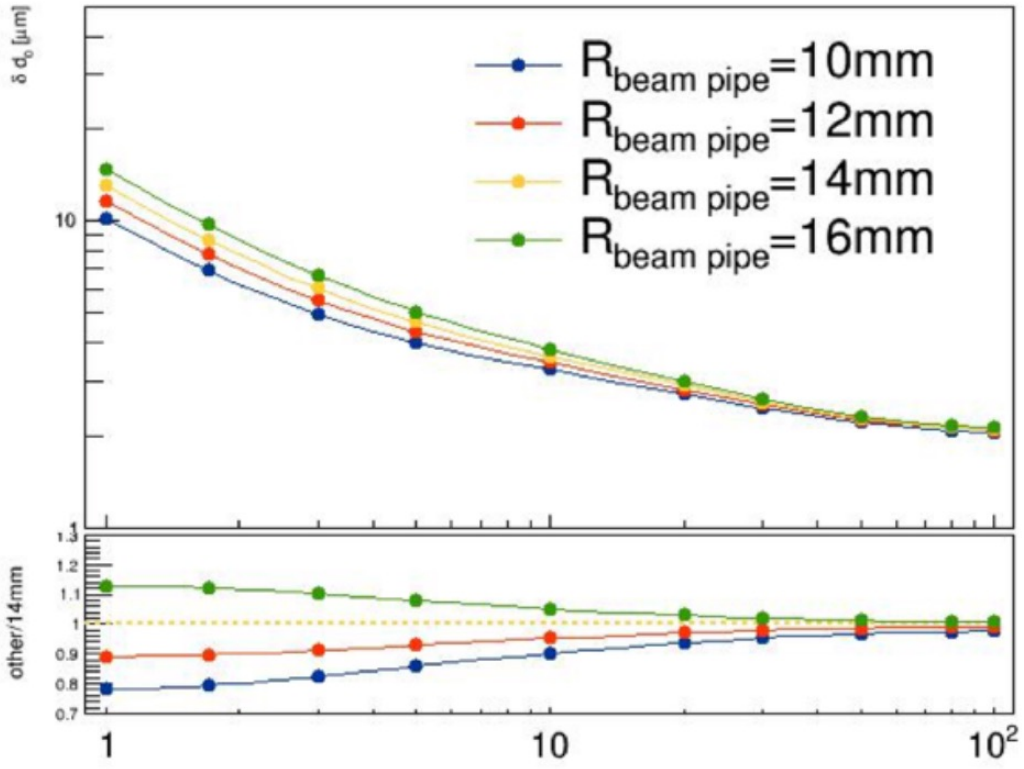
- Higgs precision measurement
  - H → bb/cc need precise vertex reconstruction
  - H → μμ (precise momentum measurement)





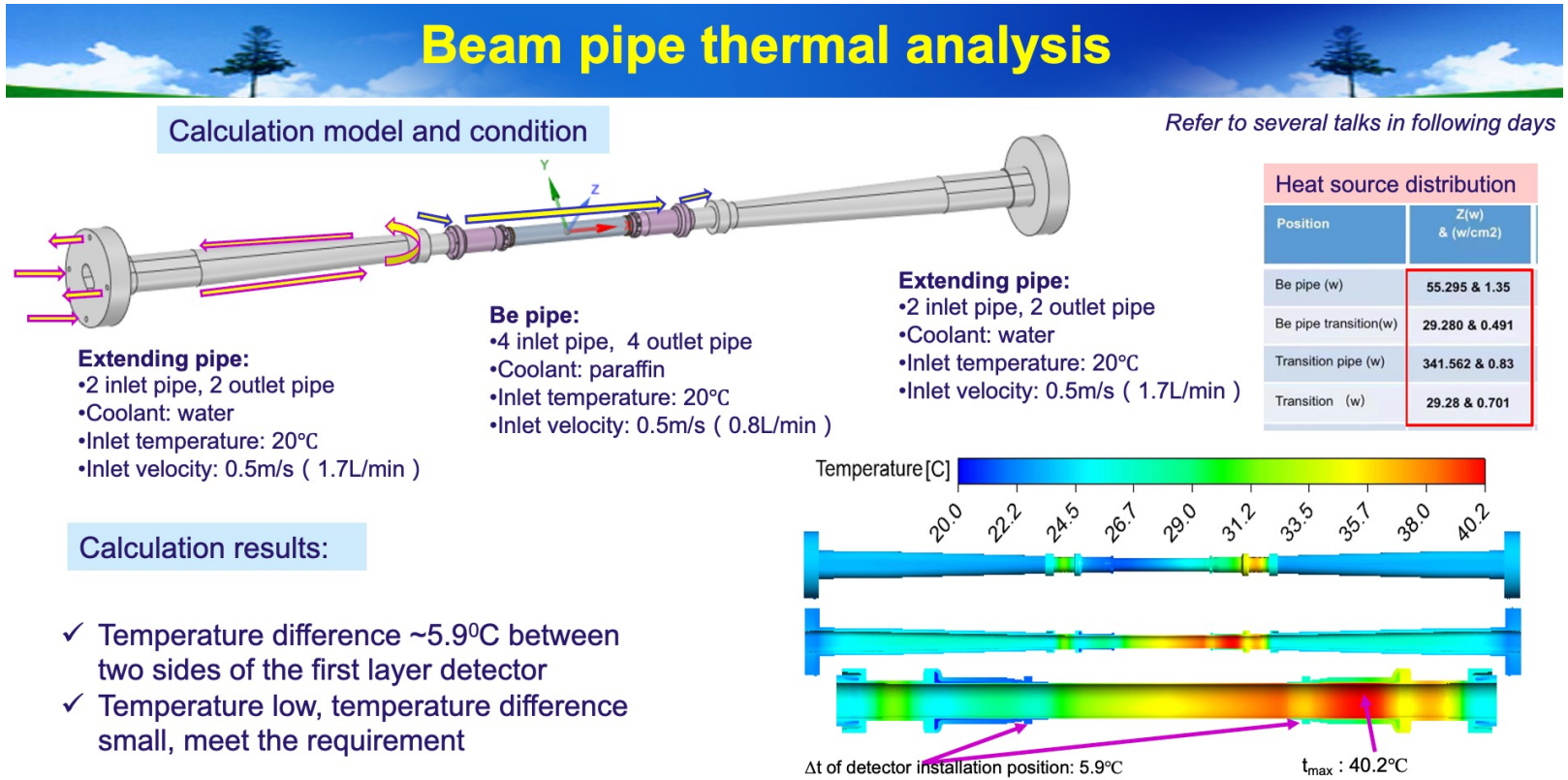
Requirement from vertex detector

- MDI related requirement
  - Temperature <= 20 C (40C+), possible to decrease the temperature
  - Temperature gradient< 10 C (<7 C)
  - Vibration < 1μm (?), possible to do some simulation on vibration ?
- Vertex internal requirement
  - Small inner radius
    - close to beam pipe
  - Low material budget
    - <0.15 X0 per layer
  - High resolution pixel sensor
    - <3μm



Requirement on vertex detector

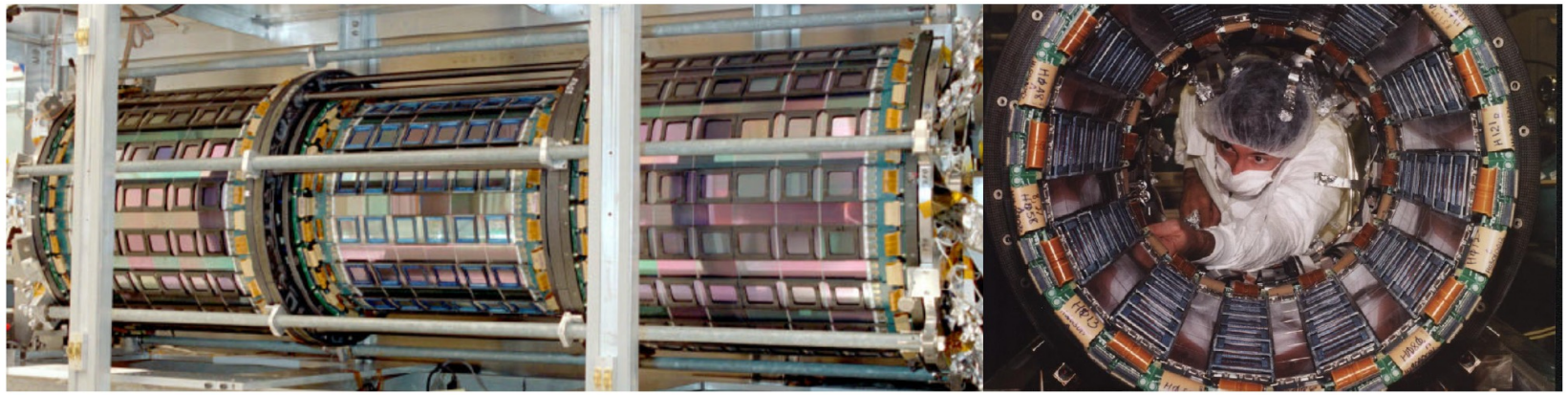
- Other requirement
  - Temperature <= 20 C (40C+), possible to decrease the temperature
  - Temperature gradient< 10 C (<6 C)
  - Vibration < 1μm (?), possible to do some simulation on vibration ?

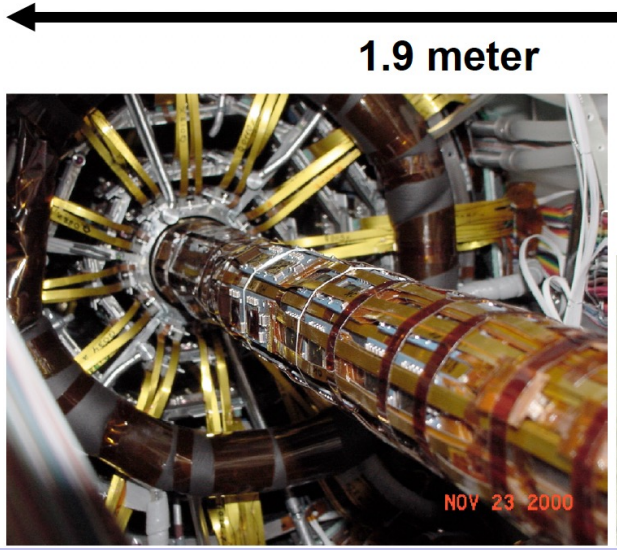


From Sha Bai

CDF vertex detector

- CDF vertex detector temperate: 6 C
  - 2007, Cooling failure a substantial leakage in the aluminum piping
  - Cooling failure period , temperature ~ 15C





1.9 meter

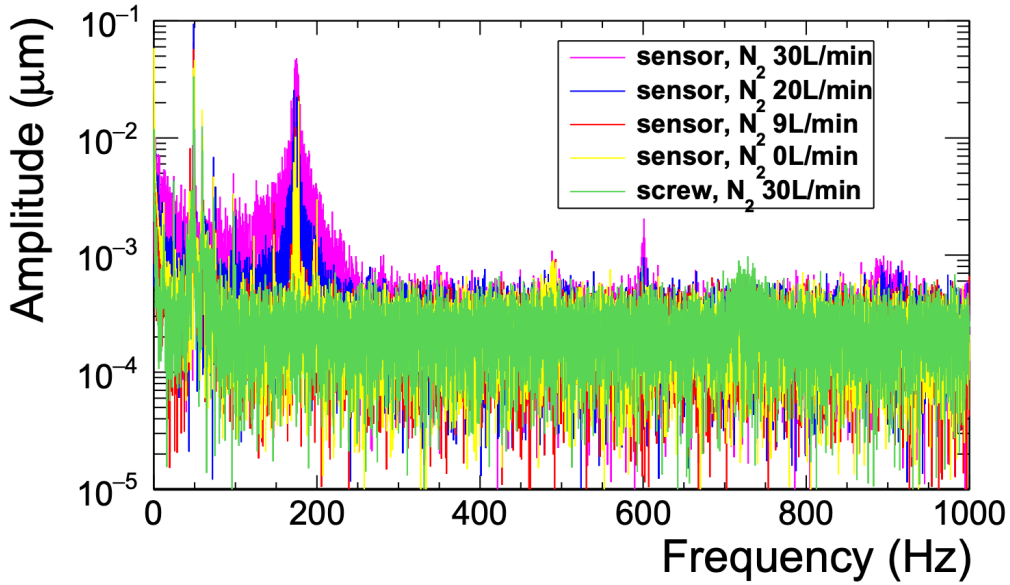
7- 8 Silicon Layers

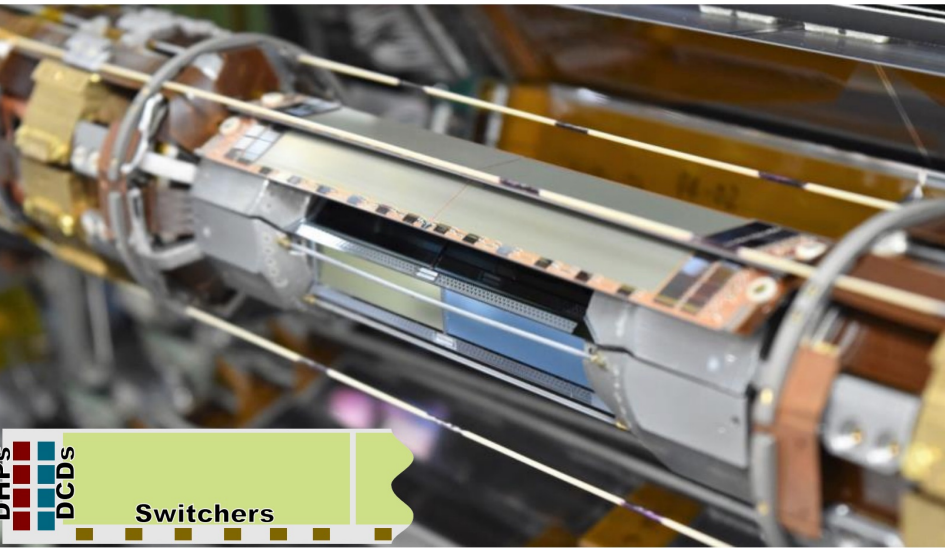
Readout channels
48,000 → 730,000

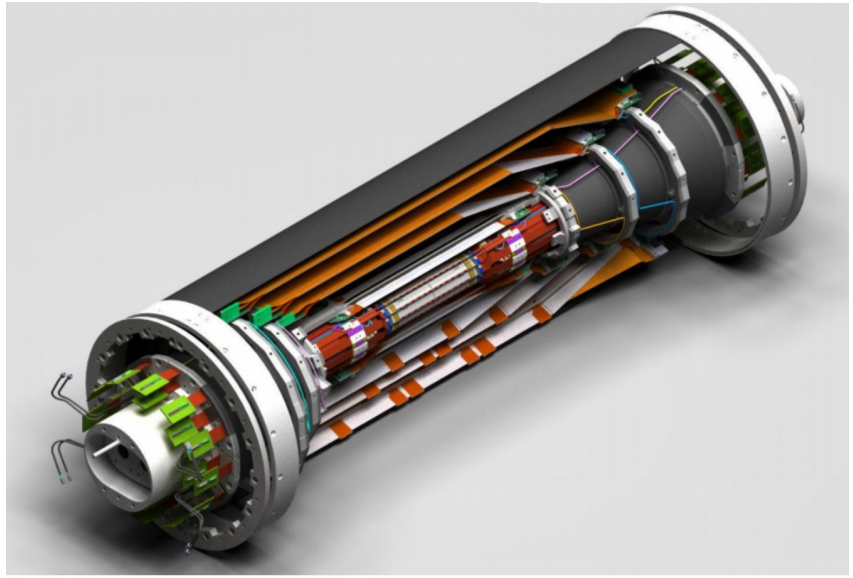
Beampipe
(the size of a quarter…. 1 Yuan)
~2.5 cm

BELLE2

- Micro-channel cooling + air cooling
  - Micro-channel cooling -20C
  - Vibration of air cooling < 1μm



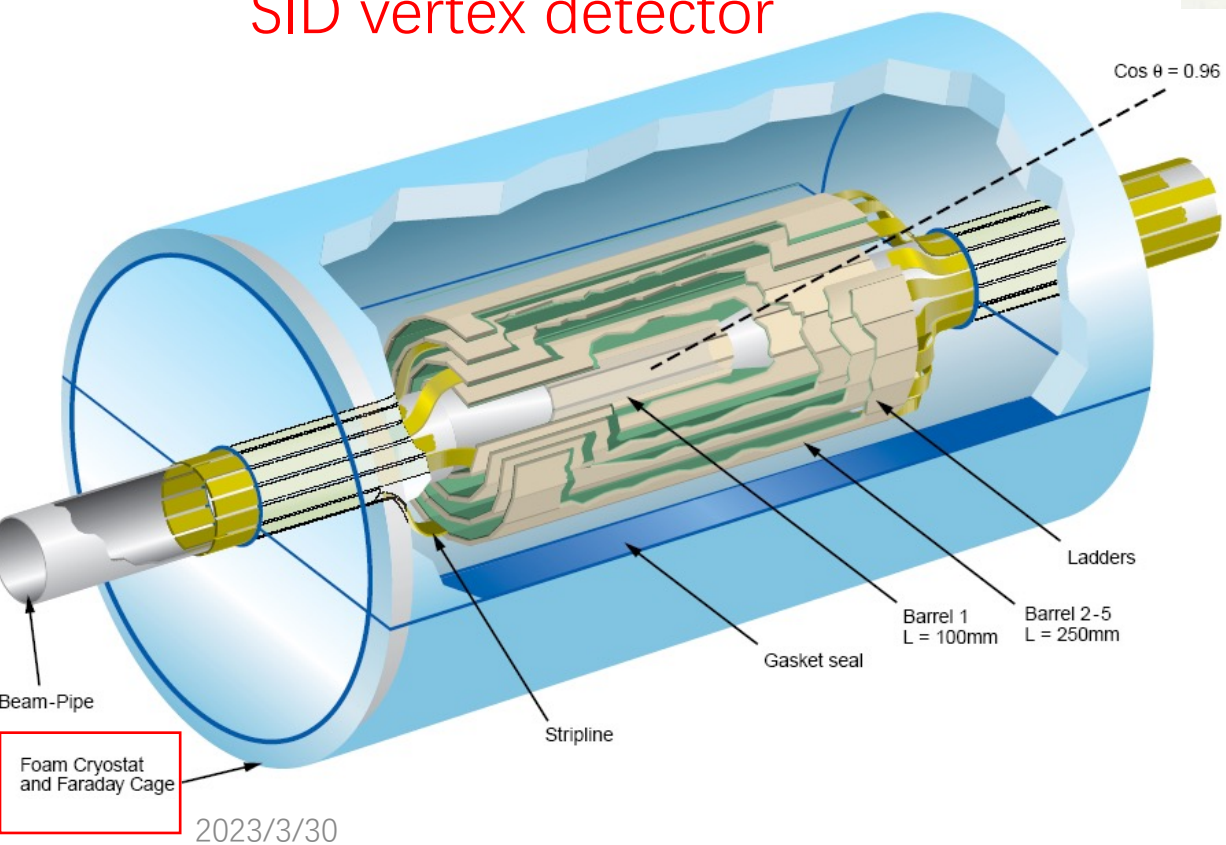




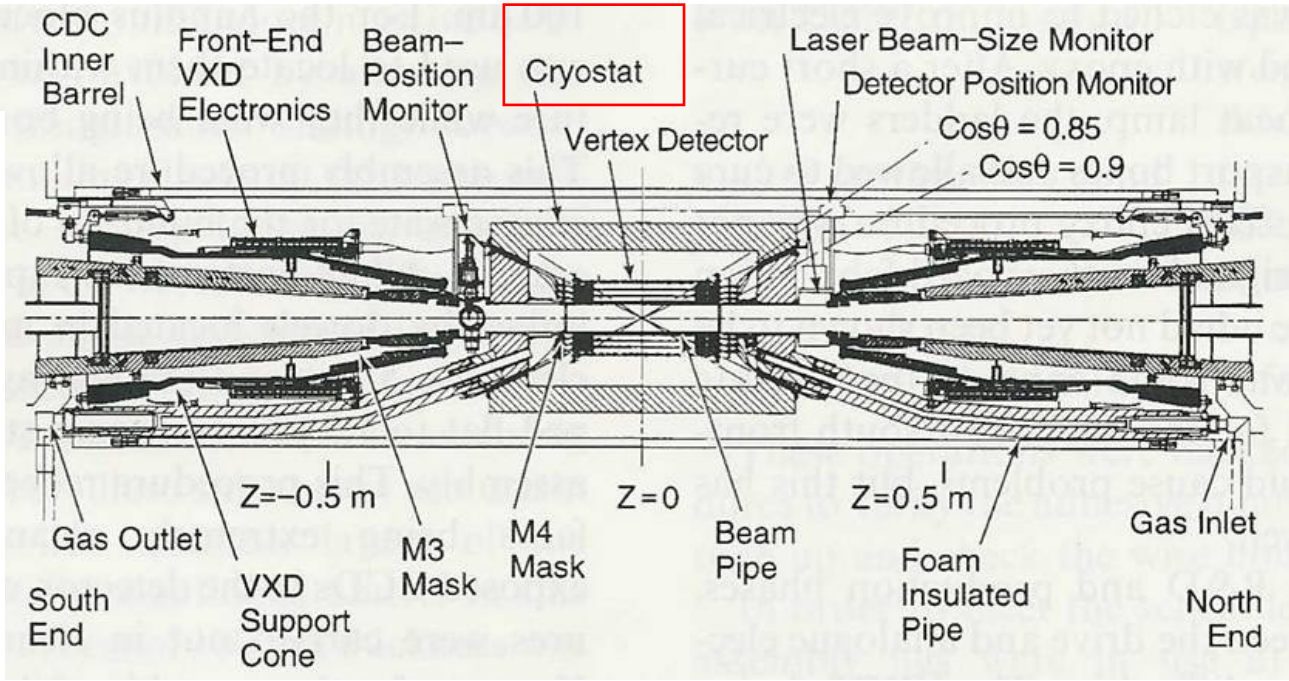
MDI interface for SID and SLD detector

- Liquid nitrogen cooling with Cryostat was used in SLAC SLD detector
- SID@ILC is also using similar design

SID vertex detector



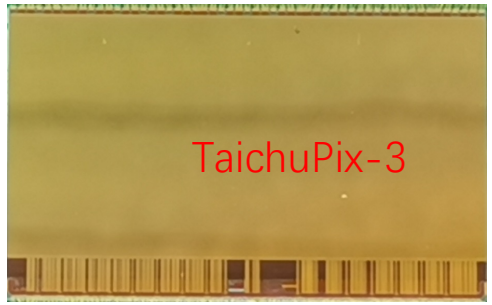
SLAC SLD detector



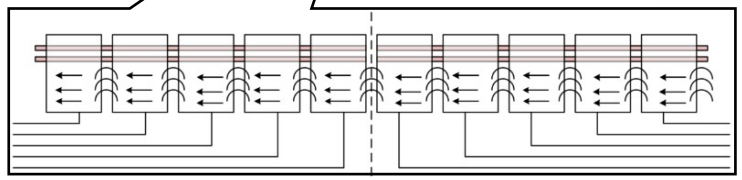
Overview of MOST2 vertex detector R&D

- **Can break down into sub-tasks**
  - CMOS Pixel Sensor chip R&D
  - Detector layout optimization, ladder and vertex detector support structure R&D
  - Detector assembly
  - Data acquisition system R&D

CMOS pixel sensor prototyping

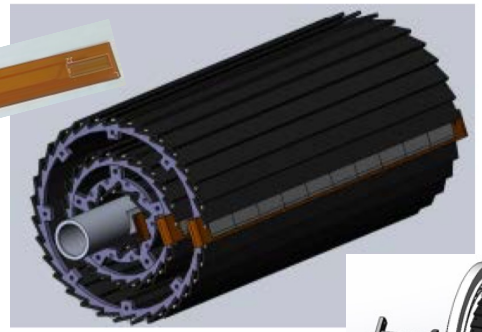


Detector module (ladder) prototyping

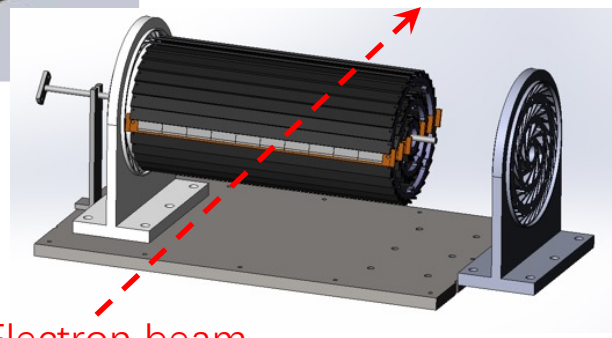


Double sided ladder
10 sensors/ladder side, read out from both ends

Full size vertex detector prototype



Beam test to verify its spatial resolution

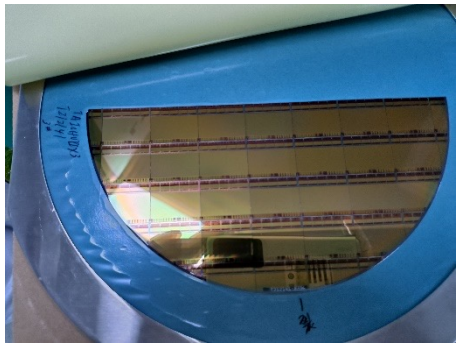


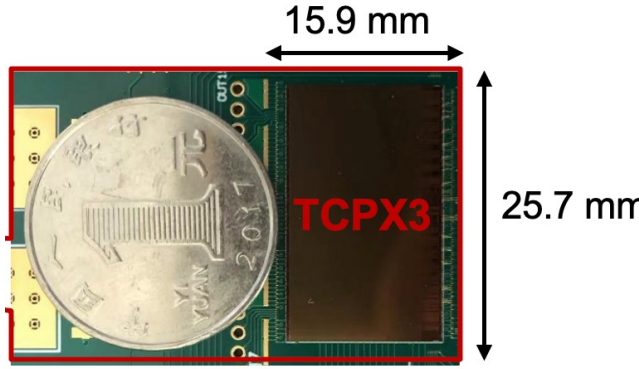
Large-scale sensor TaichuPix-3

Chip size：26 ×16 mm
Pixel size：25μm × 25μm

- **TaichuPix3 and Challenges for the CMOS sensor**
  - Small pixel size -> high resolution (3-5 μm)
  - High readout speed (<500ns deadtime @40MHz at Z pole) -> for CEPC Z pole high lumi
  - Radiation tolerance (per year): 1 MRad

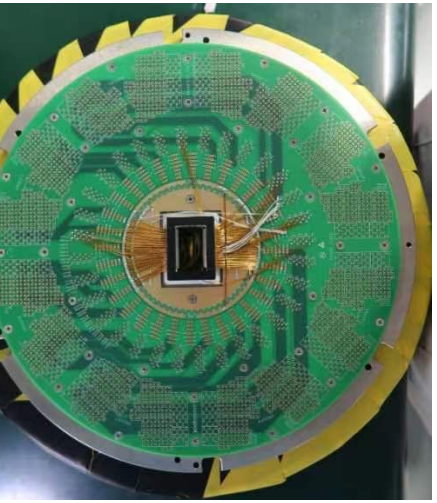
	ALPIDE	ATLAS-MAPS (MONOPIX / MALTA)	MIMOSA
Pixel size	✓	X	✓
Readout Speed	X	✓	X
TID	X (?)	✓	✓

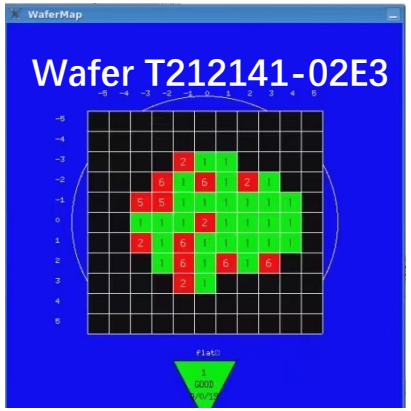




TaichuPix-3 chip vs. coin

Wei Wei, Ying Zhang
Tianya Wu


Probe card for wafer test

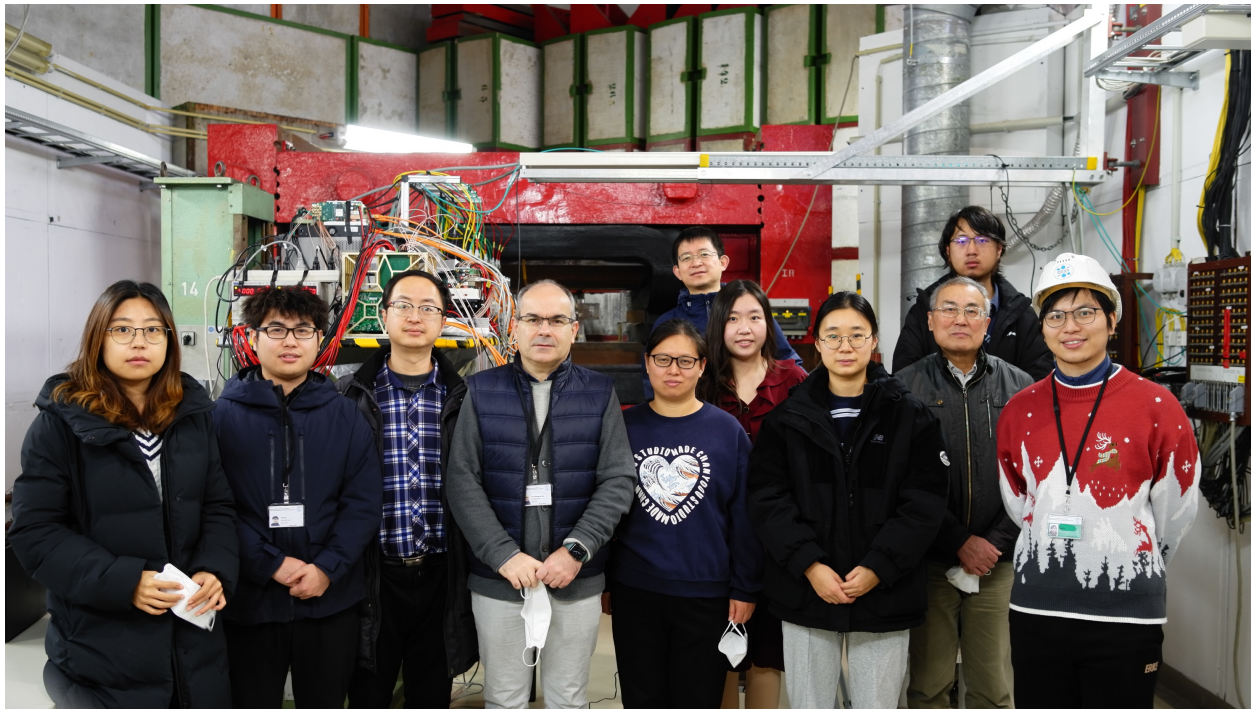


An example of wafer test result

5 wafers tested

- 2 wafer based on standard process
  - Reasonable yield achieved
- 3 wafer based on modified process
  - lower yield than the std. process

Testbeam on DESY

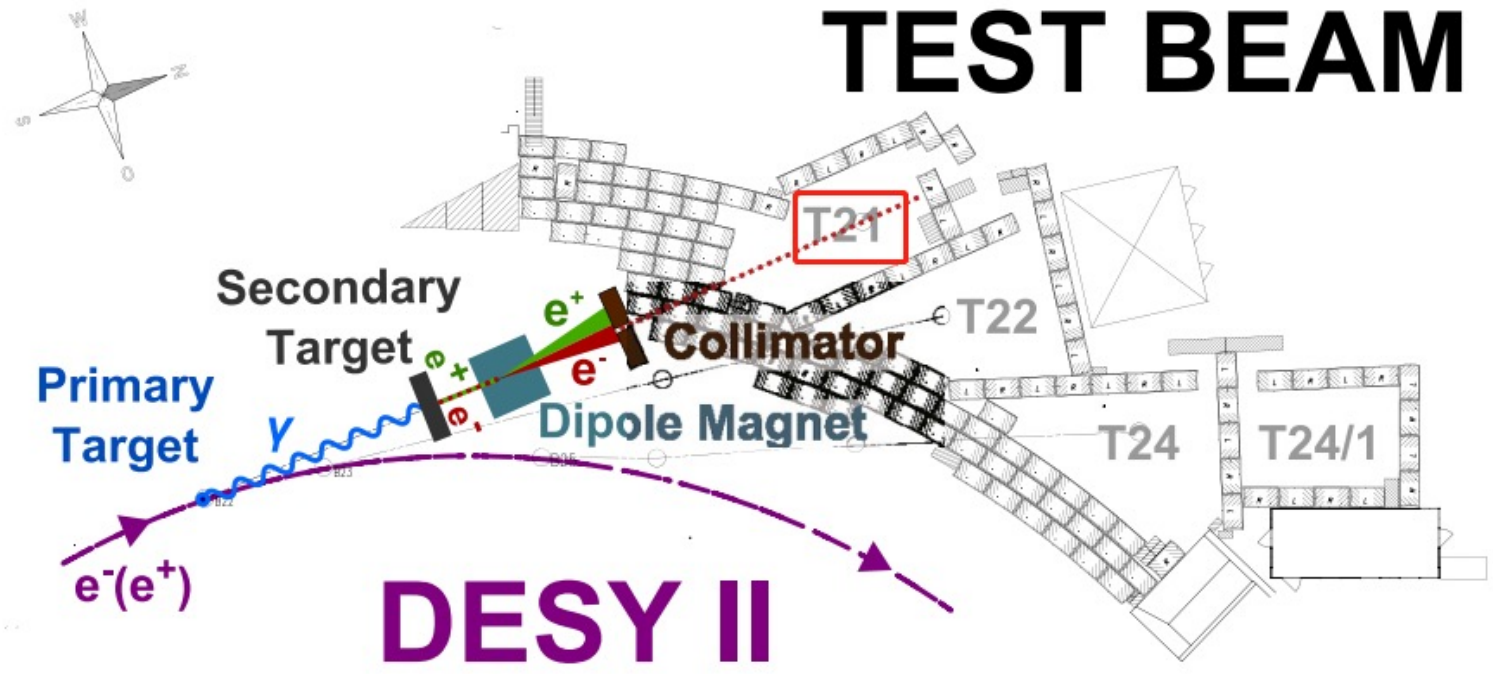


- **On Site team (DESY)**
  - Joao （IHEP）Project leader
  - Zhijun Liang (IHEP) test beam coordinator
  - Tianya Wu（IHEP）Shift leader , ASIC expert
  - Ming Qi（NJU） Shift leader
  - Lei Zhang（NJU） Shift leader
  - Xiaomin Wei（NWPU） ASIC experts
  - Jia Zhou（IHEP） DAQ
  - Xinhui Huang（IHEP）Assembly
  - Shuqi Li（IHEP) Offline
  - Hao Zeng（IHEP） Offline
  - XueWei Jia (IHEP) Offline

Romate support

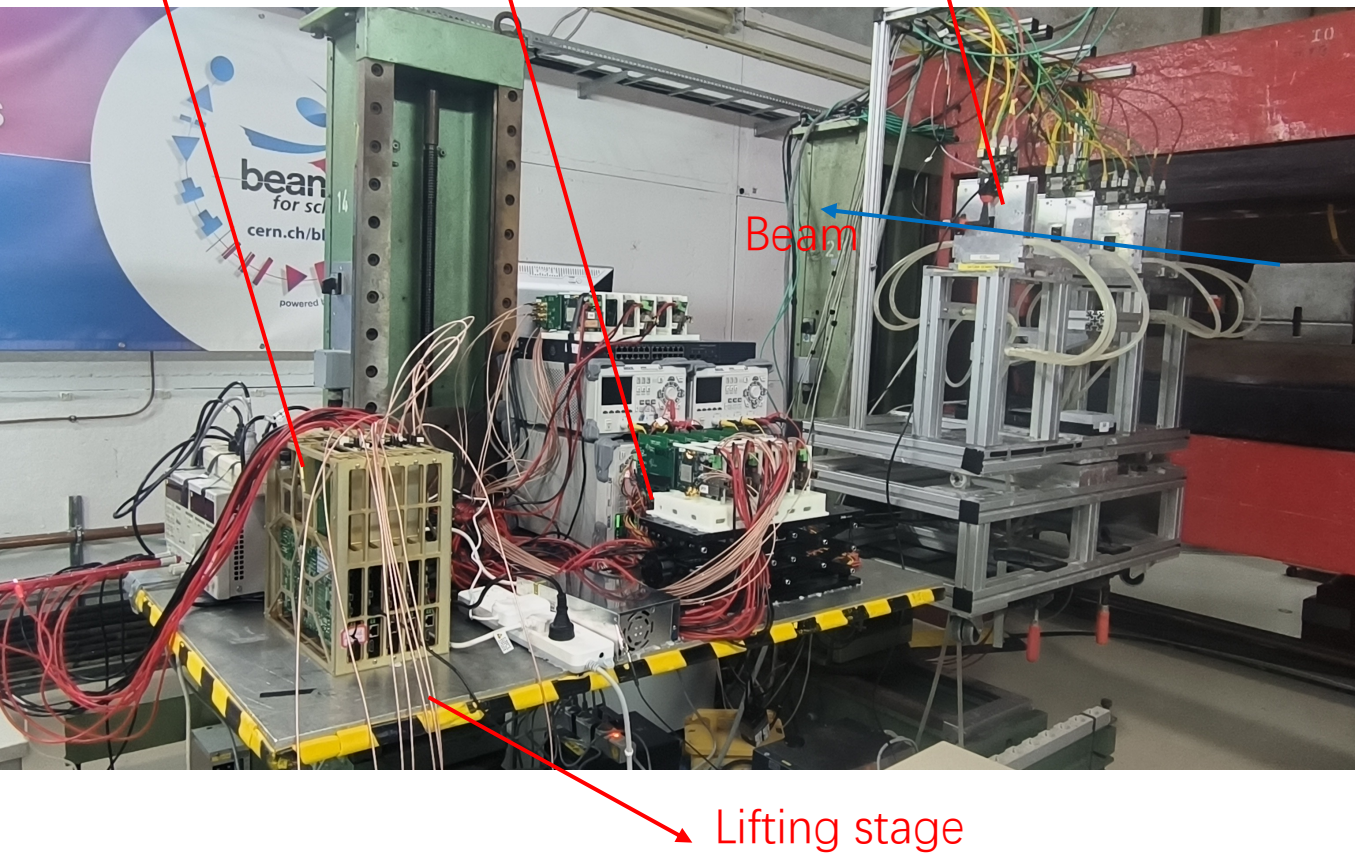
WeiWei, Ying Zhang (IHEP）ASIC
Jun Hu, Ziyue Yan（IHEP）firmware
Hongyu Zhang（IHEP）DAQ
Jinyu Fu, Mingyi Dong（IHEP） Assembly
Wei Wang, Gang Li, Linhui Wu（IHEP）Offline
Yiming Hu, Xiaoxu Zhang (NJU)…

Introduction of DESY TB21



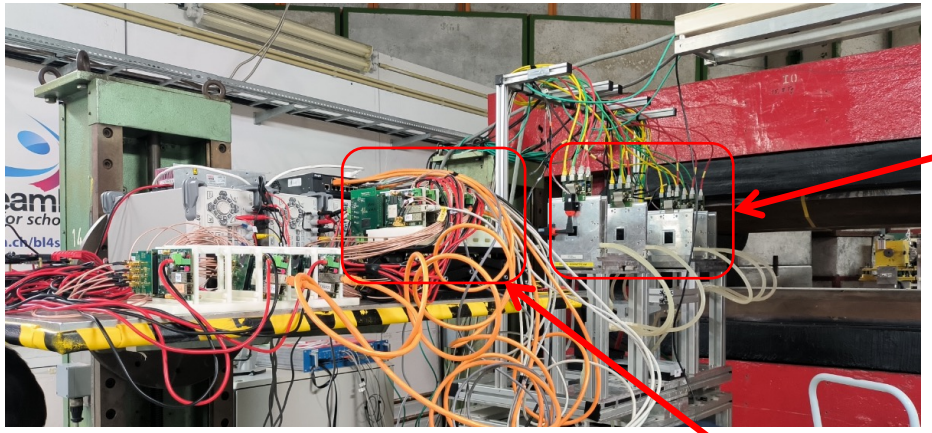
The electron or positron beams are converted bremsstrahlung beams from carbon fibre targets in the electron-positron synchrotron DESY II with up to 1000 particles per cm^2 and energies from 1 to 6 GeV, an energy spread of ~5% and a divergence of ~1mrad.

DESY Testbeam Setup

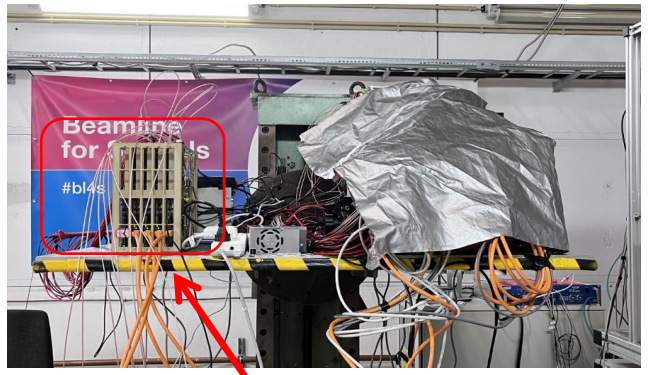


- The 6-layer of TaichuPix3 telescope was in the middle of the 5-layer MIMOSA and 4-layer JadePix telescope.
- MIMOSA is fixed there and cannot move. But it can be used to calibrate the position of the TaichuPix3 telescope

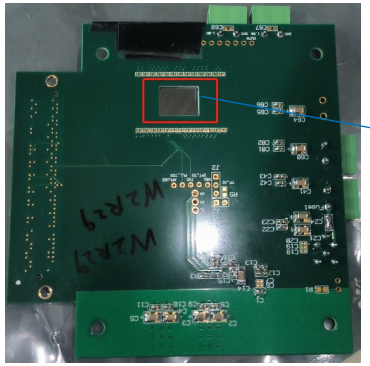
Setup of TaichuPix3



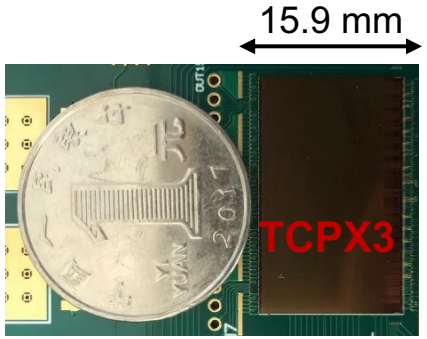
MIMOSA Telescope

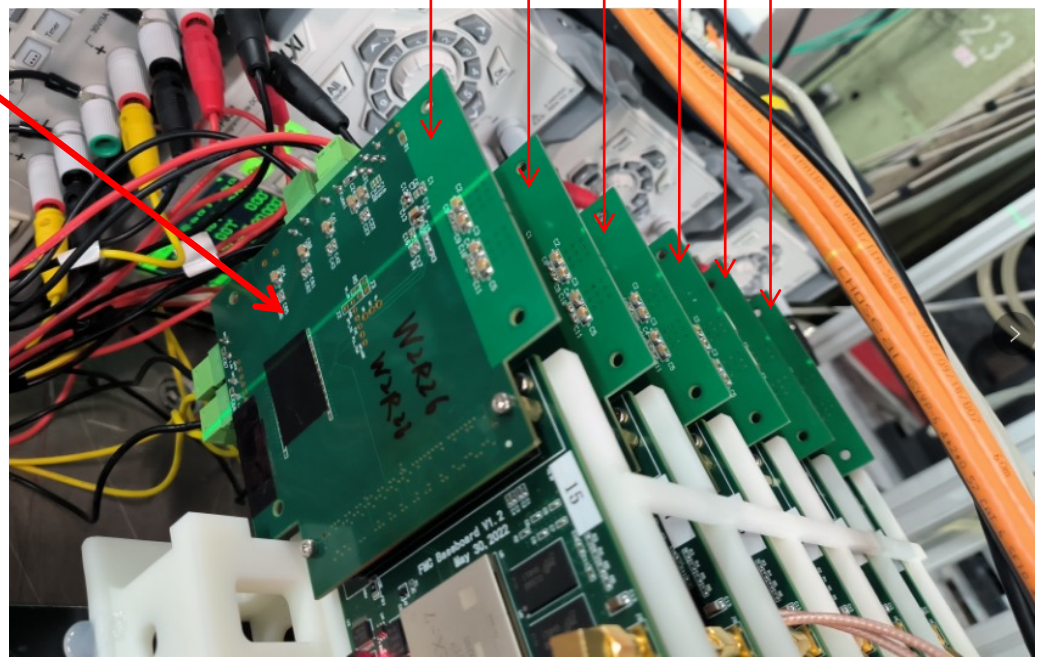


- Jadepix telescope

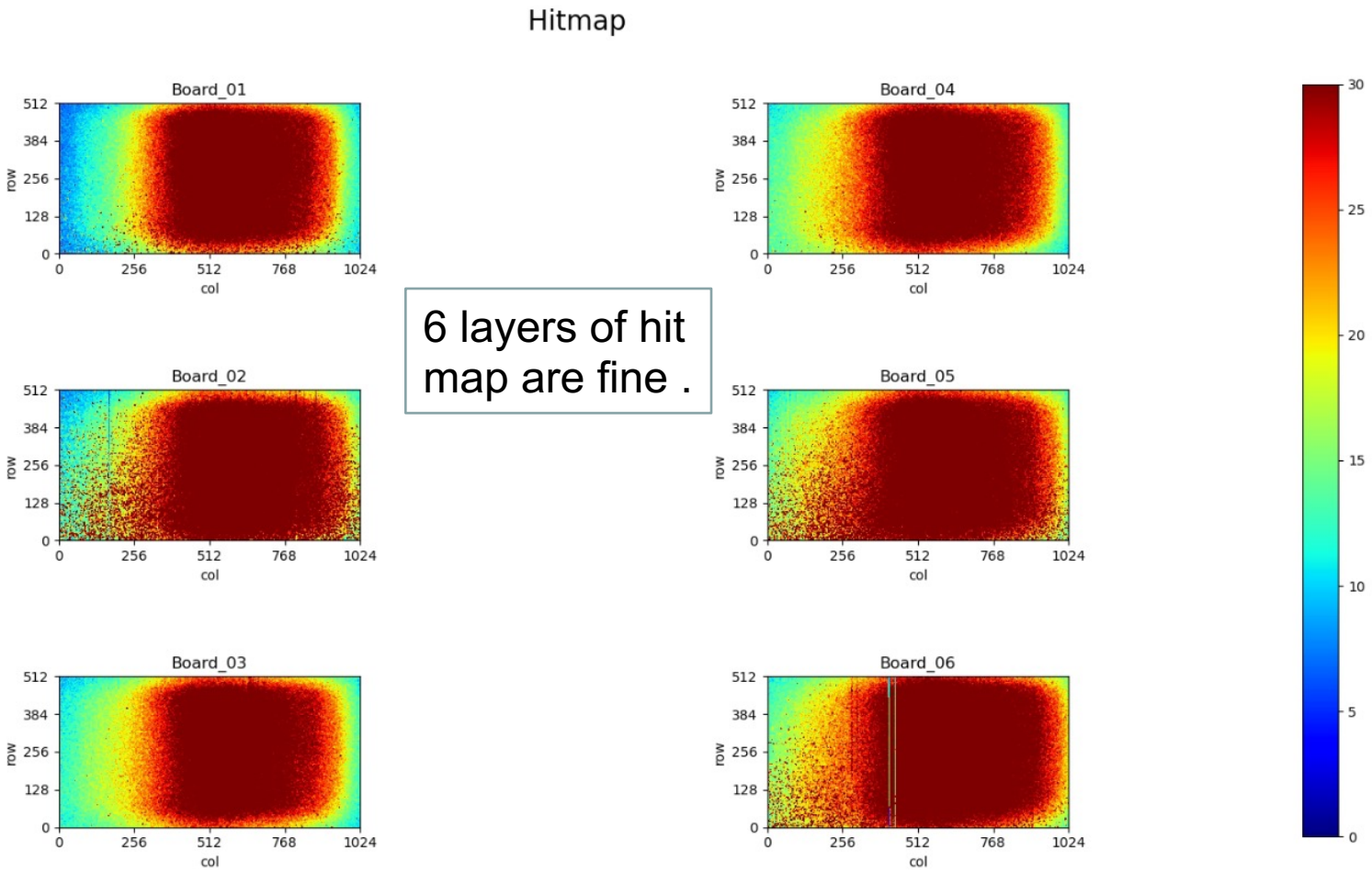


An open window in backside of PCB with a size of 12mm x 9mm





Hitmap of 4 GeV beam



6 layers of hit map are fine .

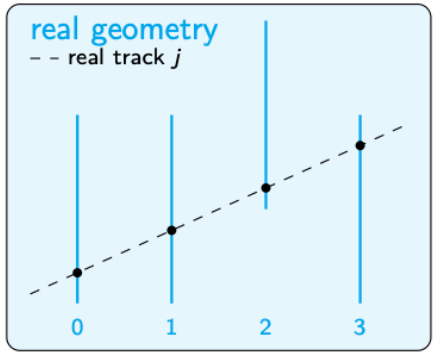
Jia Zhou
Tianya Wu
Hongyu Zhang

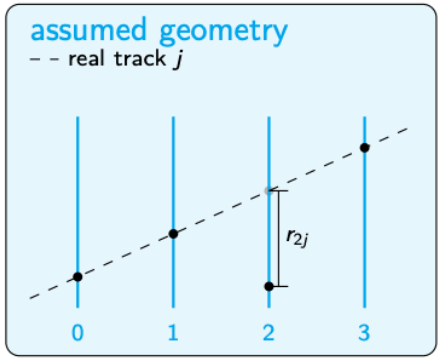
MOST2 offline reconstruction and alignment

Shuqi Li
Linghui Wu
Gang Li

Track Reconstruction

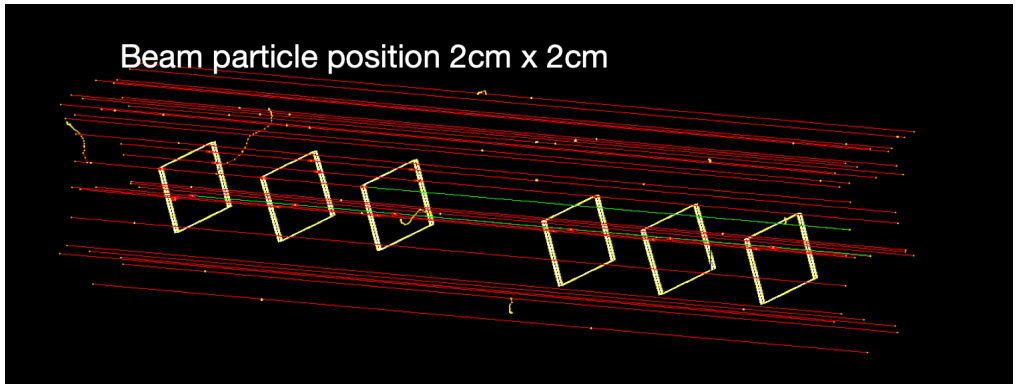
- No magnetic field
- Least squares fitting (Straight line fit)
- No considering multi-scattering now

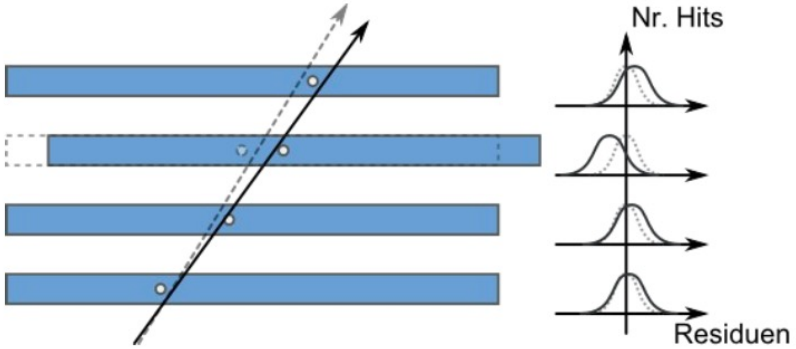




Alignment

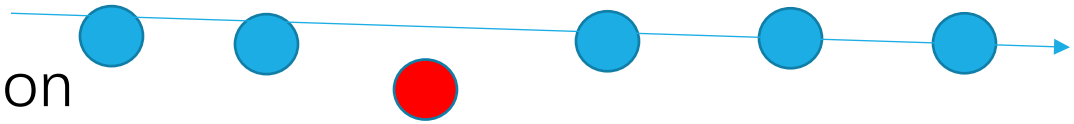
- Using Millepede (c++ version) matrix method
- Correct for the misalignment chip position
- Evaluate the influence of different alignment parameters on spatial resolution



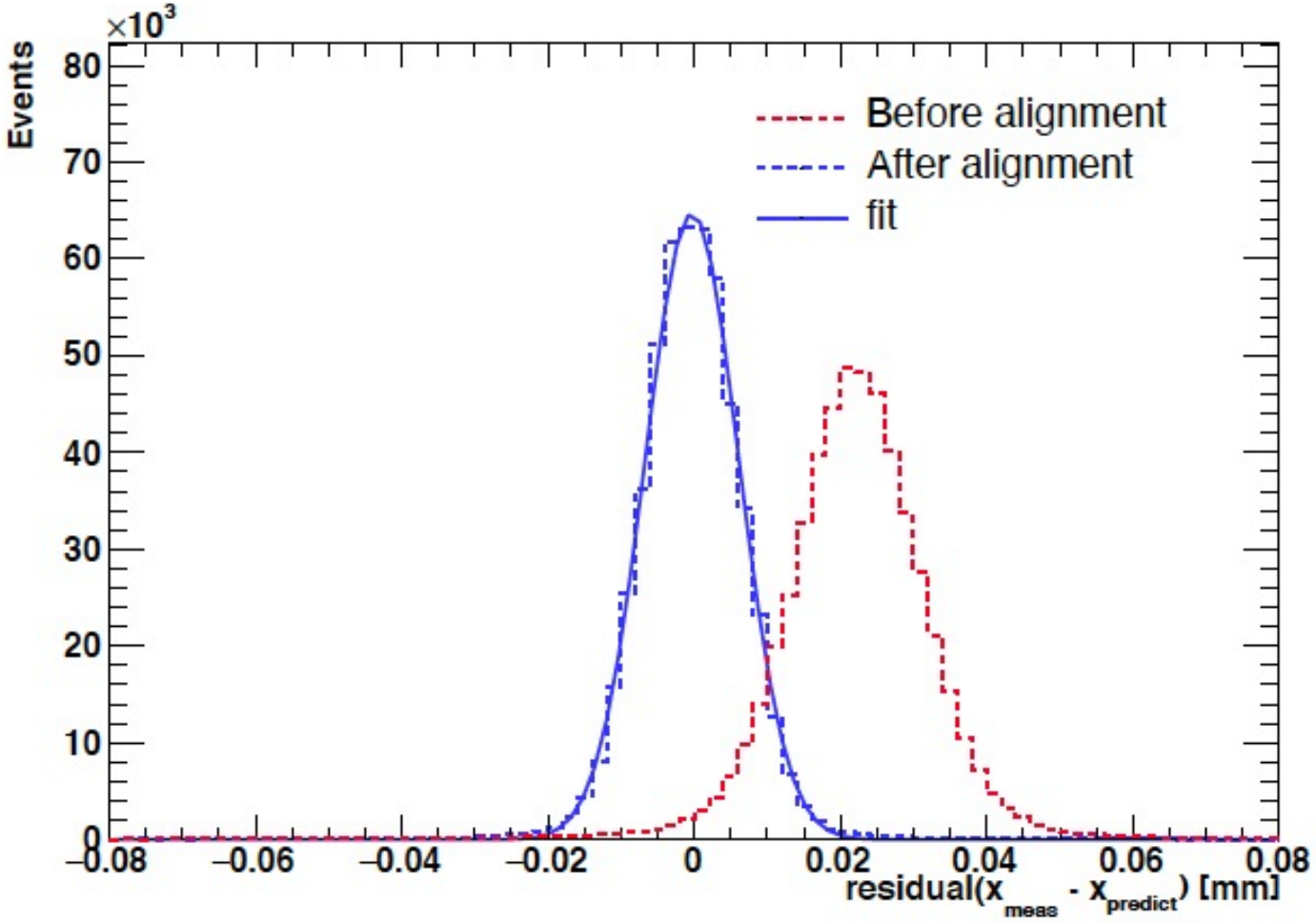


unbiased Residual plots before and after alignment (4GeV)

$$\chi^2(\alpha) = \sum_{i=1}^{n} \frac{f(x_i, \alpha) - e_i)^2}{\sigma_i^2}$$



- 20μm mis-alignment due to installation precision
- Vibration < 1μm is needed to do alignment



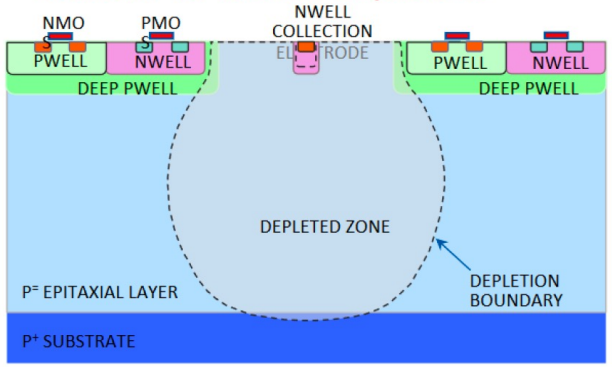
- The misalignment can be well corrected.
- The spatial resolution can reach < 5μm
- $\sigma_{meas}^2 = \sigma_{DUT}^2 + \sigma_{tel}^2$
- $\sigma_{DUT} \approx 0.91\sigma_{meas}$

Shuqi Li
Linghui Wu
Gang Li
Zhijun Liang
Xuewei Jia
Joao

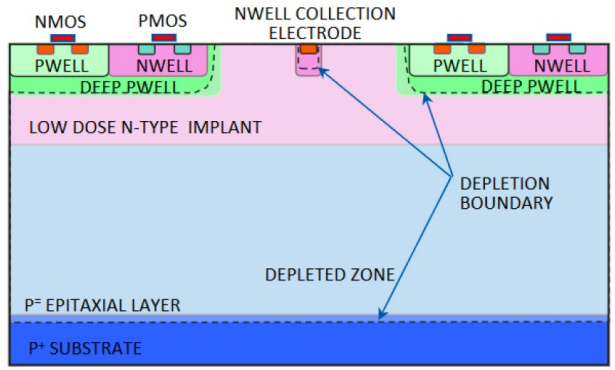
Resolution vs. chip threshold

- The spatial resolution improved by lowering the threshold
  - Can reach around 5μm resolution
  - Lower operation temperature can reduce threshold

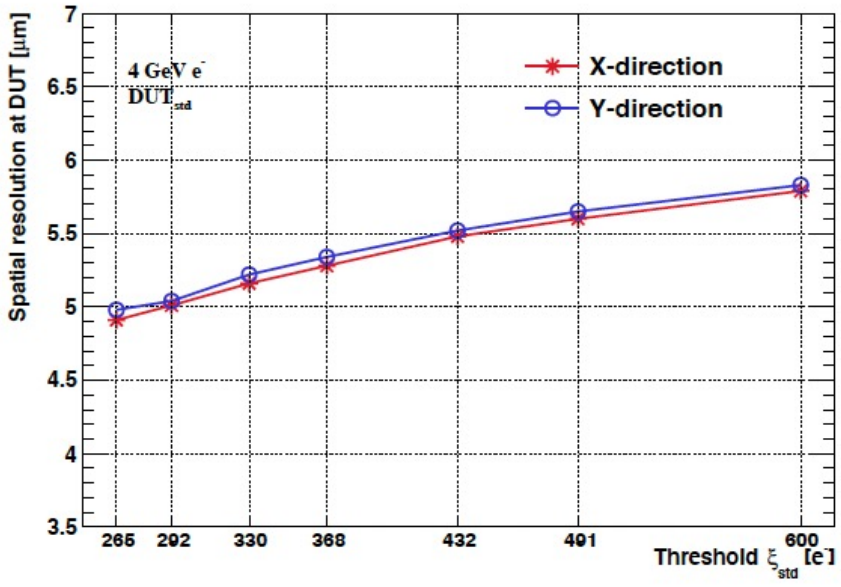
Standard : no full depletion



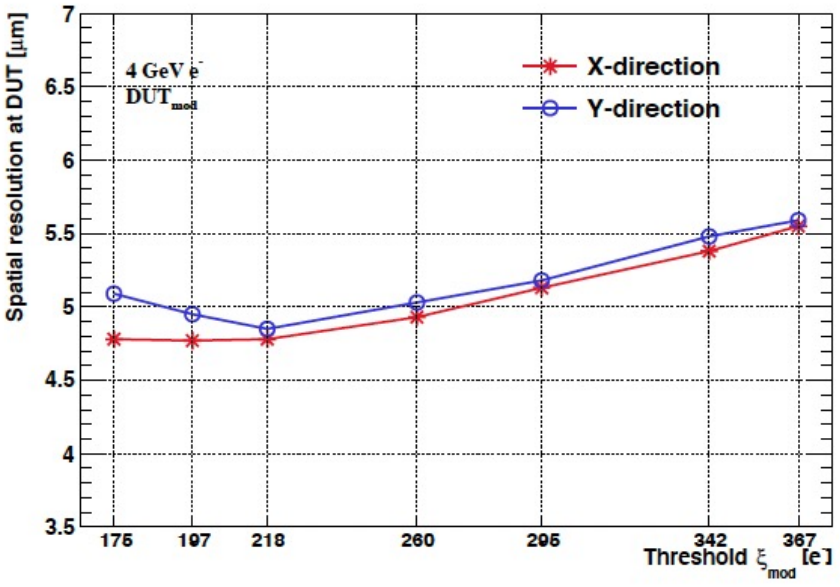
Modified : full depletion, faster charge collection



Modified process



Standard process

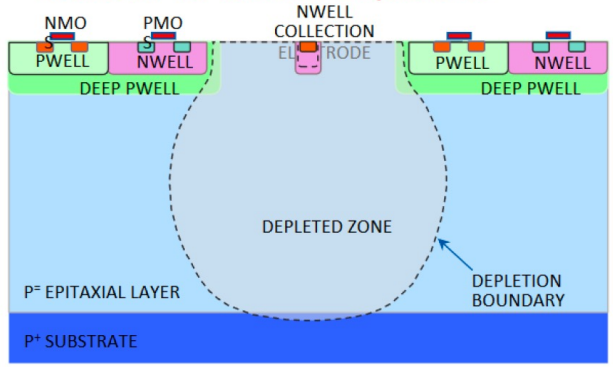


Shuqi Li
Linghui Wu
Gang Li
Zhijun Liang
Xuewei Jia
Joao

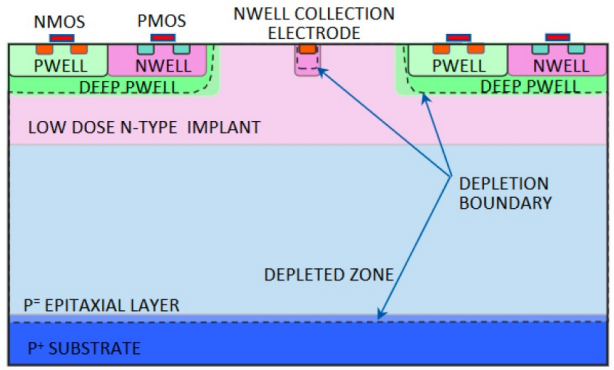
Efficiency vs. chip threshold

- Modified process chip has effectively low threshold
- Resolution is similar to the resolution with standard process

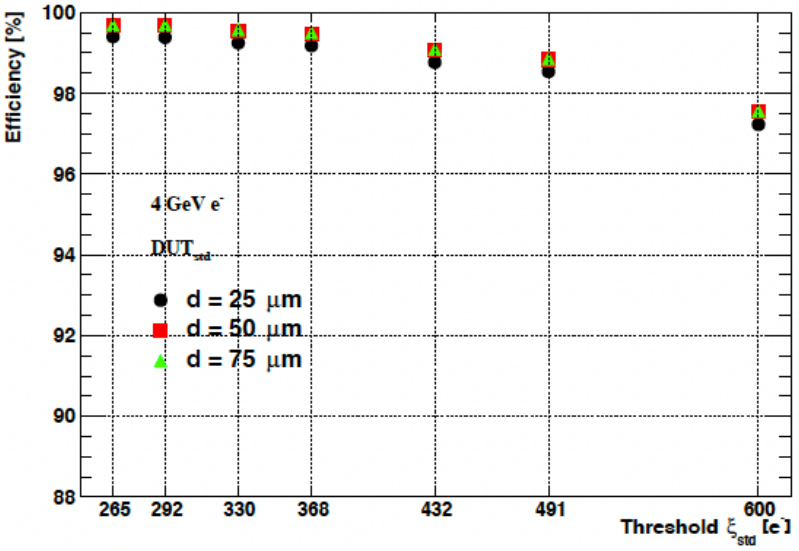
Standard : no full depletion



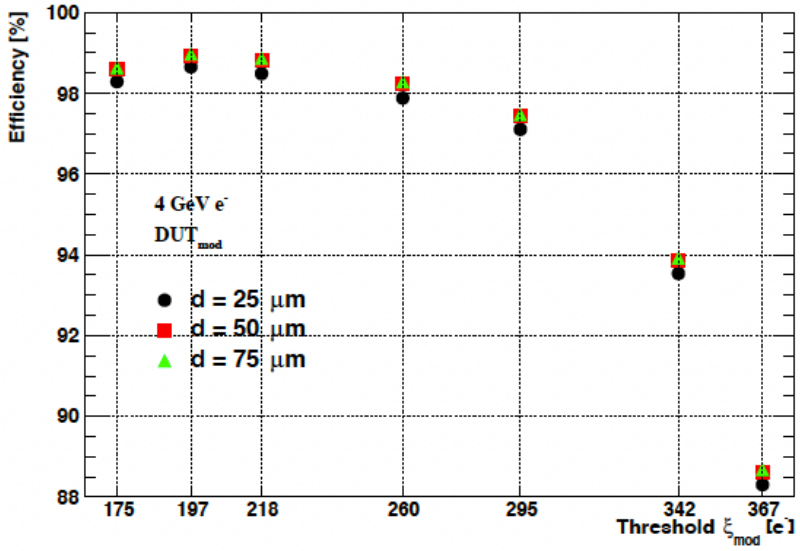
Modified : full depletion, faster charge collection



Modified process



Standard process



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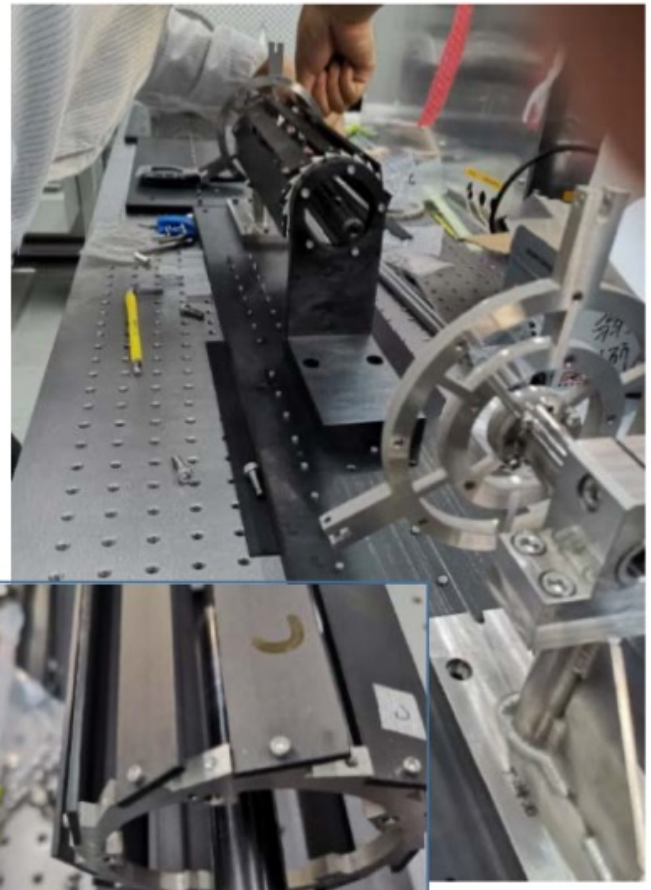
Linghui Wu
Gang Li
Zhijun Liang
Xuewei Jia
Joao

Vertex detector prototype assembly procedure(1)

- **Installation procedure of 3 double layer of vertex detector**

Inner barrel

Middle barrel
(half number of ladders)



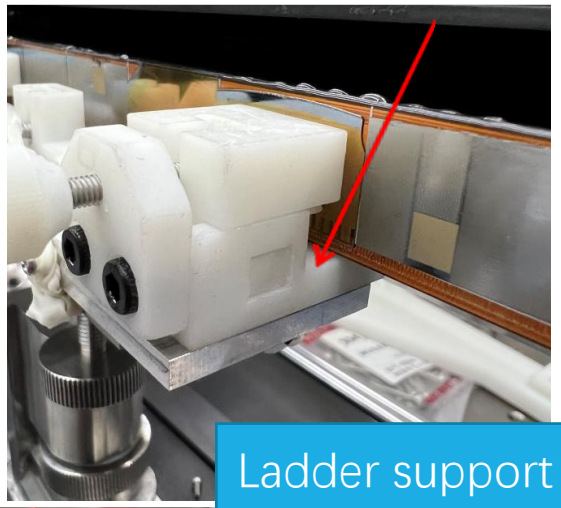
Outer barrel
(half number of ladders)

Jinyu Fu

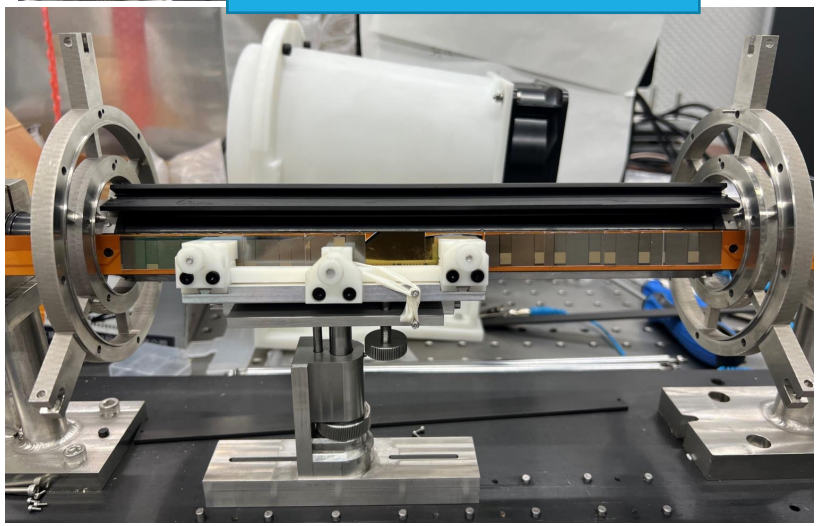
Ladder loading

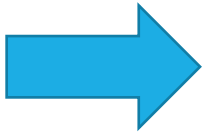
- **Loading procedure of ladder on vertex detector has been tested**
- **Ladder with one TaichuPix3 chip with wirebonds and 9 dummy silicon chip**
- **Wire-bonding was protected during loading**

Wire-bonding



Ladder support tools





Ladder loaded on vertex detector

Jinyu Fu
Xinhui Huang
Wei Wang

Cooling

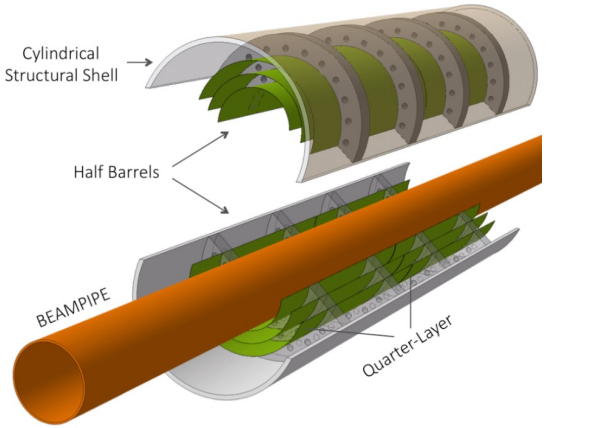
- **Air cooling is baseline design for CEPC vertex detector**
- **Sensor Power dissipation:**
  - Taichupix : ⩽ 100 mW/cm^2. (trigger mode)
  - CEPC final goal : ⩽ 50 mW/cm^2
- **Cooling simulations of a single complete ladder with detailed FPC were done.**
  - Need 2 m/s air flow to cool down the ladder

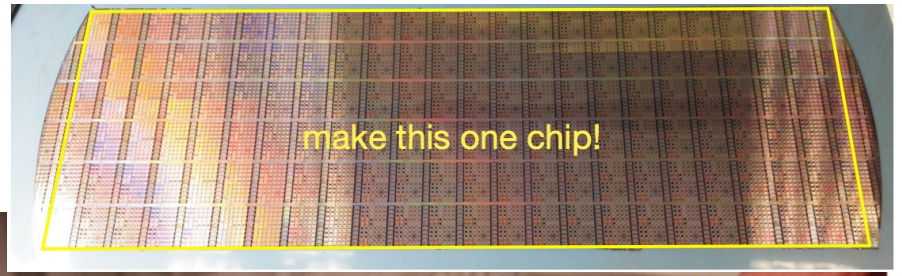
Jinyu Fu

Max temperature of ladder (℃) (air temperature 5 ℃)					
Power Dissipation (mW/cm2) \ Air speed (m/s)	5	4	3	2	1
100	19.6	21.8	25.0	*30.6*	*43.4*
150	26.9	30.1	35	*43.4*	*62.6*
200	34.2	38.6	45.1	*56.2*	*81.8*

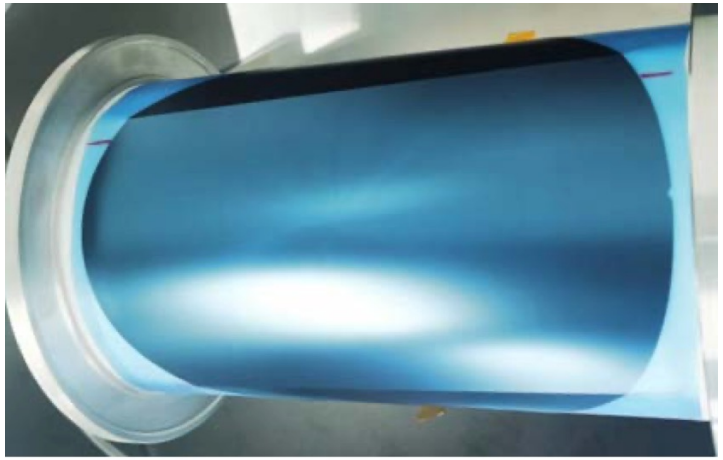
Curved MAPS & stitching

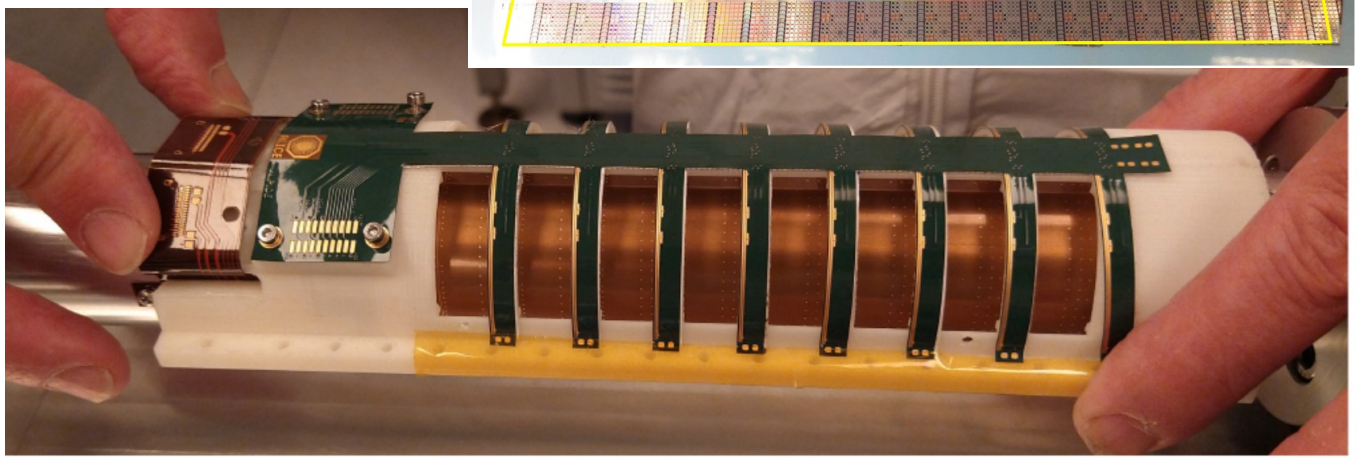
- Alice ITS3 upgrade：Cylindrical inner tracker with curved wafer
  - TowerJazz 65nm, CIS MAPS technology
  - Stitching to a large area
  - Thinned down to 50um thick
  - 曲面硅探测器 （Curved Maps）
- IHEP, Shandong U. :
  - XFAB 350nm CIS, Stitching





高能所： dummy 曲面硅





Magnus Mager *(Alice collobration)*, *ICHEP2022*

Summary

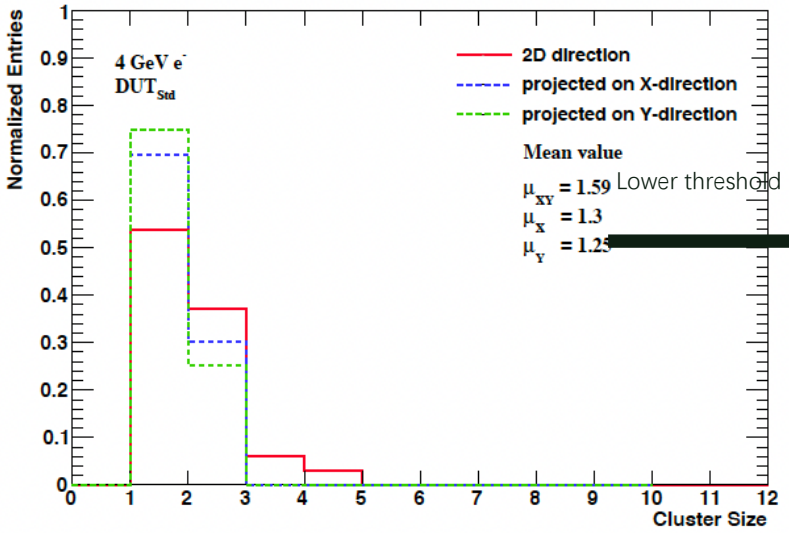
- MDI related requirement
  - Temperature <= 20 C (40C+), possible to decrease the temperature
  - Temperature gradient< 10 C (<7 C)
  - Vibration < 1μm (?), possible to do some simulation on vibration ?

- Vertex internal requirement
  - Small inner radius
    - As close to beam pipe as possible
  - Low material budget
    - <0.15 X0 per layer
  - High resolution pixel sensor
    - <3μm

Thanks for your attention!

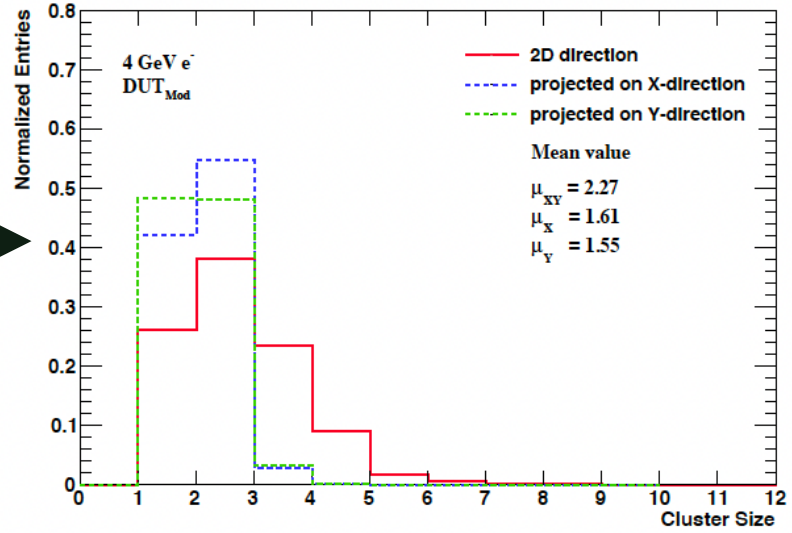
- Cluster size vs. chip threshold (4GeV)

Modified process

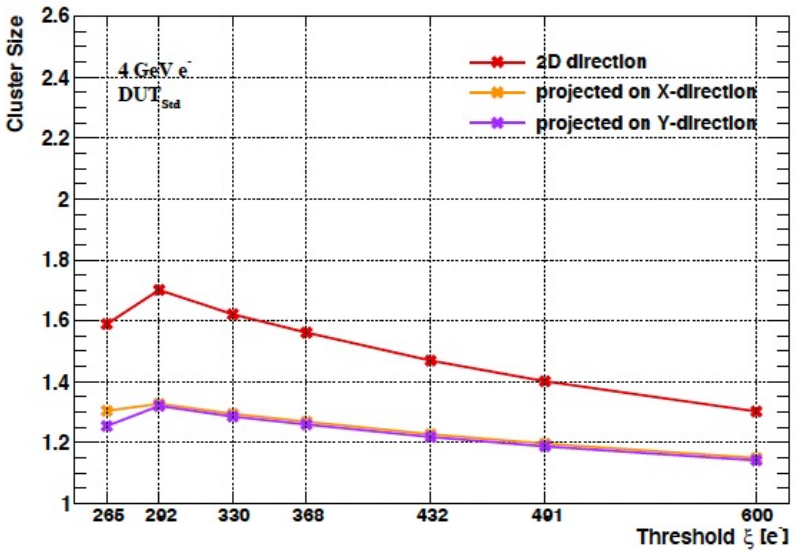


Lower threshold

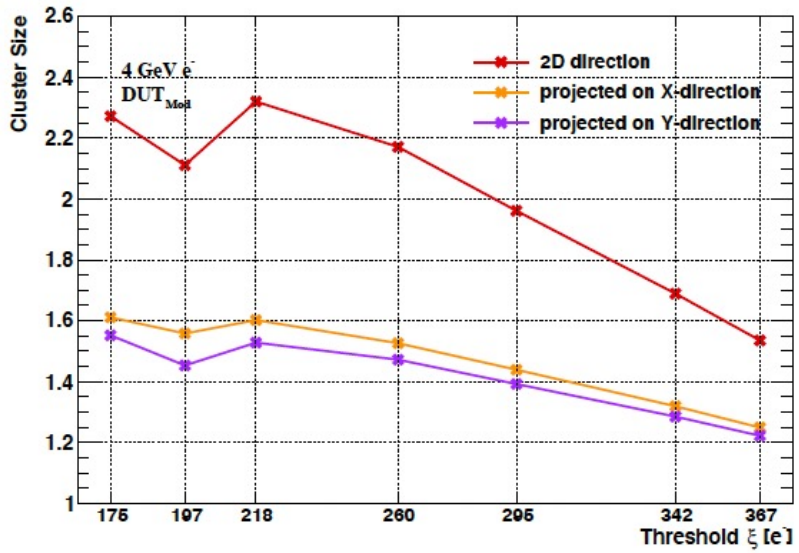
Standard process



Modified process

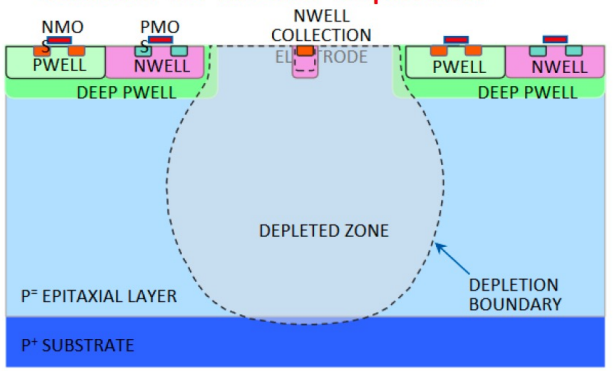


Standard process

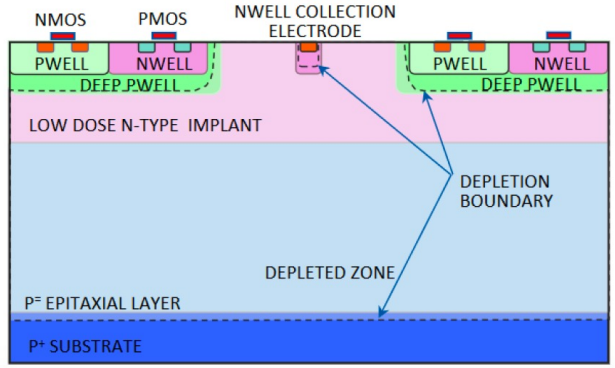


- If lowering the threshold, cluster size will be dominated by cluster with 2 hit
- In general, the higher the threshold, the smaller the cluster size

Standard : no full depletion



Modified : full depletion, faster charge collection

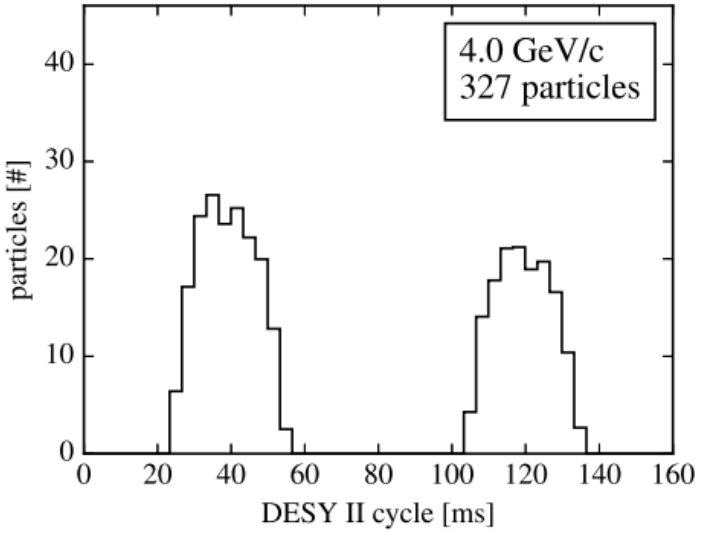


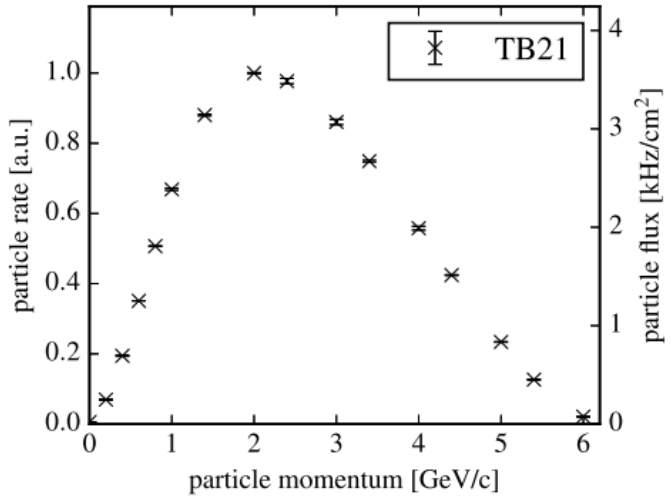
DESY testbeam Energy Opti

- From hit map, 4GeV is a moderate option.

→ Enough data and higher energy

- 4 GeV is used for Threshold scan, the data rate is around 10K B/s for a standard CMOS chip and 67.4K B/s for modified process.
- The valid coincidence tracks are around 41 tracks/ s when chi2<2
- The sensors are working for the full beam time except for the chip replacement. Totally about 100GB valid data were recorded

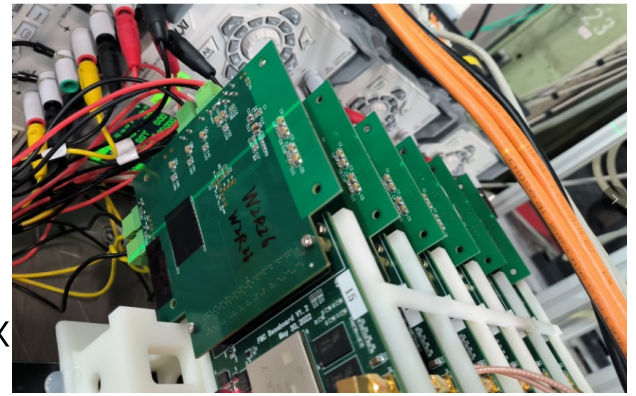




(a) at TB21

Refer from:The DESY II test beam facility"
https://doi.org/10.1016/j.nima.2018.11.133
NIMA, Volume 922, 1 April 2019, Pages 265-286

Alignment



- Method - millepede matrix method

p: alignment parameters, q: track parameters

- minimize: $\chi^2 = \sum_{i \in tracks} \vec{r}_i^{\,T} V_i^{-1} \vec{r}_i$ r is residual $\vec{r}_i(\vec{p}, \vec{q}_i)$, V is the covariance matrix

$$\frac{d\chi^2(\vec{p})}{d\vec{p}} = 0 \longrightarrow \chi^2(\vec{p}) = \chi^2(\vec{p}_0) + \left.\frac{d\chi^2(\vec{p})}{d\vec{p}}\right|_{\vec{p}=\vec{p}_0} (\vec{p} - \vec{p}_0) \longrightarrow \underbrace{(J^T V_i^{-1} J)}_{C} \Delta\vec{p} = \underbrace{J^T V_i^{-1} \vec{r}_i(\vec{p}_0)}_{b}$$

$$C \Delta\vec{p} = \vec{b}$$

Shuqi Li
Linghui Wu
Gang Li

- invert the Matrix C to find alignment correction Δp
- reduce matrix C for alignment only

$$S = C_{11} - C_{12} C_{22}^{-1} C_{21}$$

$$\left(\begin{array}{c|c} C_{11} & C_{12} \\ \hline C_{21} & C_{22} \end{array}\right)\left(\begin{array}{c} \Delta\vec{p}_1 \\ \hline \Delta\vec{p}_2 \end{array}\right) = \left(\begin{array}{c} \vec{b}_1 \\ \hline \vec{b}_2 \end{array}\right) \longrightarrow \left(\begin{array}{c} \Delta\vec{p}_1 \\ \hline \Delta\vec{p}_2 \end{array}\right) = \left(\begin{array}{c|c} S^{-1} & -S^{-1} C_{21}^T C_{22}^{-1} \\ \hline -C_{22}^{-1} C_{21} S^{-1} & C_{22}^{-1} - C_{22}^{-1} C_{21} S^{-1} C_{21}^T C_{22}^{-1} \end{array}\right)\left(\begin{array}{c} \vec{b}_1 \\ \hline \vec{b}_2 \end{array}\right) \longrightarrow \Delta\vec{p}_1 = S^{-1}\left(\vec{b}_1 - C_{21}^T C_{22}^{-1} \vec{b}_2\right)$$

- Matrix S with smaller size than C, and C_{22} is easy to invert

- Six alignment parameters considered
  - Translation along X, Y, Z direction
  - Rotation around X, Y, Z axis