Study of double-sided silicon pixel ladders with low material budget

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1. Introduction

For future high energy physics experiments, such as the CEPC, the primary goal is to study the properties of Higgs, necessitating the efficient identification of heavy flavor quarks and tau leptons. It requires precise measurement of the track parameters of charged particles near the Interaction Point to reconstruct the displaced vertices of short-lived particles. This drives the need for an extremely thin vertex detector with high position resolution. A double-sided silicon ladder prototype with low material budget of about 0.24% X_0 per sensitive layer has been designed and developed. To evaluate the performance, a beam test system was set up and tested with electron beam at IHEP.

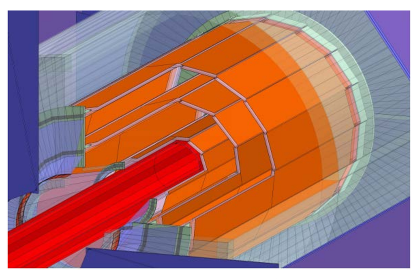


Fig.1 CEPC vertex detector

Performance Requirements from the CEPC CDR

$$\sigma_{r\varphi} = a \oplus b/(p(\mathrm{GeV})\sin^{3/2}\theta)\ (\mu m)$$

- a = 5 μm
- b = 10 μm ·GeV →
  - Single-point resolution of first layer better than 3 μm
  - Material budget of 0.15% X_0 per plane
  - First layer located at a radius of 16 mm
  - CDR baseline design: three layers of double-sided ladders

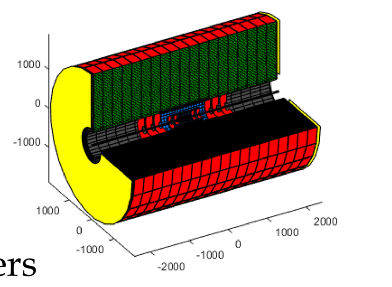


Fig.2 Fast simulation tracking system 3D structure

Fast simulation

- Fast simulation of the CEPC tracking system based on the CEPC CDR design was performed using LiC Detector Toy software (LDT).
- Three vertex detector models were simulated:
  - 5 layers of single-sided ladders with 0.35% X_0 /layer (green line);
  - 3 layers of double-sided ladders with 0.30% X_0 / layer (blue line);
  - 3 layers of double-sided ladders with 0.15% X_0 / layer (red line).
- Impact parameter resolution of the double-sided ladders with 0.15% X_0 per sensitive layer meets CEPC physics requirements in 1-100 GeV/c momentum at different incident angles.

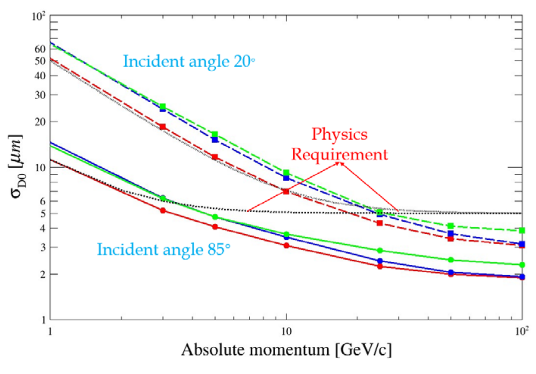


Fig.3 Impact parameter resolution as a function of the particle momentum.

2. Double-sided ladder

Ladder design and assembly

- Double-sided ladder is composed of two layers of sensors glued to both sides of the same support structure, effectively reducing its material budget.
- Each layer consists of MIMOSA28 chips thinned to 50 μm and a Kapton flex cable with copper traces. The MIMOSA28 chips contain 928 (row) × 960 (column) pixels with pitch of 20.7 μm , developed by the PICSEI at IPHC.
- The composite support consists of two layers of 150 μm thick carbon fiber and a 1500 μm thick PMI foam (~0.058 g/cm³)
- Using an assembly platform, each layer is assembled separately. After chip wire-bonding and preliminary testing, two layers are glued to both sides of the carbon fiber support.
- Average material budget per sensitive layer: ~0.24% X_0

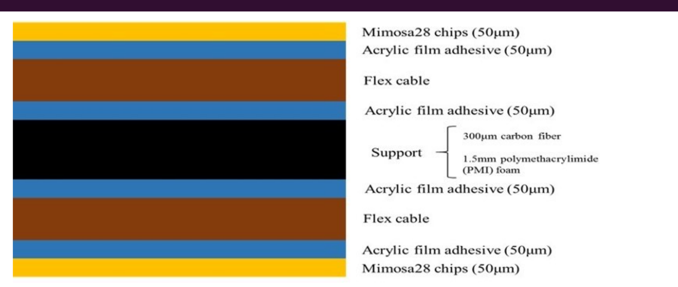


Fig.4 Material composition cross-section of the double-sided ladder

Layer	Material	Thickness(μm)	X_0(cm)	%X_0
Sensor	Si	50	9.36	0.053
	Acrylic adhesive	50	34.50	0.014
Flex cable	Cu	17.80×0.250	1.43	0.031
	Acrylic adhesive	28	34.50	0.008
	Kapton	100	28.60	0.035
	Acrylic adhesive	28	34.50	0.008
	Cu	17.8×0.100	1.43	0.012
Carbon fiber	Acrylic adhesive	50	34.50	0.014
	Carbon fiber	150	26.08	0.058
	PMI foam	1500	815.20	0.0184
	Carbon fiber	150	26.08	0.058
	Acrylic adhesive	50	34.50	0.014
Flex cable	Cu	17.8×0.100	1.43	0.012
	Acrylic adhesive	28	34.50	0.008
	Kapton	100	28.60	0.035
	Acrylic adhesive	28	34.50	0.008
	Cu	17.8×0.250	1.43	0.031
Sensor	Acrylic adhesive	50	34.50	0.014
	Si	50	9.36	0.053
Total of ladder				0.487

Table.1 Material budget of the double-sided ladder

Further optimization

- Compared to the single-sided ladder (0.35% X_0), the material budget of the double-sided ladder is reduced by about 32%. To achieve the material budget of 0.15% X_0 per sensitive layer, it is possible to optimize the ladder by:
  - Using aluminum traces instead of copper traces
  - Reducing the thickness of adhesive films
  - Reducing the thickness of Kapton flex cable

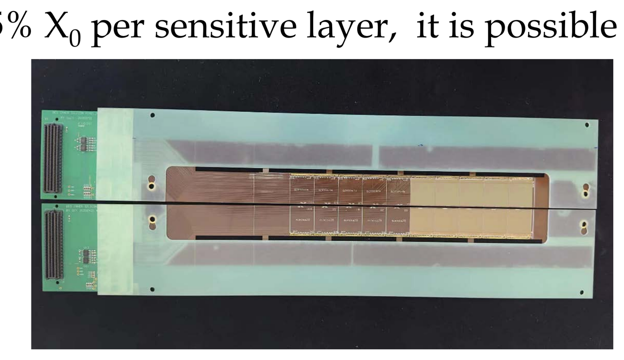


Fig.5 Double-sided ladder before glued together

3. Beam test

The test beam was performed at IHEP with ~ 1.3 GeV electrons

System setup

- A double-sided ladder in the middle as a DUT
- A beam telescope is composed of four single-sided ladders, providing reference tracks. Each single-sided ladder consists of one layer of MIMOSA28 chips, a flex cable and a carbon fiber support, with a material budget of about 0.35% X_0
- A scintillator at the end provides trigger signals

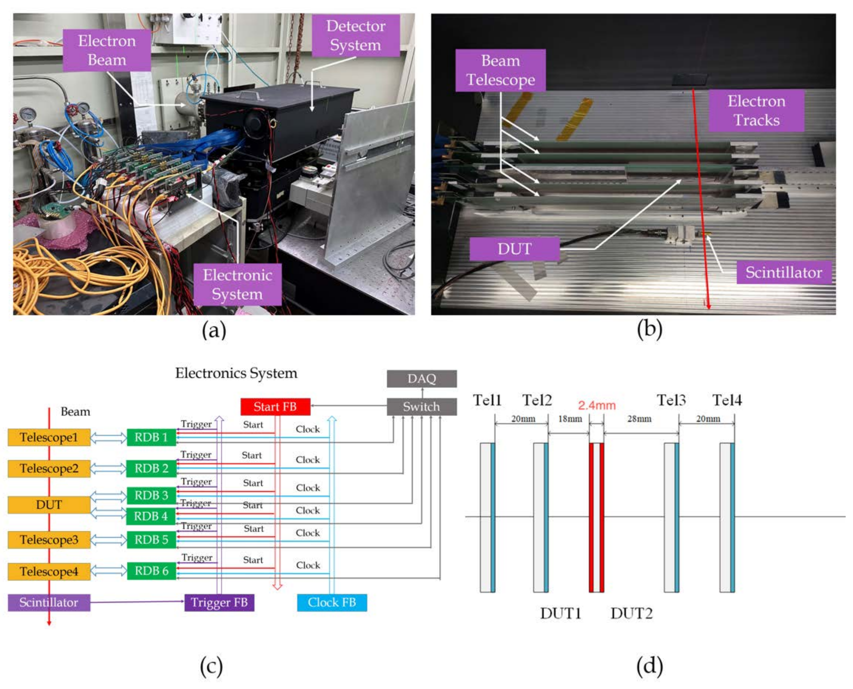


Fig.6 Setup of the beam test. (a) A photo of the test system. (b)The beam telescope and the DUT. (c) The diagram of the electronics system. (d) The layout of each layer.

Electronics system

- Read-out boards: supply power, send configuration commands to chips, receive and package data.
- Trigger fan-out board: receives and distributes trigger signals to each read-out boards.
- External clock fan-out board: provides 100 MHz clock signals to ensure synchronization operation.
- Start board: receives start and stop commands from DAQ system and distributes them to read-out boards.

4. Data analysis and results

Alignment

- Alignment parameters M (three displacement and three rotation parameters):

$$\mathbf{M} = (\Delta u, \Delta v, \Delta w, \Delta\alpha, \Delta\beta, \Delta\gamma)$$

- Calculate alignment parameters by measurement residual of tracks

$$r_j = J_j^T M^T \Longrightarrow M^T = \left(JJ^T\right)^{-1} Jr = \sum_j^N J_j J_j^T \sum_j^N J_j r_j$$

- Alignment accuracy: better than 0.2 μm

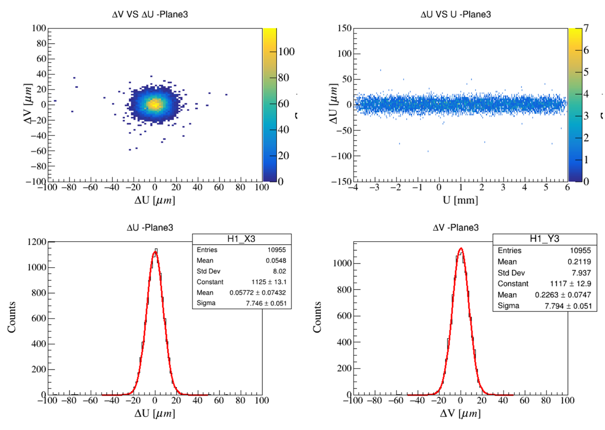


Fig.7 The correlation between residual and hit point coordinates after alignment.

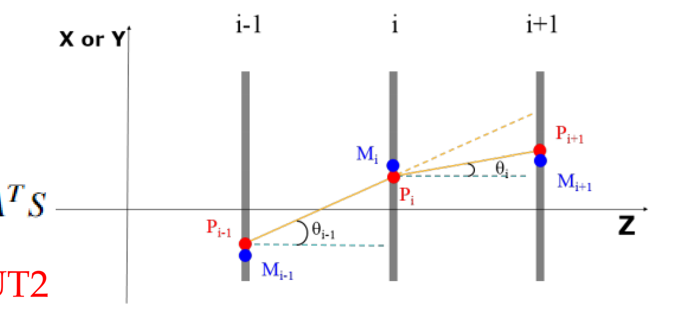
Track fitting

- X^2 function:

$$\chi^2 = \sum_{i=1, i\neq DUT}^{N} \frac{(M_i - Pi)^2}{\sigma_i^2} + \sum_{i=2}^{N-1} \left(\frac{(a_i + a_{i-1})P_i - a_{i-1}P_{i-1} - a_i P_{i+1}}{\Delta\theta_i}\right)^2$$

$$\frac{\partial\chi^2}{\partial P_i} = 0, \quad i = 1, 2, \ldots, N \Longrightarrow A_{ij} = \frac{1}{2}\frac{\partial^2\chi^2}{\partial P_i \partial P_j},\ P = \left(A^T A\right)^{-1} A^T S$$

- Measurement residual: ~7.7 μm for DUT1 and ~7.8 μm for DUT2



Allpix² simulation

- Using Allpix², beam test simulation with 1.3 GeV electrons was performed
- The material budget and the telescope layout are the same as the actual beam test setup
- Based on the same track fitting algorithm, the simulated residuals of DUT1 and DUT2 are about 7.7 μm, which are consistent with the beam test results

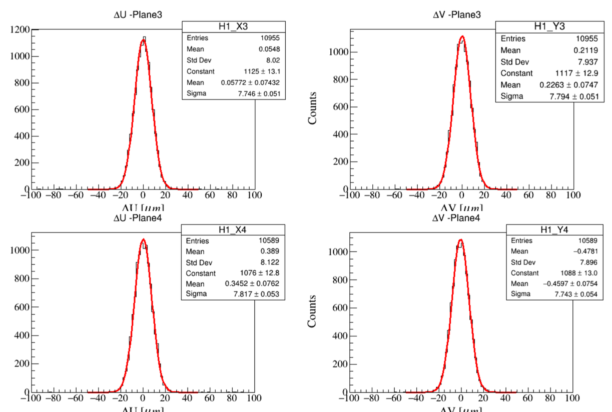


Fig.8 Measurement residual distribution of DUT1 (top) and DUT2 (bottom)

Single-point resolution

- Since the chips of the beam telescope and DUT are the same, the single-point resolution σ_{DUT} can be roughly estimated from the measurement residual σ_{meas} and the telescope resolution σ_{tel}:

$$\sigma_{meas}^2 = \sigma_{DUT}^2 + \sigma_{tel}^2 \Longrightarrow \sigma_{DUT}^2 = \frac{\sigma_{meas}^2}{1+k}, \quad \sigma_{tel}^2 = \frac{k}{1+k}\sigma_{meas}^2 \qquad k = \frac{\sum_i^N z_i^2}{N\sum_i^N z_i^2 - \left(\sum_i^N z_i\right)^2}$$

- With 1.3 GeV electrons, σ_{DUT1}: ~6.9 μm, σ_{DUT2}: ~7.0 μm, σ_{tel} : ~3.4 μm

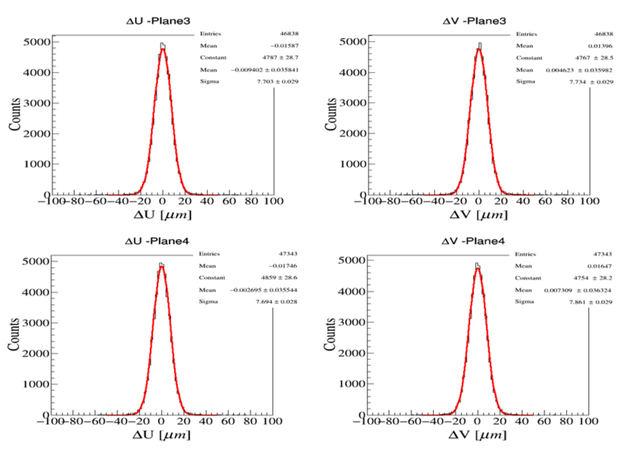


Fig.9 Simulation residual distribution of DUT1 (top) and DUT2 (bottom)

Detection efficiency

- $\varepsilon = \frac{\text{Track} \in \text{DUT} \subset \text{Referencetracks}}{\text{Track} \in \text{Referencetracks}}$
- Detection efficiency of about 99.5% is achieved. DUT2 performs little worse than DUT1 due to its little higher noise and the threshold

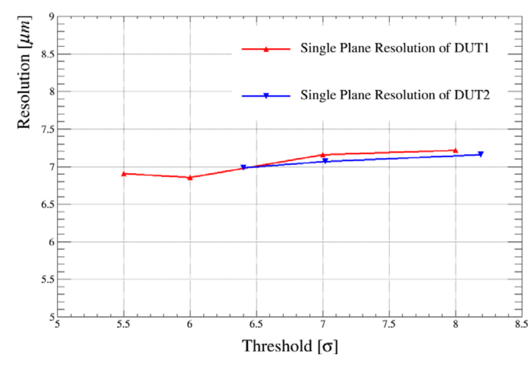


Fig.10 Single-point resolution as a function of the threshold

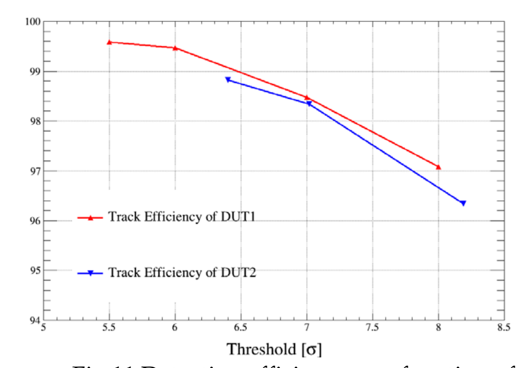


Fig.11 Detection efficiency as a function of the threshold

Mini-Vector

- Combined DUT1 + DUT2 → Mini-Vector → Provide better resolution and track angle
- With 1.3 GeV, spatial resolution of mini-Vector is about 5.0 μm (exclude telescope resolution)
- Angle resolution is about 1.9 mrad

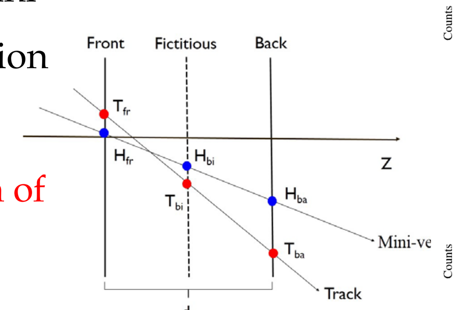


Fig.12 Definition diagram of mini-Vector

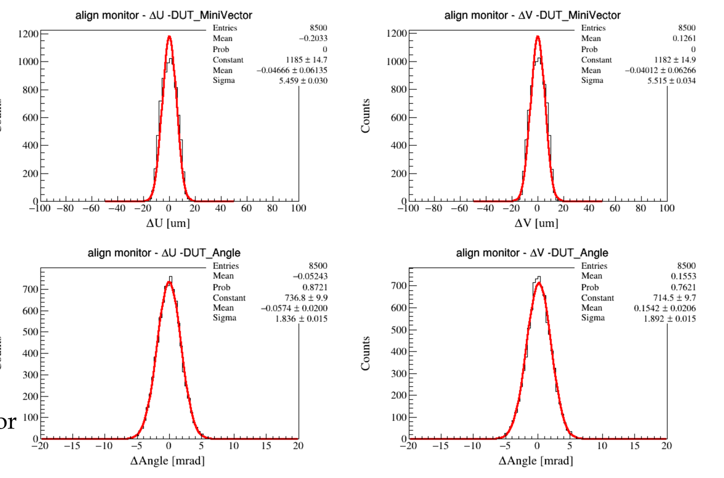


Fig.13 Spatial resolution(top) and angle resolution(bottom) of the mini-Vector

5. Summary

- Double-sided silicon pixel ladders based on MAPS with a low material budget of about 0.24% X_0 per plane have been developed, representing a reduction of about 32% compared to the single-sided ladder.
- To validate the design and evaluate the performance of the double-sided ladder, a test beam was performed at IHEP.
- With 1.3 GeV electrons, the single-point resolution is about 7.0 μm and the detection efficiency is about 99.5%.
- Two hits from two layers of the double-sided ladder can be used to construct a mini-Vector with a better resolution of about 5.0 μm and an angle resolution of about 1.9 mrad.
- To achieve the material budget of 0.15% X_0 per sensitive layer, it is possible to further optimize the ladder by using aluminum traces, and reducing the thickness of adhesive films.

This study was supported by the National Natural Science Foundation of China (No.11875274 and No.U1232202)