CMOS Pixel Sensor for CEPC Vertex Detector

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Outline

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- CMOS Pixel Sensor (CPS)
- CPS for the CEPC vertex detector
- Summary and outlook

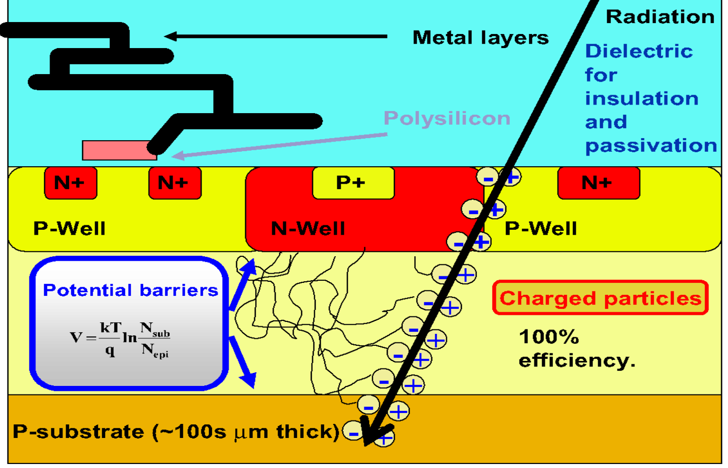
Introduction

- Impact parameter resolution required for the identification of heavy quarks and τ-leptons (essential for CEPC physics):

$$\sigma_{\mathrm{IP}} = 5 \oplus 10/p \cdot \sin^{3/2}\theta \ \mu\mathrm{m}$$

- Translating to requirements on the CEPC vertex detector:
  - Single point resolution $\sigma_{SP} \sim 3\ \mu m$ → high granularity
  - Material budget $\leq 0.15\%\ X_0$ per layer
    - Sensor+ASIC thickness ~ 50 µm → monolithic sensors
    - Air cooling → low power consumption (extremely challenging without power-pulsing)
  - Radiation tolerance ~100 kRad/y & $10^{11} n_{eq}/cm^2$
  - Low detector occupancy ~0.5% → fast readout

CMOS Pixel Sensor



- Front-end electronics and sensor (utilising the epitaxial-layer) integrated on the same silicon bulk, featuring:
  - High granularity → high spatial resolution
  - Sensor thinned down to 50 µm → low material budget
  - Standard CMOS fabrication technology → cost effective
  - Signal processing on-chip → relaxing down-stream data processing
  - Radiation tolerance (moderate) → usable for electron machines
- Example CPS sensors designed by IPHC
  - Mimosa26 (EUDET beam telescope), Mimosa28 (STAR PXL)
  - MISTRAL/ASTRAL (ALICE ITS Upgrade, CBM-MVD)
  - Adaption to the ILD VTX

CPS for CEPC

- CEPC CPS project supported by the **State Key Laboratory of Particle Detection and Electronics**
  - “Semiconductor detectors for CPEC”, 2014- 2015, 400k CNY
- Project kick-off meeting on 21 July 2014; defined the following tasks for this one-year project:
  - To form a strong development team with sufficient expertise and identify the most critical R&D items
  - To compete the prototype design with the selected CMOS process and prepare for MPW submission (request for additional funding)
  - MPW submission and preparation for sensor characterisation, including DAQ development, beam telescope construction etc.
  - To define the roadmap for future development

Building up the Team

- Collaborative team members with great enthusiasm

	Affiliation	Responsibilities	
Hongbo Zhu	IHEP	Project leader & beam telescope	
Min Fu	OUC	TCAD simulation	
Ying Zhang	IHEP	Front-end electronics	***PhDs from IPHC***
Liang Zhang	SDU	Front-end electronics	
Ke Wang	IHEP	Readout electronics	
Pelian Liu	IHEP	DAQ and detector simulation	
Qinglei Xiu	IHEP	DAQ and background simulation	

Yet more electronics/detector experts and students (!) are welcome to join the adventure.

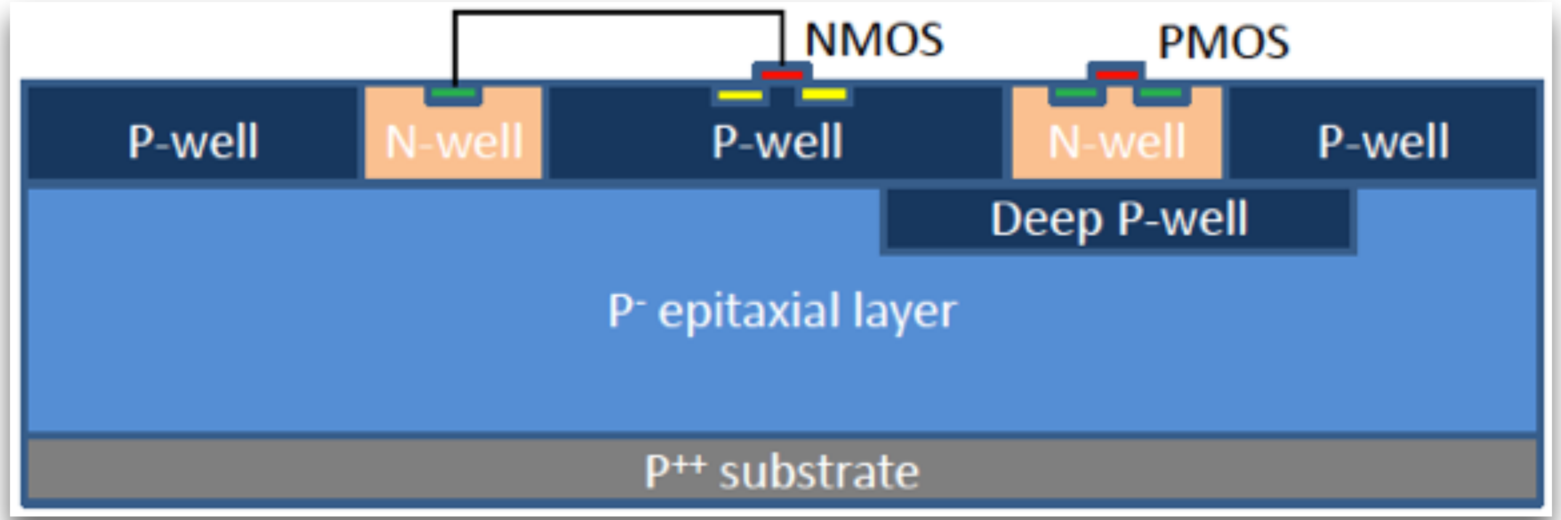
TowerJazz 0.18 CIS and XFAB XO035 under consideration

CMOS Processes

- Basic requirements: EPI-layer (≥ 10 μm, high resistivity), Deep N/P-well (to implemented in-pixel circuit)

	Feature size (μm)	EPI thickness	EPI resistivity	MPW avalability	Cost
TowerJazz	0.18 CIS	5-18 μm	1 kΩ · cm	TBC	600k CNY
	0.18 BCD	TBC	10 Ω · cm	YES	
XFAB	XH035	P-5/15 μm	8 Ω · cm	YES	
	XO035	P-14 μm	0.55 - 2 kΩ · cm	YES	TBC
	XH018	P-10 μm	15 Ω · cm	YES	125k CNY/10 mm
SMIC	0.13/0.18 CIS	P-7 μm	0.55 - 2 kΩ · cm	UNLIKELY	
GF	0.18 BCDlite	7 μm	1 Ω · cm	YES	30k CNY/9 mm
CSMC	0.25 BCD	7 μm	TBC	TBC	
TSMC	CMOS	7-8 μm	8.5 -11.5 Ω · cm	UNLIKELY	
	CIS	TBC	TBC	UNLIKELY	

TowerJazz® CMOS Process



- Feature size: 0.18 µm
- Thick epitaxial layer: 5-18 µm, $1 < \rho < 6\ k\Omega \cdot cm$
- Six metal layers
- Deep P-well option (P-layer underneath N-well protecting from parasitic charge collection) allows usage of PMOS transistors
- Stitching option → to make large area detector

Ideal for the fabrication of CPS, but rather expensive!

Power Consumption

- Air-cooling desirable for the CECP vertex detector to minimise material budget but power-pulsing not optional → imposing stringent requirement on power consumption: 50 mW/cm^2

Table 2.2: Chip design options.

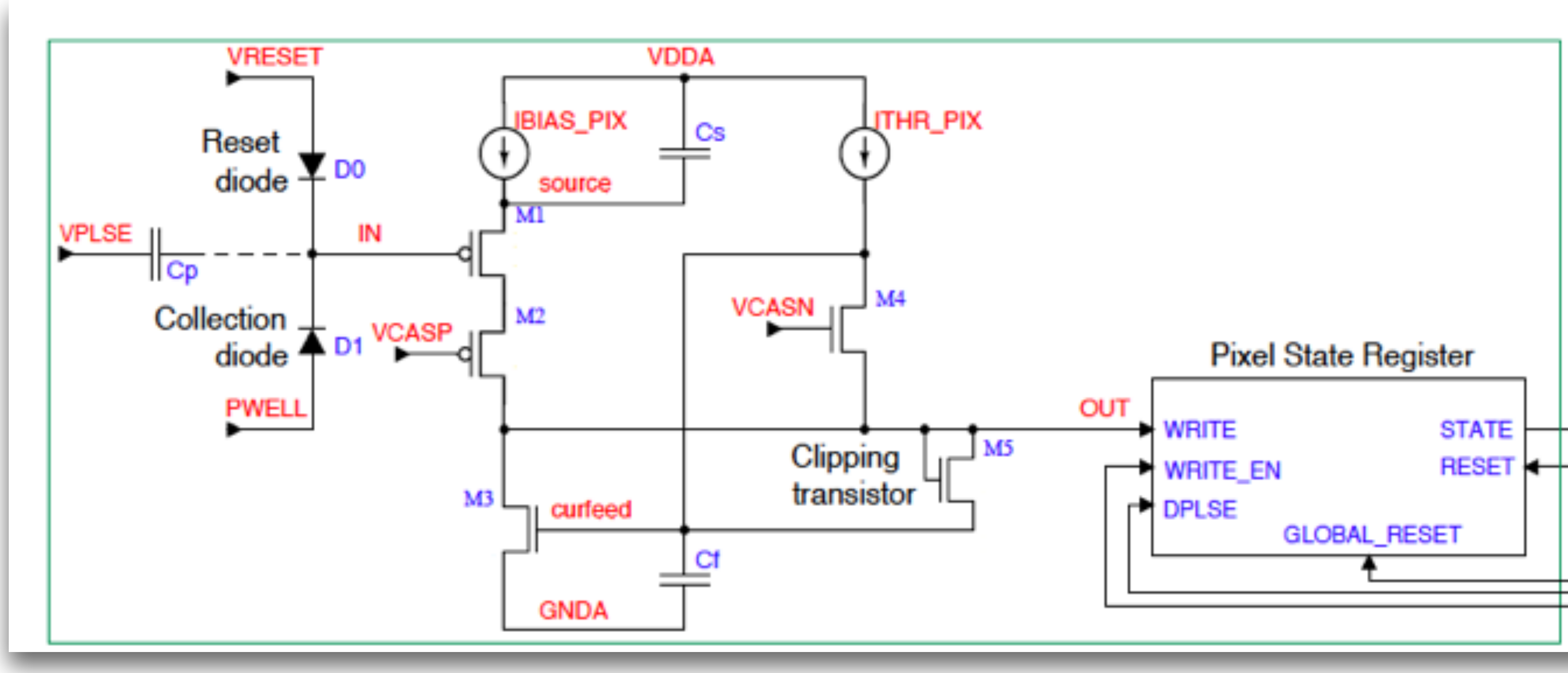
Architecture (discriminator, read-out)	Pitch ($r\phi \times z$) (μm^2)	Integration time (μs)	Power consumption (mW cm^{-2})
MISTRAL (end-of-column, rolling-shutter)	22×33.3	30	200
ASTRAL (in-pixel, rolling-shutter)	24×31 36×31	20	85 60
CHERWELL (in-strixel[a], rolling-shutter)	20×20	30	90
ALPIDE (in-pixel, in-matrix sparsification)	28×28	4	< 50

[a] A strixel is a 128-pixel column over which the electronics are distributed.

ALICE ITS Upgrade TDR

Readout Architecture

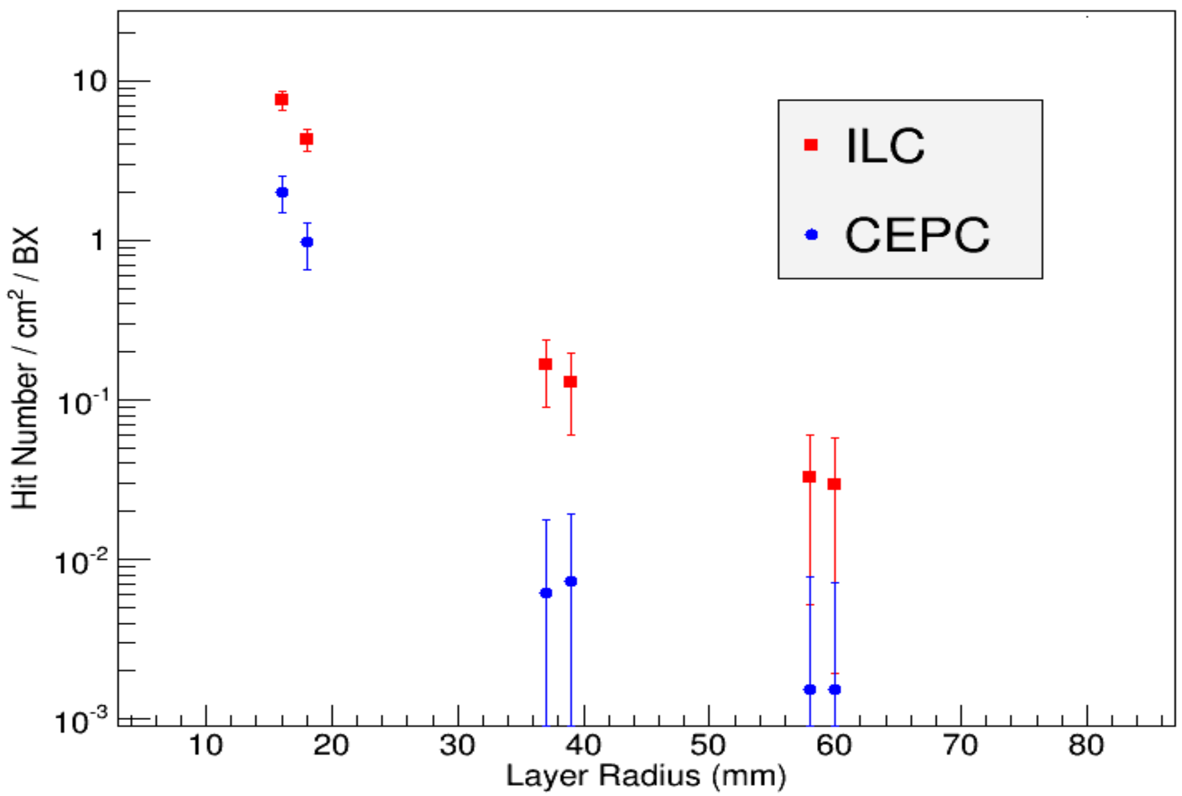
- The classical rolling shutter with end-of-column discriminators yields a long integration time (~ 200 μs) and high power consumption (~ 200 mW/cm²). Moving discriminators to in-pixel improves the performance. → optional for CEPC
- New readout architectures, e.g. in-matrix sparsification, make possible shorter integration time and lower power dissipation.



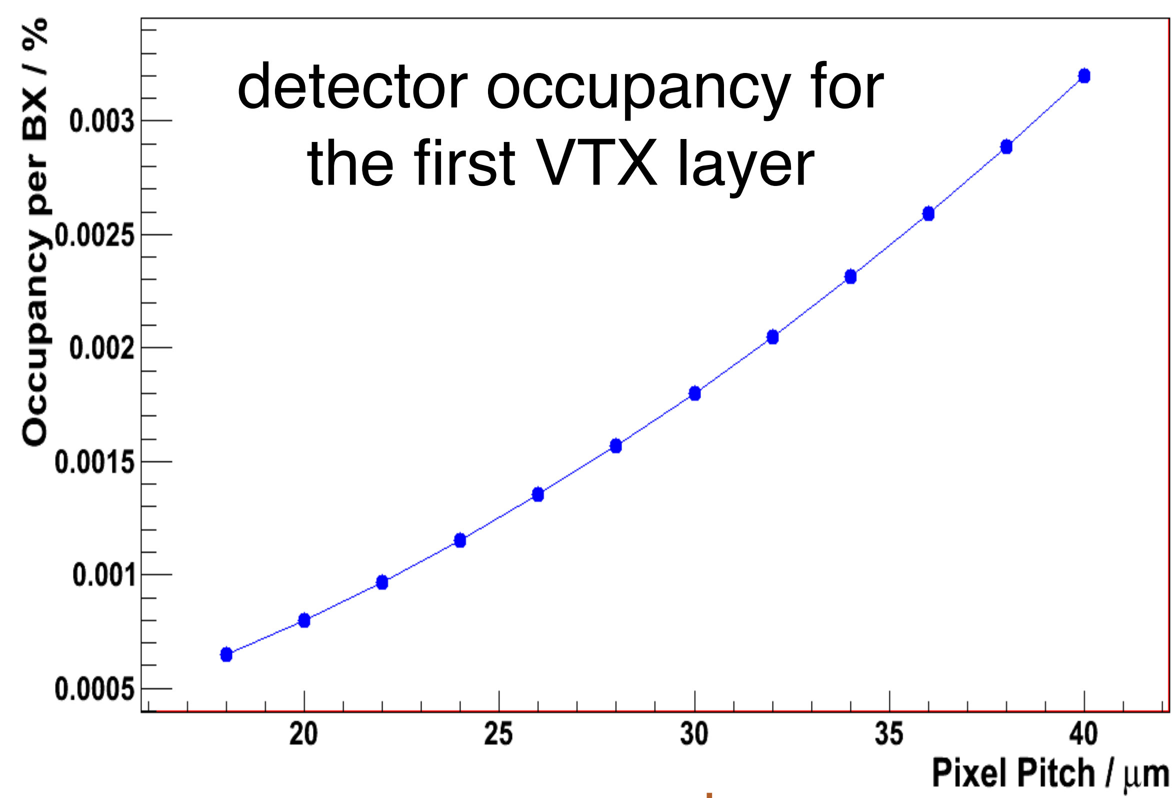
ALPIDE for ALICE

Radiation Background

- Estimated the hit density and detector occupancy of the CEPC vertex detector → to provide reference for sensor design



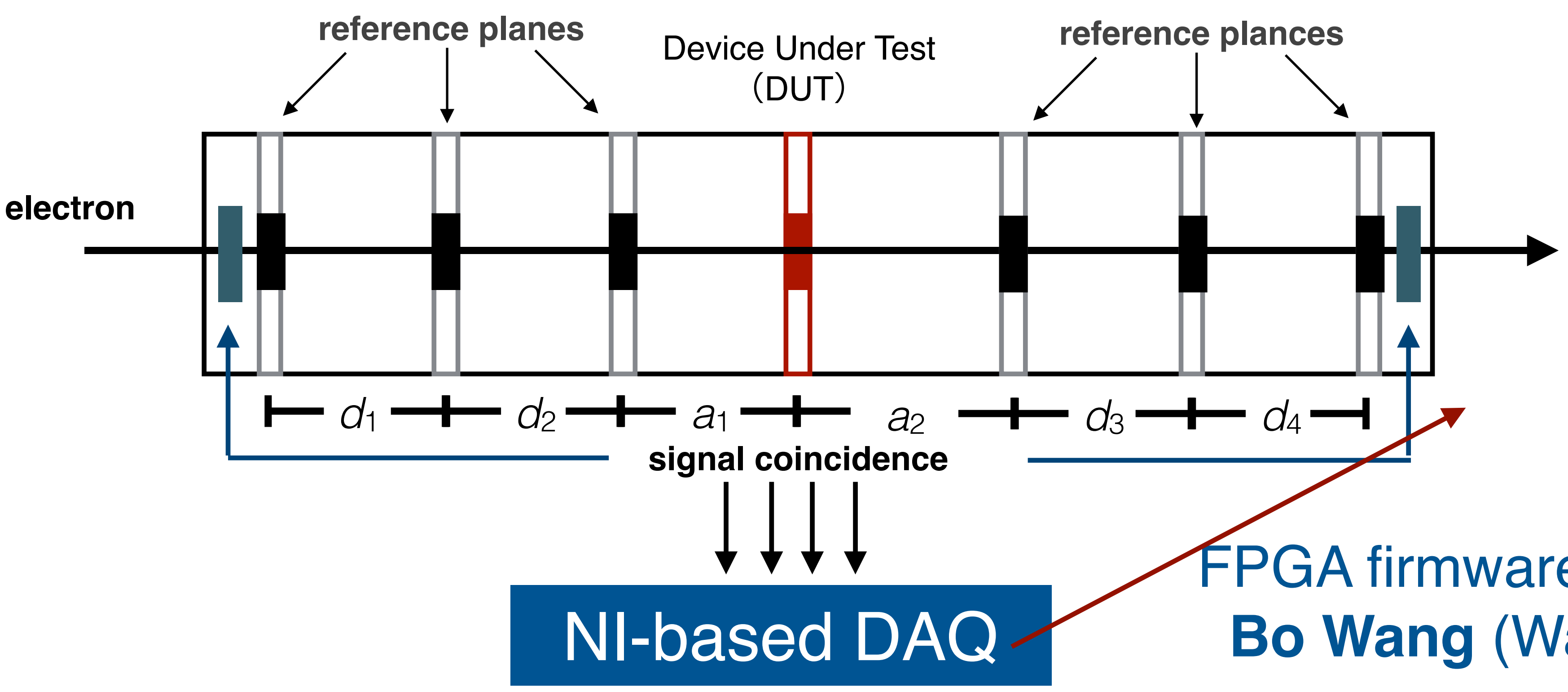
Radiation background conditions better for CEPC than ILC



No constraint for CEPC (empirical requirement of 0.5%)

Preparation for Sensor Tests

- Semiconductor Lab@IHEP maintains a class-10000 clean room (150 m^2) equipped with probe station, wire-bonder, etc.
  - I-V/C-V curves, laser/radioactive source responses
- High resolution beam telescope in preparation
  - Similar design to the EUDET telescope but with larger pixel sensors (MIMOSA28) and improved DAQ



FPGA firmware developed by summer student **Bo Wang** (Washington Univ.), ready for test

Summary and Outlook

- CMOS pixel sensor, a promising candidate for the CEPC vertex detector, relies on an appropriate CMOS process and may achieve fast readout with low power consumption.
- We have formed a team, aiming to address a few critical R&D items for the application of CPS to CEPC. Design efforts have started but experts/students are always welcome to join us.
- We have defined the expected achievements of the one-year project and shall request for additional funding for MPW submission and follow-up sensor tests.

ultimate design goal:

- Spacial resolution: ≤ 3 μm
- Detection efficiency: ≥ 99% (fake rate $<10^{-5}$)
- Readout time: < 20 μs
- Power consumption: < 50 mW/cm^2
- Radiation tolerance: close to ILC requirement