R&D on BES-III Inner Tracker using CMOS Pixel Sensors

OUYANG Qun (IHEP), **WANG Meng** (SDU), Marc WINTER (IPHC)

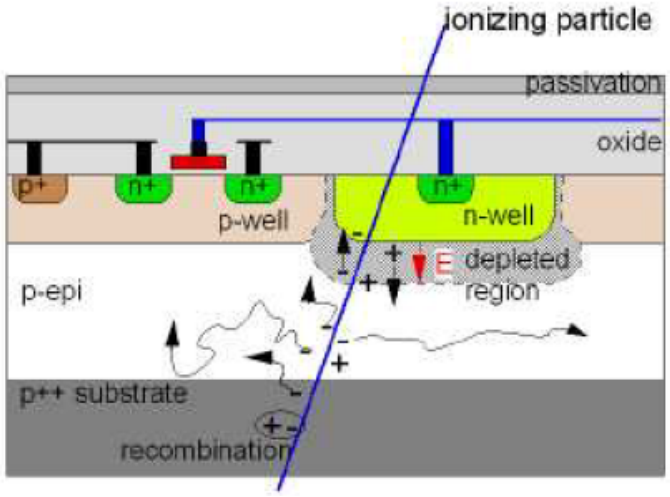
FCPPL 2013, Nanjing

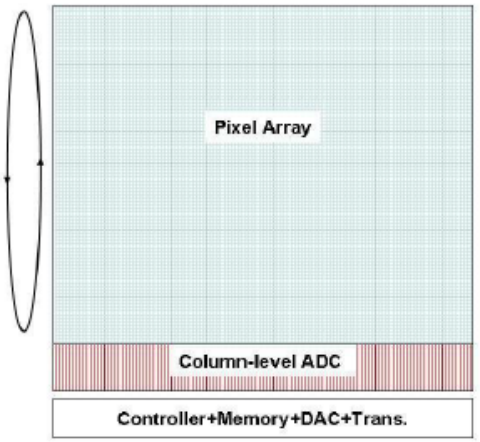
Outline

- Introduction to CMOS Pixel Sensors
- Status of BES-III inner tracking
- R&D Project
- Summary

CMOS Pixel Sensors

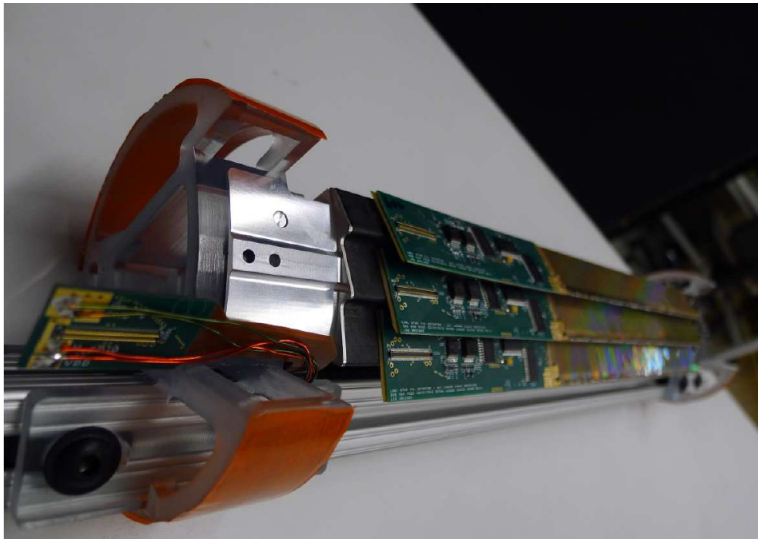
- prominent features of CMOS Pixel Sensors (CPS, aka *MAPS*)
  - high granularity ➔ micronic spatial resolution
  - very thin (signal generated in 10-20 µm thin epitaxial layer)
  - signal processing circuits integrated on sensor substrate
- organisation of MIMOSA sensors
  - manufactured in **0.35 µm** technology, currently transferring to **0.18 µm** technology
  - signal sensing and analogy processing in pixel array
  - mixed and digital circuitry integrated in chip periphery
  - read-out in **rolling shutter mode** (pixel grouped in columns read out by rows)

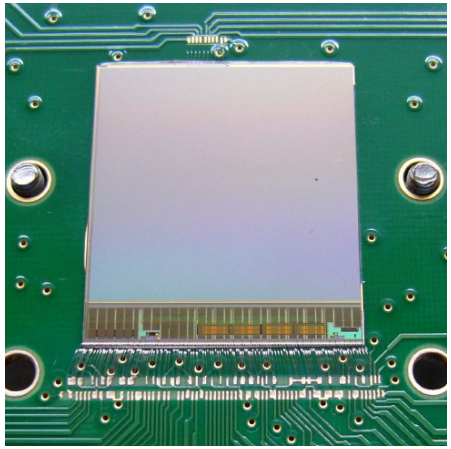




State-of-the-Art: MIMOSA-28 for STAR

- main characteristics of MIMOSA-28
  - 0.35 µm process with high-resistivity epitaxial layer
  - architecture with in-pixel correlated double sampling and amplification
  - end-of-column discrimination and binary charge encoding
  - on-chip zero-suppression
  - **active area: 960 × 928 pixels (19.9 × 19.2 mm²)**
  - **pitch: 20.7 µm ➔ charge sharing: σ_{sp} ~ 3.5 µm**
  - JTAG programmable
  - **readout time < 200 µs (5 × 10³ frames/s) ➔ 10⁶ part./cm²/s**
  - 2 outputs at 160 MHz
  - **power consumption ~ 150 mW/cm²**
- sensors almost fully evaluated
  - < 15 e ENC at 30-35 °C (as MIMOSA-22AHR)
  - CCE (^{55}Fe) similar to MIMOSA-22AHR
  - **radiation tolerance at 30 °C: 150 kRad, 3 × 10¹² n_{eq}/cm²**
- **commissioning in 2013**





Towards Higher Readout Speed and Radiation Tolerance

- **Next generation of experiments calls for improved sensor performances :**

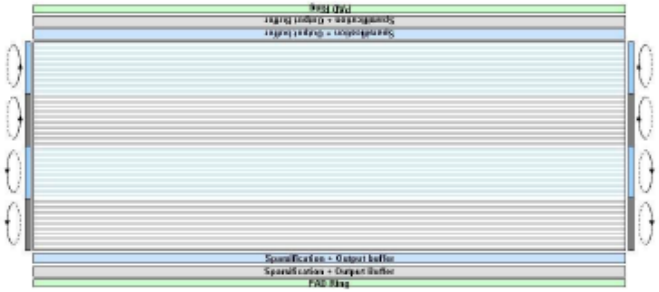
Expt-System	σ_t	σ_{sp}	TID	Fluence	T_{op}
STAR-PXL	$\lesssim 200\ \mu s$ ⇓ ?	$\sim 5\ \mu m$	150 kRad ⇓ ?	$3{\cdot}10^{12}$ n_{eq}/cm^2 ⇓ ?	30°C
ALICE-ITS	10-30 μs	$\sim 5\ \mu m$	700 kRad	10^{13} n_{eq}/cm^2	30°C
CBM-MVD	10-30 μs	$\sim 5\ \mu m$	$\lesssim$ 10 MRad	$\lesssim 10^{14}$ n_{eq}/cm^2	$\ll$ 0°C
ILD-VXD	$\lesssim 10\ \mu s$	$\lesssim 3\ \mu m$	O(100) kRad	O(10^{11}) n_{eq}/cm^2	$\lesssim$ 30°C

- **Main improvements required to comply with forthcoming experiments' specifications :**
  - **aim for higher epitaxial layer resistivity**
  - **reduce nb(pixels) / read-out unit (column)**
  - **aim for smaller feature size process** **&** **more parallelised read-out**

- **How to accelerate the pixel read-out**
  - elongated pixels ⇛ less pixels /col. & in-pixel discri. ⇛ 3-8 faster r.o.
  - read out simultaneously 2 or 4 rows ⇛ 2-4 faster r.o./side
  - subdivide pixel area in 4-8 sub-arrays read out in // ⇛ 2-4 faster r.o./side
  - conservative step: 2 discri./col. **end** (22 μm wide) ⇛ simult. 2 row r.o.

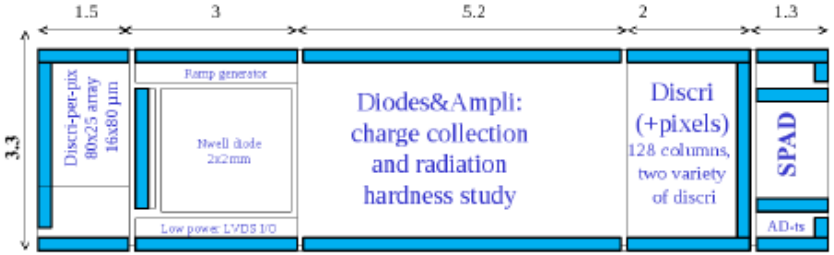
↻ remain inside virtuous circle: spatial resol., power, flex mat. budget, ...

⇛ 0.18 μm process needed instead of currently used 0.35 μm process

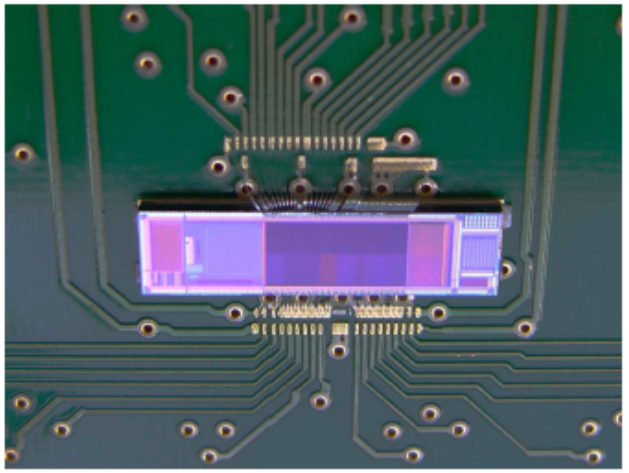


MIMOSA-32: Prototyping 0.18 µm Process

- **0.18 μm imaging technology options used :**
  - Epitaxial layer: **High-Resistivity (1-5 $k\Omega \cdot cm$)** & "18 μm" thick $\Rightarrow$ SNR, rad. tol., ...
  - Quadruple well: deep P-type skin embedding N-well hosting P-MOS transistors $\Rightarrow$ compactness, power, ...
  - 6 Metal Layers
  - MIM capacitors
  - etc.



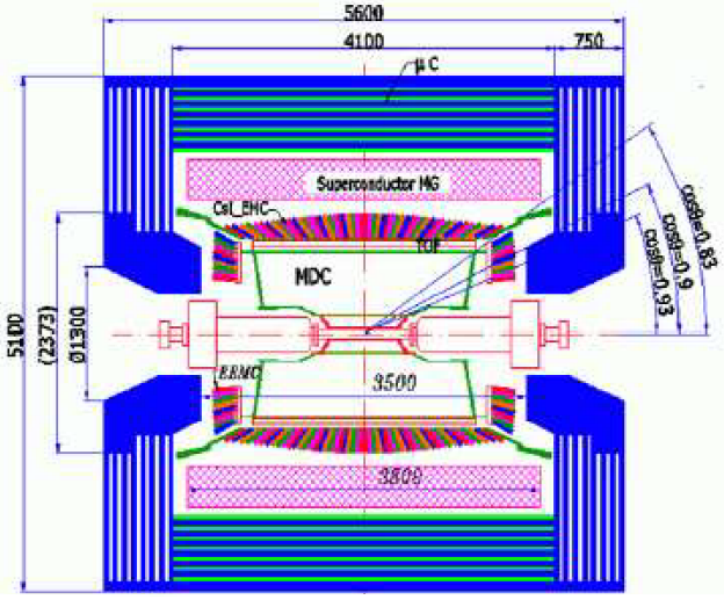
- **Prototype sub-divided in several blocks :** ▷ ▷ ▷
  - Sensing elements and in-pixel amplifiers :
    - pixel dimensions : $20 \times 20/40/80\ \mu m^2$
    - 2 different types of sensing elements : diodes of $\sim$ 9–15 μm^2
    - N-MOS and P-MOS transistor based amplifiers
  - Discriminators :
    - Col. // pixel array ended with 1 discriminator/col. (2 variants)
    - Pixel array with in-pixel discriminator ($16 \times 80\ \mu m^2$ pixels)
  - Total surface $\sim$ 43 mm^2

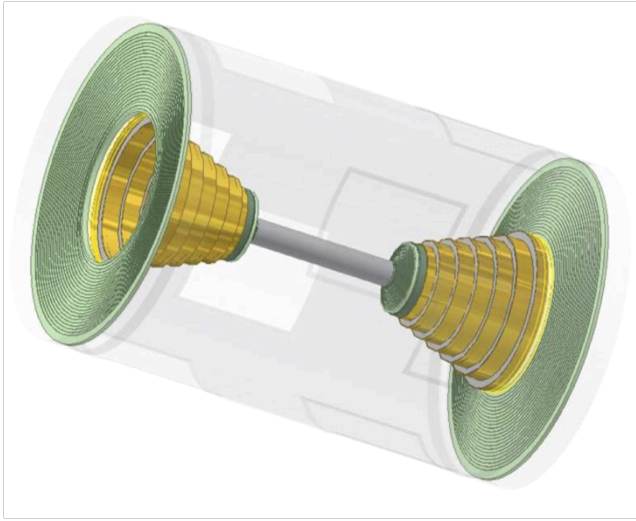


several prototypes (MIMOSA-32xx) fabricated in 2011/2012
➔ tests since April 2012

The BES-III Experiment

- the BES-III experiment
  - general purpose detector at BEPC-II
    E_{cm} ~ 2-4.6 GeV, L_{peak} ~ $10^{33}/cm^2/s$
  - versatile researches in τ-charm physics
- Main Drift Chamber (MDC)
  - key tracking component
  - radii: 59 – 810 mm, max length ~ 2.6 m
  - 43 wire layers, 1T magnetic field
  - σ_{xy} = 130 μm, σ_p/p = 0.5% @ 1GeV, dE/dx = 6%
- innermost layers of MDC
  - high background encountered
  - dark current for the 1st layer up to 1 μA per sense wire
  - reducing HV of innermost 4 layers, gas gain decreased to 31% of normal one
  - performance deteriorated (the worst case):
    σ_{xy} ~ 300 μm, ε_{cell} ~ 70%





Keep the MDC alive

BES-III: data taking for the coming years

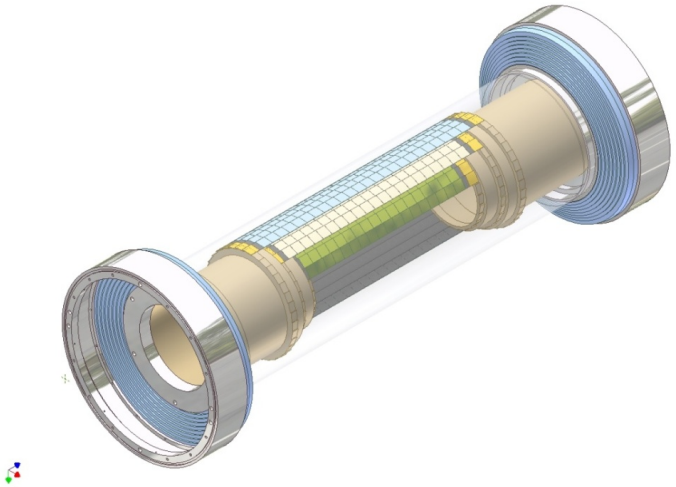
- J/ψ： 1.2B ➔ 10B events
- Ψ′： 0.5B ➔1B events
- ψ(3770)： 2.9 fb^{-1} ➔ 20 fb^{-1}
- R scan…

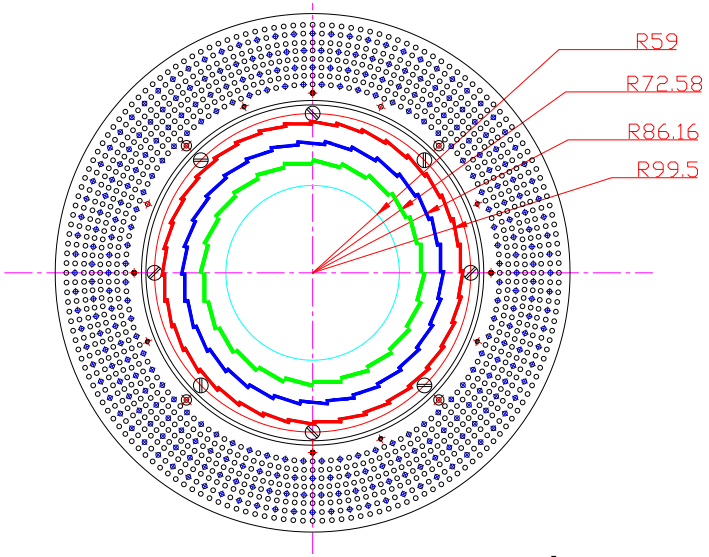
Actions: possible luminosity increasing

- Construct a new inner drift chamber: 3 years project approved
  - demo prototype to test replacing process
  - new inner drift chamber ➔ starting from 2013
- Investigate new technologies: CMOS pixel sensor,…

R&D for tracker upgrade around 2018

Inner MDC upgrade with CPS





baseline design

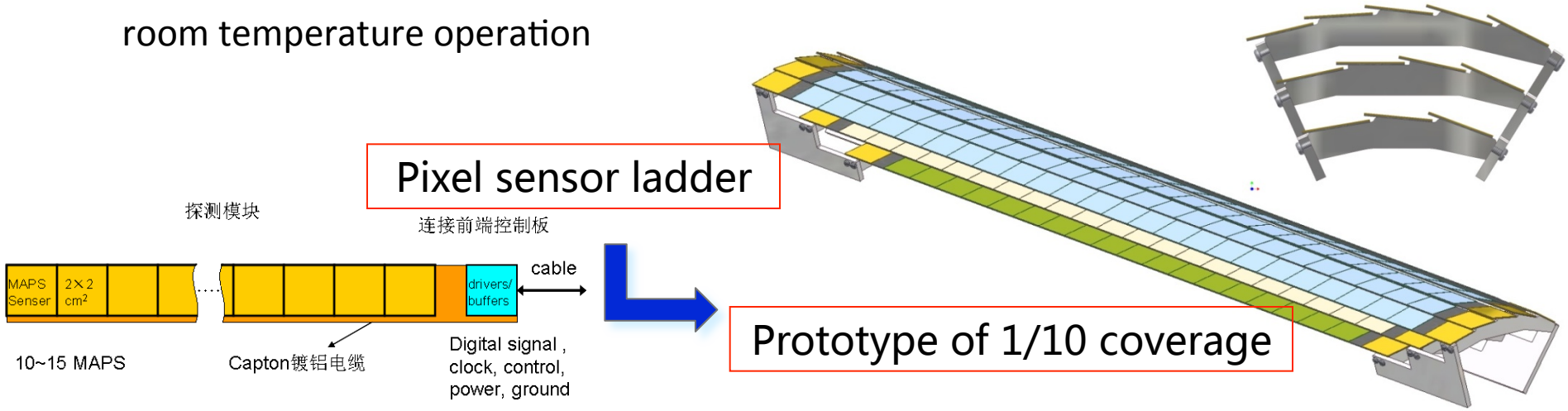
- 3 layers of single sided CPS or 2 layers of double sided CPS
- similar ladder structure as STAR or ALICE

R&D project approved

- budget: 2.8 M CNY
- duration: 2013 – 2016
- institutions: IHEP + SDU
  ➔ *collaboration with IPHC*

R&D target: a CPS prototype

density:	~ 20 µm pixel pitch ~ 0.9 M pixels/chip
spatial resolution:	a few µm
coverage:	1/10 ~ 800 cm^2 ➔ 200 chips ➔ 200 M pixels
rating capability:	~ 10^6 Hz/cm^2
material budget:	~ 50 µm thick
radiation tolerance:	~ 1 MRad, 10^{13} n_{eq} $/cm^2$
power consumption:	0.2 – 0.3 W/cm^2
room temperature operation	



Collaboration with Strasbourg IPHC

Critical techniques:

Sensors: pixel size, RO speed, power consumption, zero suppression…

Ladder structure: ultra light material very thin flex bonding…

RO electronics: 8GB band width, xTCA structure…

Data transmission: radiation tolerance…

Alignment and reconstruction scheme: …

About 800cm^2 pixel chips (1/10 prototype)

➔ Almost a complete system of CMOS pixel sensors at STAR

Schedule

- 2013: development of PCB ladders and RO electronics
  - 20 chips (MIMOSA-28) for 2 ladders
  - training on wafer/chip test, …
  - mechanical design
- 2014: one or two Kapton ladders and RO electronics
  - bonding on flex (CERN/China)
  - mechanical structure, test,…
  - RO/DAQ system
  - simulation/alignment/reconstruction software
- 2015: development of 1/10 inner tracker prototype
  - 800 cm^2 pixel system – very hard job
  - RO/DAQ system adjustment/improvement
- 2016: beam test
  - software improvement

Summary

- IHEP-SDU-IPHC partnership has established to study the adaption of CMOS pixel sensors for BES-III inner tracking.
- An ambitious R&D project targeted a 1/10 coverage prototype has been approved.
- The partnership benefits from/to global effort towards large area trackers, e.g. STAR, ALICE, ILC, …