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

Photon-Counting Pixel Detector Designs for ITER X-Ray Crystal Spectroscopy System

Mujin Li
Institute of High Energy Physics, Chinese Academy of Sciences
X-ray Sensor Joint Workshop, 13 January 2026, Zürich
On behalf of the X-ray detector team, IHEP

Outline

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- Introduction of ITER XRCS
- MAPS Development for XRCS with CPPM
- Hybrid Detector System Test based on BPIX
- Future Development Plan: BPIX + LGAD
- Prospect

Outline

- Introduction of ITER XRCS
  - Requirements of XRCS Pixel Detector
- MAPS Development for XRCS with CPPM
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ITER XRCS

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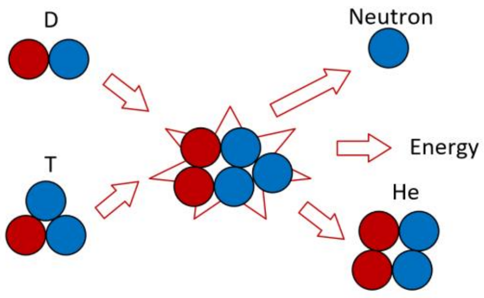
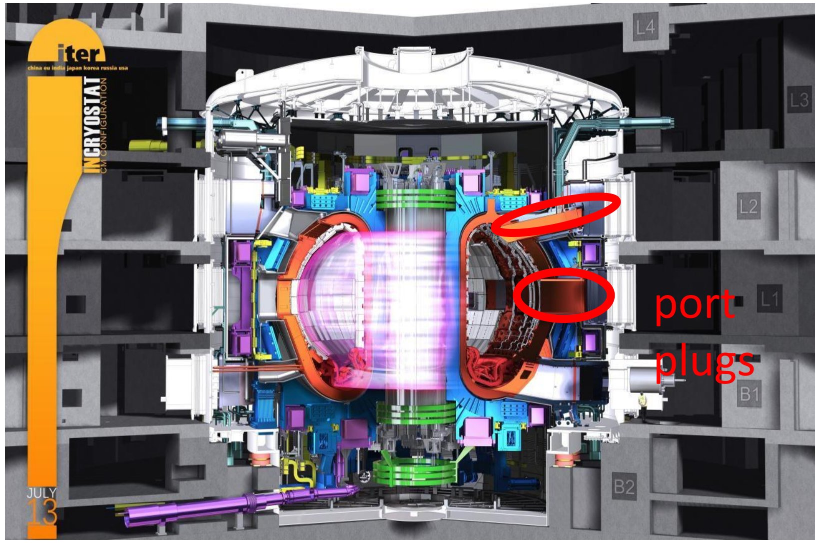
ITER: International Thermonuclear Experimental Reactor



D-T Fusion Process

ITER Location



ITER Vacuum and Port Plugs

- ITER 7 Cooperators：CN, EU, IN, JA, KO, RF, US
- Diagnose system： “Multi-messenger” (Visible/UV/X-ray/neutron…)
- **XRCS: X-Ray Crystal Spectrometer**
  - **Measure ion temperature and plasma rotation profiles within the ITER core plasma**
  - **Monitor the first wall material**

Ref: Raphael TIEULENT, TWEPP2023, Sardinia Italy, October 2023

ITER and Diagnose System

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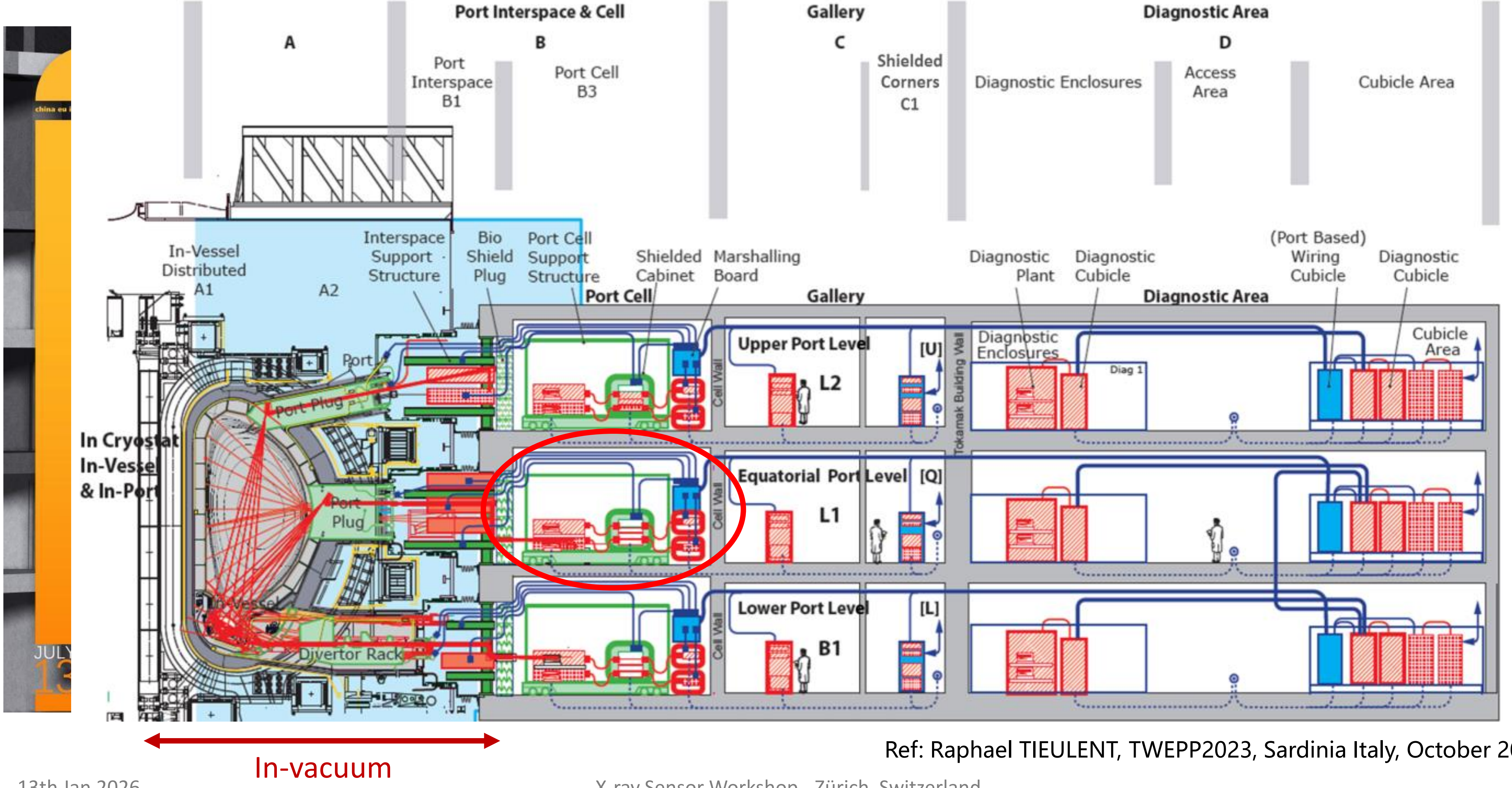
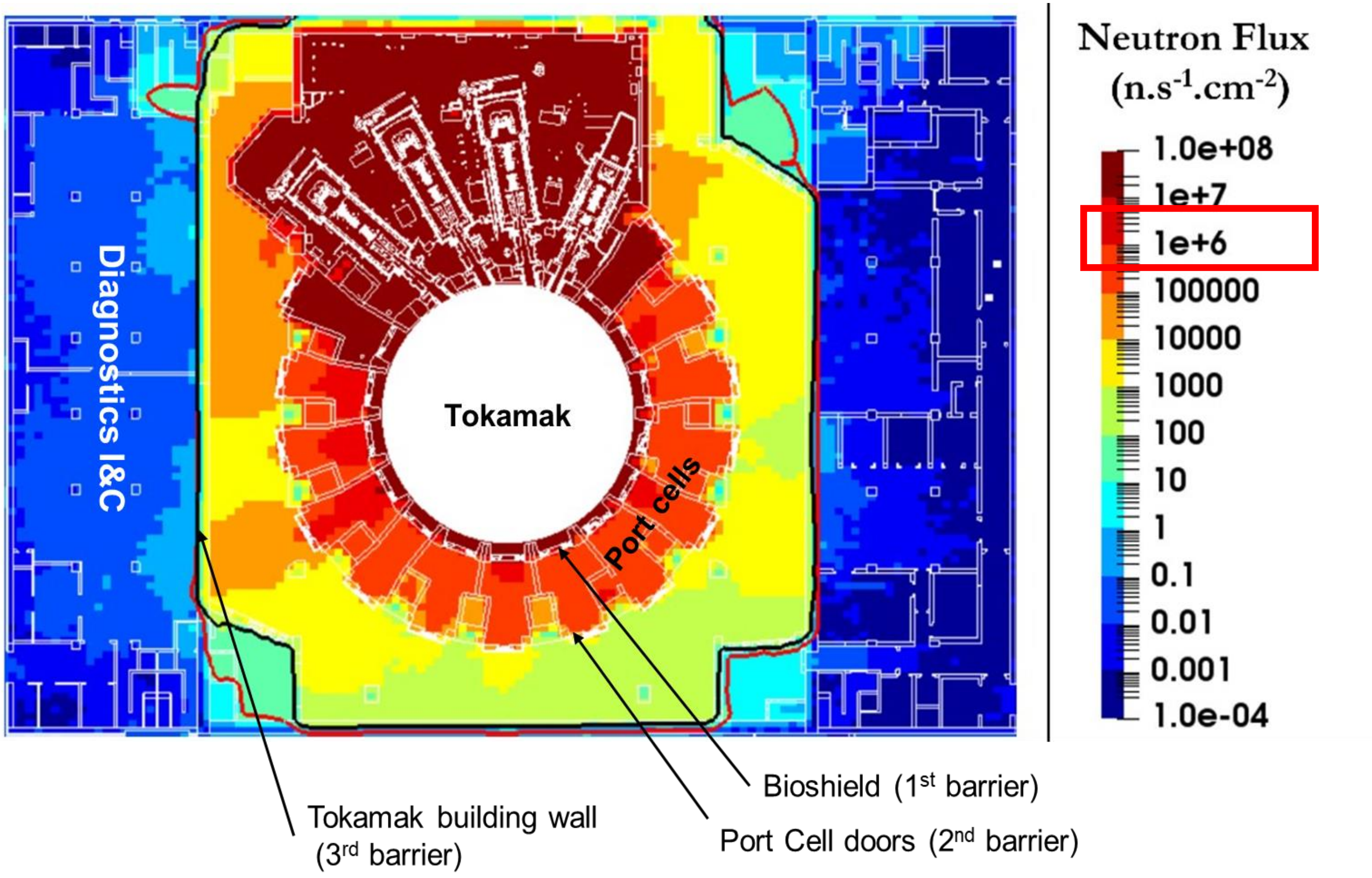


Ref: Raphael TIEULENT, TWEPP2023, Sardinia Italy, October 2023

ITER Neutron Flux



Ref: Raphael TIEULENT, TWEPP2023, Sardinia Italy, October 2023

Specifications of ITER XRCS Pixel Detector

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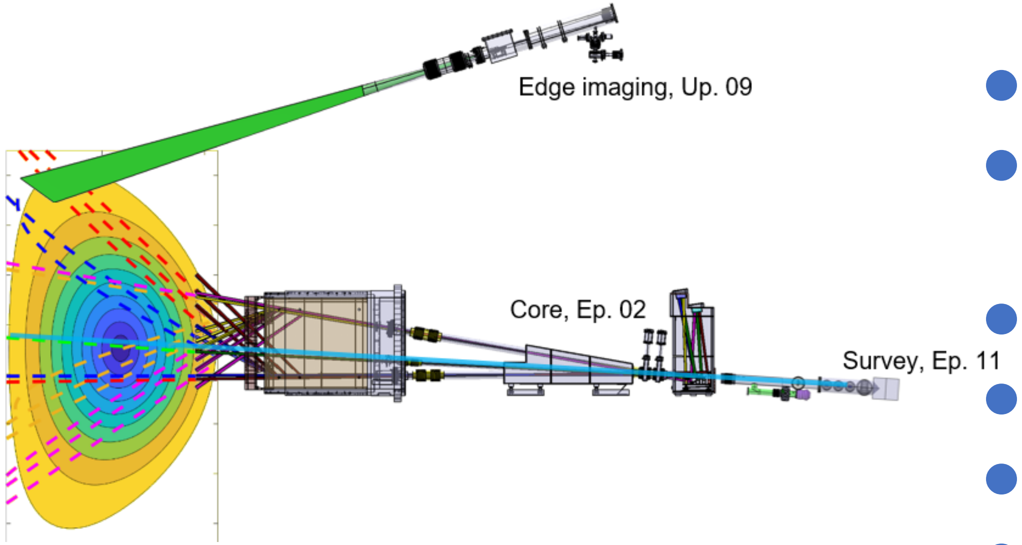


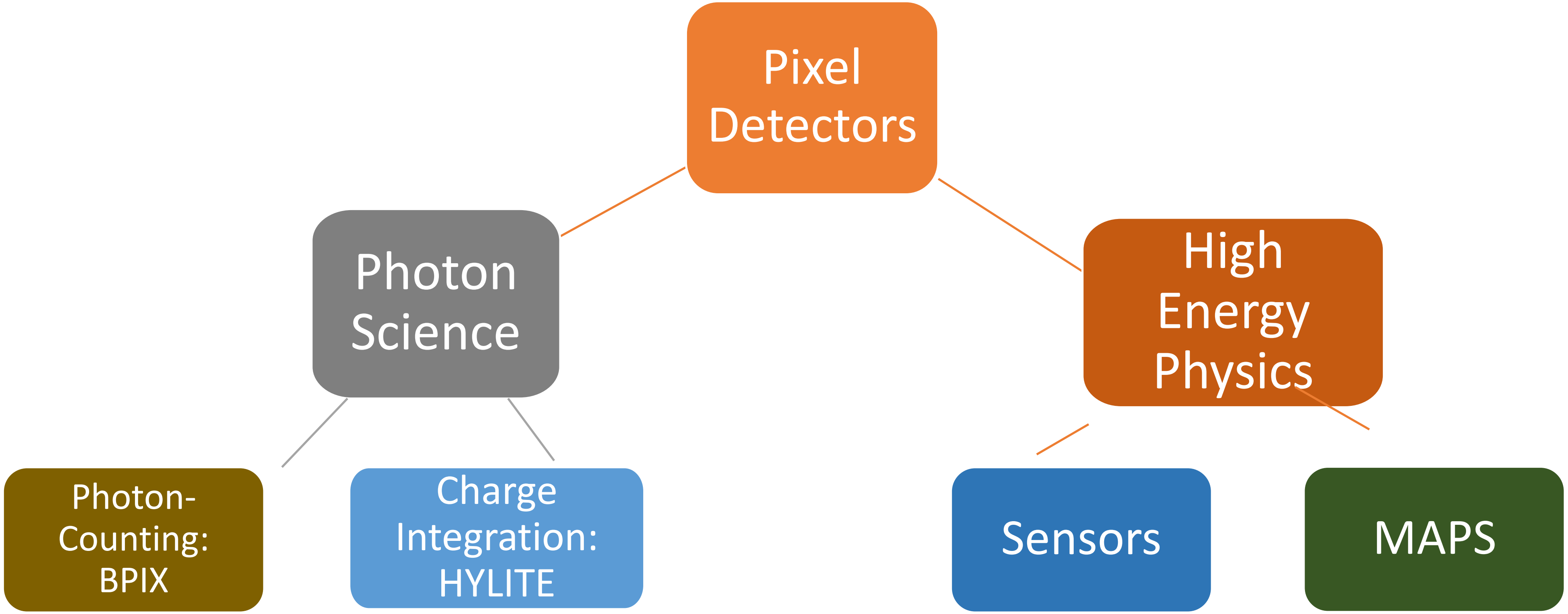
Red, **Green-1** and **Magenta** Sights: Xe_{44+} **(2.5525 Å)** and Xe_{47+} **(2.5572 Å)** from 0a to 0.85a
Blue and **Yellow** sights: Xe_{51+} 2.1899 Å for 0 ~ 0.55a
Green-2 View: W_{64+} (1.354 Å) passing through plasma center

- Core & Edge：Single-photon resolution @ 3 keV
- Detector Panel Neutron Flux：10^6 s^{-1}·cm^2
  - Separated front-end and back-end
- Panel Size：180 mm × 85 mm
- Vacuum： UHV (10^{-5} ~ 10^{-6} pa)
- Magnet：0.2 T
- Run-time control latency： < 10 ms
- Maximum Counting Rate：10^7 counts/s/mm^2

Sub-system	**XRCS Core**	**XRCS Survey**	**XRCS Edge**
Wavelength (Å)	2.555 (4.852 keV) 2.189 (5.663 keV) 1.354 (9.156 keV)	1 ~ 100 (0.12 keV ~ 12 keV)	3.97 (3.12 keV) 3.73 (3.32 keV)

Ref: Zhifeng Cheng, ITER Spectroscopic Diagnostics and Atomic Data Needs, 2023 Vienna

Pixel Detectors in IHEP



Outline

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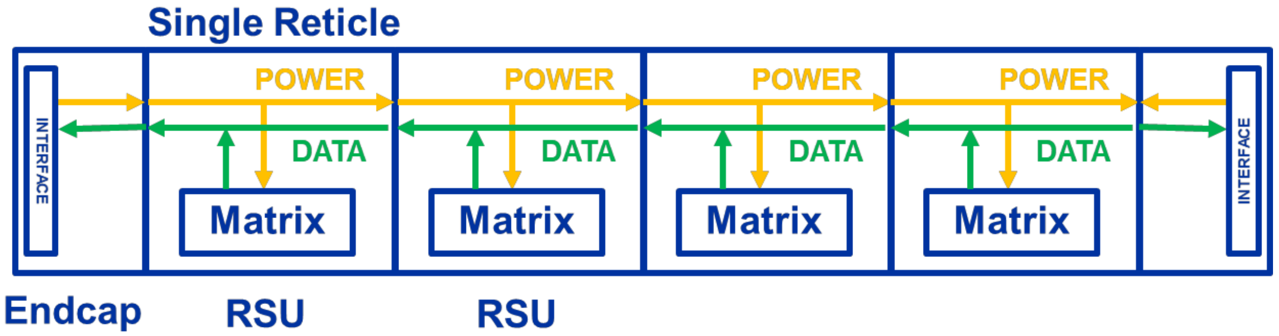
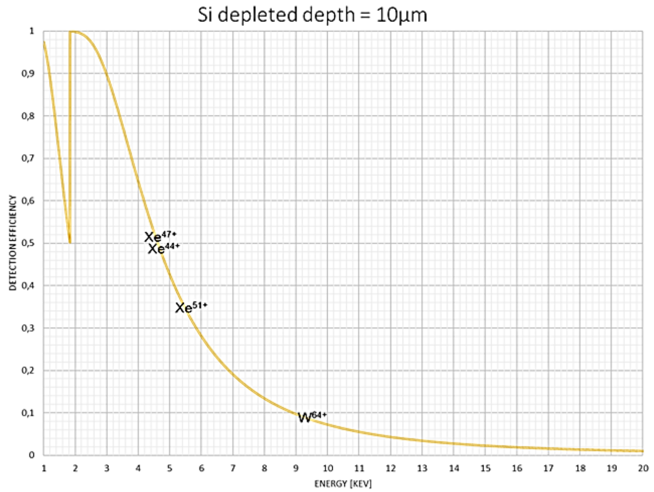
- Introduction of ITER XRCS
- MAPS Development for XRCS with CPPM
  - Architecture of the Detector
  - Front-end Circuit Design
- Hybrid Detector System Test based on BPIX
- Future Development Plan: BPIX + LGAD
- Prospect

Architecture

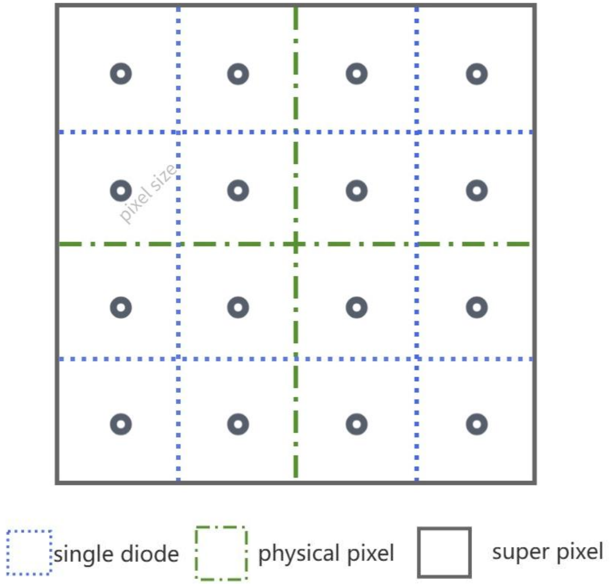
- Corporation with CPPM (Mujin Li, Wei Wei, Patrick Pangaud, Marlon Barbero, Danwei Xu)
- Single-photon resolution @ 3 keV
  - MAPS + photon-counting
  - Energy of threshold: 1.5 keV, ENC<40 e-
- Large-area panel and less dead zone
  - Stitching
- Pixel Size: 100 μm × 100 μm
  - Physical pixel: 25 μm × 25 μm
  - 16 diodes per pixel
- High flux of neutron
  - Double threshold to reject neutron hits
- Latency < 10 ms
  - Frame rate > 100 Hz -> 200 Hz
  - Double Counter/pixel, ping-pong



Stitching Structure

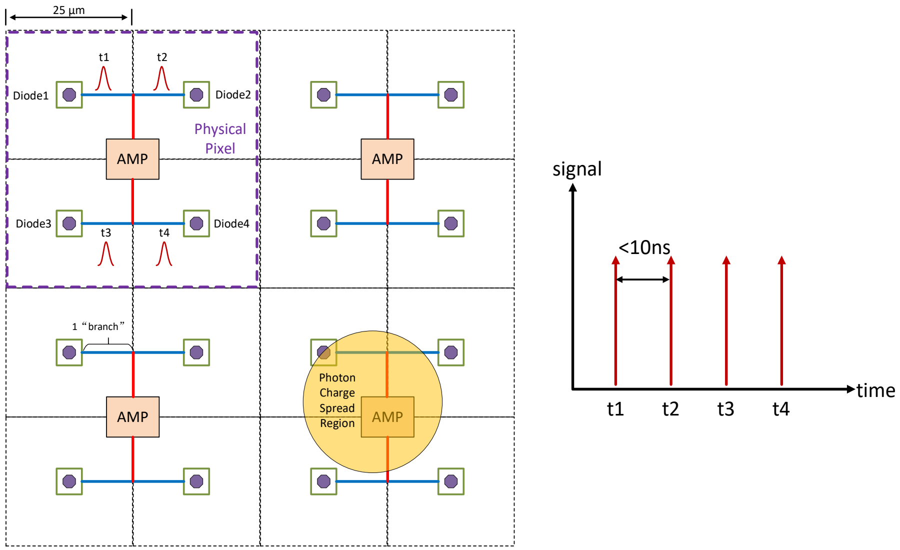


Detect Efficiency of the Isotopes with 10-μm thick depletion silicon

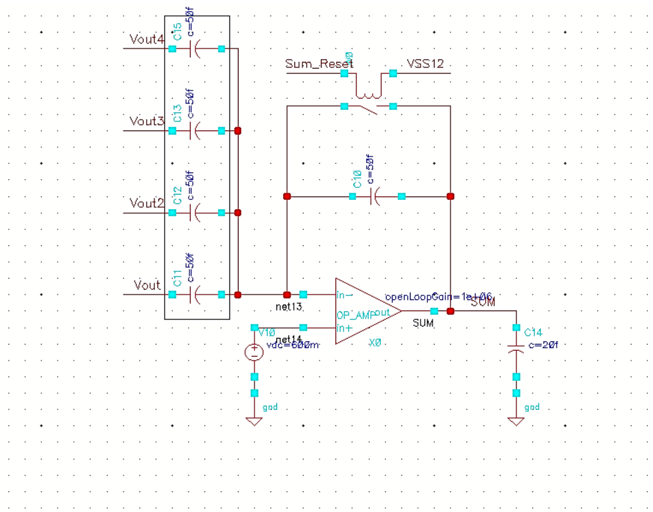


Pixels Illustration

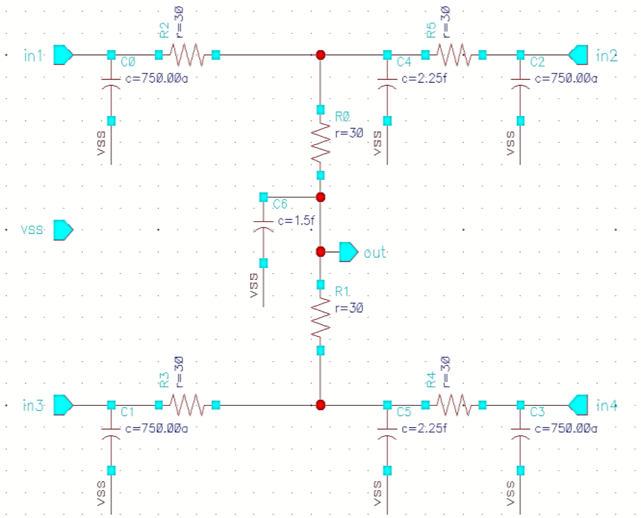
CSA + Analog Sum



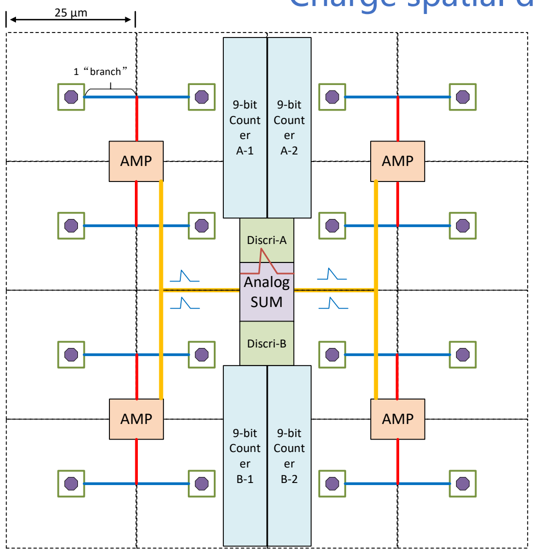
Charge spatial distribution



Analog sum circuit



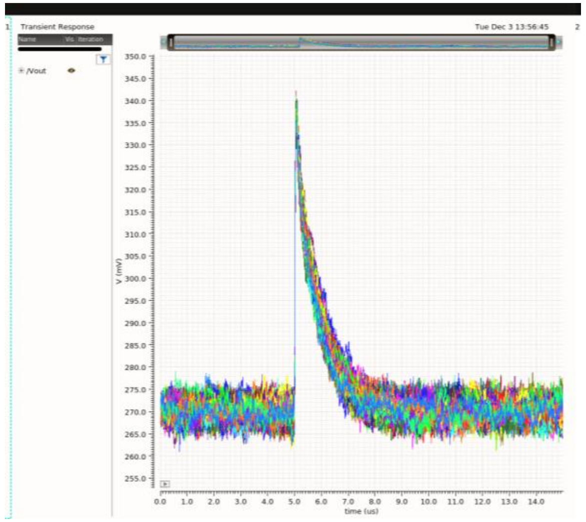
CSA input network model



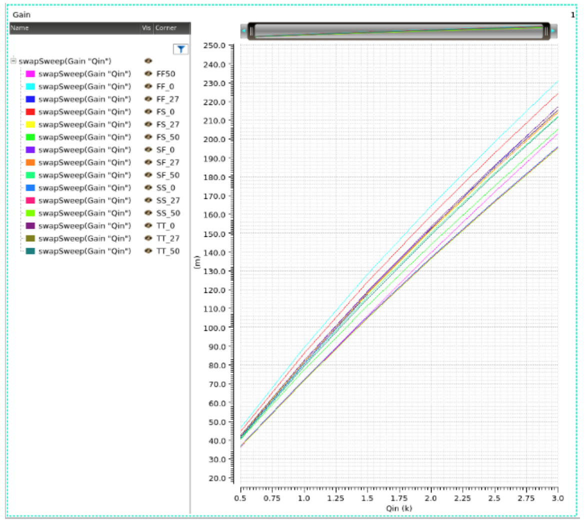
Analog sum scheme

- Classical CSA structure
  - 4 diodes/CSA， PEX and modeling of the input network
- Double threshold, de-offset discriminator
  - Depth of the counter: 9-bits
  - 4 counters/pixel
- Arriving time difference: 10 ns maximum
- Power Consumption： ~7.5 μW

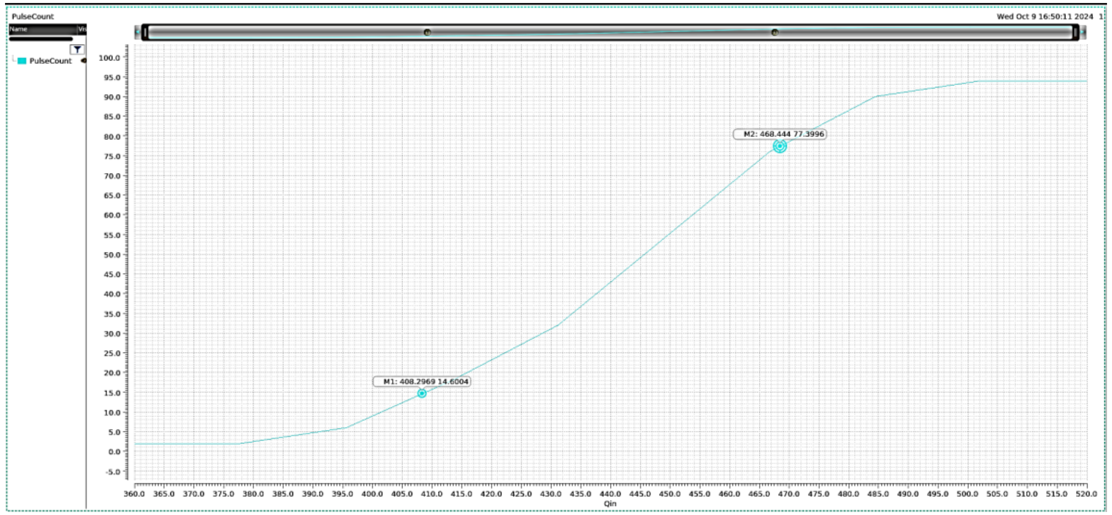
CSA + Analog Sum



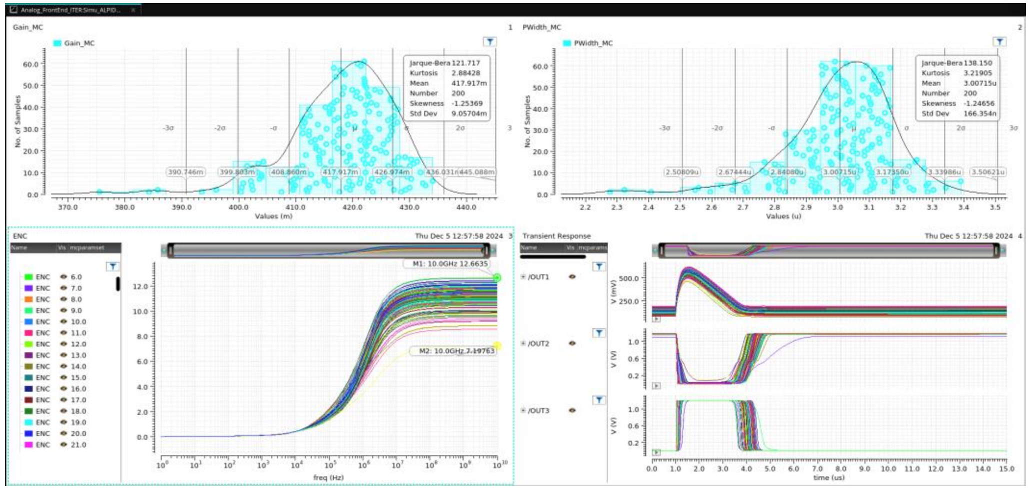
Qin=800e- transient noise simulation



Qin=800e-~3000e- Energy Linearity Simulation



S-Curve



Noise and transient 15 corners

Spec	Mean	Std
Gain (mV/ke-)	81.45	6.43
Phase Margin	84.23	2.41

Spec	Maximum	Minimum
ENC (e-)	32.50	21.53
Baseline (mV)	313.88	203.87

Simulation results of gain and noise

ALPIDE-like front-end + Digital Sum

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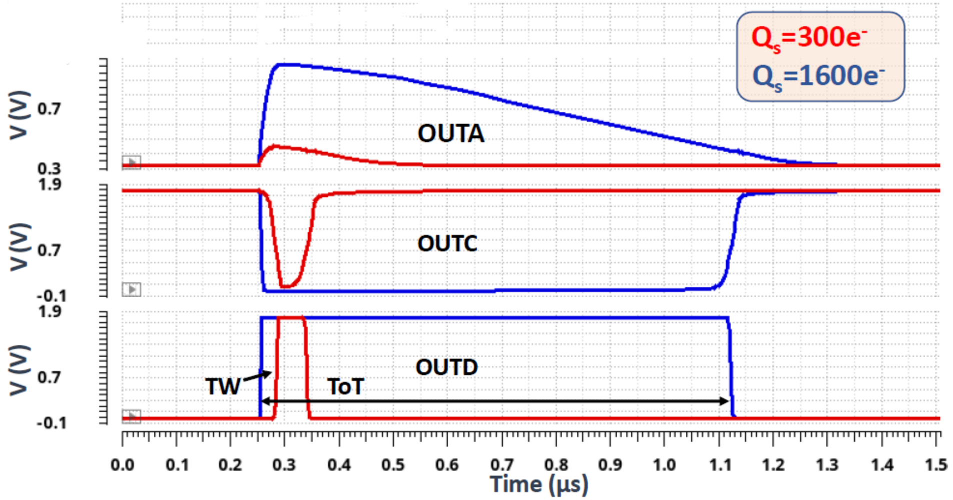
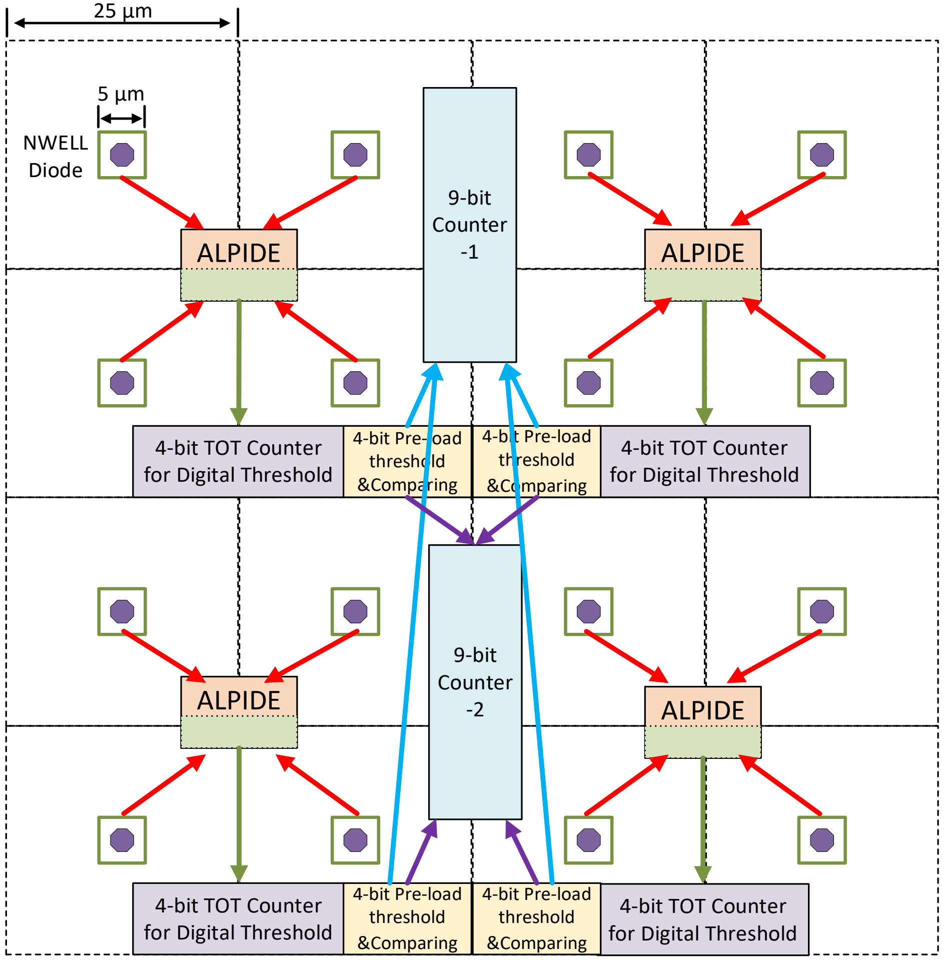


ALPIDE-like(TJ-Monopix1) TOT

Ref: Konstantinos Moustakas, PHD thesis, 2021

- Cannot take advantage of low C_{in} by adopting CSA
- ALPIDE-like front-end
  - Low noise, compact
- How to achieve double threshold?
  - Low threshold: ALPIDE charge threshold
  - High threshold: TOT （Digital threshold）
  - Set different threshold by different counting depth and clock frequency



Digital Sum structure

ALPIDE-like front-end + Digital Sum

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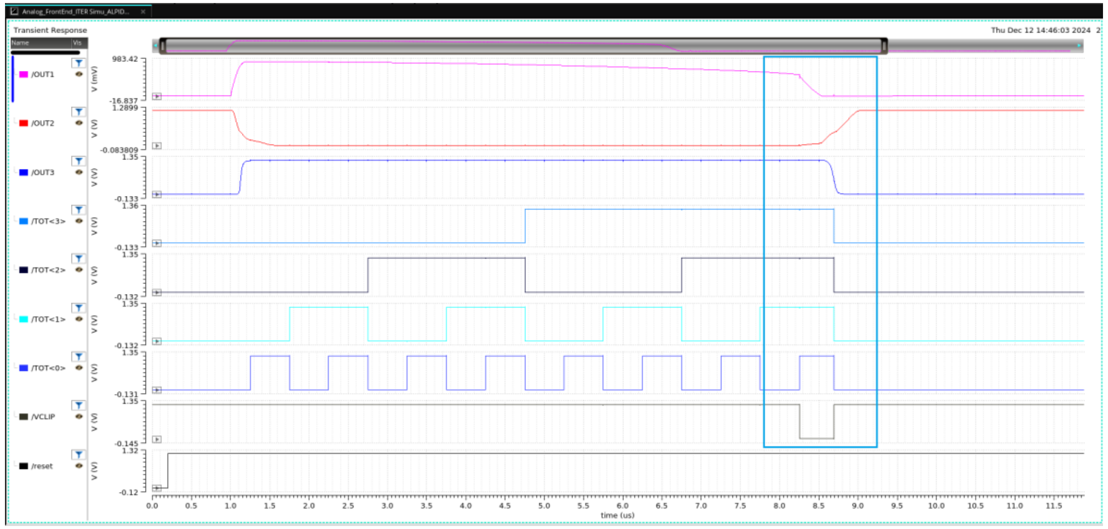
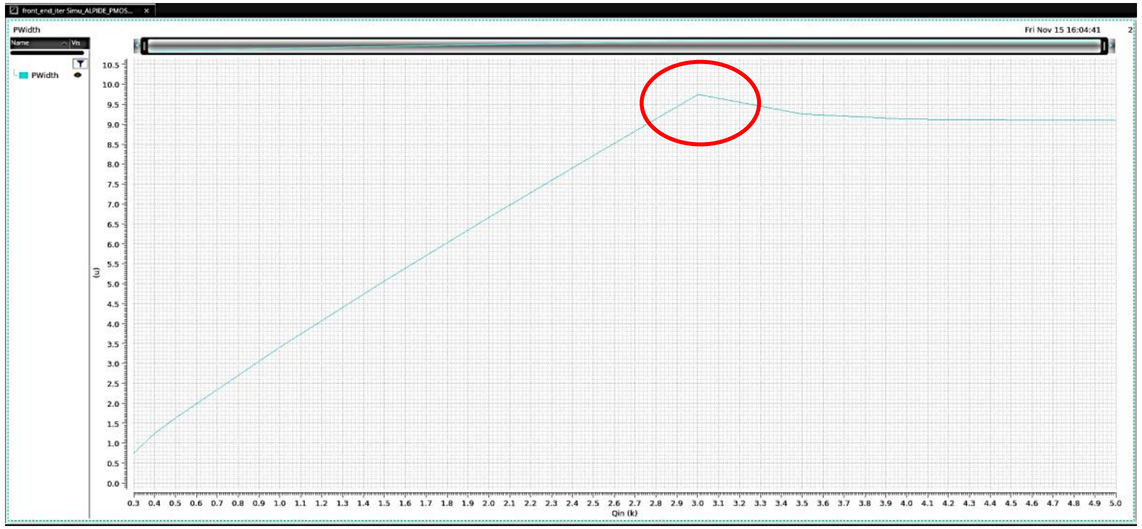
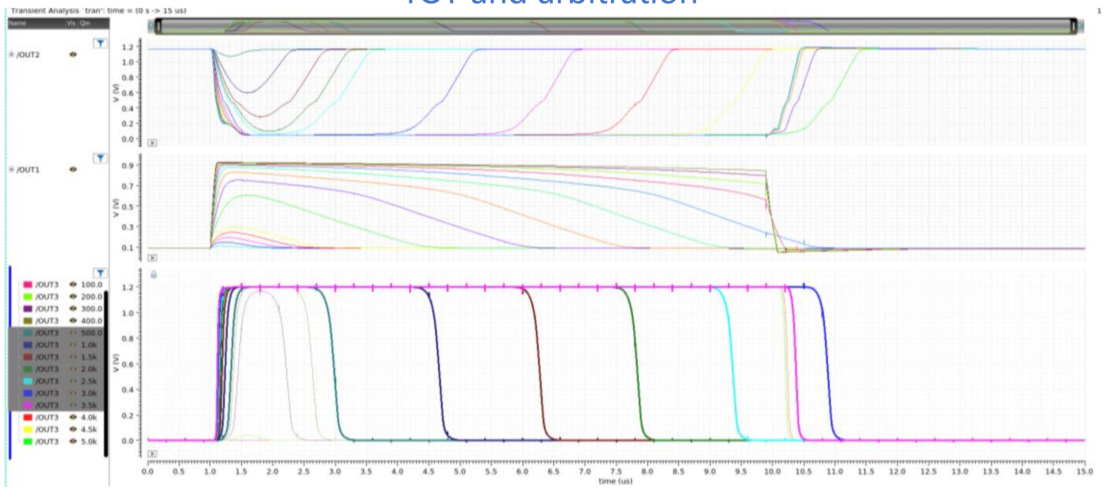


TOT and arbitration



Qin-TOT (300e-~5ke-)



Qin 800e-~3000e- transient simulation

SPEC	Mean	Standard Deviation
Charge Gain/ (mV/ke-)	417.9	9.057
Pulse width/us	3.007	0.166

- Power consumption: ~7 μW
- ENC Monte Carlo (Qin=800 e-):
  - maximum: 12.66 e-
  - minimum: 7.20 e-

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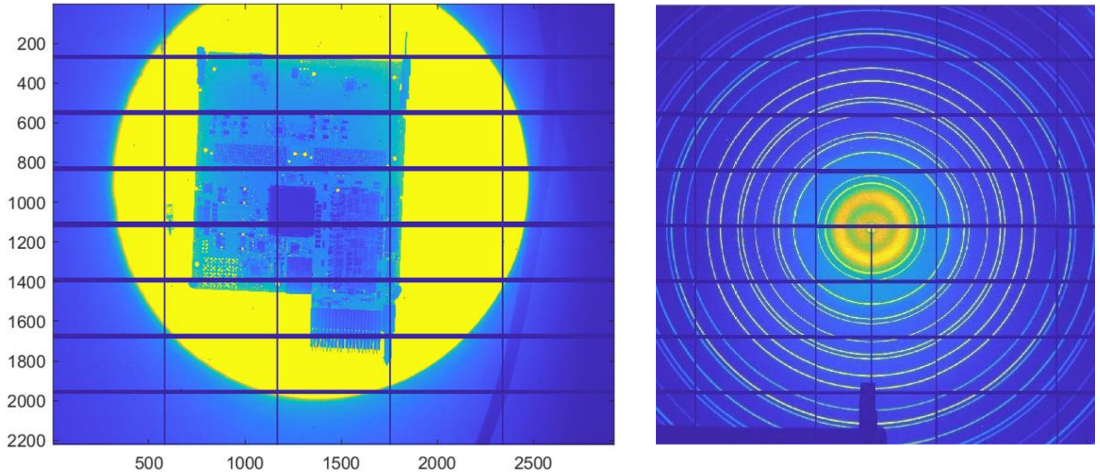
BPIX

- A hybrid photon-counting pixel detector for synchrotron (HEPS).
- New BPIX-40: A 6M system assembled for the HEPS beamline BA.
- A series of detectors in different dimensions (2M/1M ...) are also scheduled

Specs	BPIX-20	BPIX-40
Pixel size	150 μm×150 μm	140 μm×140 μm
Pixel Array	104×72	128×96
Threshold	1	2
Gain	Fixed	2 bits tunable
Counting rate	> 2Mcps	> 2Mcps @ Med gain
Frame rate	1.2kHz	2kHz
Counting Depth	20 bit	14 bit
Detector Module	2×4 (208×288)	2×6 (256×576)
Module Gap	3mm by TSV	2.7mm by WB

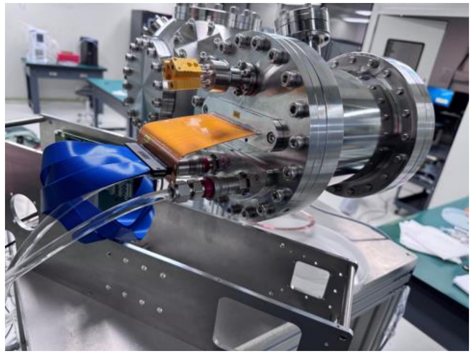

6M BPIX-40 pixel detector



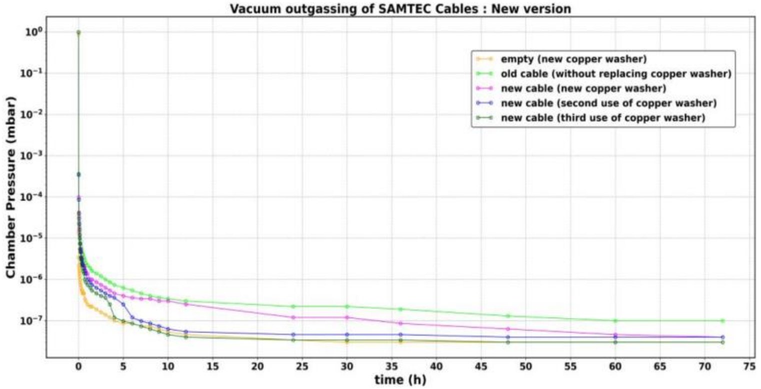
6M pixel detector Imaging Test

BPIX System Test for ITER

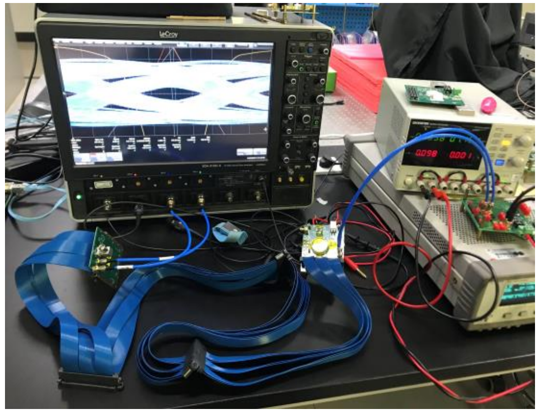
- Vacuum Compatibility
  - All components must meet ITER VQC-1 vacuum quality requirements.
  - Test result: < 10^{-7} mbar
- X-ray Energy Sensitivity
  - Target: 3 keV
  - Test result: 6 keV
- Magnetic Field Resistance:
  - Target: 0.2 T
  - Test result: pass
- Neutron Radiation Tolerance
  - To be specified
  - Long-cable data transfer test: 2.56 Gbps via 1.6-m cable

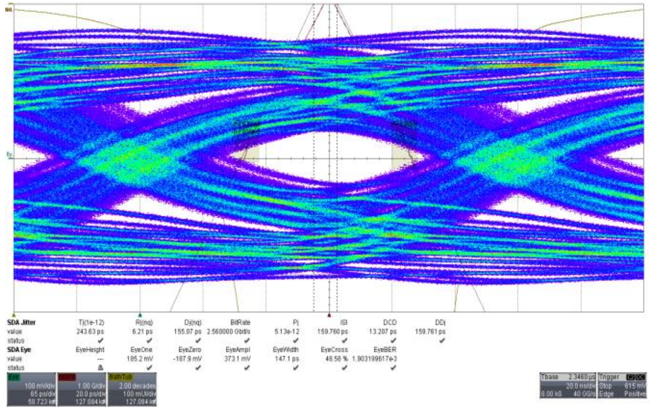


Vacuum feedthrough and test structure



Vacuum outgassing of the feedthrough cables





Test setup and eye gram of the data port on the speed of 2.56 Gbps via a 1.6-m long cable

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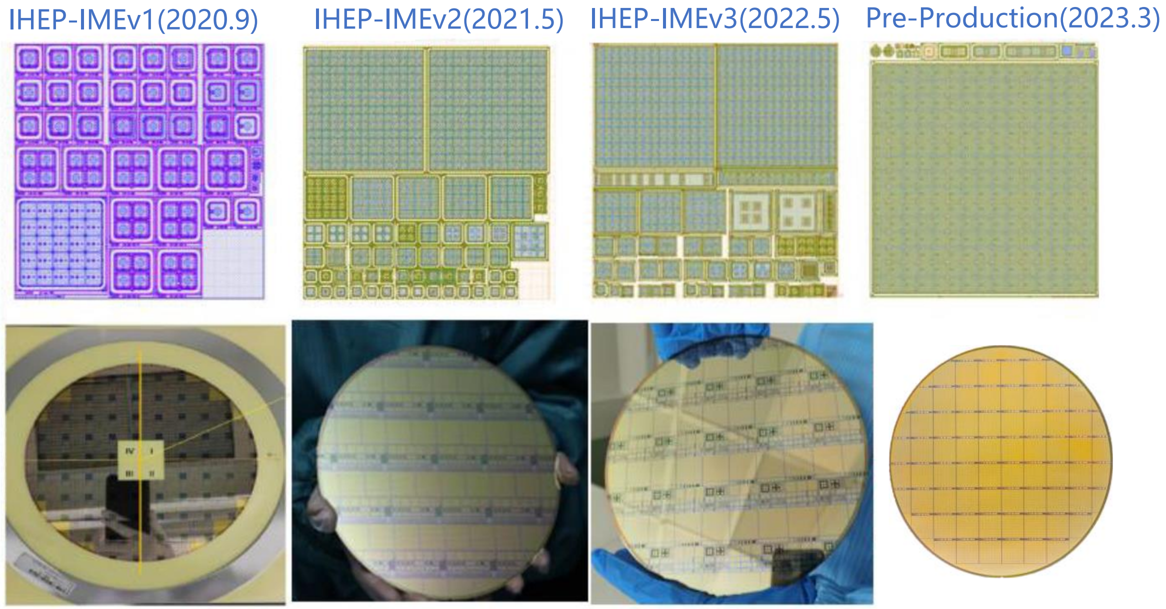
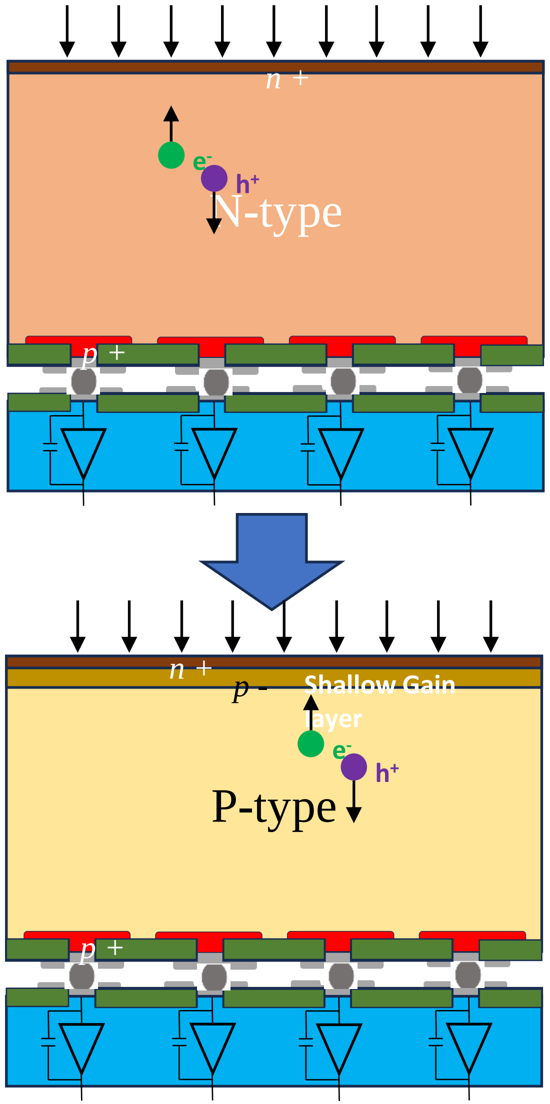
LGAD



IHEP-IME LGAD History



Standard Hybrid detector > 6 keV with BPIX40 ASIC

Hybrid detector with BPIX40 ASIC and Gain Sensor

- LGAD research in IHEP since 2019 for ATLAS HGTD
  - 90 % production share
  - Main contributor: Zhao Mei
- Adaption for photon science is needed
  - Type: inversed DC coupled
  - P-type substrate

iLGAD for BPIX: Preliminary Results

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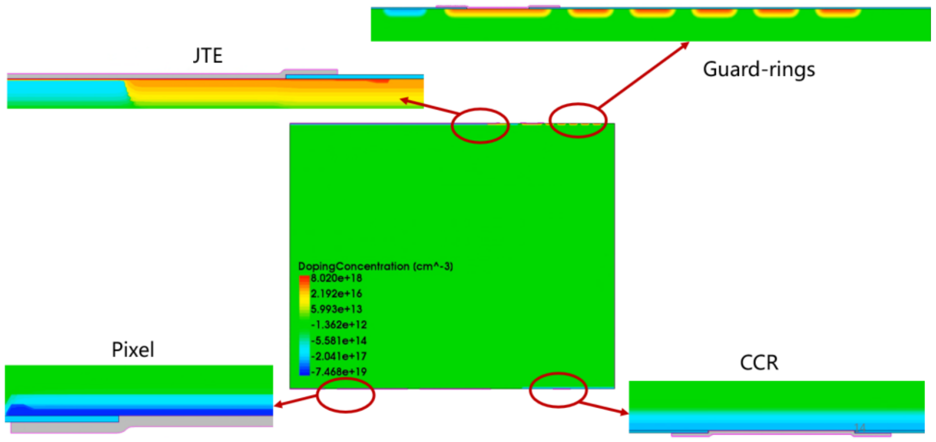
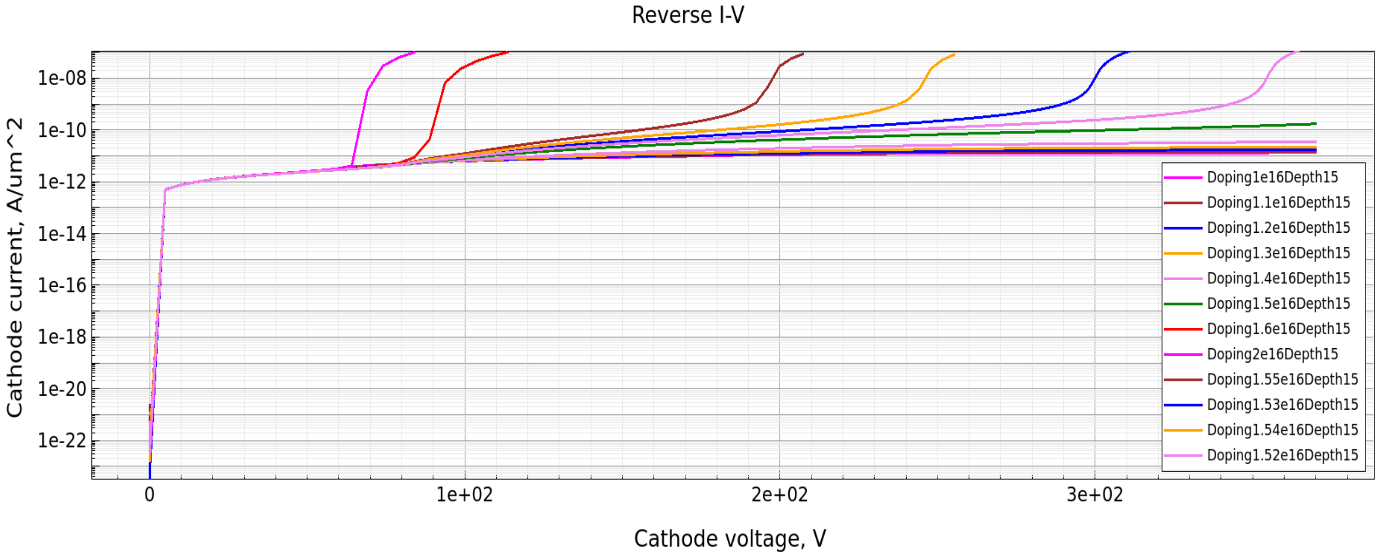


Simulation of the structure



Breakdown voltage Simulation

- Pixel size: 140 μm × 140 μm
- 100% fill factor
- Gain with 10 ~ 20 for 500 eV
- Gain layer: located at the entrance window
- Shallow Gain layer: 500 nm ~ 1000 nm
- Double-side process

The sensor will be manufactured and bonded to the BPIX40 ASIC in 2026.

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Prospect

- XRCS is an important part of ITER diagnose system, the pixel detector need to be magnet and neutron tolerant with single-photon resolution at an energy of ~ 3 keV.
- Two main technical paths: MAPS and LGAD.
  - MAPS: Low input capacitance and low noise.
  - LGAD: Sensor with gain.
- System level design and test is on-going. Neutron tolerance test and low-energy calibration will be finished soon.
- The iLGAD which is compatible with BPIX40 has been designed, and the detect region can be pushed to lower energy hopefully.

Thank you !

Back Up Slides

ITER VQC

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		Maximum Steady State Outgassing rate $Pa.m^3.s^{-1}.m^{-2}$		
VQC⁺	**Outgas temperature °C**	**Hydrogen isotopes**	**Impurities**	**Testing Guidelines**
1	100‡	1×10^{-7}	1×10^{-9}	Appendix 17
2	20	$1 \times 10^{-7*}$		Appendix 17
3	20	1×10^{-8}		Appendix 17
4	20	1×10^{-7}		Published data and conformity to clean work plan.

For VQC 2, 3 and 4, the outgassing rate excludes the partial outgassing rates for water and hydrogen.

‡ The outgas test temperature can be reduced to 20 °C for components which normally operate at cryogenic temperatures.

+ For CFC refer to section 26.7

* In the case of resins for magnets it is considered that this target outgassing rate will be achievable. However, a factor of 10 increase will be permitted as an acceptance criterion.

CSA-Pixel Structure

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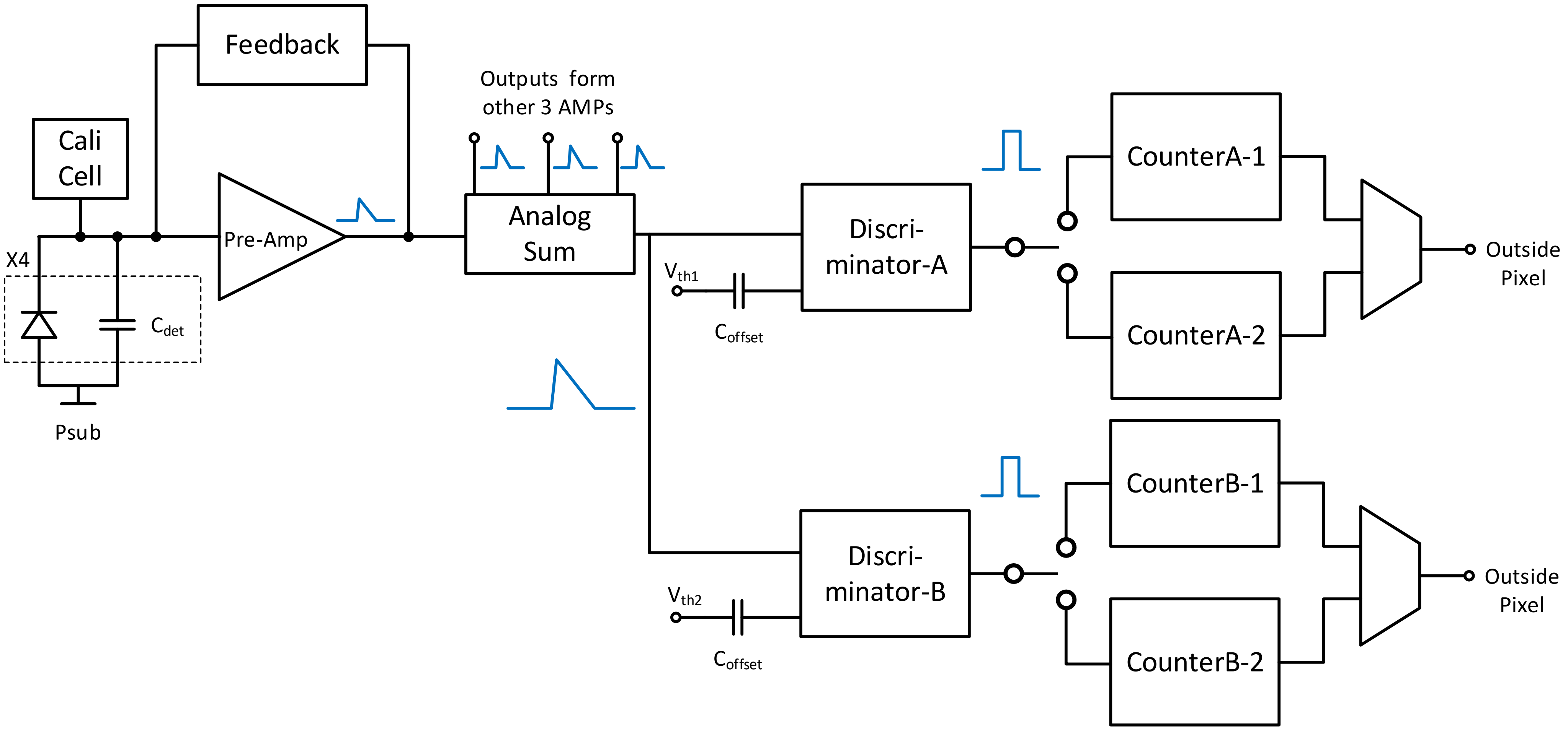
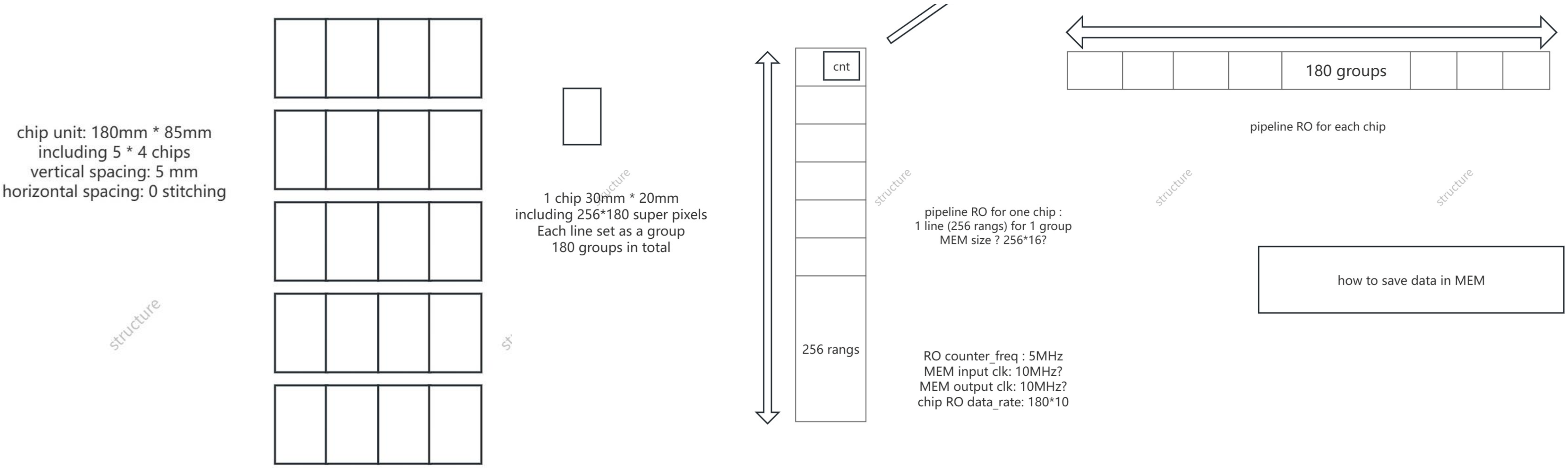


Architecture



- Frame Rate : 200Hz Count Rate : 10^5 cps/pixel(for 1 super pixel)
- Chip Size : 30 mm×20 mm   Super Pixel Numbers : 256 × 180
- Set 256 (each line) as a group, 180 groups in total
- Module size : 180 mm x 85 mm. Totally includes 5×4 chips for one module
- Main clk : ~160 MHz, Output data_rate for one module is 5~10 Gb/s

HEP: LGAD

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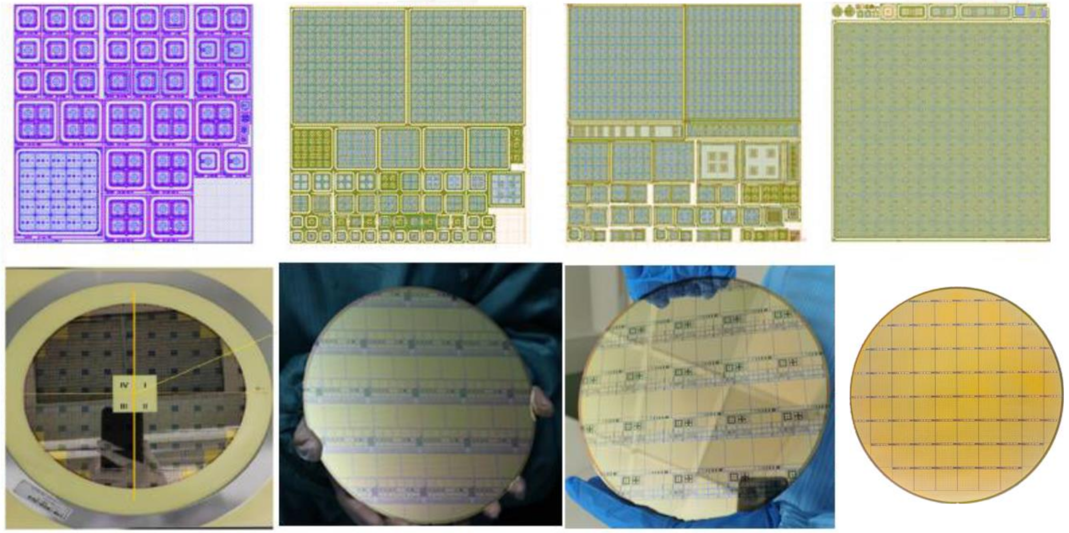
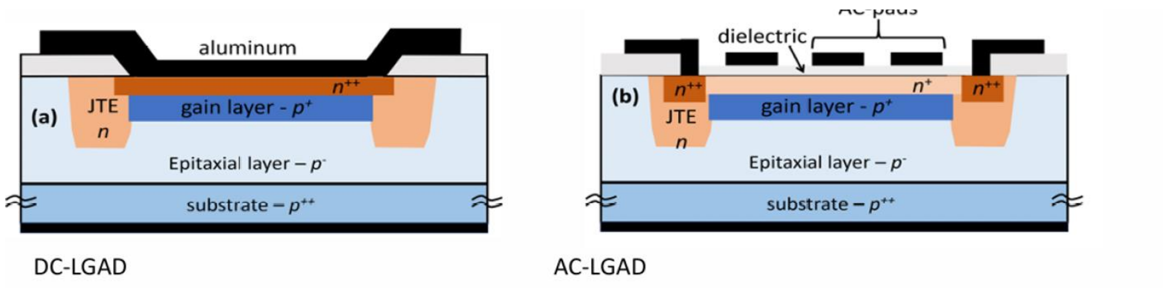
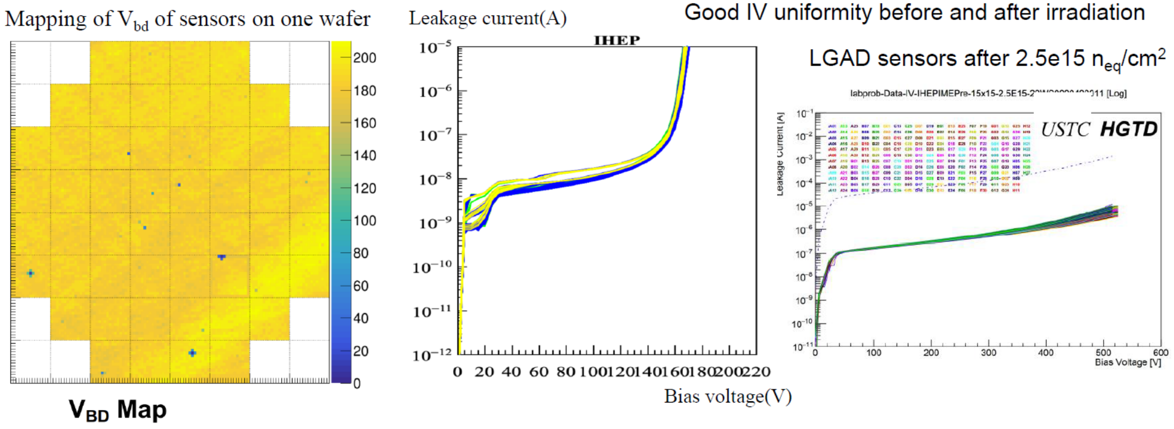
IHEP-IMEv1(2020.9) IHEP-IMEv2(2021.5) IHEP-IMEv3(2022.5) Pre-Production(2023.3)



IHEP-IME LGAD History



- Main contributor: Zhao Mei
- ATLAS HGTD: 100 % procurement share
- Breakdown voltage deviation for 225 pads is less than 5%.
- Beam Test at DESY and CERN:
  - Collected charge: more than 15 fC charge before irradiation and >4 fC charge after.
  - Timing resolution: better than 35 ps before and after irradiation.
- Performance fulfills HGTD requirement.



Good IV uniformity before and after irradiation

BPIX System Test for ITER

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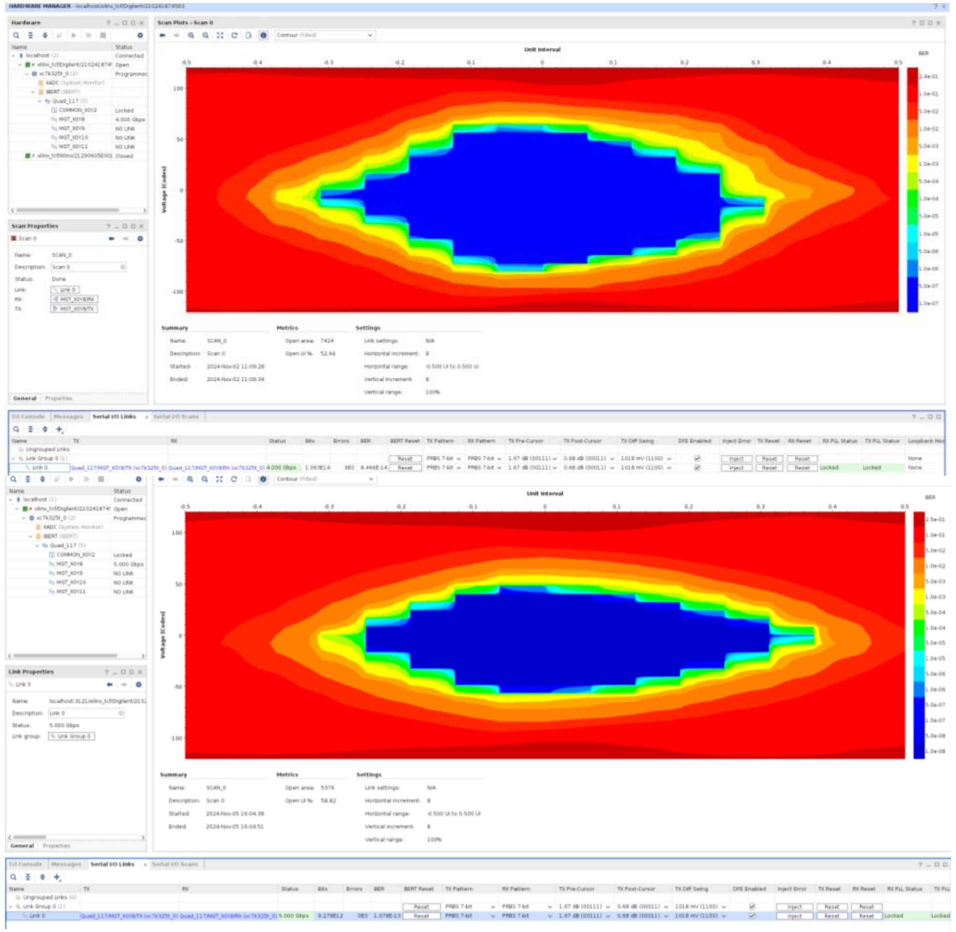

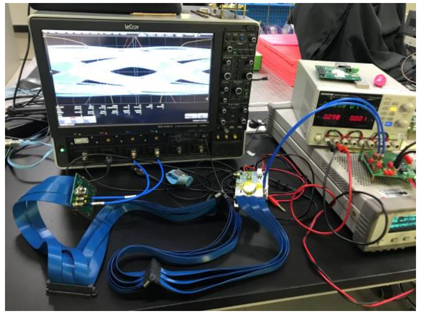

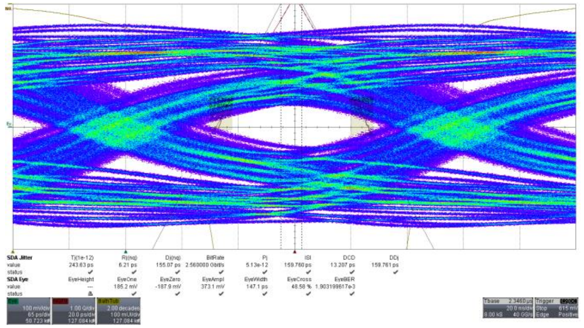

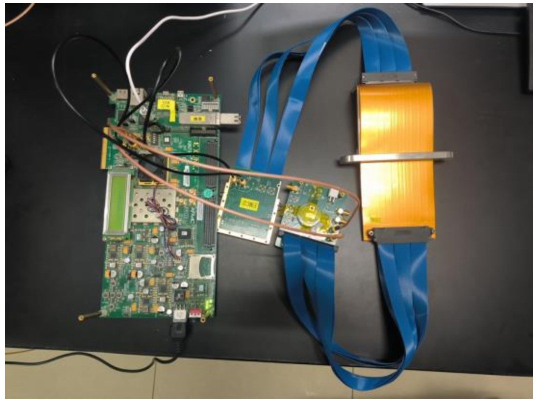

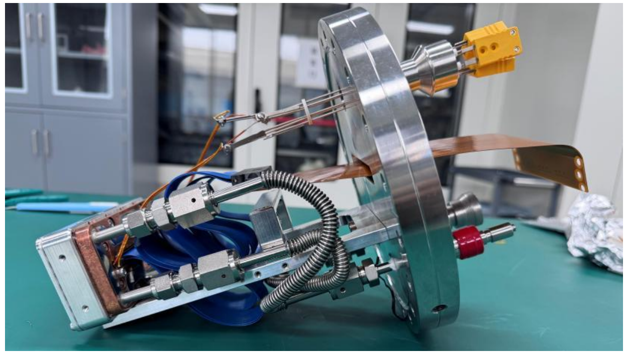

IBERT（up：4 G， down：5G)