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

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

面向ITER诊断系统的单片型X射线像素探测器设计

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Outline

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- ITER及其诊断系统简介
- XRCS探测器需求
- MAPS方案
  - CSA + Analog sum
  - ALIPIDE-like + Digital sum
- 总结

ITER and Diagnose System

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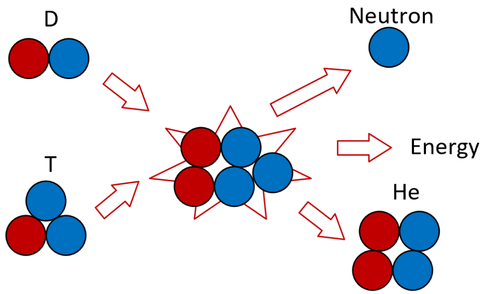
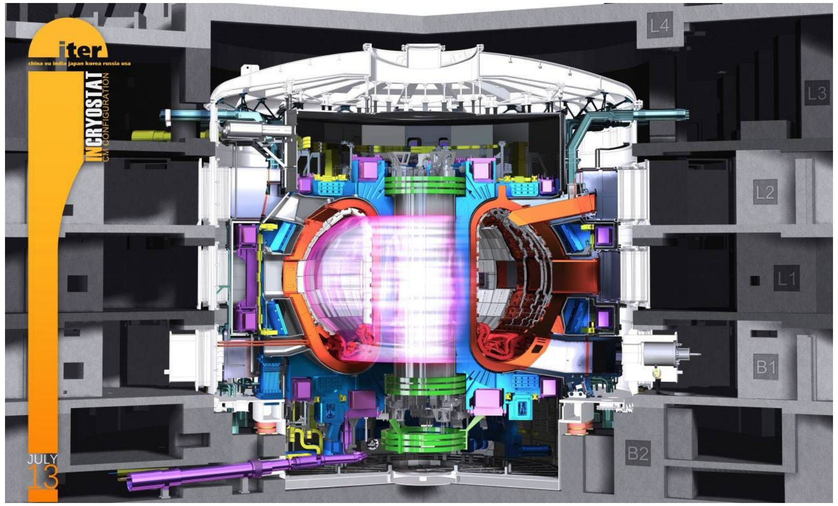
ITER: International Thermonuclear Experimental Reactor

- 7个合作方：CN, EU, IN, JA, KO, RF, US
- ITER预计启动时间： 2030-2032
- 诊断系统： “多信使” （Visible/UV/X-ray/neutron…)
- **XRCS: X-Ray Crystal Spectrometer:** 等离子体温度、旋转速度/第一壁材料



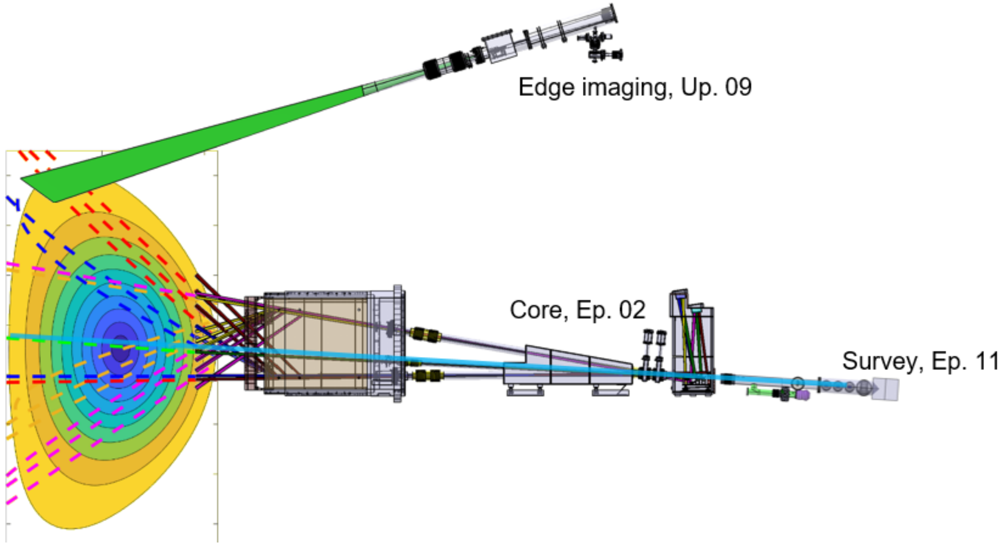
D-T聚变过程

ITER Location



ITER真空腔室

ITER XRCS像素探测器需求



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

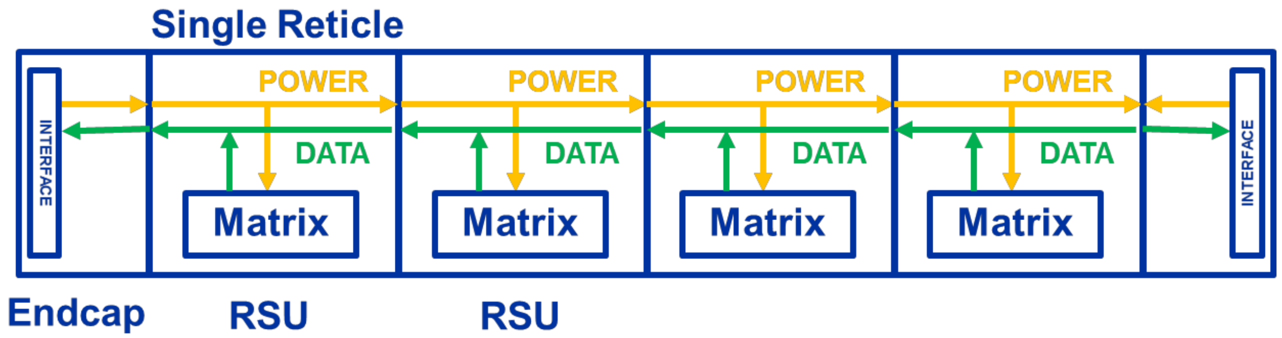
- XRCS系统：Core/Edge/Survey：探测能量不同
  - Core & Edge：3keV单光子分辨
- 探测器面板中子流强：10^6/s·cm^2
  - 前后端分离
- 面板尺寸：180mm × 85mm
  - 水平方向死区：8 %
  - 垂直方向死区：5 mm
- 真空度： UHV (10^{-5}~10^{-6} pa)
- 磁场：0.2 T
- 实时控制延迟：<10ms
- 最高计数率：10^7 counts/s/mm^2

子系统	XRCS Core	XRCS Survey	XRCS Edge
波长范围 (Å)	2.555 (4.852keV) 2.189 (5.663keV) 1.354 (9.156keV)	1-100 (0.12keV - 12keV)	3.97 (3.12keV) 3.73 (3.32keV)

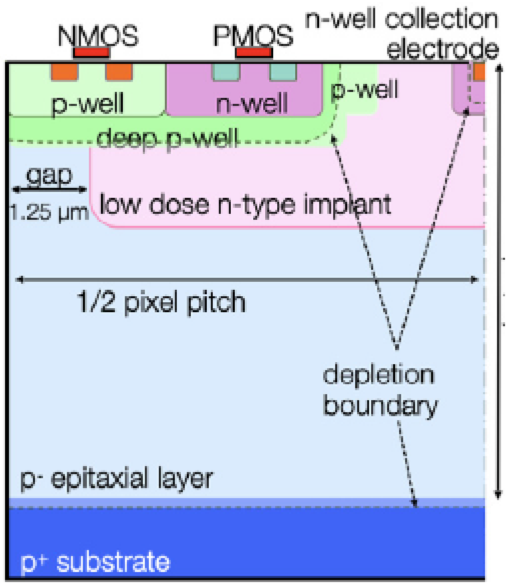
Ref: Zhifeng Cheng, ITER Spectroscopic Diagnostics and Atomic Data Needs,2023 Vienna

整体方案

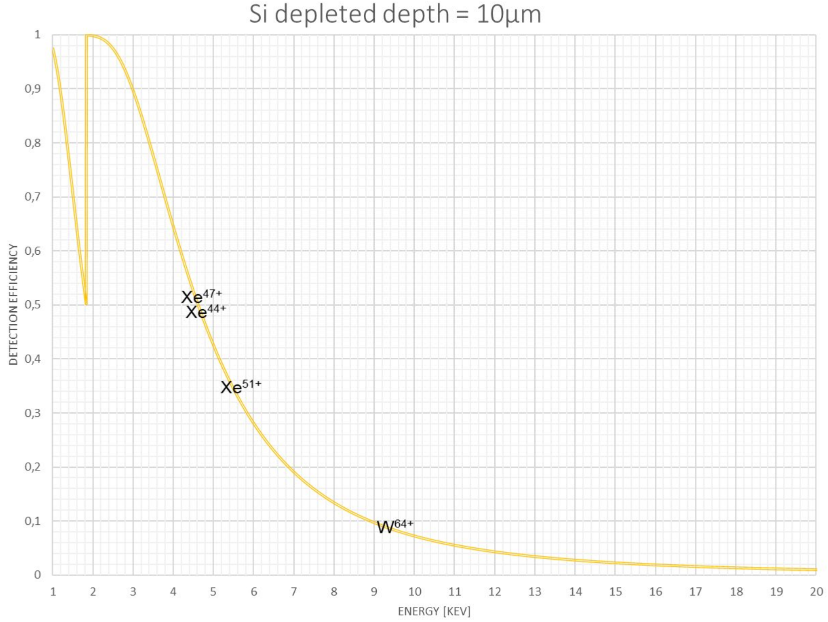
- 3keV单光子分辨
  - MAPS+光子计数方案，CIS 65nm
  - C_{in}<1fF/diode
  - 能量阈值：1.5keV->ENC<40e-
  - Cons: 外延层厚度仅10μm
- 低死区大面积探头
  - Stitching
- 像素尺寸: 100μm×100μm
  - 物理像素尺寸：25μm×25μm
  - 单像素对应：16 diodes
- 高中子通量
  - 双阈值，排除中子造成误计数
- 实时控制延时<10ms
  - 帧刷新率>100Hz -> 200Hz
  - 双计数器/像素，ping-pang



Stitching结构示意图

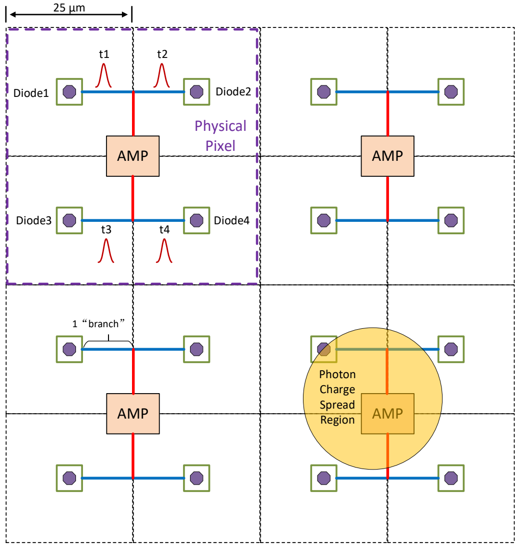


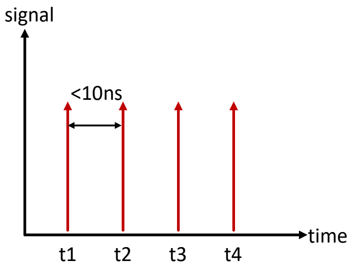
65nmCIS工艺剖面图



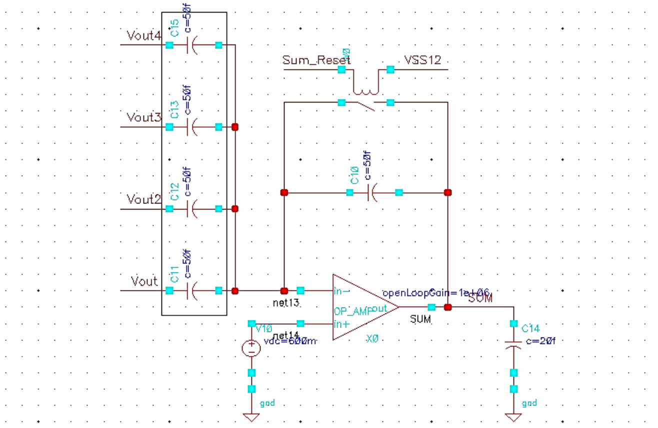
10μm外延层光子吸收效率

CSA前端+Analog Sum

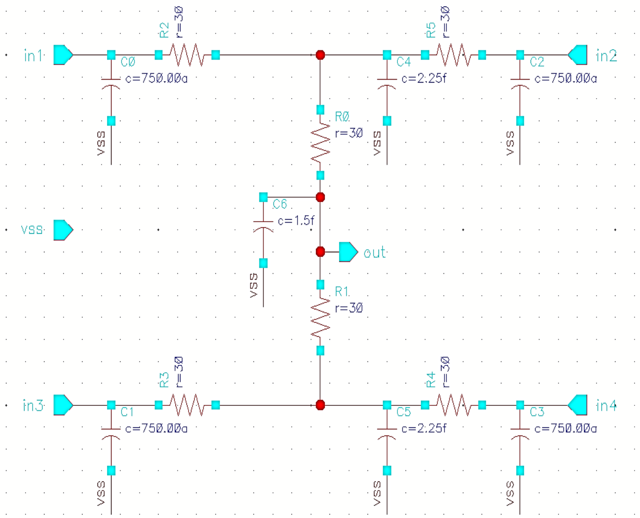




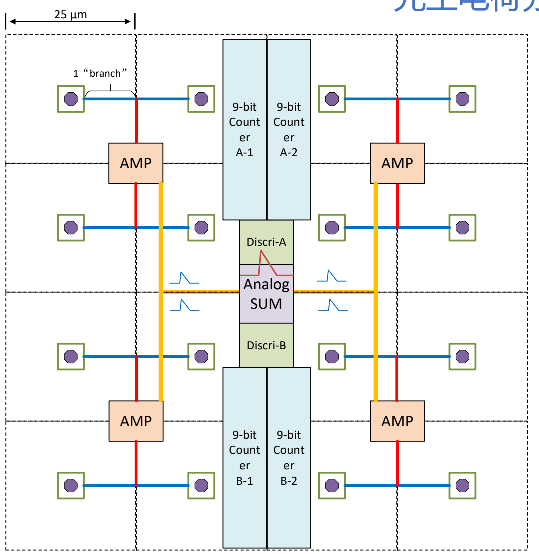
光生电荷分布



模拟求和电路



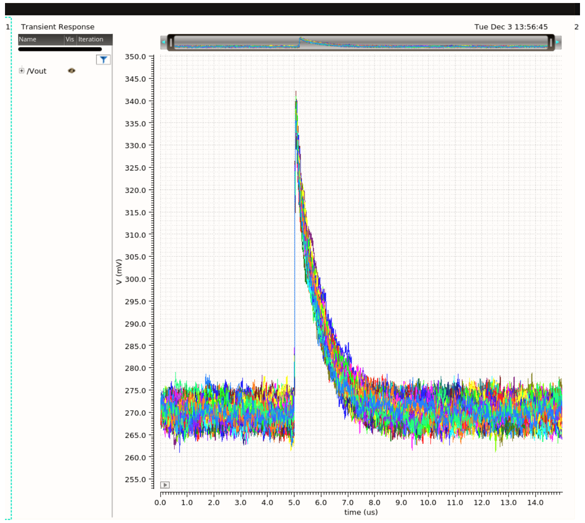
CSA输入节点阻容网络



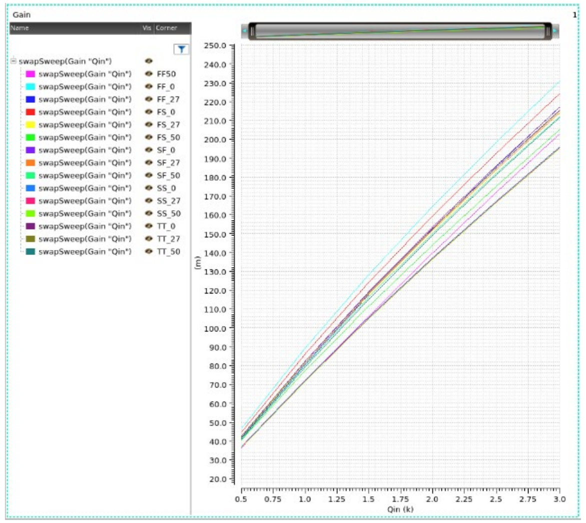
模拟求和方案

- 经典Krum反馈CSA
  - 4 diodes/CSA，对输入节点走线进行参数提取和建模
- 双阈值设计，电容采样去offset
  - 考虑计数率，单计数器计数深度9-bits
  - 4 counters/pixel
- 电荷到达4个diode的时间差以最大间隔10ns考虑（较极端）
- 功耗：~7.5uW

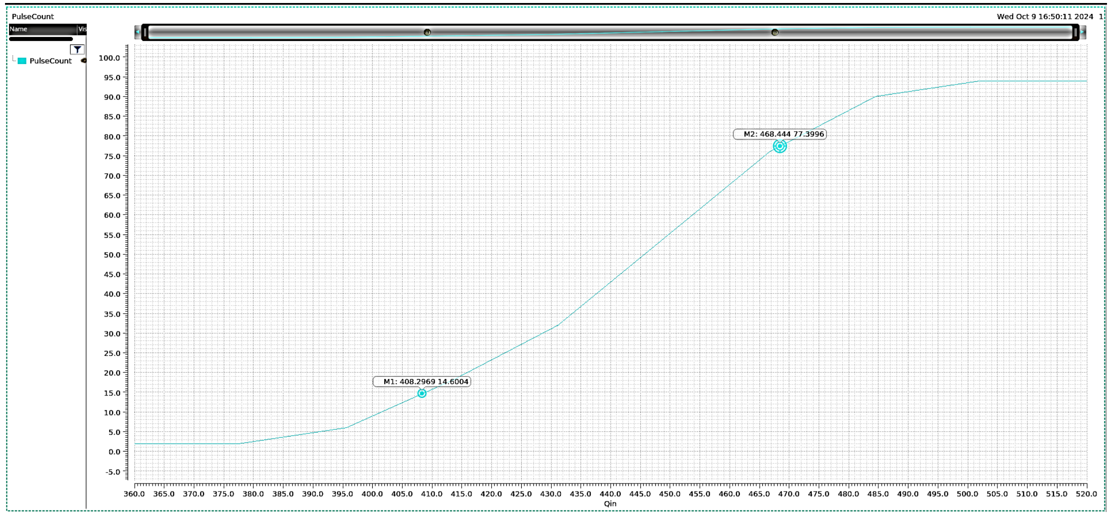
CSA前端+Analog Sum



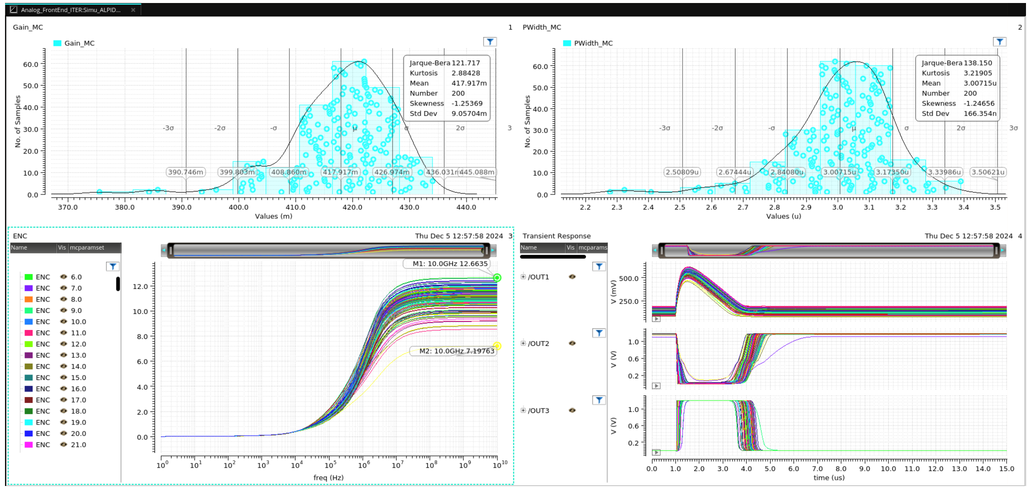
Qin=800e-瞬态噪声仿真



Qin=800e-~3000e-能量线性仿真



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

增益、噪声仿真结果

ALPIDE-like前端+Digital Sum

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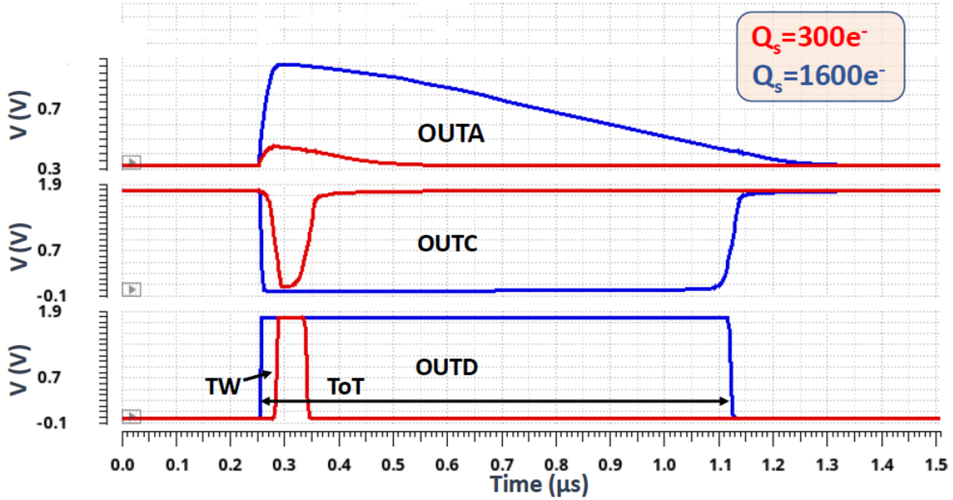
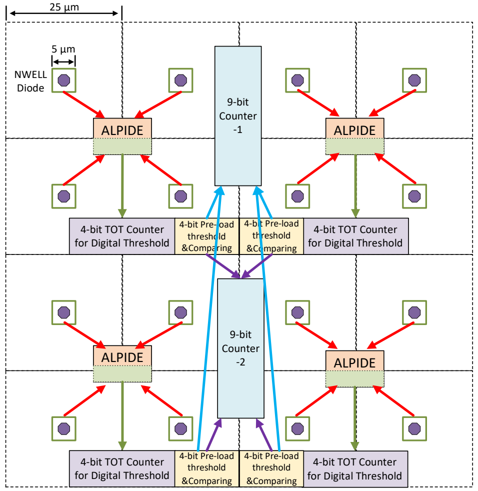
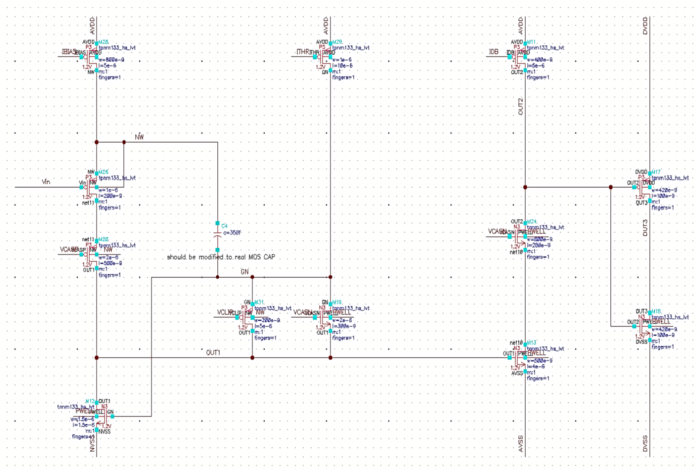


ALPDE-like(TJ-Monopix1)TOT特性

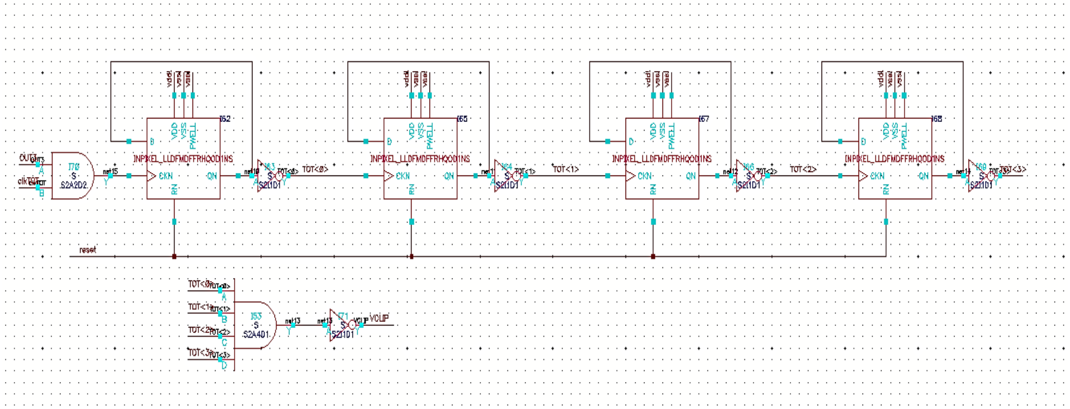
Ref: Konstantinos Moustakas, PHD thesis, 2021



Digital Sum结构



前端电路结构



大电荷注入Clip判决逻辑

- CSA结构难以发挥MAPS输入电容低的优势
- ALPIDE-like前端
  - 噪声低，结构紧凑
- 如何实现双阈值?
  - ALPIDE电荷阈值作为低阈值
  - 利用TOT特性实现高阈值（数字阈值）
  - 通过合适的计数深度和时钟可设定不同的阈值

ALPIDE-like前端+Digital Sum

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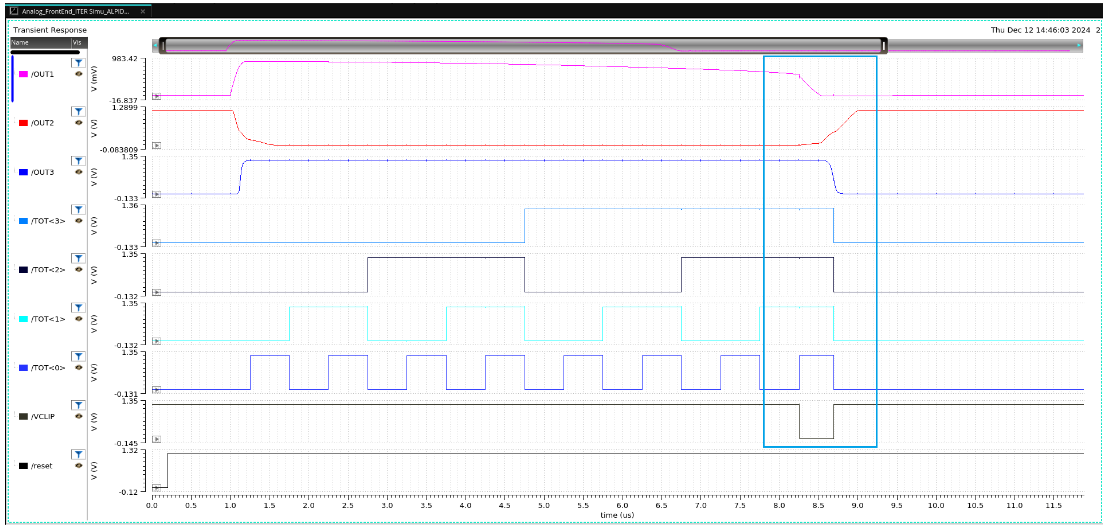
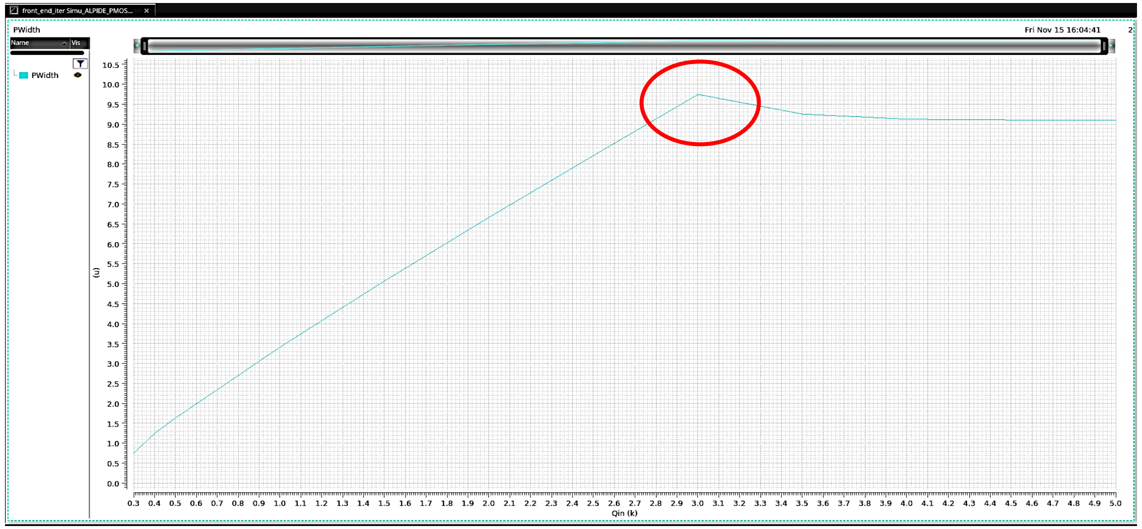
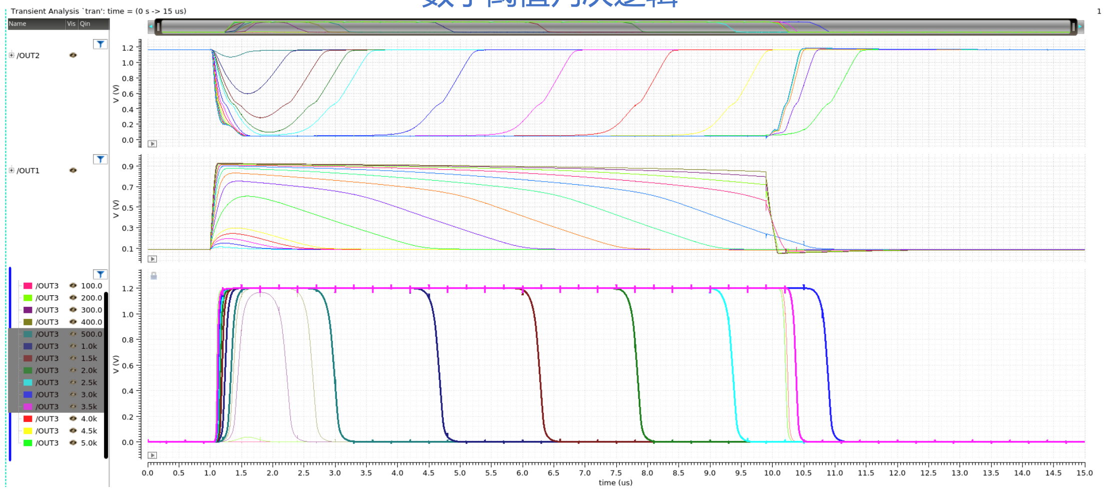


数字阈值判决逻辑



Qin-TOT曲线(300e-~5ke-)



Qin 800e-~3000e-瞬态仿真波形

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

- 功耗：~7μW 低阈值：~200e-（可调）
- ENC Monte Carlo (Qin=800 e-):
  - maximum: 12.66 e-
  - minimum: 7.20 e-

总结

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- ITER XRCS诊断系统是ITER诊断系统的重要组成部分，其对像素探测器的主要需求为:
  - 3keV能量下的单光子分辨
  - 中子击中的排除
- 本研究给出了两种可行的像素组织方案：
  - CSA前端 + analog sum方案, ENC<32e-
  - ALPIDE-Like 前端 + digital sum方案实现了数字阈值，ENC<13e-