ATLAS EXPERIMENT

STREAM

Radiationhard monolithic CMOS sensors with small electrodes for HL-LHC

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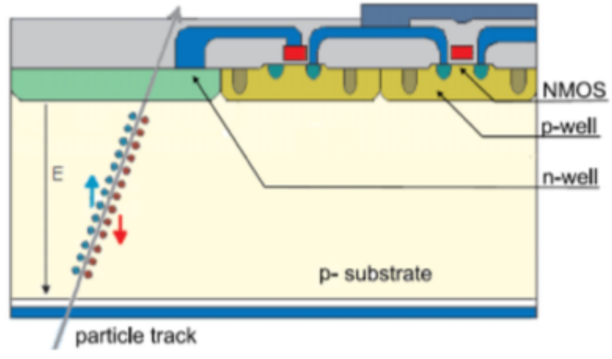
Monolithic Silicon Pixel Detectors

Depleted Monolithic Active Pixel Sensors for ATLAS



- **Thin detector with high granularity**
- **Low cost** cf hybrid pixel due to large-scale CMOS production without bump-bonding
- Allows very thin sensors to achieve ultimate **low mass trackers** (0.3% X/X_0)

MAPS in HEP & Heavy Ion Physics:

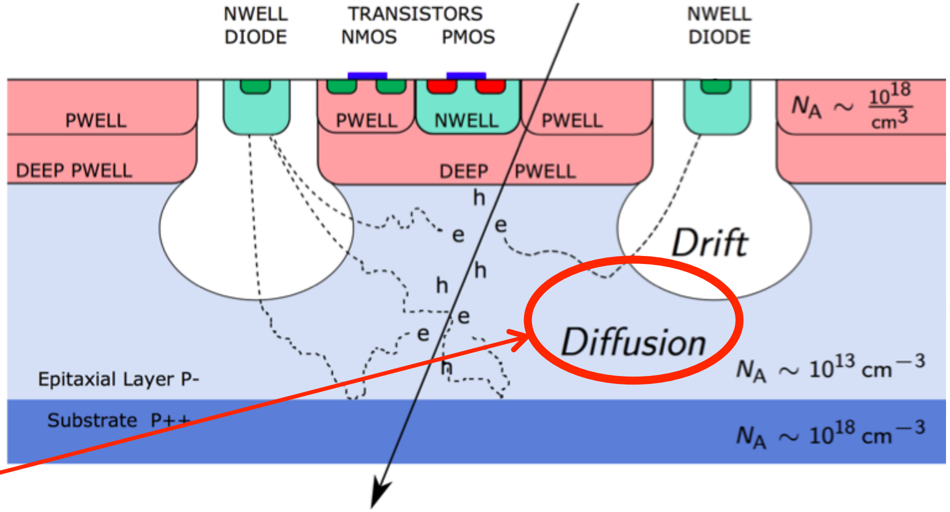
- E.g. STAR HFT, ALICE ITS ALPIDE chip from TJ 180 nm to be installed during ALICE tracker upgrade in LS2
- Typically collect charge via diffusion, but need depletion to go above 1e13 n_{eq}/cm^2

For ATLAS ITk L4: Rad hardness: NIEL 1e15 n_{eq}/cm^2, TID >80 MRad & Hit rate > 100 Mhz/cm^2 based on original specs for ITK outermost pixel layer

- **Innermost layers: CMOS** interesting option for future upgrades (>LS3) for biggest physics gain: small pixel (~25μm) & thin (~50μm?) - tough specifications will require strong R&D

Towards radiation hard MAPS…

…there **were** several obstacles to overcome:



Depletion is key:

- At high radiation levels (>10^{16} n_{eq}/cm^2) the ionization charge is trapped in the non-depleted part
- Diffusion makes signal collection slower than typical requirements for pp-colliders for pixel pitches around typical 50μm

Readout architectures are low power but not designed for high hit-rates of pp experiments at LHC or future pp colliders

ATLAS CMOS Pixel Collaboration

- Collaboration of ~25 institutions

universitätbonn
UNIVERSITY OF CALIFORNIA SANTA CRUZ
Yale University
SLAC NATIONAL ACCELERATOR LABORATORY
UNIVERSITY OF LIVERPOOL
University of Tsukuba 筑波大学

BROOKHAVEN NATIONAL LABORATORY
University of Glasgow
Institut "Jožef Stefan" Ljubljana, Slovenija
Lancaster University
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UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES
BERGISCHE UNIVERSITÄT WUPPERTAL
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
INFN Istituto Nazionale di Fisica Nucleare

KIT Karlsruher Institut für Technologie
IFAE
Argonne NATIONAL LABORATORY
CERN

UNIVERSITÄT BERN
AEC ALBERT EINSTEIN CENTER FOR FUNDAMENTAL PHYSICS
UNIVERSITY OF OXFORD
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

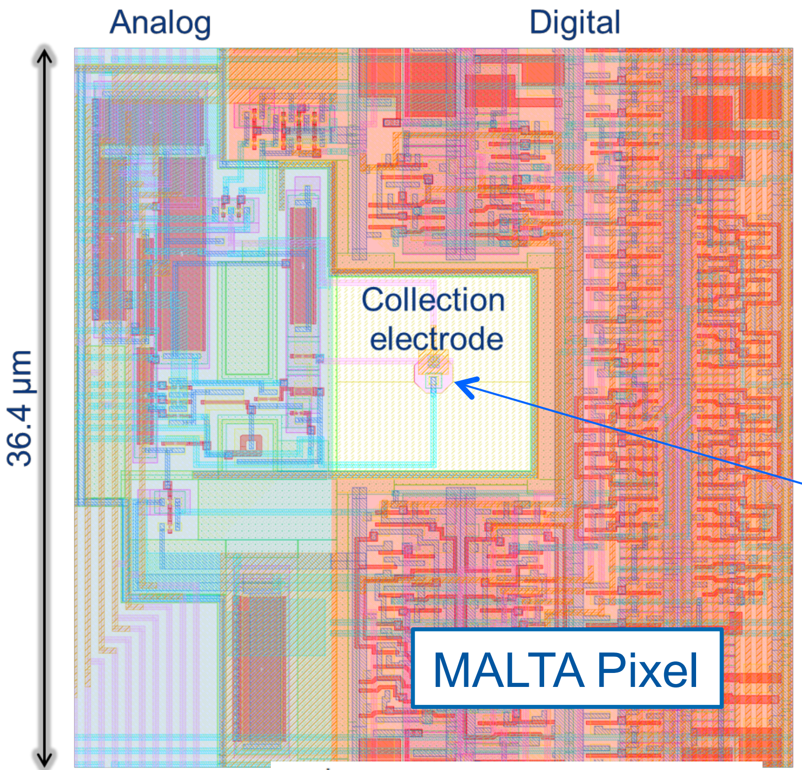
For ATLAS Prototypes from LFoundry 150 nm, AMS 180 nm, and Tower Jazz 180 nm designed for ATLAS radiation specifications

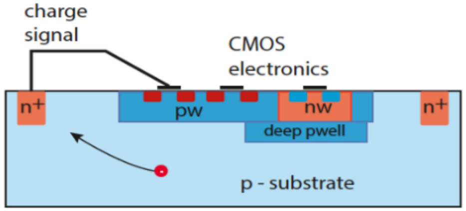
The STREAM Project

- The STREAM Project is the Marie Skłodowska Curie **Innovative Training Network for CMOS Sensor Development** in the context of LHC experiments and for selected industrial applications
- The STREAM research and training program focuses on the development of **radiation hard CMOS sensor technologies** for innovative scientific and industrial instruments.
- STREAM offers **17 fellowships for the Early-stage researchers** to participate in the design and test of novel radiation hard CMOS sensors
- Parts of the ATLAS CMOS RD on CMOS sensors are supported through the STREAM MC fellows
- **STREAM Website:** http://stream.web.cern.ch/

Small electrode designs

- Small electrode design allows for **small pixel size, low capacitance and low power** but require **special measures for full radiation hardness**

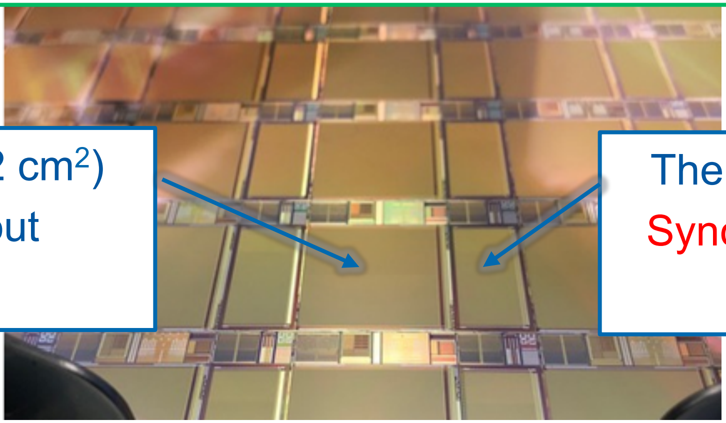




- Electrode separated from circuitry
  - No analog-digital cross-talk
  - Smaller pixels
- Allows for **small pixels** and **high spatial resolution** (<50x50μm^2)
- **Small diameter electrode** (3μm diameters) to achieve **minimal capacitance** (<3fF)
- **Low power** due to low capacitance: bias current 500nA/pixel or <70mW/cm^2

MALTA & MonoPix – Depleted CMOS sensors with small electrodes

Design of two large scale demonstrators to match ATLAS specifications for outer pixel layers



The "MALTA" chip (2 x 2 cm^2)

Asynchronous readout architecture

The "TJ-Monopix" chip (2 x 1 cm^2)

Synchronous readout architecture.

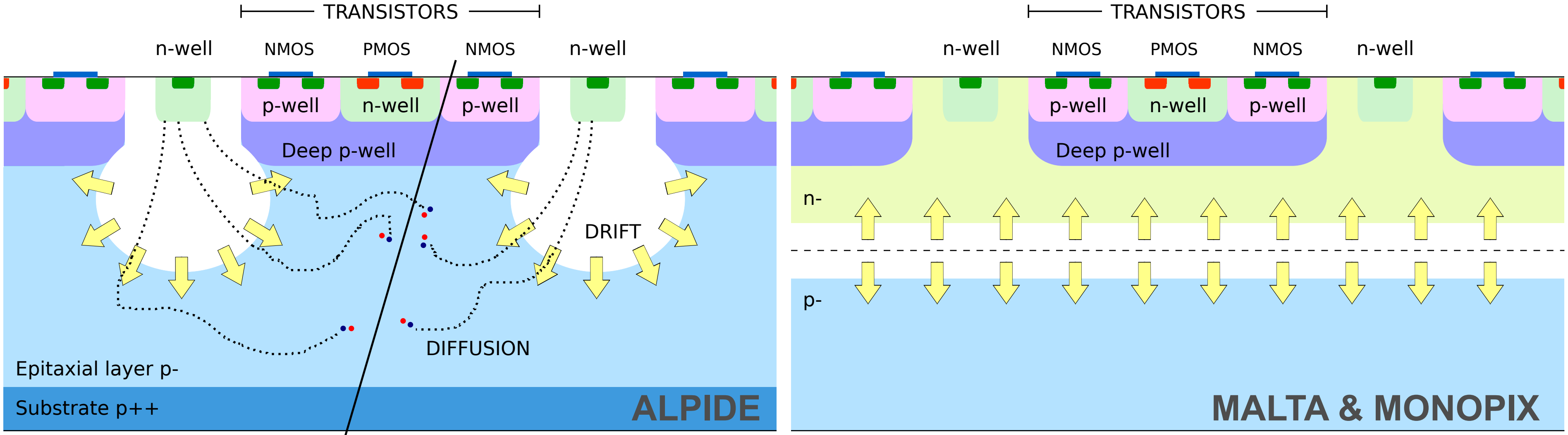
See poster L. Flores, P. Riedler

See talk C. Bespin

- **The ATLAS "MALTA" and "MonoPix" chips** for **high hit rate suitable for HL-LHC pp-collisions**
  - **Radiation hard to >10^{15} n/cm^2 & Shaping time 25ns** (BC = 25ns)
  - **MALTA: Asynchronous readout** architecture for high hit rates and fast signal response
  - **MonoPix: Synchronous Column drain** readout architecture with ToT measurement

Novel CMOS Depleted MAPS with small electrodes

- Small collection electrode (few um²)
- **Small input capacitance (<3fF) allows for fast & low-noise Front-end (ENC<10e⁻)**
- High S/N for a depletion depth of >20um
- To ensure full lateral depletion, uniform n-implant in the epi layer (modified process with inital tests on Alice Investigator, then ATLAS MALTA, MiniMALTA, MonoPIX)



TJ180nm Standard Process

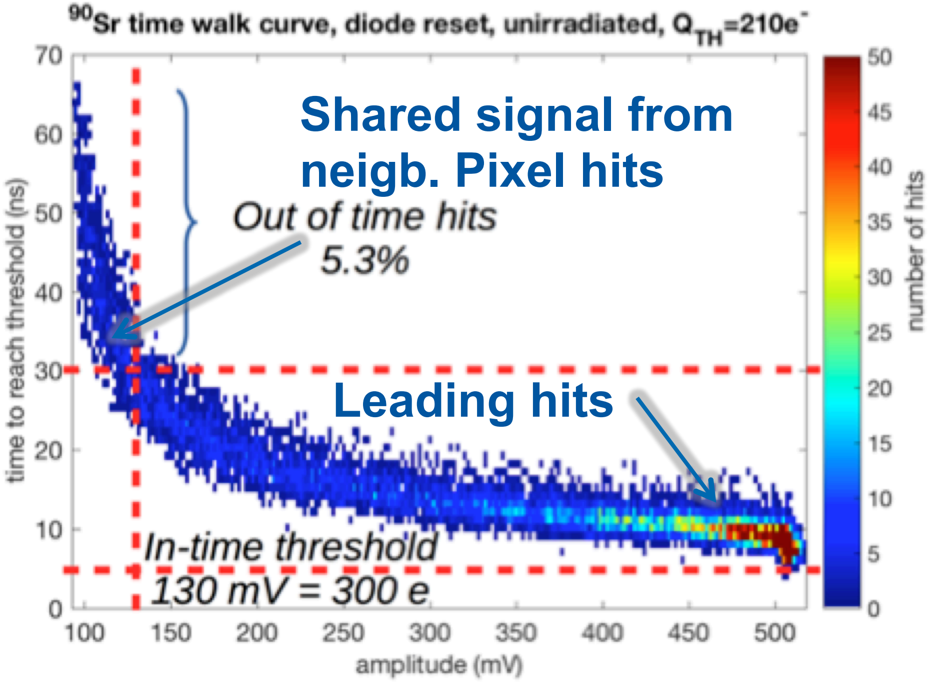
TJ180nm Modified Process

W. Snoeys et al. DOI 10.1016/j.nima.2017.07.046

H. Pernegger et al 2017 JINST 12 P06008

MALTA after irradiation

- Good analog performance for ENC and timing
- But not sufficient efficiency after $10^{15} n_{eq}/cm^2$



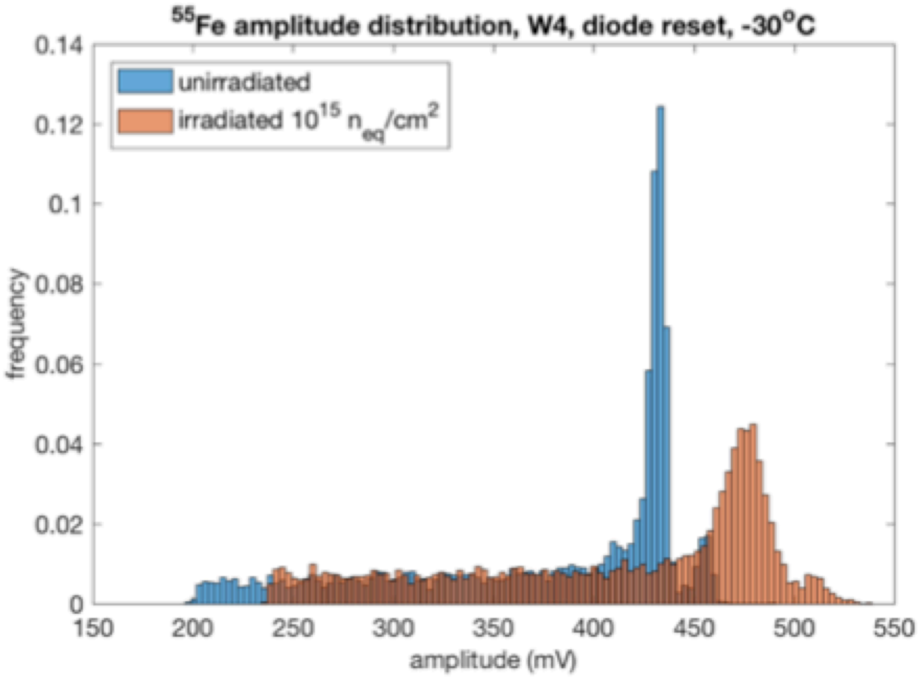
^{90}Sr time walk curve, diode reset, unirradiated, Q_{TH}=210e$^-$

Shared signal from neigb. Pixel hits

Out of time hits 5.3%

Leading hits

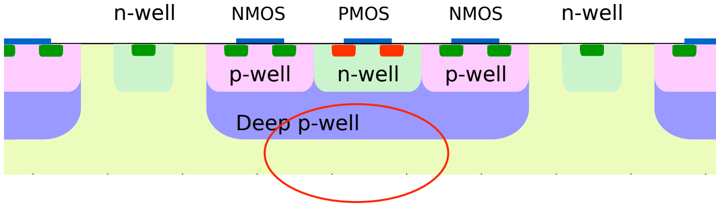
In-time threshold 130 mV = 300 e



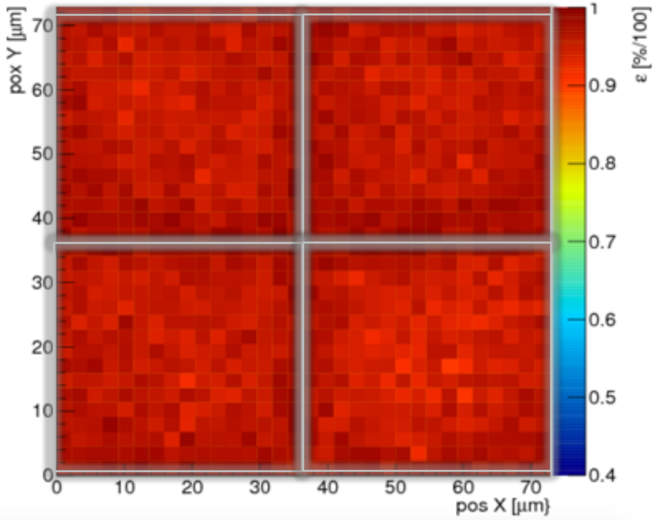
^{55}Fe amplitude distribution, W4, diode reset, -30°C

Efficiency with small electrodes

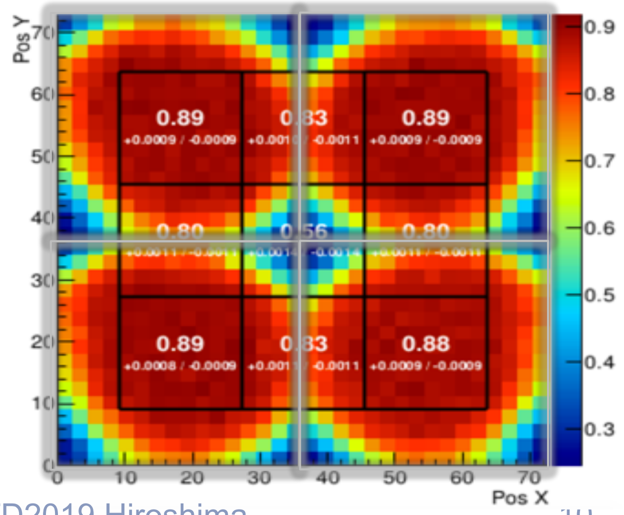
- Due to small collection electrode, the field configuration and charge collection under DPW in pixel corner is critical
  - Require full depletion under the DPW
  - Operating at low threshold is essential
  - Transversal field components in corner is needed for radiation hardness



Unirradiated @ 250e- threshold
2x2 pixel at 36μm pitch



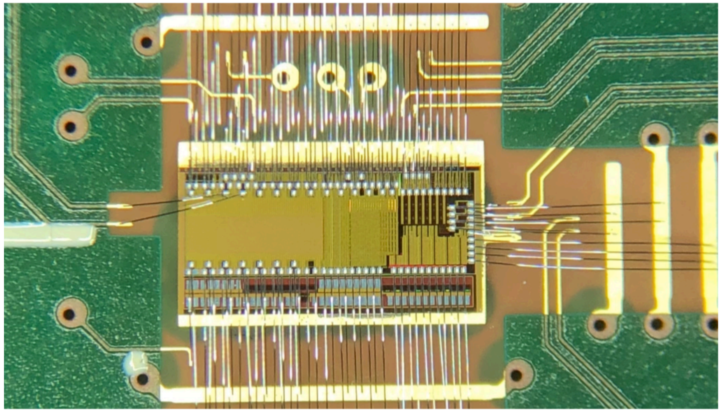
Irradiated 10^{15}n/cm^2 @ 350e- threshold
2x2 pixel at 36μm pitch

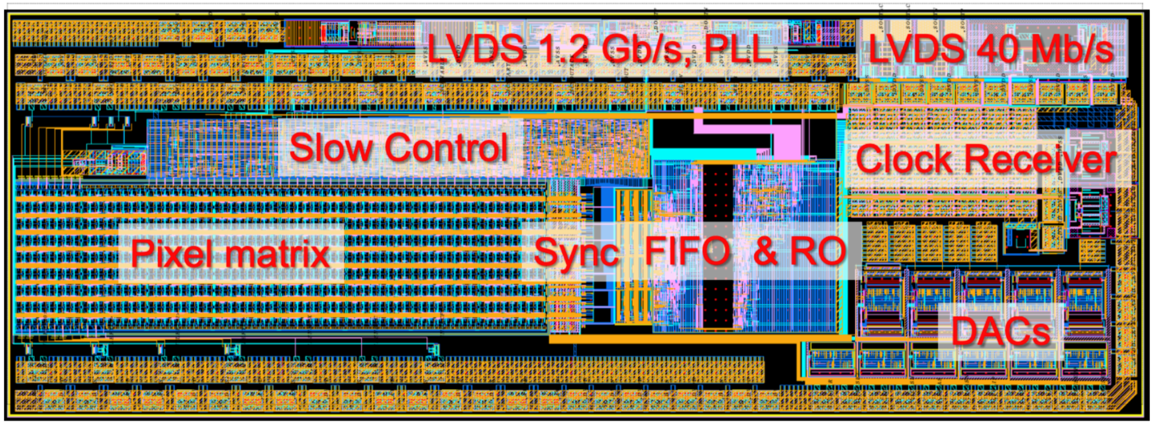


The MiniMALTA sensor

- MPW/TJ180nm run in 2019 to prototype further improvements in implant structure and front-end

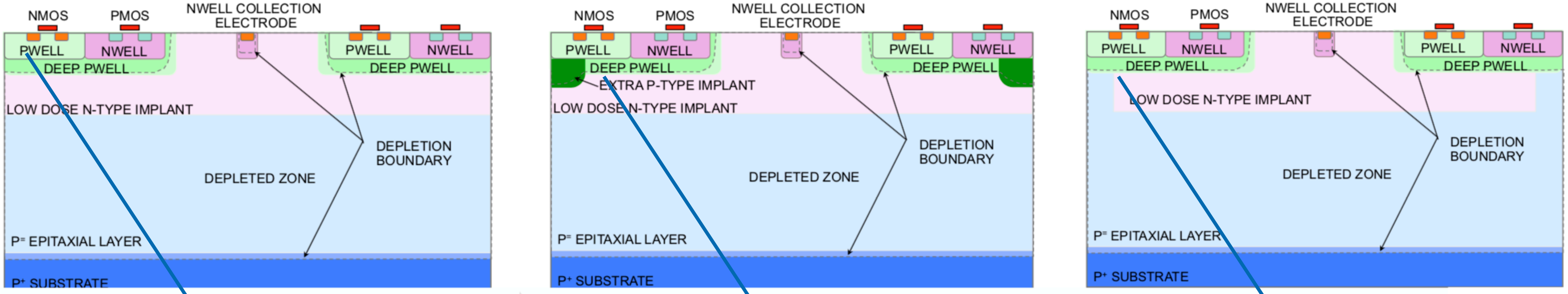
- Matrix with 64x16 pixels in 8 sectors
- 36.4μm pixel pitch
- Asynchronous column design (MALTA)
- synchronization memory at EoC (end-of-coulmn) to synchronize with 320/640Mhz clk





Optimization for radiation hardness The MiniMALTA sensor

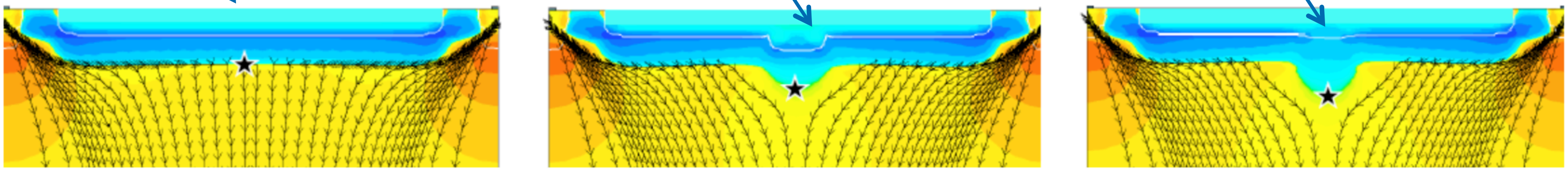
- Special layouts for deep p and n wells to optimize field configuration and charge collection
- Increase lateral field near pixel edge to “focus” charge to electrode
- Also can improve time-resolution and charge sharing (see poster by T. Kugathasan on FastPix & presentation by M. Munker on CLIC)



Modified process:

Modified process with additional p-implant:

Modified process with gap in n-layer:



M. Munker PIXEL 2018 / 10.1088/1748-0221/14/05/C05013

Common development with CLICTD (presentation M. Munker)

Optimized Front-End

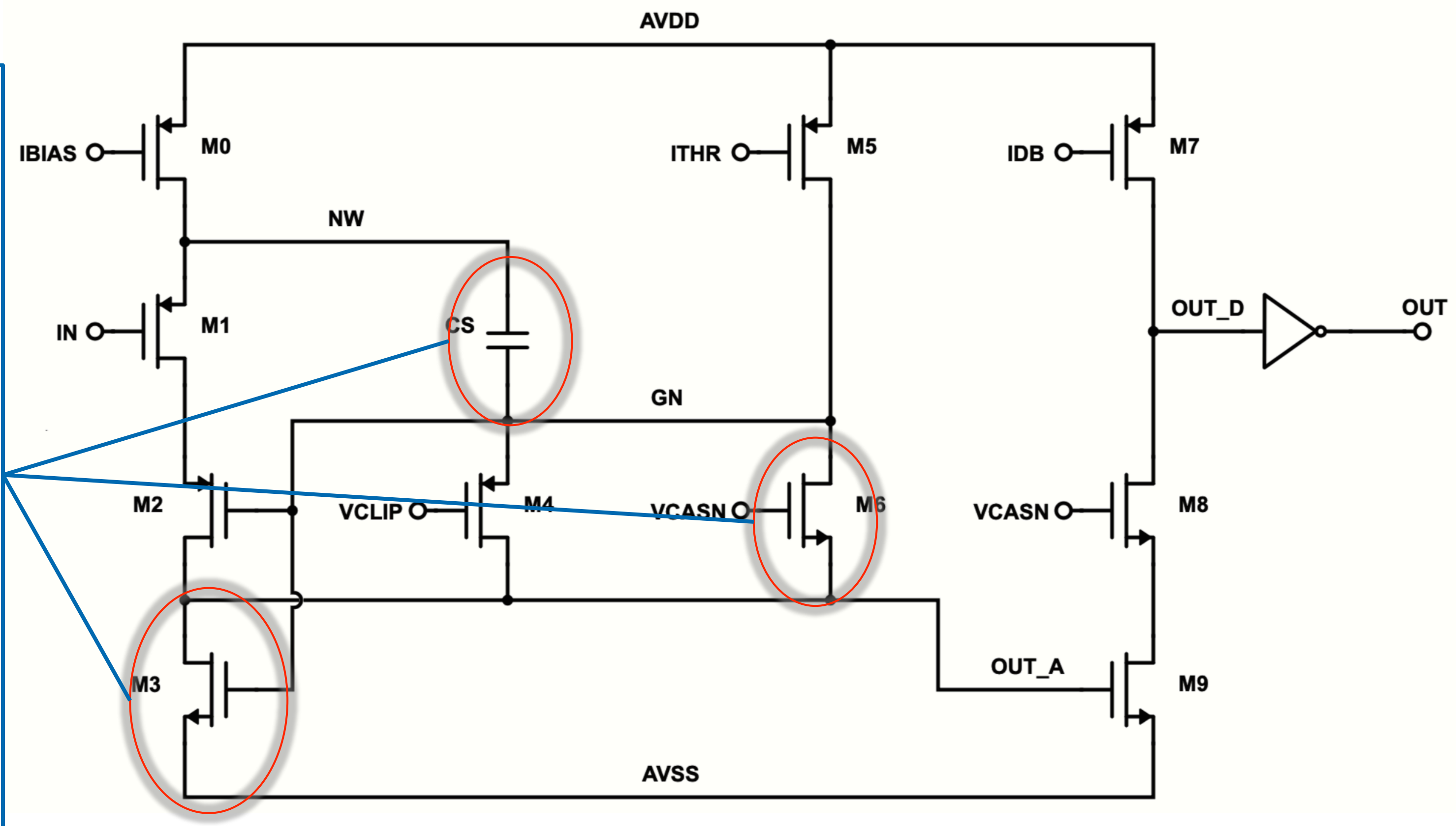
- MALTA/MonoPix Front-End improvements prototyped in MiniMALTA to increase gain and reduce noise

Increased C_s & Transistor sizes:

Increased gain

Reduce ENC noise & threshold dispersion

Reduce RTS noise (observed in MALTA and MonoPix)



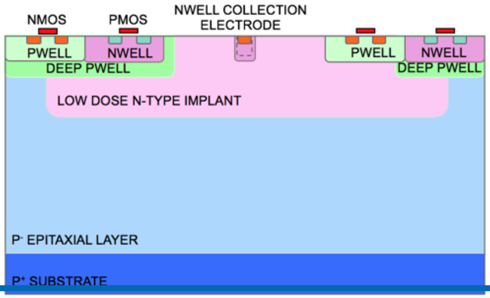
Malta & MonoPix Front-end design

The MiniMALTA Sensor – improved radiation hardness

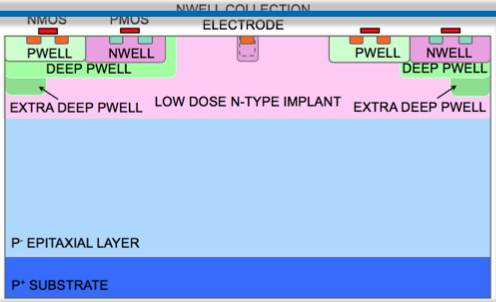
64x16 pixels in 8 sectors to investigate **different implant structures** and **FE transistors**

M. Dyndal et al., arXiv:1909.11987

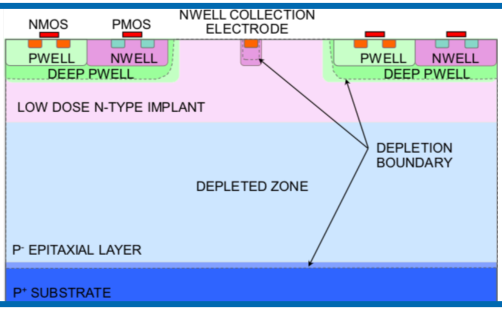
Modified Process with gap in n- layer

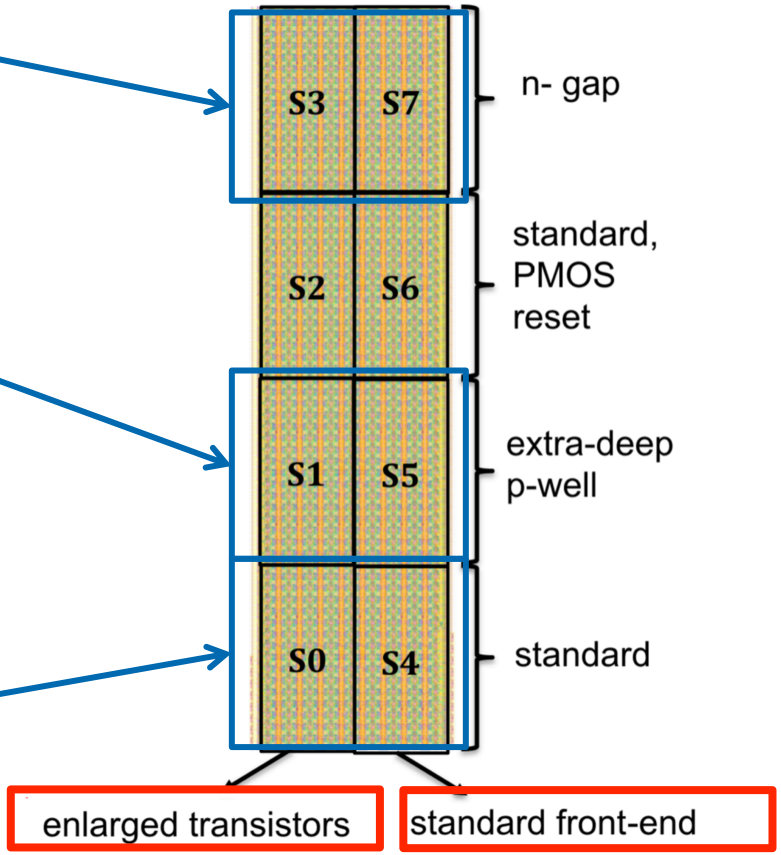


Modified Process plus additional DPW



Modified Process

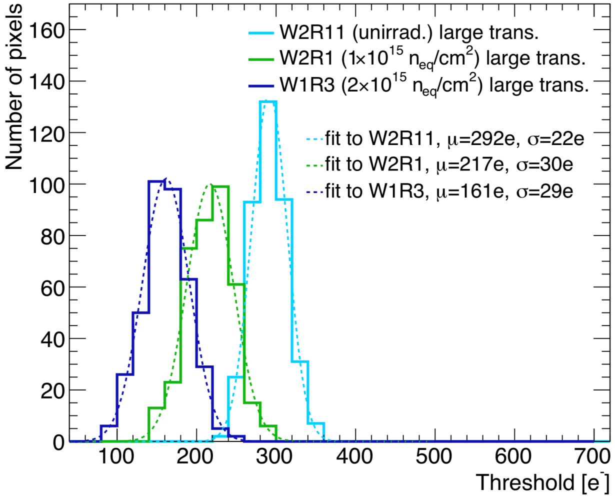


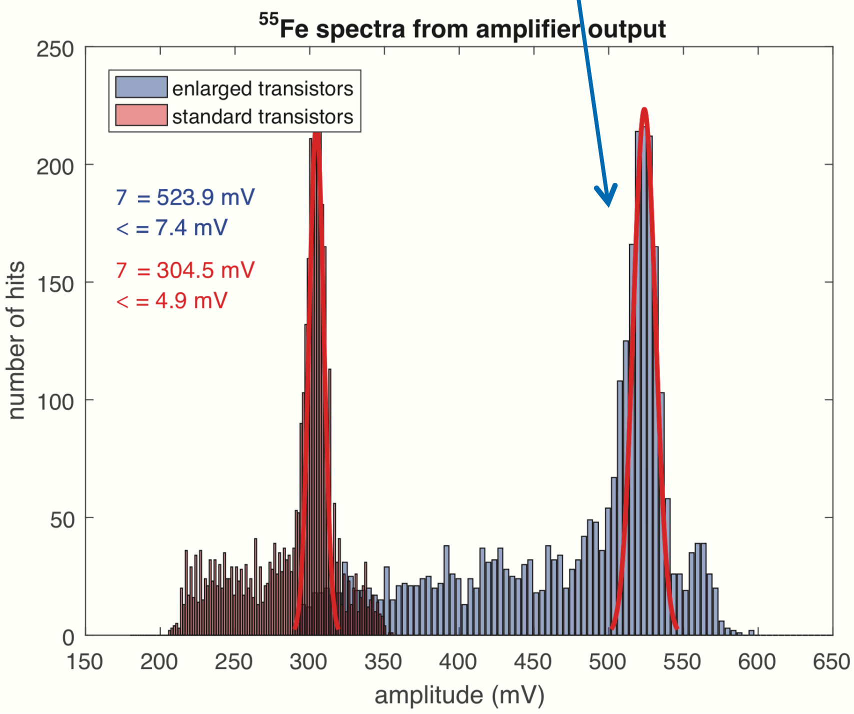


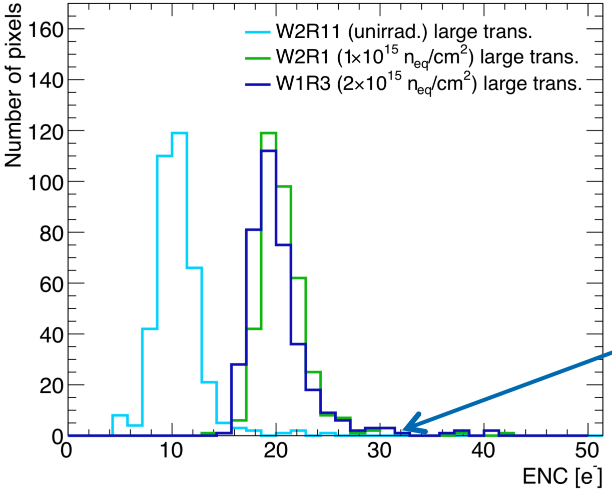
MiniMALTA analog

Threshold reduced by factor ~x2 over original front-end design (300e- to 570e- at same setting) .
Threshold **dispersion** was 30-50e- now **22-30e-**

Gain increased by factor 1.7



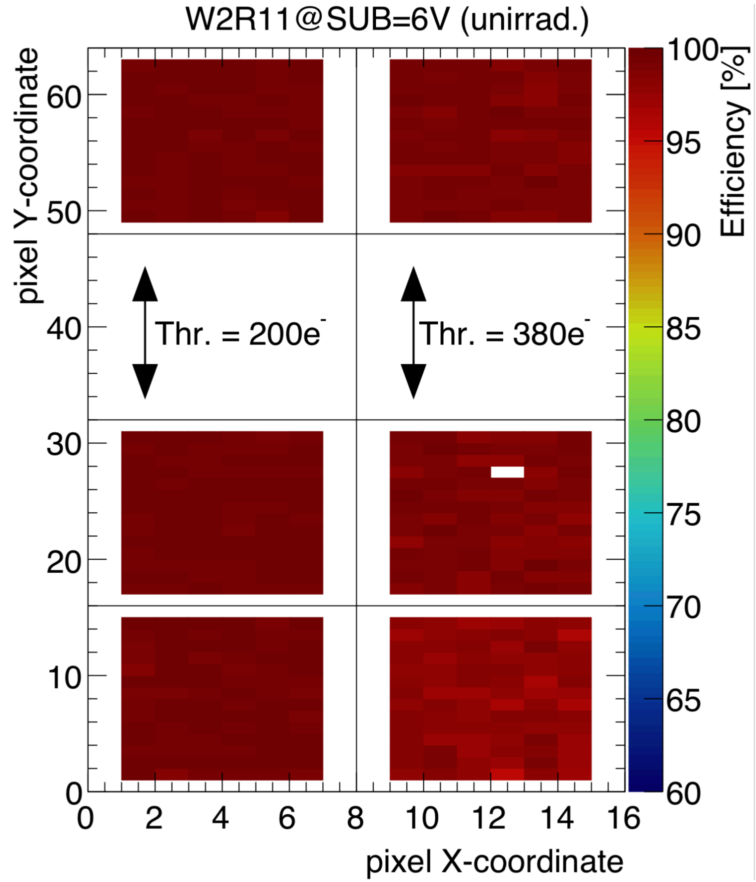




ENC noise similar mean (10e- pre-irrad, 20e- after irradiation) but substantially less RTS noise

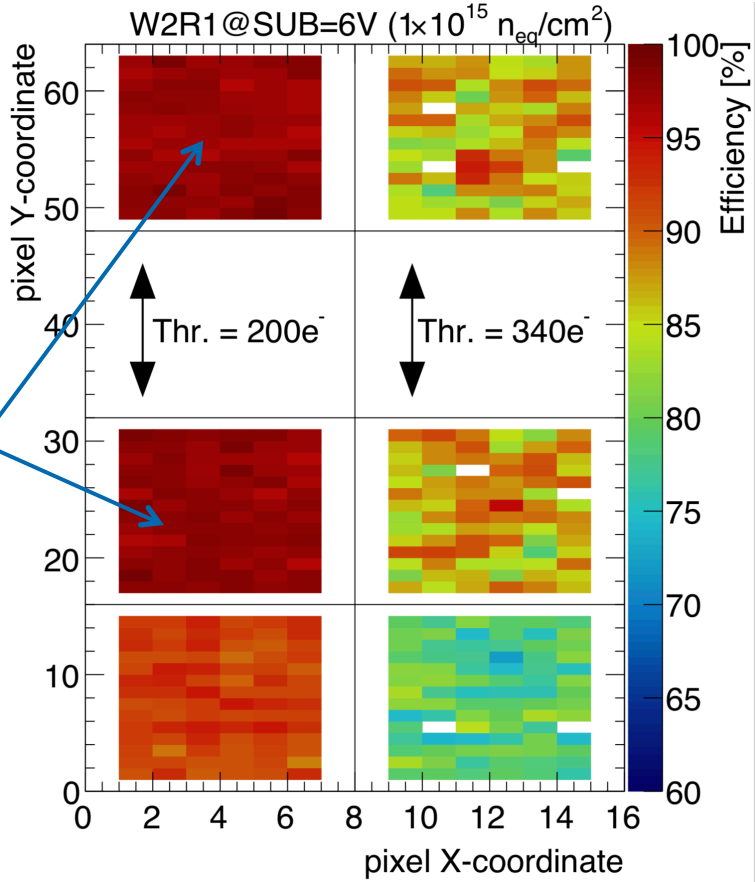
Efficiency before/after 10^{15} n_{eq}/cm^2 irradiation

Beam test results show that **>98% efficiency is reached after 10^{15} n_{eq}/cm^2** through the combination of FE improvement and charge collection improvement in pixel corners on high resistivity epitaxial p-type substrate (25-30μm)



MiniMALTA
TJ180nm
$36x36\mu m^2$

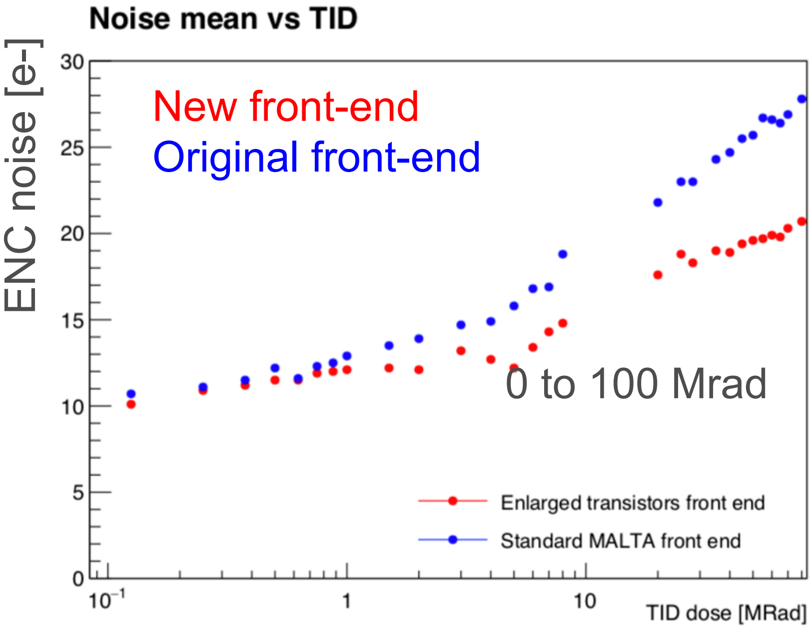
98% efficiency after 10^{15} n_{eq}/cm^2

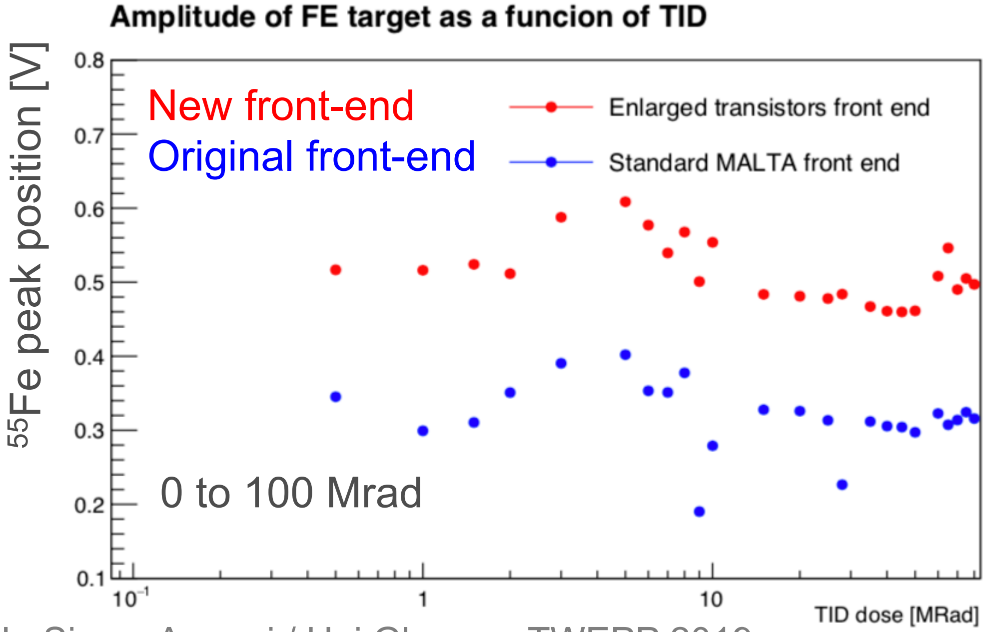


M. Dyndal et al., arXiv: 1909.11987

γ-irradiation to 100Mrad

- Irradiated MiniMALTA to 100Mrad
- Measured analog performance during irradiation
  - No substantial annealing carried out, always use pre-irrad setting (no optimization)
- ENC increase from 10e$^-$ to 20e$^-$ @100Mrad, Gain unchanged to 100Mrad
  - Some “bump” between 1 to 10Mrad – under investigation

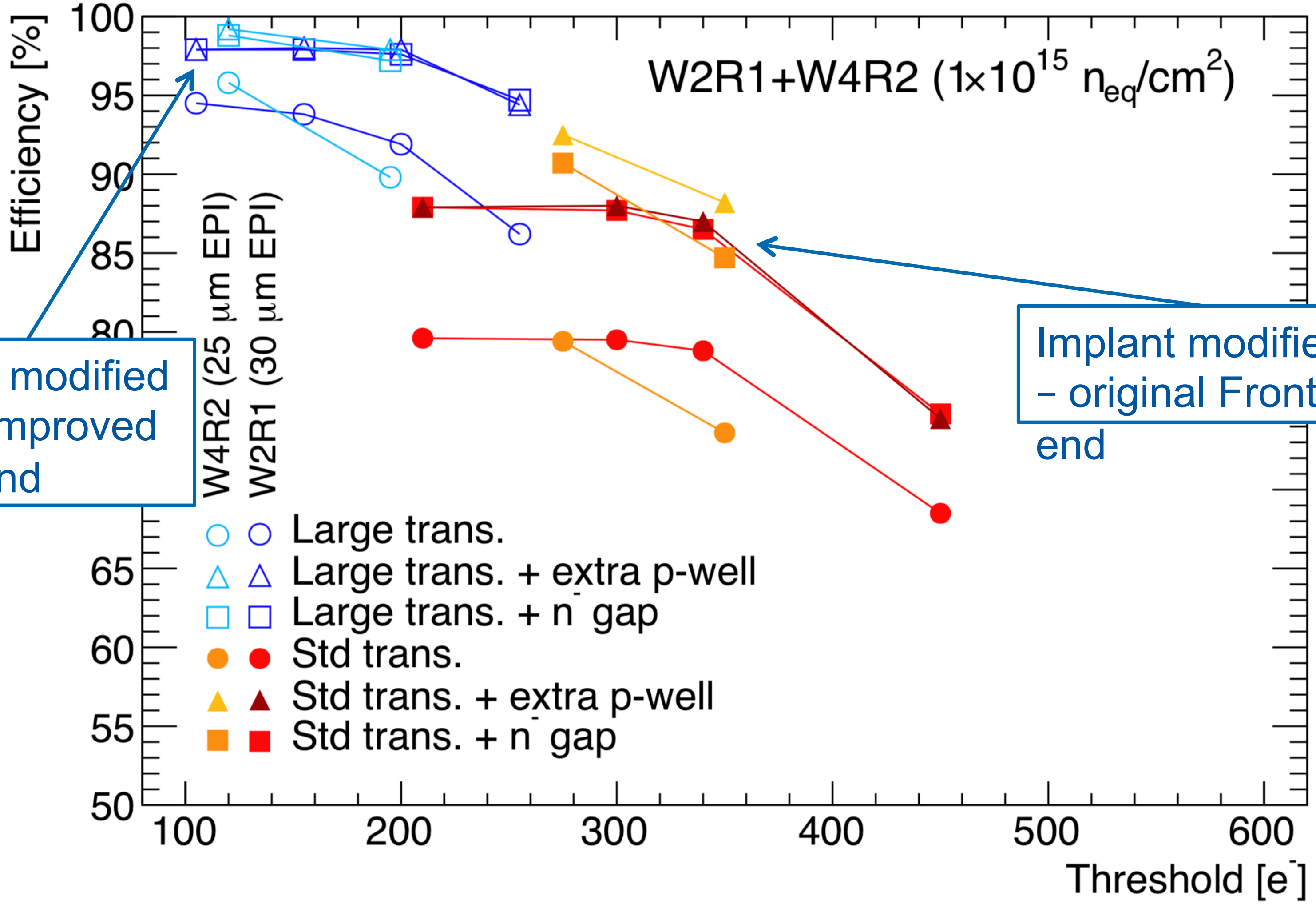




See L. Simon Argemi / Uni Glasgow TWEPP 2019

Efficiency vs threshold

For **full efficiency after irradiation** on **epitaxial substrate** need improved **front-end plus implant modification**

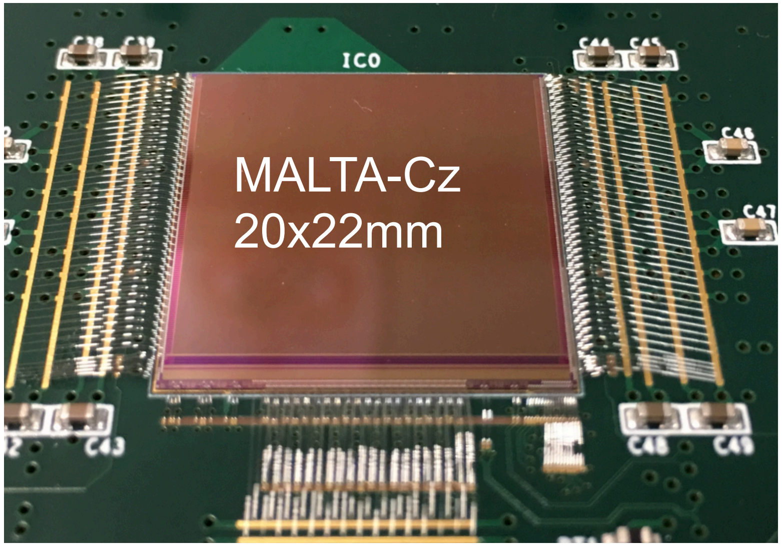


Implant modified PLUS Improved Front-end

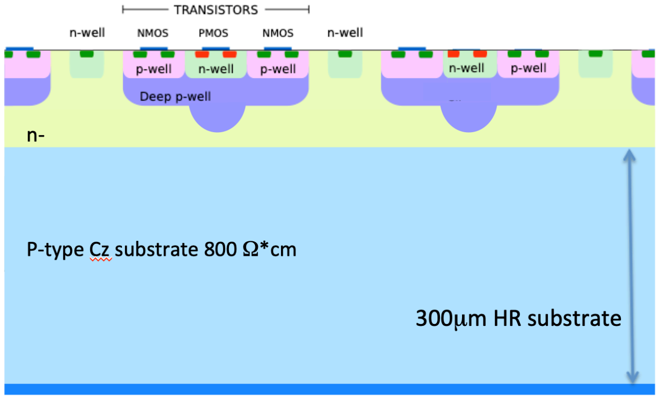
Implant modified – original Front-end

New MALTA on HR Cz substrate

- Original MALTA & MonoPix matrix reprocessed on **high resistivity Cz substrate** material
- Allows for **significant larger depletion and signal** -> prospects for **even higher radiation hardness** and possible improved **time-resolution with O(1ns)**



MALTA-Cz main features	
Pixel Pitch	36.4x36.4 μm^2
Matrix size / active area	512x512 /18.3x18mm^2
Hit rate capability	>> 100MHz/cm^2
Time resolution	<10ns (under test)
TID radiation hardness	>100Mrad
NIEL radiation hardness	>10^{15} n_{eq}/cm^2

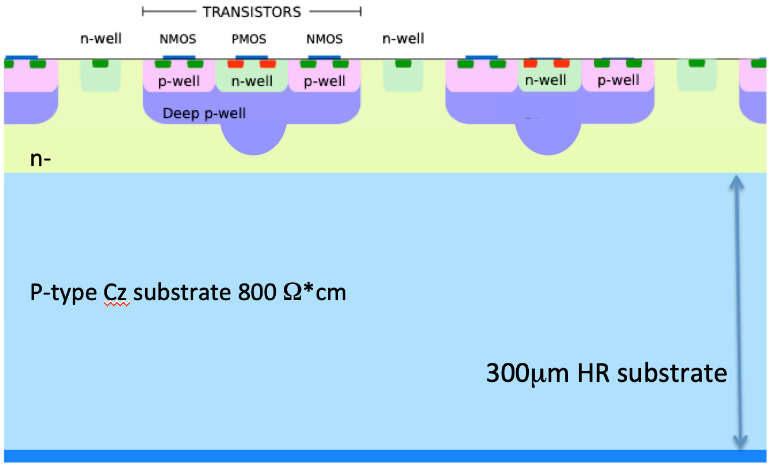


Key objectives for MALTA-Cz

- **Objective : improve radiation hardness**
  - n- layer gap and 2nd DPW as already implemented in MiniMalta
  - Enlarge signal through thick substrate (100 to 300μm p-type high resistivity Cz substrate biased to ~50V)
- **Objective : cluster size / better timing**
  - Better slew rate with thin pCz 100um operating at ~50V
  - Cluster size: EPI vs Cz – if clusters are larger on Cz due to different drift path we can improve spatial resolution through charge weighting
  - Must avoid punch-through on Cz to allow higher operation voltage $V_{sub} >> V_{pwell}$

Produced Summer 2019 – First irradiation and beam test results now

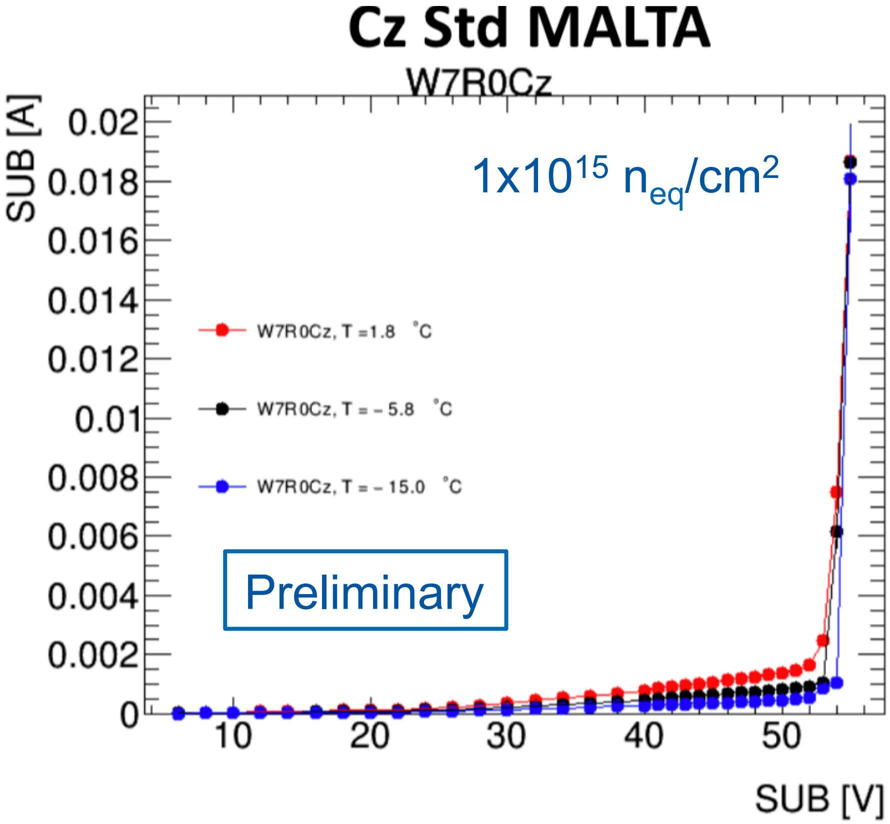
Substrate	**Implant configuration**
EPI (30μm)	N- gap and 2nd DPW
Cz HR	Continuous n- layer, n- gap and 2nd DPW



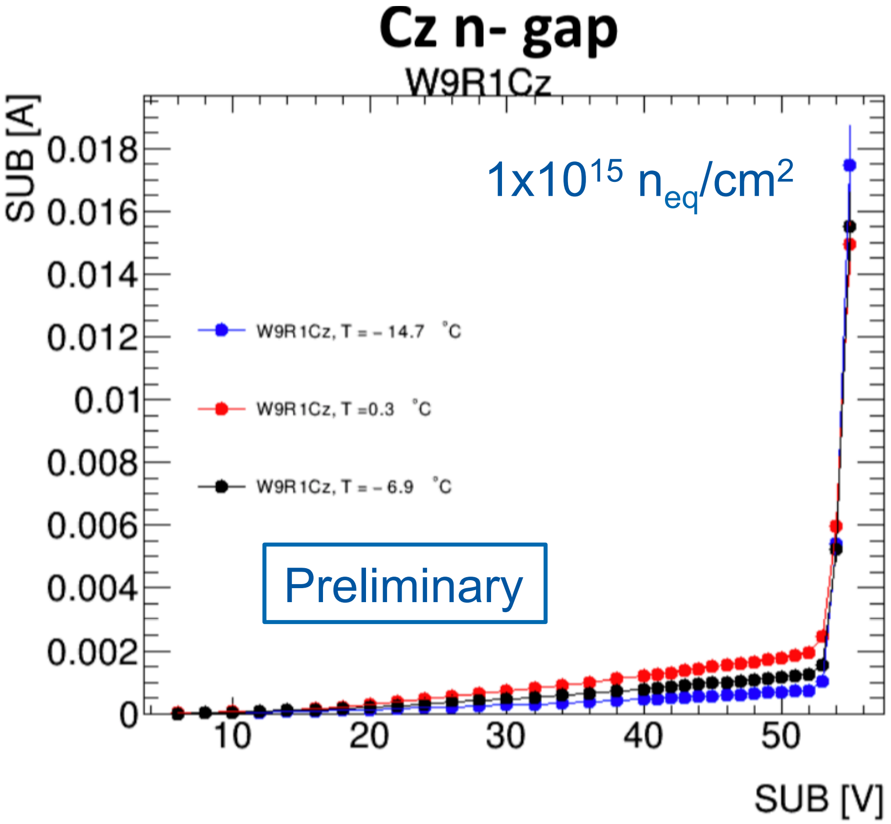
Operation voltage MALTA-Cz

- Received **MALTA-Cz** August 2019 - neutron irradiated full-size MALTA-Cz ($2 \times 2 cm^2$) at Triga reactor IJS/Slovenia
- **Breakdown voltage > 50V** , even on sensor with gap in n-layer
  - TCAD predicts lower V_{bd} – under investigation
- Good prospects for high depletion depth (larger than EPI – substrates)

High operation voltage achieved



Cz Std MALTA



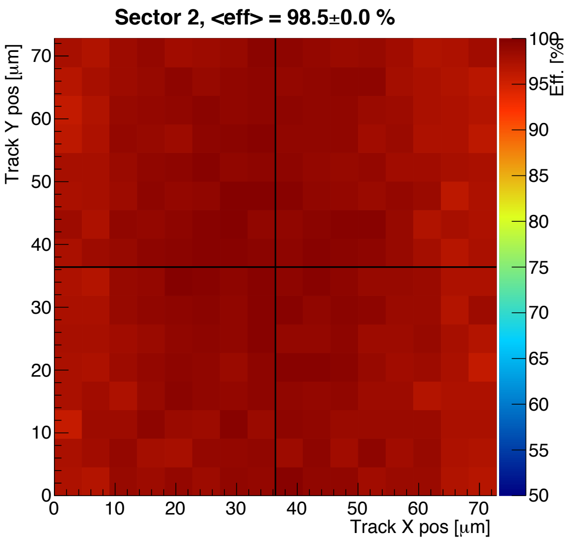
Cz n- gap

Efficiency MALTA-Cz

- n-irradiated (IJS) to $2\text{x}10^{15}$ n_{eq}/cm^2 followed by DESY beam test
- Full-size MALTA sensor with original front-end design on HR pCz
- Preliminary Efficiency (shown as 2x2 pixel x-y dependency) compared unirradiated – $1\text{x}10^{15}$ n_{eq}/cm^2 - $2\text{x}10^{15}$ n_{eq}/cm^2

MALTA Cz unirradiated

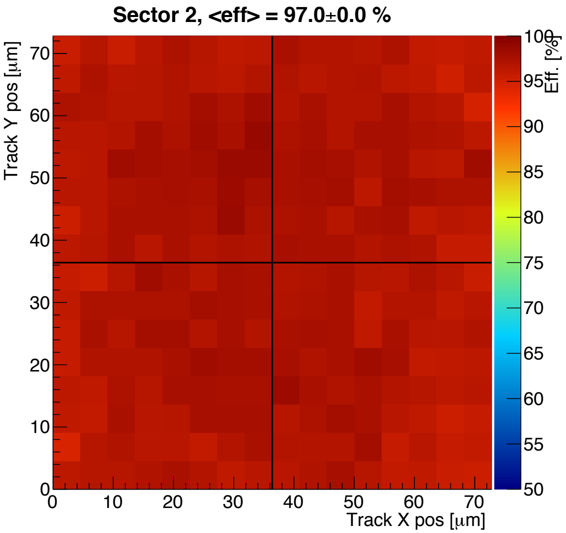
ε = 98.5%



Thres = 427e$^-$
ENC = 9.8 e$^-$

MALTA Cz n-gap $1\text{x}10^{15}$ n_{eq}/cm^2

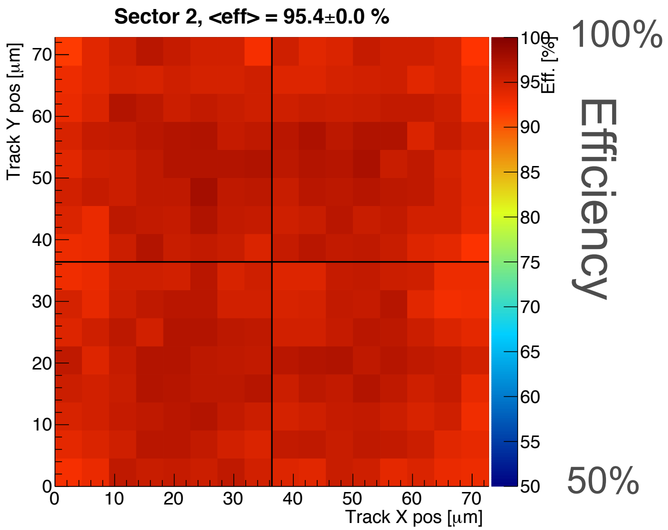
ε = 97.0%



Thres = 260 e$^-$
ENC = 12.7 e$^-$

MALTA Cz n-gap $2\text{x}10^{15}$ n_{eq}/cm^2

ε = 95.4%

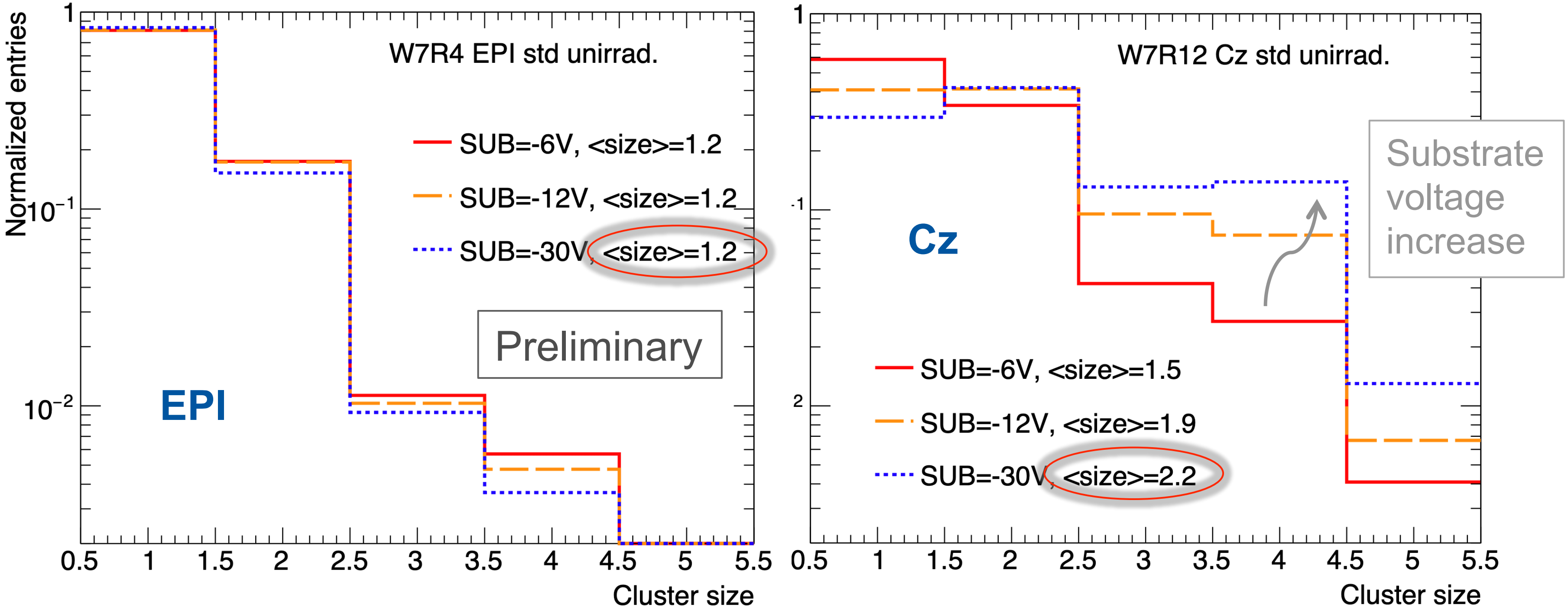


Thres = 226 e$^-$
ENC = 14 e$^-$

Cluster size MALTA-Cz vs EPI

- Unirradiated MALTA sensor substrate comparison

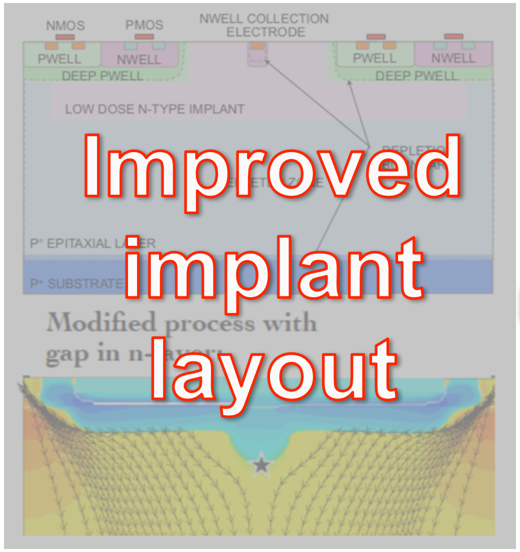
Log Scale !



- Substantially **more charge sharing in Cz** material
- **Cluster size increases with substrate voltage** as depletion depth & drift path length increases in Cz substrate
- Expect better spatial resolution in Cz due to charge interpolation -> to verify in high energy beam test

Next in TJ180: **MALTA & MonoPix Version 2**

- Based on recent 2 years R&D on radiation hard high-granularity monolithic sensors with small electrodes in TJ180nm



Improved implant layout

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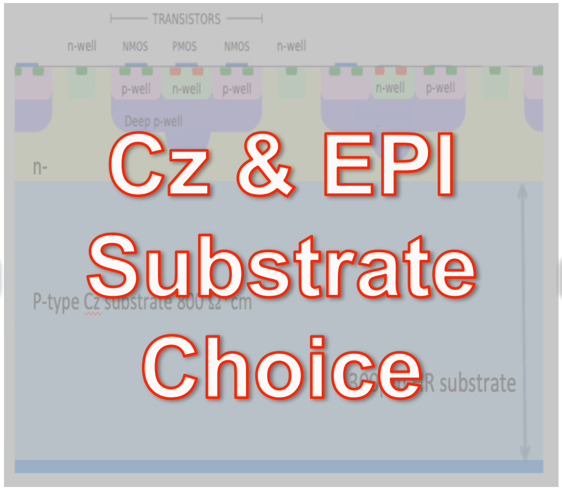

Cz & EPI Substrate Choice

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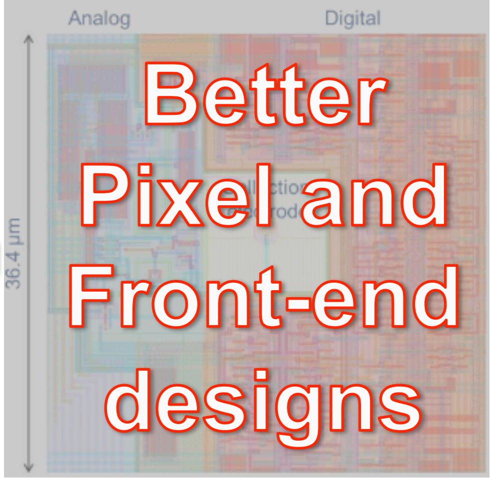


Better Pixel and Front-end designs

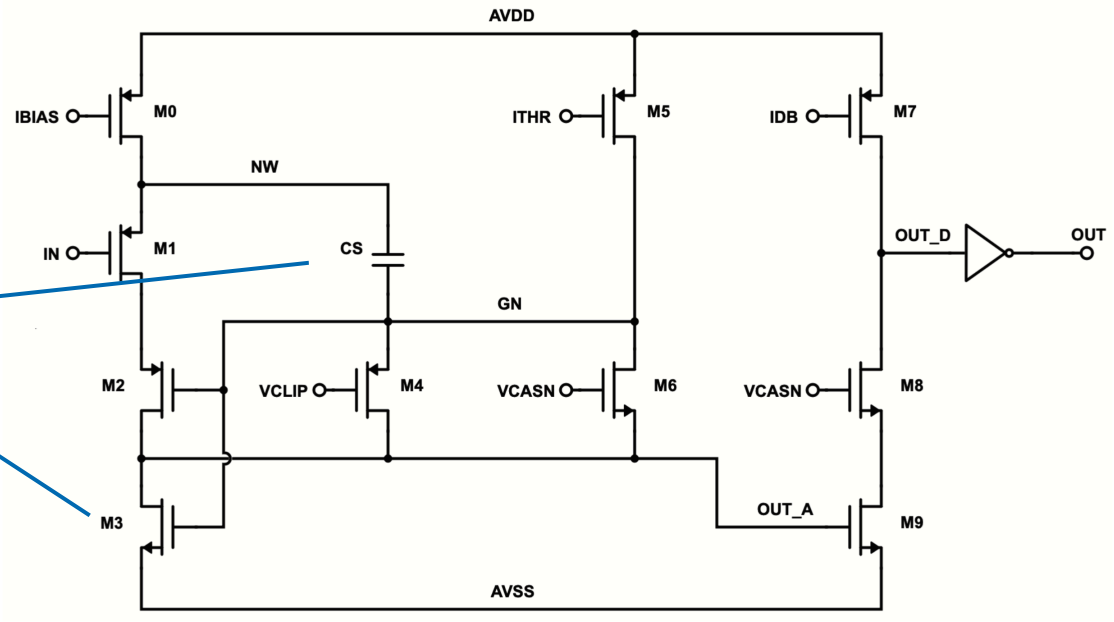
Next in TJ180: **MALTA & MonoPix Version 2**

- New Front-End design for ~x2-x3 higher gain, less noise
- Threshold adjustment on pixel level
- New implant designs, reset optimization
- New HR pCz substrate as well as EPI substrate

Increased Cs & Transistor sizes (now minimum length)

Increased gain, reduced threshold dispersion & reduced RTS noise

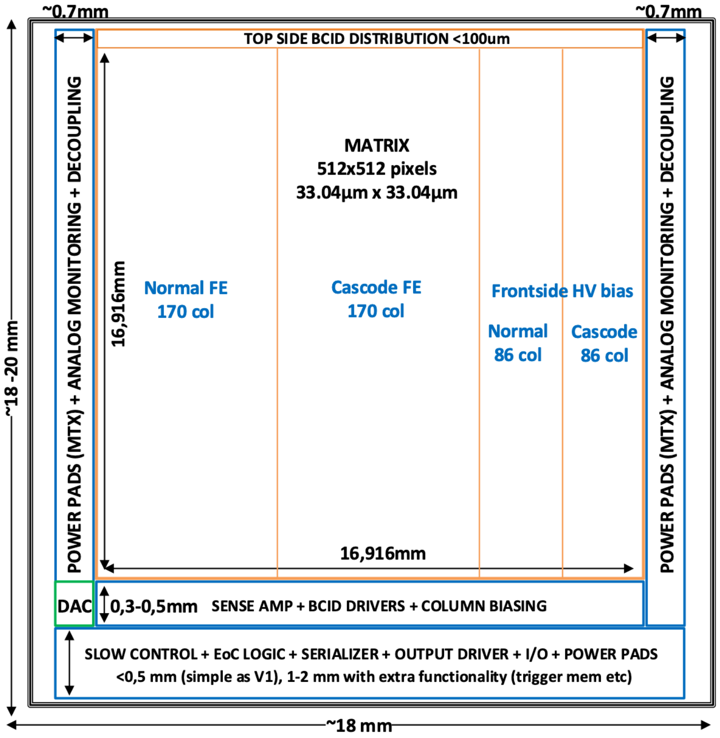
Diode reset for increased TID robustness



MALTA & MonoPix Version 2

- New Matrix designs 512x512 and 512x226 for MonoPix V2 and MALTA V2
- 7-bit ToT for analog measurements (MonoPix)
- Reduced column latency (~4ns) and timewalk for best time resolution (MALTA)
- Submission : Q1/2020 – Tests & Results Q2- Q3/2020

HSTD 2019 See Presentation and Poster by Christian Bespin & Leyre Flores



Summary & Outlook

- The development of new **depleted monolithic CMOS sensors** in HR/HV CMOS process progresses rapidly

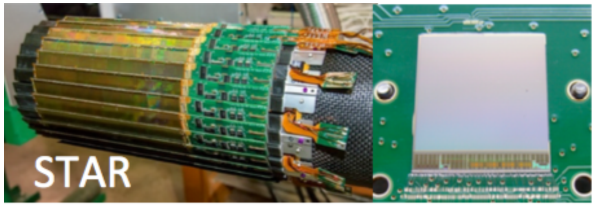
- **Small electrode designs** like TJ180nm produced MALTA and MonoPix sensor matrices offer **low capacitance, low noise and low power** solutions **for fine-pitch** (<50μm) pixel sensors

- For the first time we have achieved **full radiation hardness** to 100Mrad & 10^{15} n_{eq}/cm^2 with **small electrodes** on **MALTA sensors**
  - Significant improvement in front-end performance
  - Substantially larger signal on pCz substrate - High substrate bias voltage of 50V

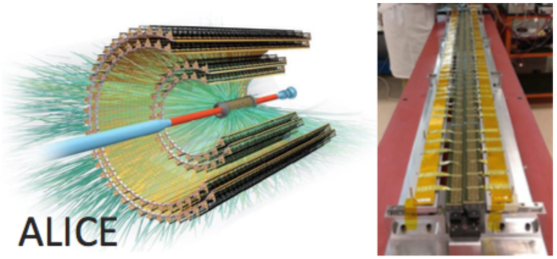
- We are now implementing all knowledge in **next generation sensors** designs of **MALTA & MonoPix Version 2** in two large-size matrices for submission in Q1/2020

DMAPS/CMOS for Future Trackers

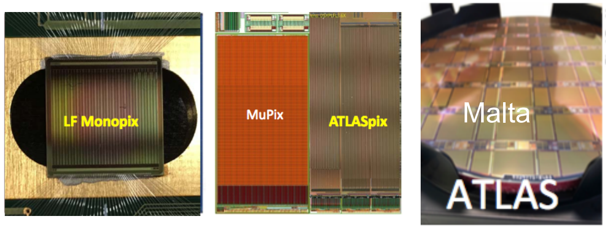
	RHIC STAR	LHC - ALICE ITS	CLIC	HL-LHC Outer Pixel	HL-LHC Inner Pixel	FCC pp
NIEL [n_{eq}/cm^2]	10^{12}	10^{13}	$<10^{12}$	10^{15}	10^{16}	10^{15}-10^{17}
TID	0.2Mrad	<3Mrad	<1Mrad	80 Mrad	2x500Mrad	>1Grad
Hit rate [MHz/cm^2]	0.4	10	<0.3	100-200	2000	200-20000



Ultimate Sensor



Alpide Sensor



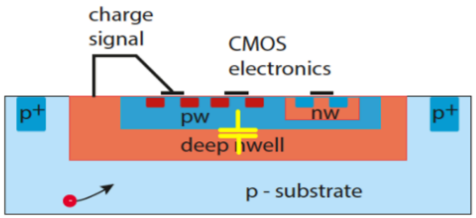
Monopix & AtlasPix & Malta Sensor

- **Strong interest for R&D to fully exploit potential of MAPS in future Trackers**
  - **High granularity, Low material budget and power, Large area at reduced cost (cf hybrid)**
  - **CMOS foundries offer substantial processing power to enable significant performance gains**

CMOS sensor designs

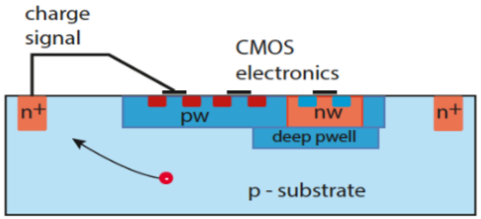
- Purse different design approaches for optimal performance

- Large electrodes



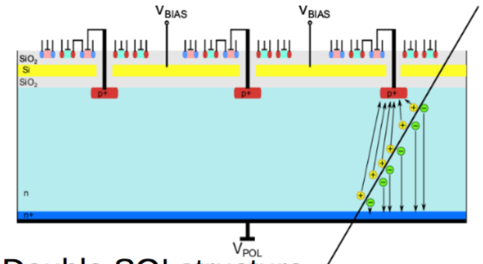
- Electronics in collection well
- No or little low field regions
- Short drift path for high radiation hardness
- Large(r) sensor capacitance (dpw/dnw) ->higher noise and slower @ given pwr
- Potential cross talk between digital and analog section

- Small electrodes



- Electronics outside collection well
- Small capacitance for high SNR and fast signals
- Separate analog and digital electronics
- Large drift path -> need process modification to usual CMOS processes for radiation hardness

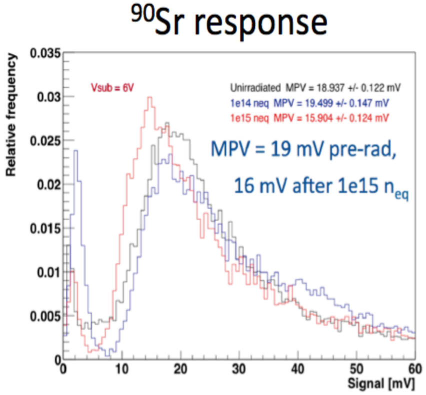
- “Burried” electrodes (SOI)

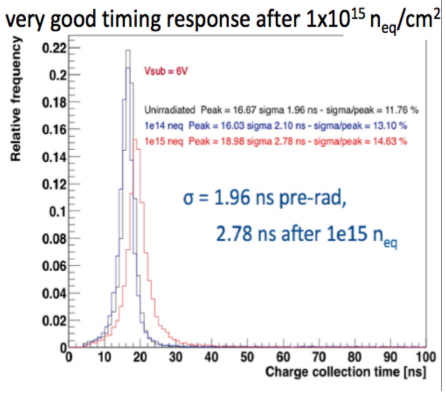


Double SOI structure

- Electronics and sensor in separate layer
- Can use thick or thin high resistivity material and HV (>200V)
- Special design/ processing to overcome radiation induced charge up of oxides

Initial results on small electrodes

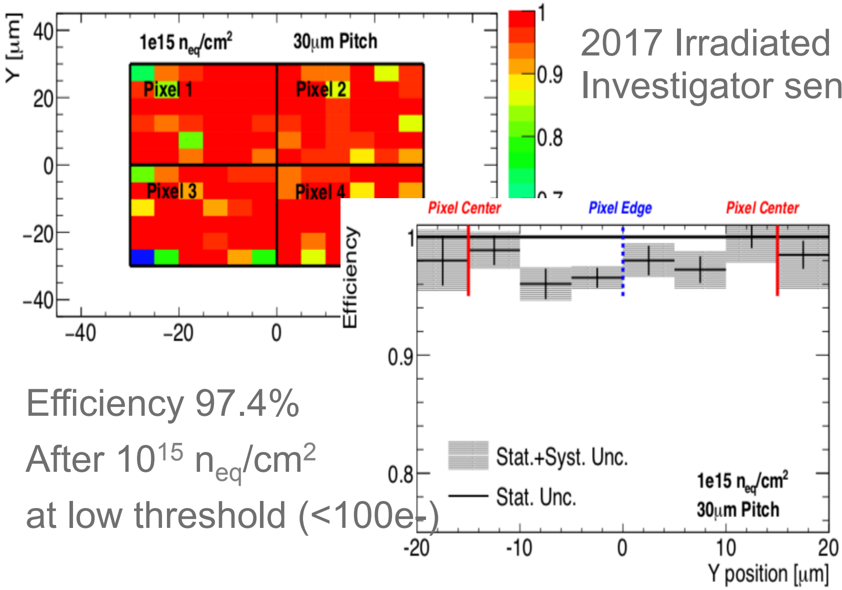




2018 MALTA & TJMonoPix measurements

- Both chips work – same FE design, different readout architecture
- Tests ongoing (lab, beam tests, irradiations) show excellent ENC ~ 8e-

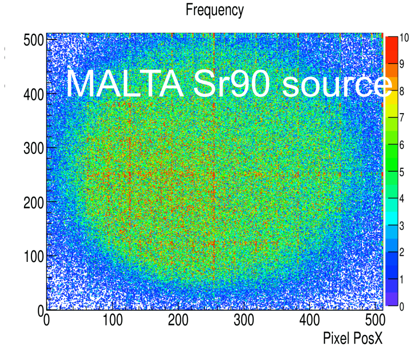
2017 Irradiated TJ Investigator sensor

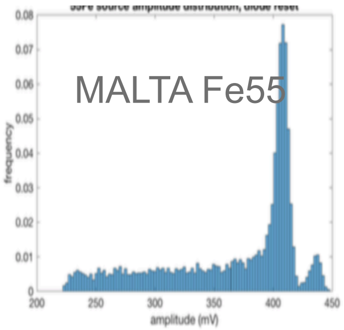


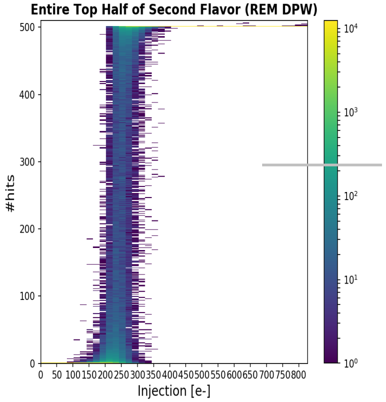
Efficiency 97.4%

After 10^{15} n$_{eq}$/cm^2

at low threshold (<100e-)



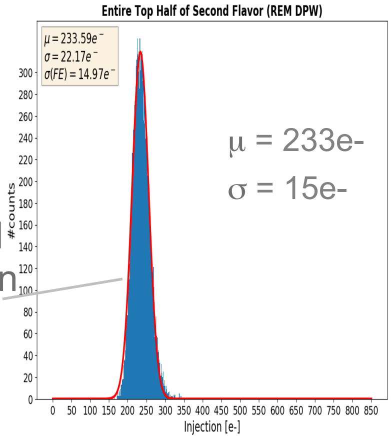




MonoPix:

S-curves

Threshold distribution



μ = 233e-

σ = 15e-

H. Pernegger et al 2017 JINST 12 P06008

MALTA readout architecture

- Matrix design optimize **for very high hit-rate** (in circuit simulation 1 GHz/cm^2)
- **Each pixel hit** is generates a LE signal (0.5 to 2ns) on its line of the pixel bus
- **Group number** encoded on 5-bit group address bus
- **One fast "HitOR"** generated for blue and red groups
- All signals are transmitted **asynchronously** at the time of the discriminator output (plus gate delays)