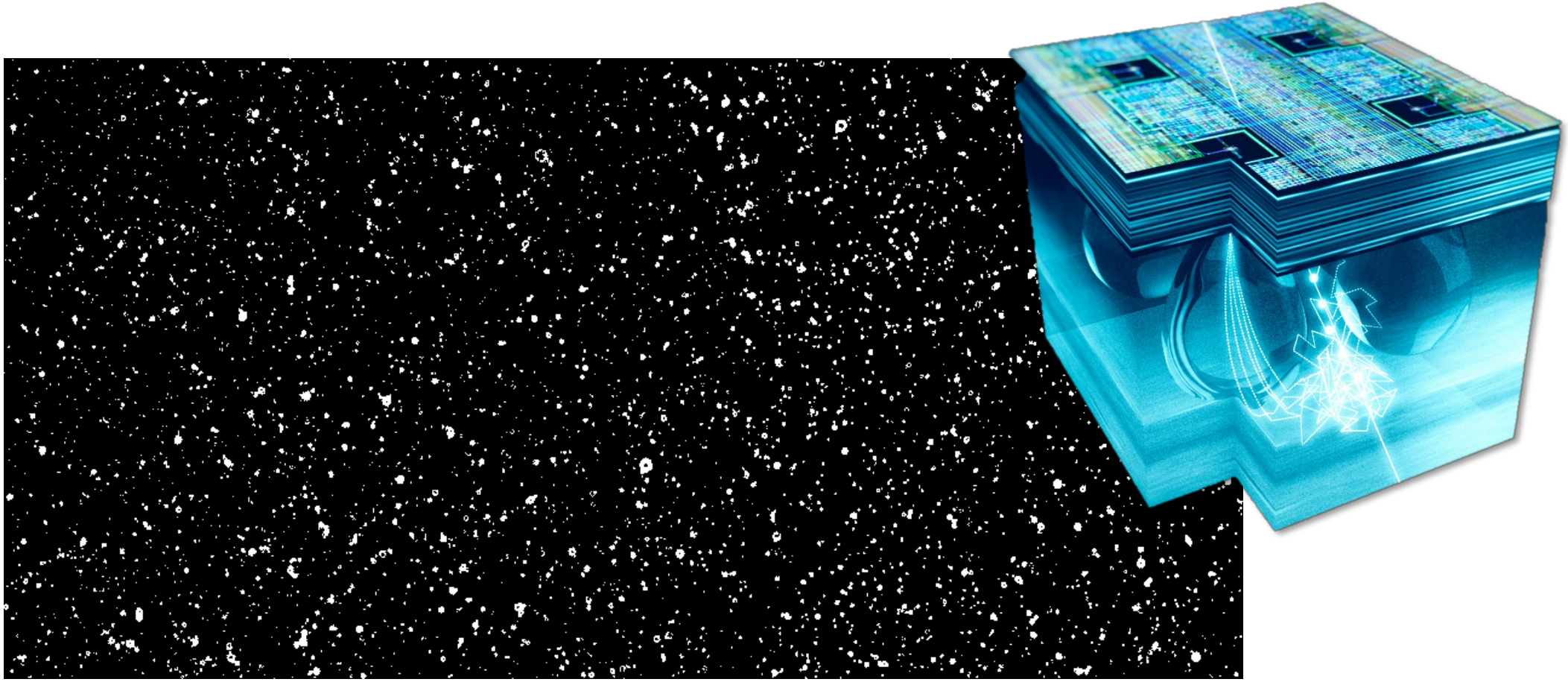
Challenges for CMOS monolithic sensors



ALPIDE prototype: 200 MeV protons at PSI

W. Snoeys

Geneva, Switzerland

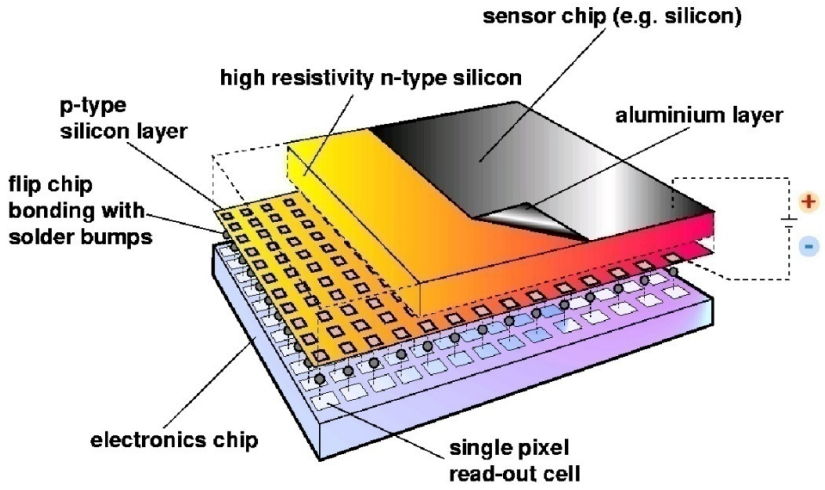
CEPC Meeting, October 24th, 2022

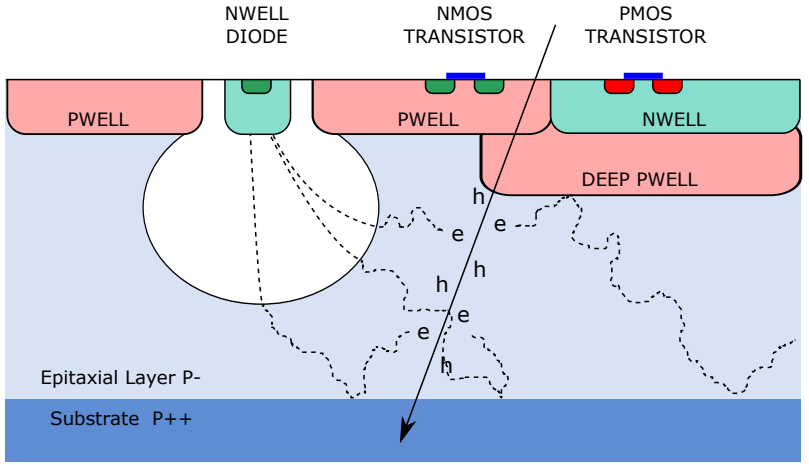
Acknowledgements

- The workshop organizers
- T. Kugathasan, G. Aglieri, E. Buschmann, M. Campbell, T. Kugathasan, M. Muenker, K. Dort, J. Hasenbichler, L. Musa, H. Pernegger, P. Riedler, N. Guerrini, C. Hu, P. Giubilato, D. Dannheim, T. Hirono, I. Peric, A. Schoening
- S. Parker, C. Kenney, J. Plummer, J. Segal
- G. Anelli, F. Anghinolfi, P. Aspell, R. Ballabriga, S. Bonacini, M. Campbell, J. Christiansen, R. De Oliveira, F. Faccio, P. Farthouat, E. Heijne, P. Jarron, J. Kaplon, K. Kloukinas, A. Kluge, T. Kugathashan, X. Llopart, A. Marchioro, S. Michelis, P. Moreira, F. Vasey, K. Wyllie, M. Mager, M. Keil, D. Kim, A. Dorokhov, A. Collu, C. Gao, P. Yang, X. Sun, H. Hillemanns, S. Hristozkov, A. Junique, M. Kofarago, M. Keil, A. Lattuca, M. Lupi, C. Marin Tobon, D. Marras, M. Mager, P. Martinengo, S. Mattiazzo, G. Mazza, H. Mugnier, H. Pham, F. Piro, L. Cecconi, W. Deng, G. H. Hong, J. De Melo, J. Rousset, F. Reidt, P. Riedler, J. Van Hoorne, P. Yang, D. Gajanana, A. Sharma, B. Blochet, C. Sbarra, C. Solans Sanchez, C. Riegel, C. Buttar, D. Michael Schaefer, D. Maneuski, I. Berdalovic, K. Moustakas, M. Dalla, N. Wermes, N. Egidos Plaja, R. Bates, R. Cardella, T. Wang, T. Hemperek, C. Bespin, T. Hirono, W. Wong, G. Iacobucci, M. Barbero, P. Pangaud, A. Habib, S. Bhat, S. Grinstein, Y. Degerli, F. Guilloux, P. Schwemling, W. Riegler, E. Schioppa, V. Dao, L. Flores, M. Dyndal, C. Colledani, M. Winter, A. Dorokhov, S. Bugiel, S. Mathew, I. Sedgwick, C. Reckleben, K. Hansen, V. Gromov, D. Gajanana, R. Kluit, Y. Kwon, …

and other colleagues from CERN, the ALICE ITS and ITS3 upgrade, ATLAS Itk, WP1.2 …

Hybrid vs Monolithic





Hybrid

- Large majority of presently installed systems
- 100 % fill factor easily obtained
- Sensor and ASIC can be optimized separately
- Spin-off from HEP developments:

  for example spectral photon counting chips in this workshop

Monolithic

- Easier integration, lower cost
- Potentially better power-performance ratio and strong impact on material budget

Motivation for intense R&D since more than 30 years

- Trend towards more standard technologies

New technologies (TSV's, microbumps, wafer stacking…) make the distinction more vague.

CMOS Monolithic Active Pixel Sensors revolutionized the imaging world

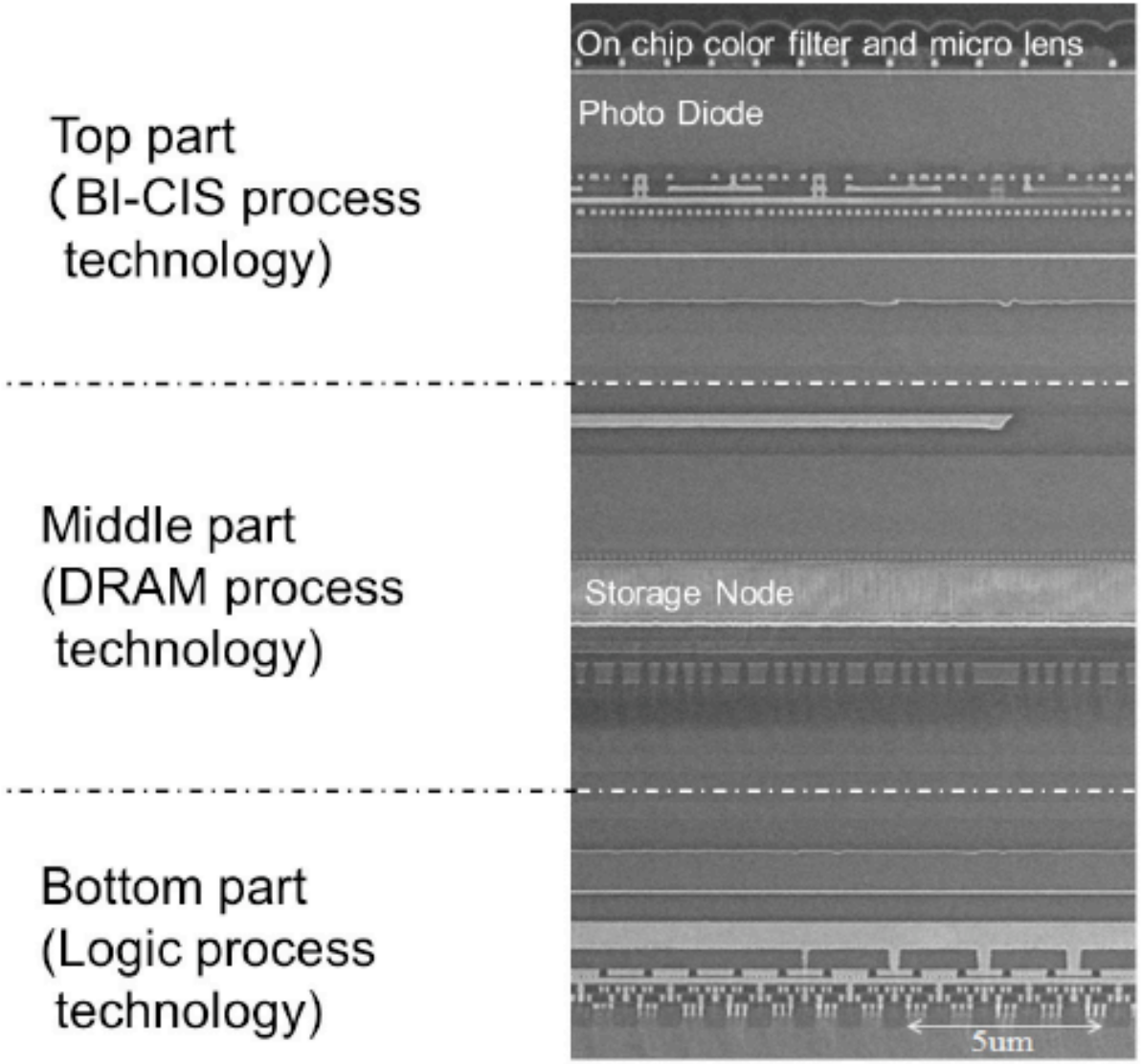
reaching:

- less than 1 e^- noise
- > 40 Mpixels
- Wafer scale integration
- Wafer stacking
- …

Silicon has become the standard in tracking applications both for sensor and readout

… and now CMOS MAPS make their way in High Energy Physics !

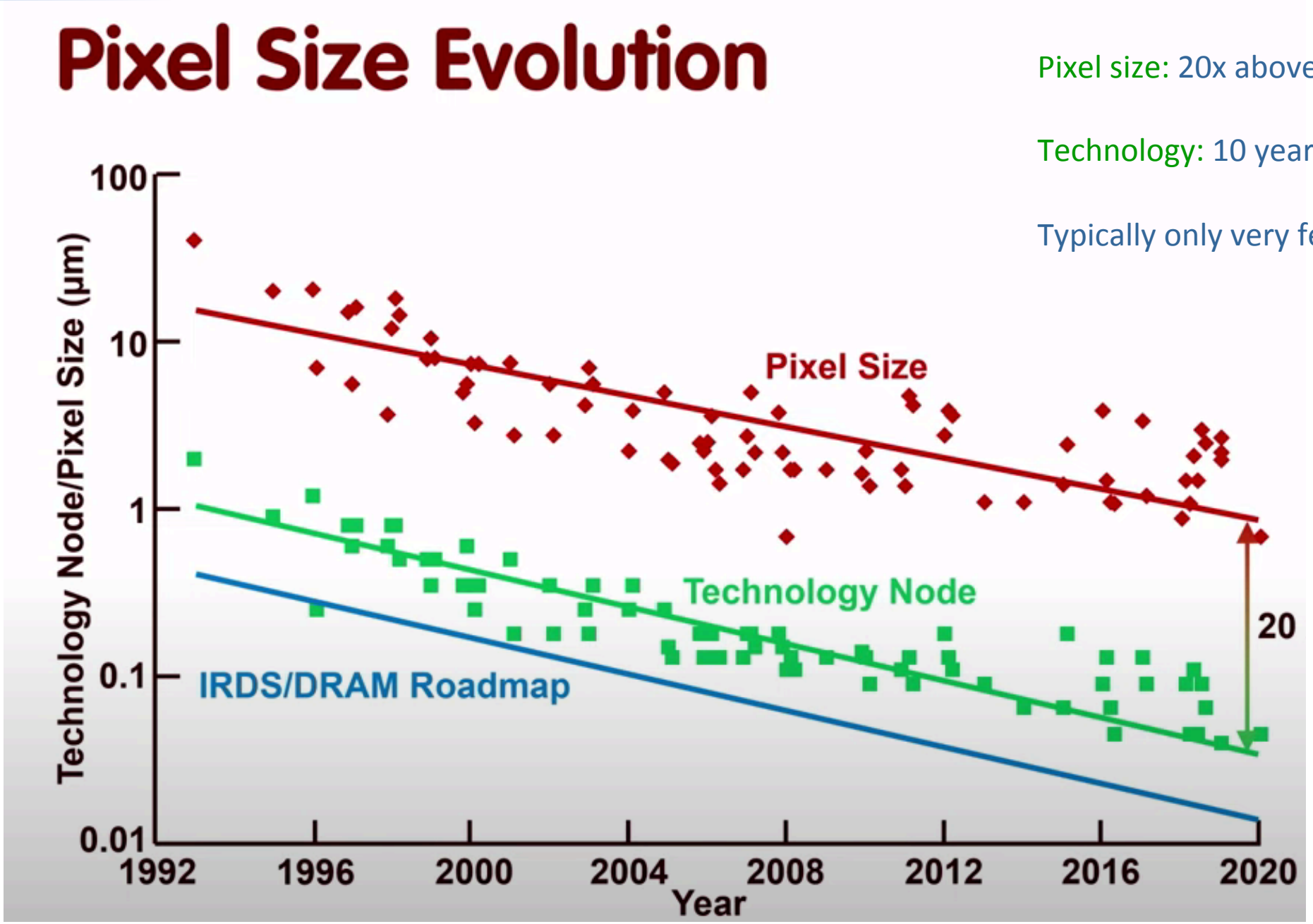
Hybrid still in majority in presently installed systems



Sony, ISSCC 2017

New technologies (TSV's, microbumps, wafer stacking…) make the distinction more vague.

Evolution of pixel size and technology node for visible:



Pixel size: 20x above technology feature size

Technology: 10 years behind DRAM technology

Typically only very few (1-4) transistors per pixel

Albert Theuwissen, ISSCC 2021

Requirements for High Energy Physics

	Dose (Mgy)	Fluence (10^{16} 1MeVn_{eq}/cm^2)
ALICE ITS	**0.01**	**10^{-3}**
LHC	**1**	**0.1…0.3**
HL-LHC 3ab^{-1}	**5**	**1.5**
FCC	**10-350**	**3-100**

Radiation tolerance

- CMOS circuit typically more sensitive to ionizing radiation
- Sensor to non-ionizing radiation (displacement damage)

Single particle hits instead of continuously collected signal in visible imaging

- Sparse images < or << 1% pixels hit per event
- Near 100% efficiency, full CMOS in-pixel needed, often circuit (much) more complex

Position resolution (~µm)

Low power consumption is the key for low mass

- Now tens of mW/cm^2 for silicon trackers and hundreds of mW/cm^2 for pixels
- Despite enhanced detector functionality for upgrades, material penalty limits power consumption increase

More bandwidth

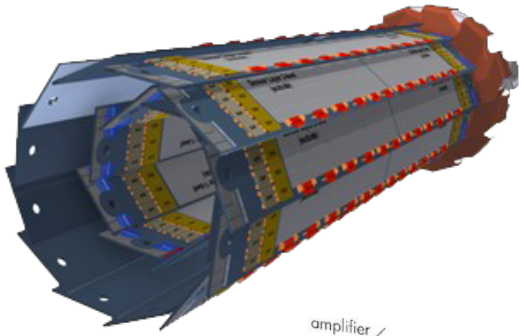
Time resolution

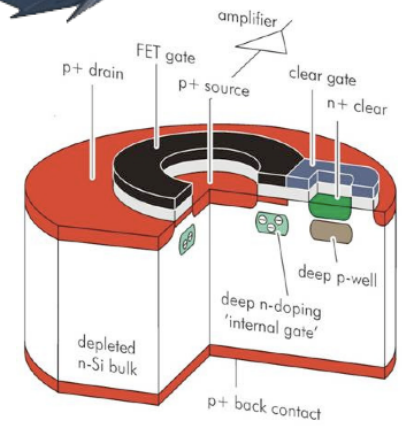
- Time stamping ~ 25 ns or even lower, ... much lower (10s of ps)

Larger and larger areas

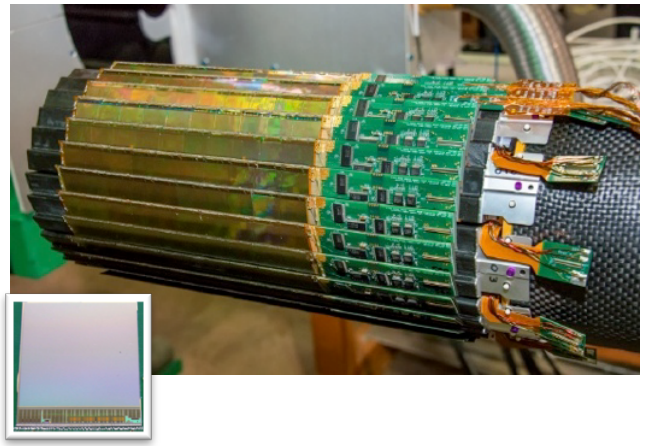
- ALICE ITS2 10 m^2, discussions on hundreds to even thousands square m^2,
- Interest for versatile sensors programmable for different applications (P. Allport CERN EP seminar 2020)

Monolithic sensors in HEP move into mainstream technology





DEPFET in Belle



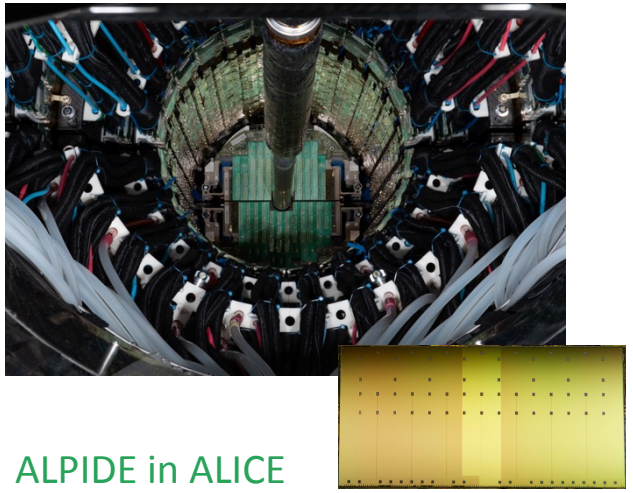
MIMOSA28 (ULTIMATE) in STAR

IPHC Strasbourg

First MAPS system in HEP

Twin well 0.35 µm CMOS

- Integration time 190 µs
- No reverse bias -> NIEL few 10^{12} 1 MeV n_{eq}/cm^2
- Rolling shutter readout



ALPIDE in ALICE

First MAPS in HEP with sparse readout similar to hybrid sensors

Quadruple well 0.18 µm CMOS

- Integration time <10 µs
- Reverse bias but no full depletion -> NIEL ~10^{14} 1 MeV n_{eq}/cm^2

DEPLETED MAPS for better time resolution and radiation tolerance

Large collection electrode

LF Monopix, MuPix,…

Extreme radiation tolerance and timing uniformity, but large capacitance

Small collection electrode

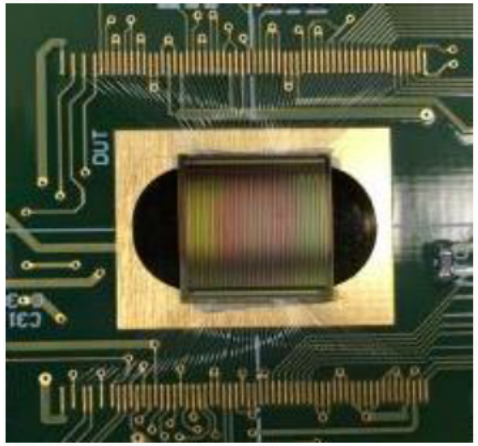
ARCADIA LF, TJ Malta, TJ Monopix, Fastpix, CLICTD, …

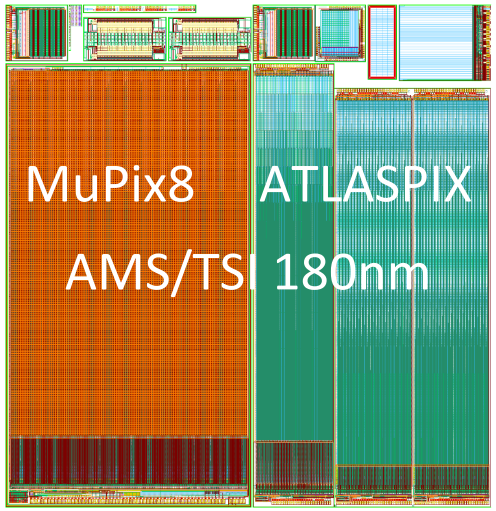
- Sub-ns timing
- NIEL >10^{15} 1 MeV n_{eq}/cm^2 and beyond

Commercial deep submicron CMOS technology evolved “naturally” towards

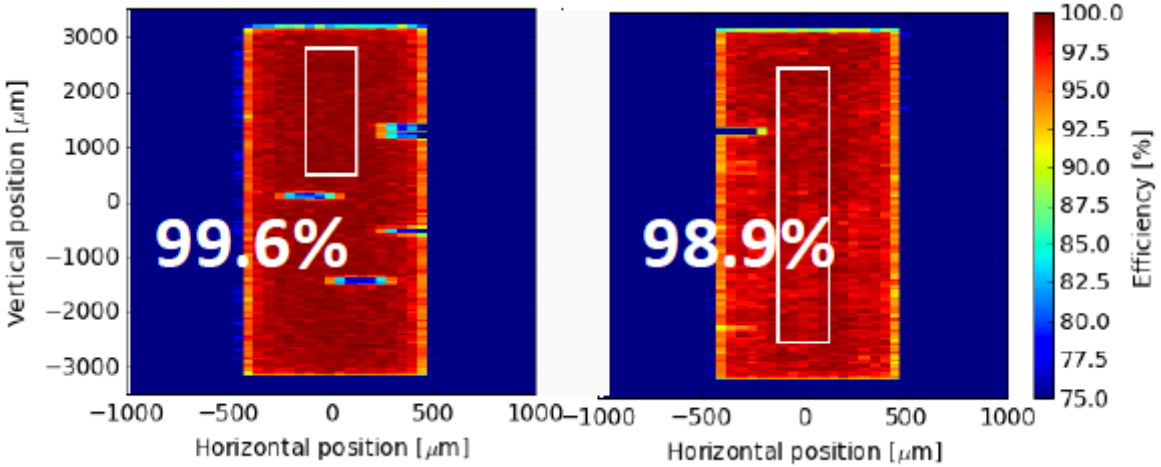
- Very high tolerance to ionizing radiation (some caveats, cfr G. Borghello, F. Faccio et al.)
- Availability of substrates compatible with particle detection
- Imaging technology not absolutely required, but some flexibility/features very beneficial for sensor optimization, both for small and large collection electrode structures.

Better sensor radiation tolerance and timing: Large collection electrode: rad hard, but large C (100fF or more)

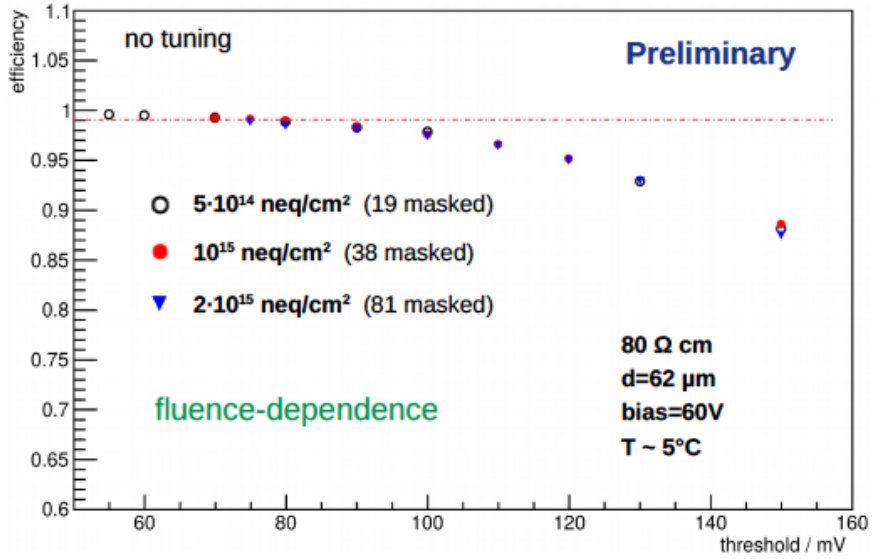




Efficiency non-irradiated **after 1.14 E15 n_{eq}/cm^2**

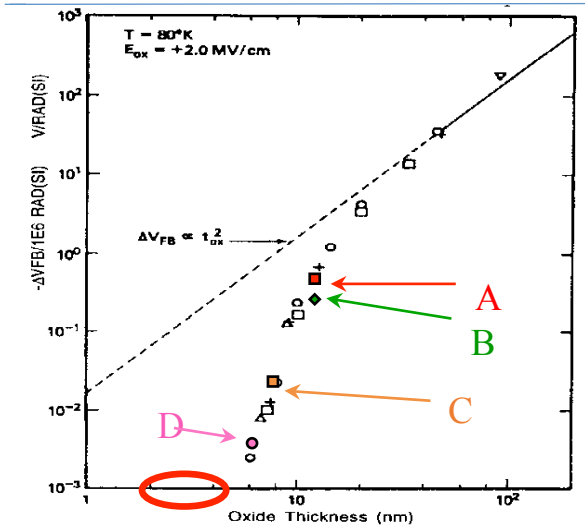


T. Hirono et al., https://doi.org/10.1016/j.nima.2018.10.059



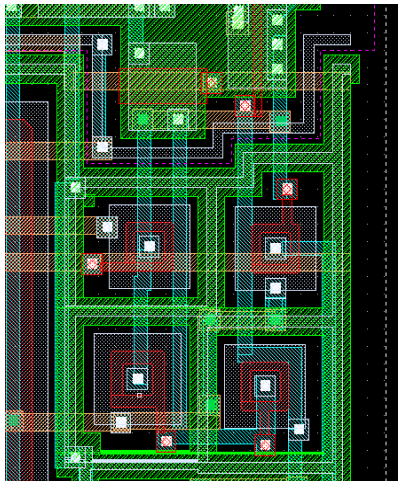
Courtesy I.Peric and A. Schoening

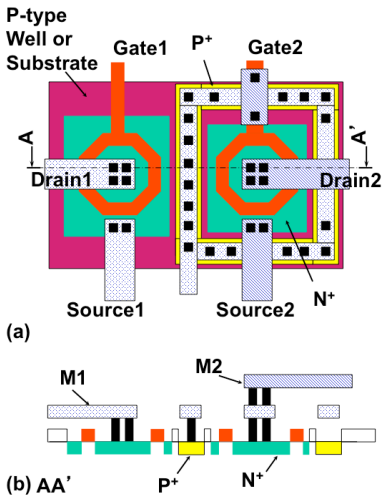
Circuit radiation tolerance: like standard CMOS



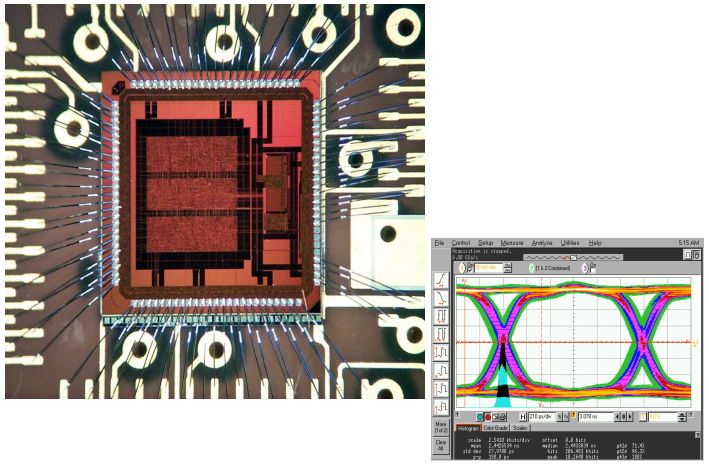
Now here

After N.S. Saks et al, IEEE TNS, Vol. NS-31 (1984) 1249





G. Anelli et al., IEEE TNS-46 (6) (1999) 1690



P. Moreira et al.
http://proj-gol.web.cern.ch/proj-gol/

Total ionizing dose:

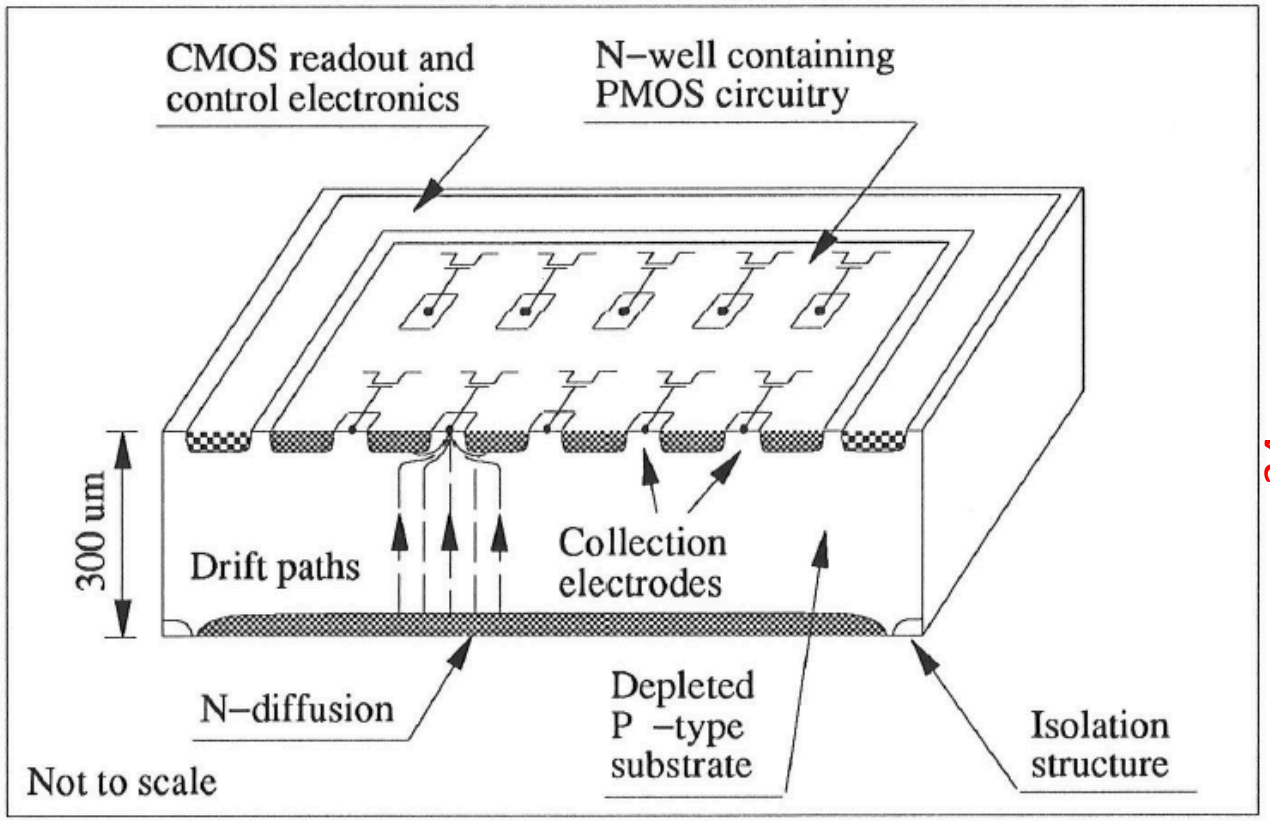
- Intrinsic transistor has become more and more radiation tolerant due to thinner gate oxide
- In LHC enclosed NMOS transistors and guard rings in 0.25 µm CMOS to avoid large leakage current
- In deeper submicron enclosed geometry usually no longer necessary for leakage, but for small dimensions parasitic effects dominate e.g. from spacers, new gate dielectrics, **requires extensive measurement campaigns**

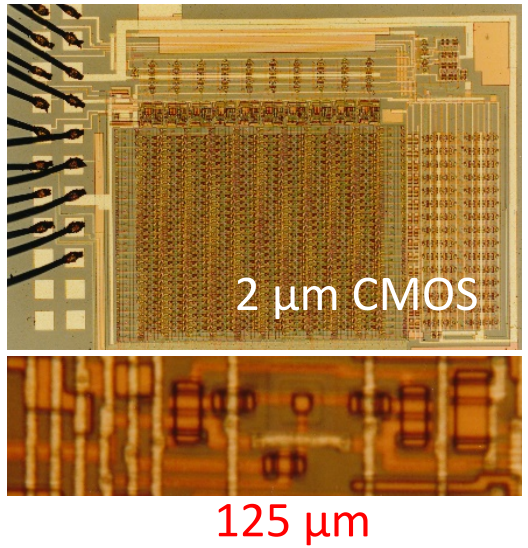
F. Faccio et al. IEEE TNS-65 (1) 164, 2018

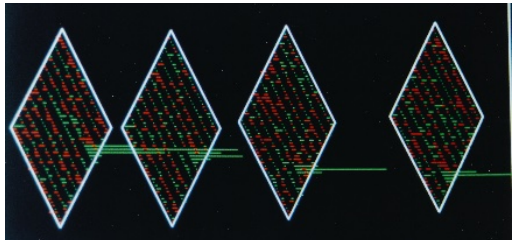
Single event effects:

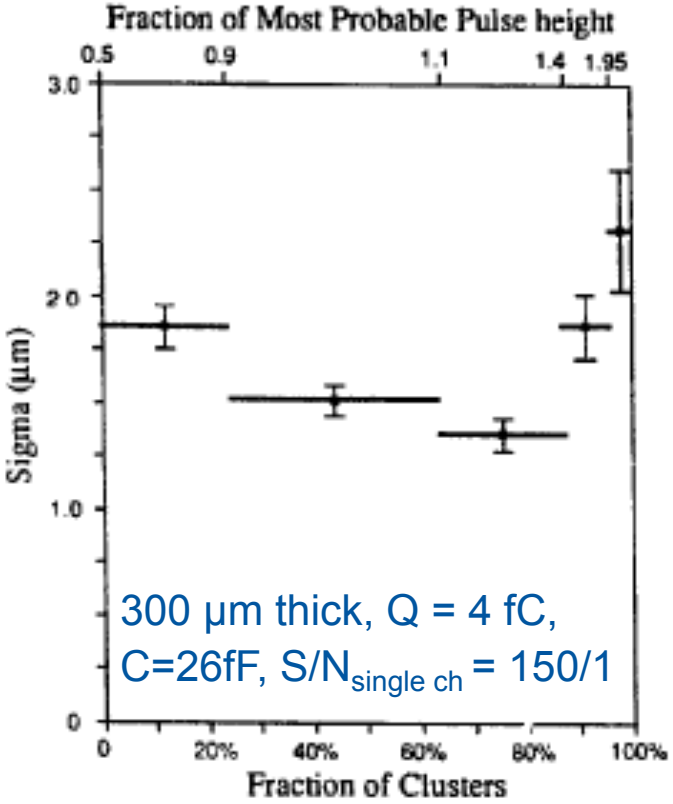
- Single Event Upset : triple redundancy with majority voting (now special scripts S. Kulis)
- Latch-up not observed so far in LHC, but observed on MAPs at STAR, and in new technologies => **need attention in the design**

Towards standard technology, but double-sided processing

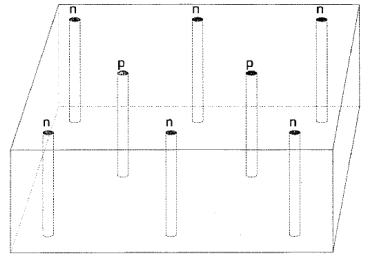








- Separation of junction from collection electrode
- Better than 2 µm position resolution even at large pitch due to good S/N
- Improved back side isolation with trenches lead to sensors with 3D electrodes (S.Parker) →

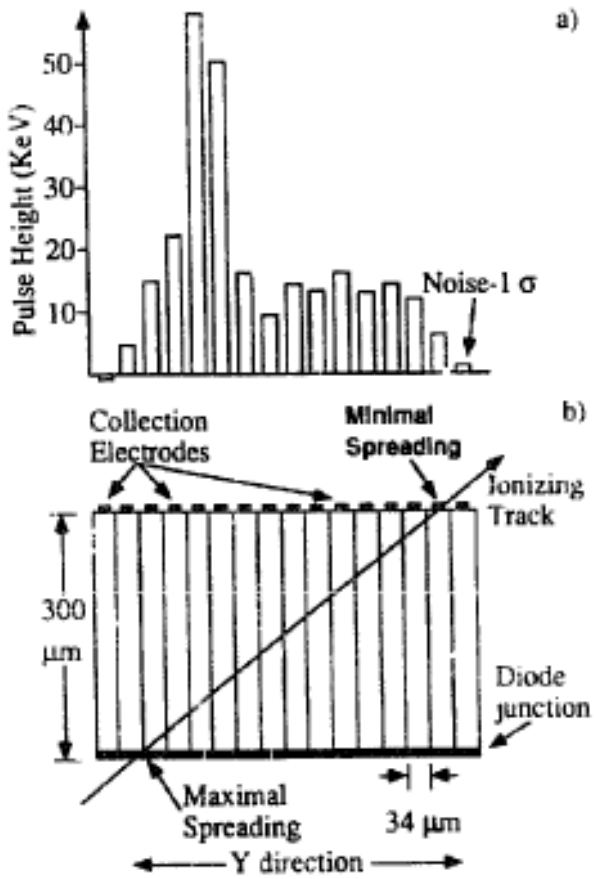


C. Kenney, S. Parker, J. Plummer, J. Segal, W. Snoeys et al. NIM A (1994) 258-265, IEEE TNS 41 (6) (1994), IEEE TNS 46 (4) (1999)

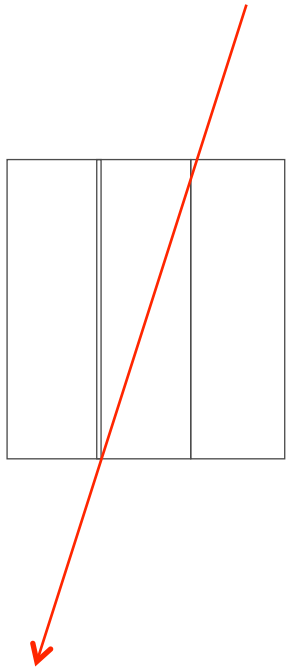
Other examples: ~ 1 µm resolution: SOI sensor, pitch 13.75 µm *M. Battaglia et al. NIM A 654 (2011) 258-265, NIM A 676 (2012) 50-53*

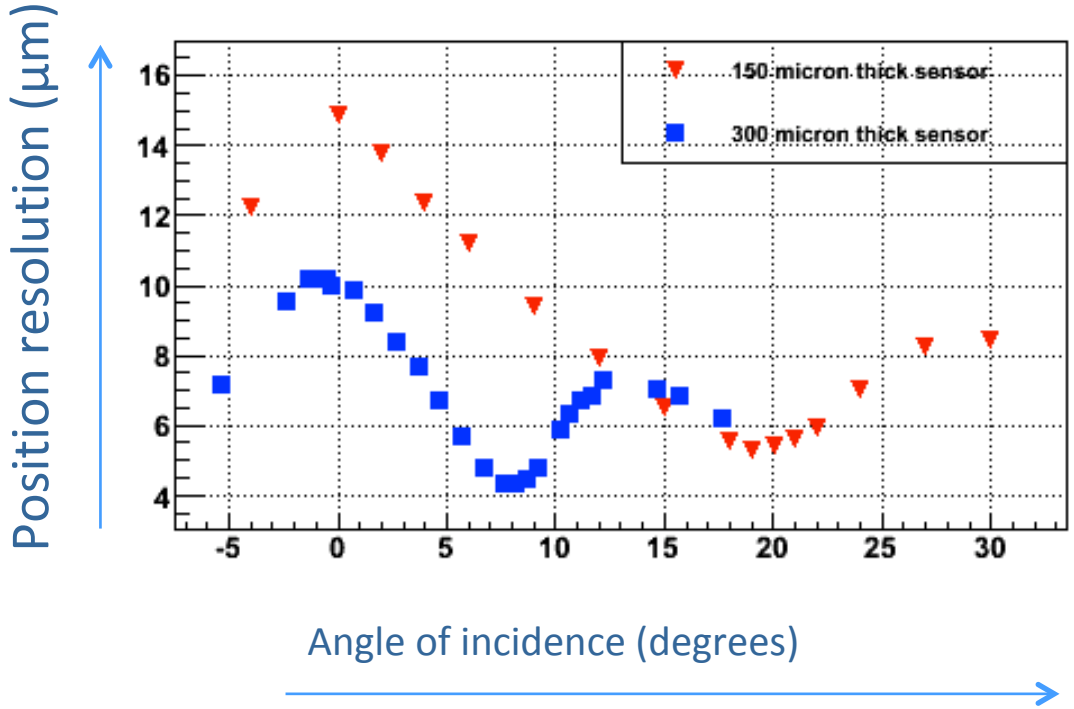
Position resolution: good S/N for interpolation Junction separation and back side processing: see below

Position resolution: inclined tracks



C. Kenney et al. NIM A 654 (2011) 258-265





Timepix3: X. Llopart, J. Buytaert, M. Campbell, P. Collins et al.

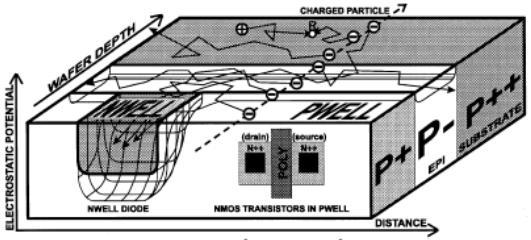
Average of extreme pixels in the cluster gives better results
In this case the signal (and the S/N) for a single channel reduces with track inclination

Can optimize resolution using track inclination to enhance charge sharing, can also be done using a magnetic field

Single point resolution and S/N

- Sensor can deliver ~ 1µm point resolution if granularity and S/N sufficient
- Examples used analog interpolation. With binary readout, single point resolution can be achieved as well. Need sufficient granularity, but also sufficient S/N.
- Unless S/N is very large, detector depth and pixel pitch should be comparable to avoid degradation in S/N and hence resolution for inclined tracks.

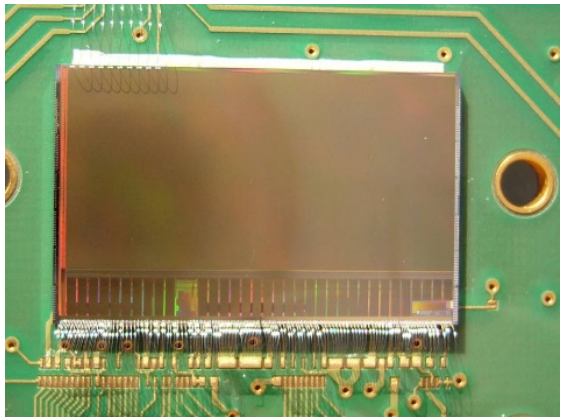
Mimosa series – IPHC Strasbourg



NIM A 458 (2001) 677-689

A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology

R. Turchetta[a,*], J.D. Berst[a], B. Casadei[a], G. Claus[a], C. Colledani[a], W. Dulinski[a], Y. Hu[a], D. Husson[a], J.P. Le Normand[a], J.L. Riester[a], G. Deptuch[b,1], U. Goerlach[b], S. Higueret[b], M. Winter[b]



Rolling shutter readout

Mimosa26 – 2008

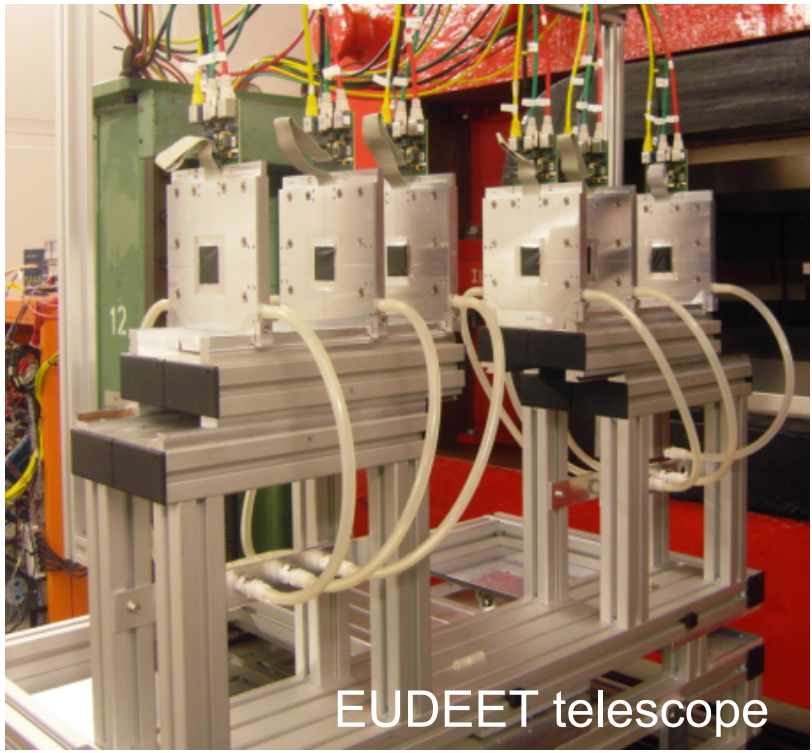
Courtesy of C. Hu IPHC Strasbourg

AMS 0.35 µm

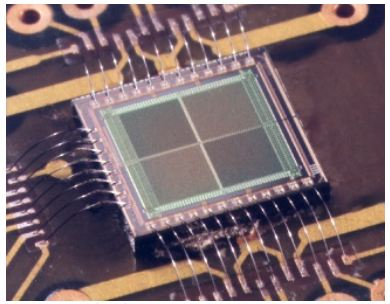
18.4 µm pixel pitch 576x1152 pixels

First MAPS with integrated zero-suppressed readout

First MAPS used for several applications, also for EUDEET telescope



Mimosa1 – 1999
AMS 0.6 µm

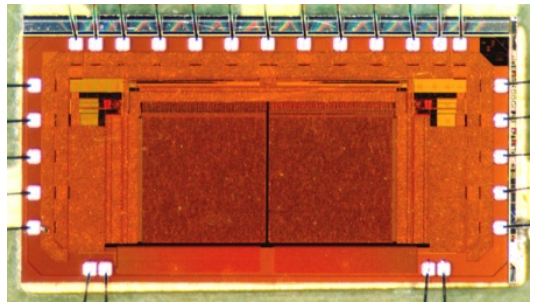


20µm pixel

Mimosa2 – 2000
MIETEC 0.35 µm

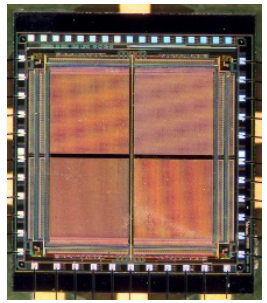
20µm pixel

Mimosa3 – 2001
IBM 0.25 µm



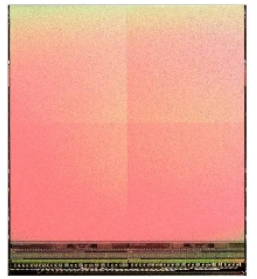
8µm pixel

Mimosa4 – 2001
AMS 0.35 µm



20 µm pixel

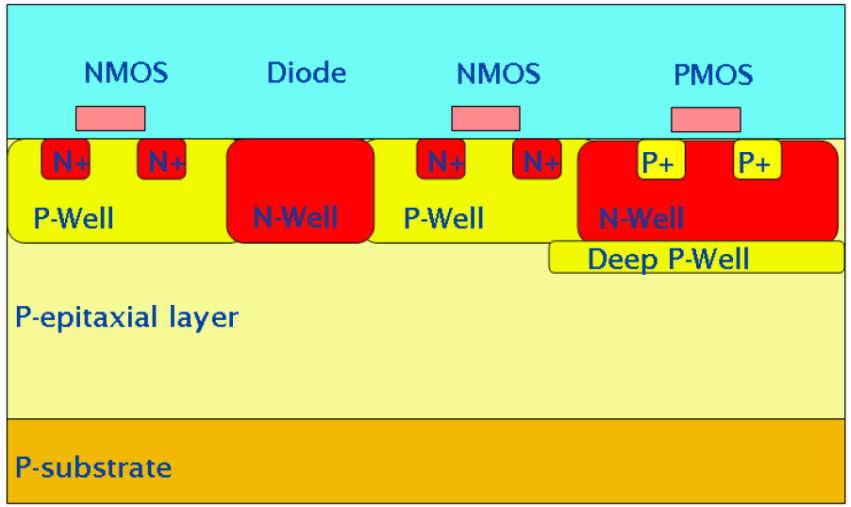
Mimosa5 – 2001
AMS 0.6 µm



17 µm pixel

....

The INMAPS process: quadruple well for full CMOS in the pixel



STFC development, in collaboration with TowerJazz

Additional deep P-well implant allows complex in-pixel CMOS and 100 % fill-factor

New generation of CMOS sensors for scientific applications (TowerJazz CIS 180nm

Also 5Gb/s transmitter in development

Sensors 2008 (8) 5336, DOI:10.3390/s8095336

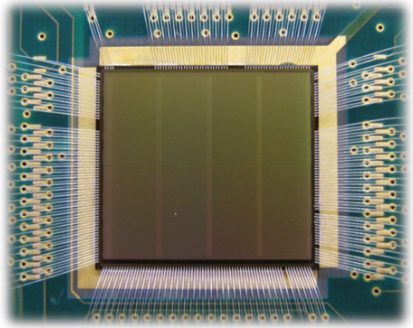
https://iopscience.iop.org/article/10.1088/1748-0221/7/08/C08001/meta

https://iopscience.iop.org/article/10.1088/1748-0221/14/01/C01006/meta

http://pimms.chem.ox.ac.uk/publications.php ...

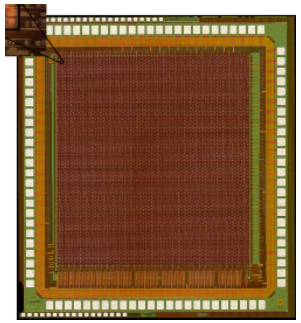
courtesy of N. Guerrini, STFC

TPAC
ILC ECAL (CALICE)



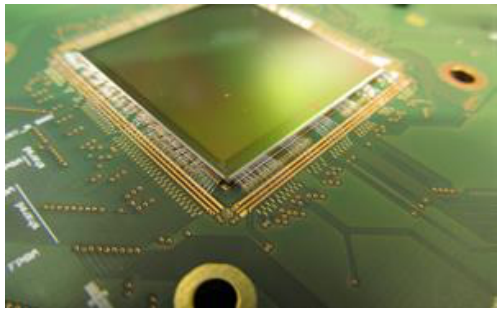
50μm pixel

DECAL
Calorimetry



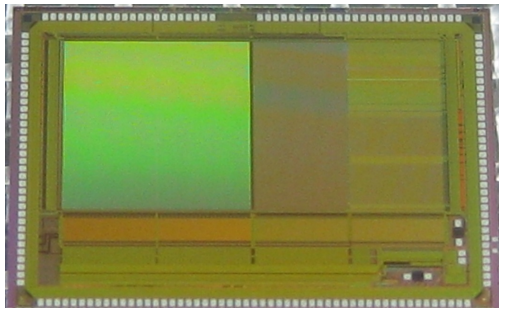
50μm pixel

PIMMS
TOF mass spectroscopy

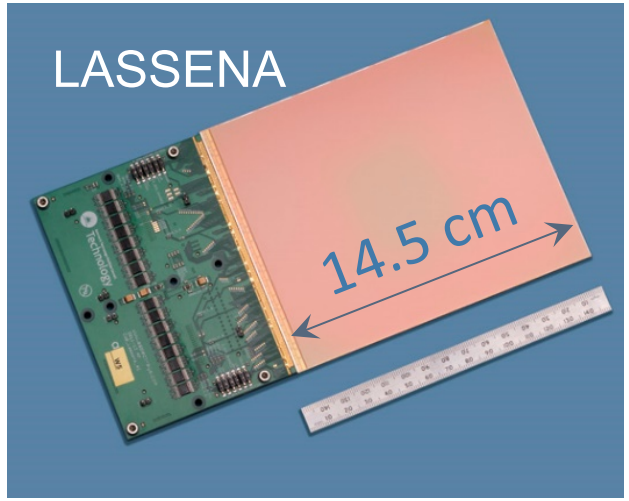


70μm pixel

CHERWELL
Calorimetry/Tracking



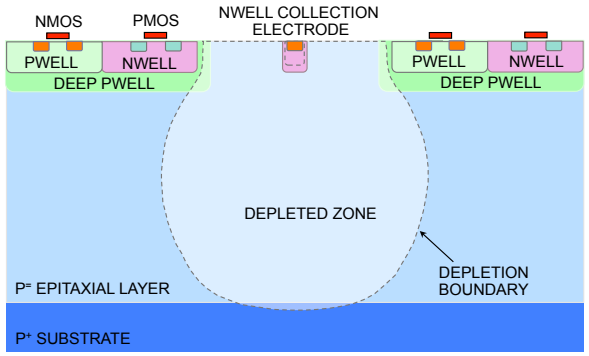
48 μm x 96 μm pixel

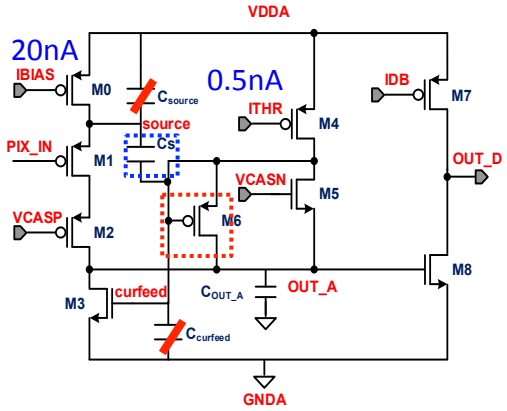


50μm pixel, waferscale

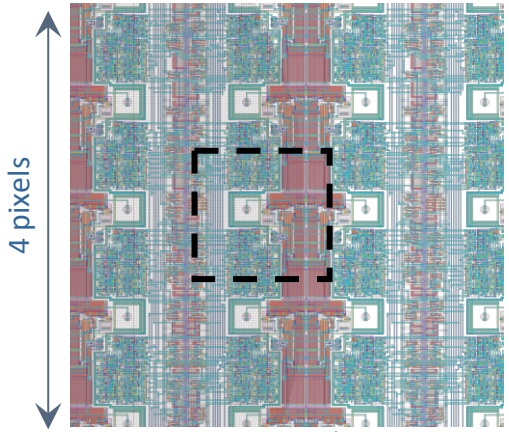
Standard INMAPS process also used for the ALPIDE (27 μm x 29 μm pixel) and MIMOSIS (CBM)

ALPIDE chip in ALICE ITS2

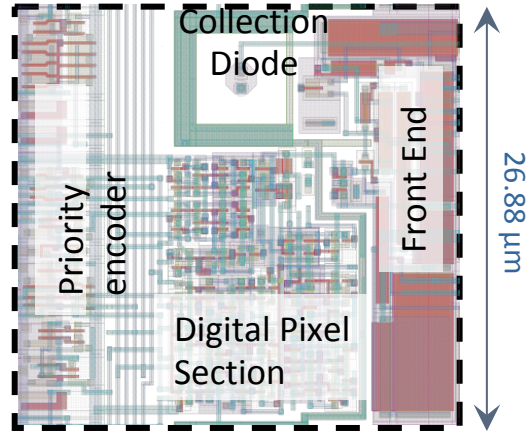




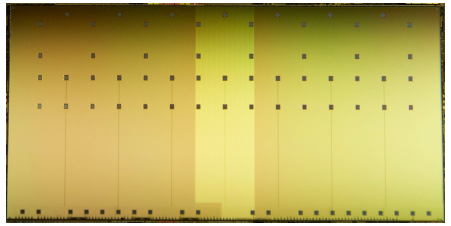
Matrix layout

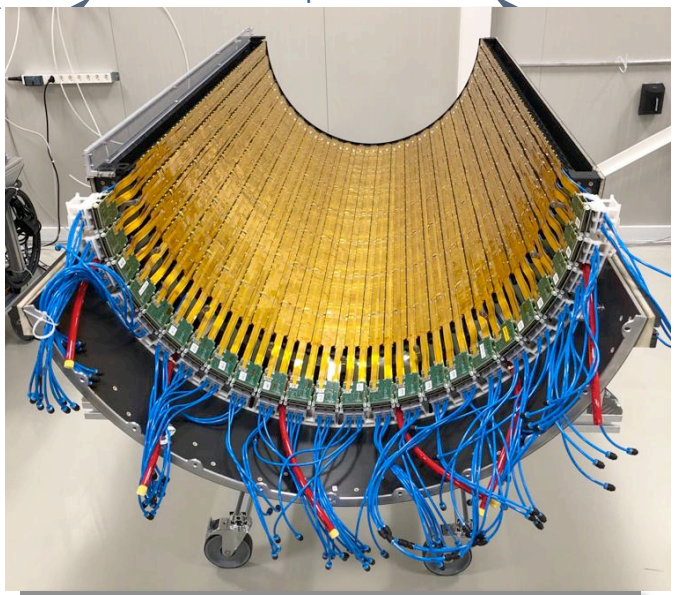


Pixel layout

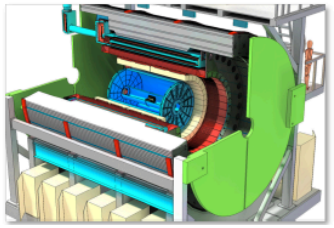


- TJ CMOS 180 nm INMAPS imaging process (TJ) > 1kΩ cm p-type epitaxial layer
- Small 2 µm n-well diode and reverse bias for low capacitance C(sensor+circuit) < 5 fF
- 40 nW continuously active front end D. Kim et al. DOI 10.1088/1748-0221/11/02/C02042
- Q_{in}/C ~ 50 mV, analog power ~ $(Q/C)^{-2}$ NIM A 731 (2013) 125
- Zero-suppressed readout, no hits no digital power G. Aglieri et al. NIM A 845 (2017) 583-587
- Ratio between 15 x 30 mm^2 and 10 m^2 in the experiment not ideal -> stitching -> P. Riedler's presentation
- ALPIDE (ALICE Pixel Detector) to be used for several other physics experiments, in space and for medical applications

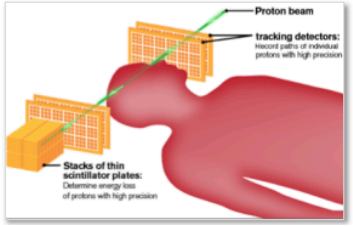




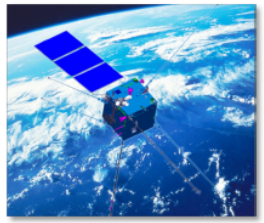
Half outer barrel (layer 6)
~ 2.47 Gpixels covering ~ 2 m^2 sensitive area



sPHENIX



Proton CT (tracking)



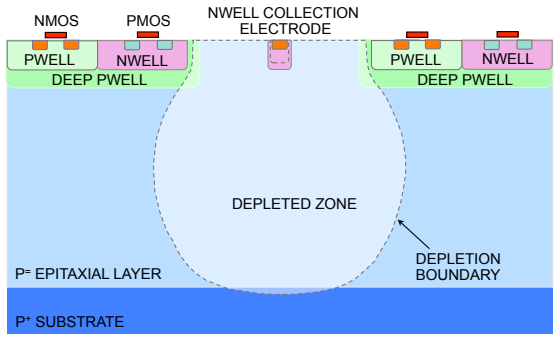
CSES – HEPD2

Design team: G. Aglieri, C. Cavicchioli, Y. Degerli, C. Flouzat, D. Gajanana, C. Gao, F. Guilloux, S. Hristozkov, D. Kim, T. Kugathasan, A. Lattuca, S. Lee, M. Lupi, D. Marras, C.A. Marin Tobon, G. Mazza, H. Mugnier, J. Rousset, G. Usai, A. Dorokhov, H. Pham, P. Yang, W. Snoeys (Institutes: CERN, INFN, CCNU, YONSEI, NIKHEF, IRFU, IPHC) and comparable team for test
1 MPW run and 5 engineering runs 2012-2016, production 2017-2018

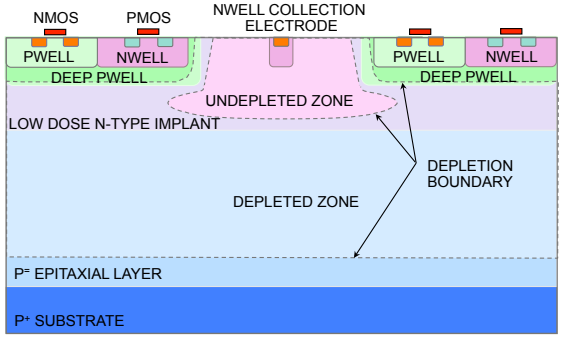
Sensor optimization: Moving the junction away from the collection electrode

for full depletion, better time resolution and radiation hardness… and better efficiency, especially for thin sensors

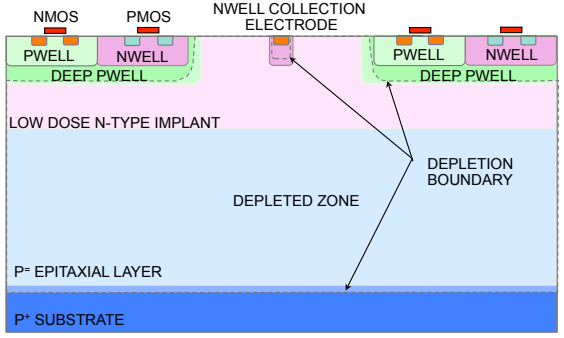
Main damage mechanism: displacement damage (Non-Ionizing Energy Loss or NIEL)
Collect signal charge FAST before it gets trapped => depletion and large electric field…



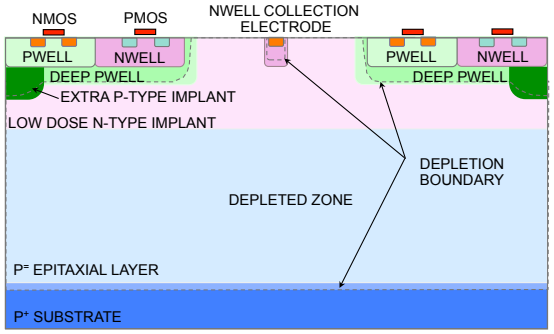
Standard, not fully depleted (ALPIDE)



Not fully depleted at low reverse bias



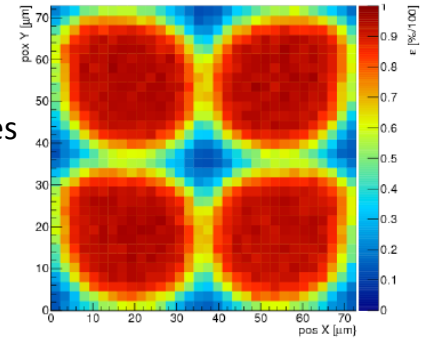
Depletion at higher reverse bias (MALTA1, MONOPIX)



Further improvements by influencing the lateral field

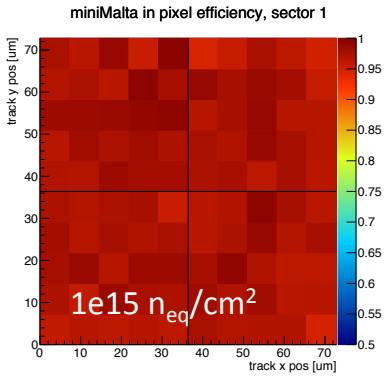
Additional implant for full depletion
=> order of magnitude improvement
Side development of ALICE for ALPIDE
NIMA 871 (2017) pp. 90-96
Triggered development in ATLAS
H. Pernegger et al, 2017 JINST 12 P06008

Efficiency drop at pixel edges after irradiation for 36.4 x 36.4 µm² pixel needs improvement
E. Schioppa et al, VCI 2019



3D TCAD simulation
M. Munker et al. PIXEL2018

Significant improvement verified
Also encouraging results with Cz
H. Pernegger et al., Hiroshima 2019
M. Dyndal et al., arXiv:1909.11987



Other similar developments for fast charge collection and depletion:

T.G. Etoh et al., Sensors 17(3) (2017) 483, https://doi.org/10.3390/s17030483
H. Kamehama et al., Sensors 18(1) (2017) 27, https://doi.org/10.3390/s18010027…
L. Pancheri et al., PIXEL 2018, https://doi.org/10.3390/s18010027
C. Kenney et al. NIM A (1994) 258-265, IEEE TNS 41 (6) (1994), IEEE TNS 46 (4) (1999)

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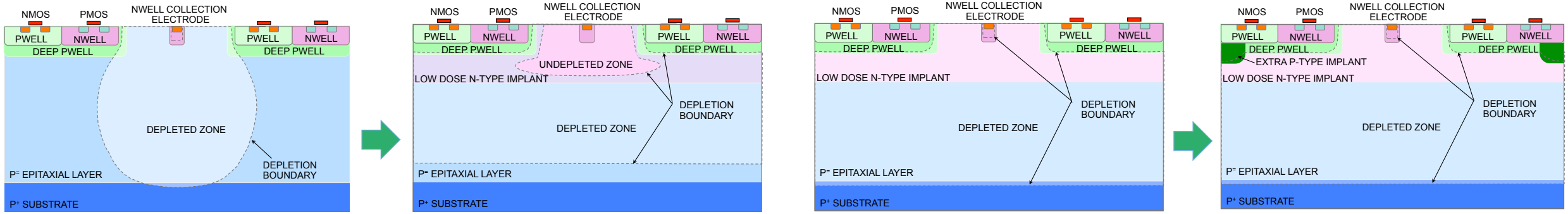


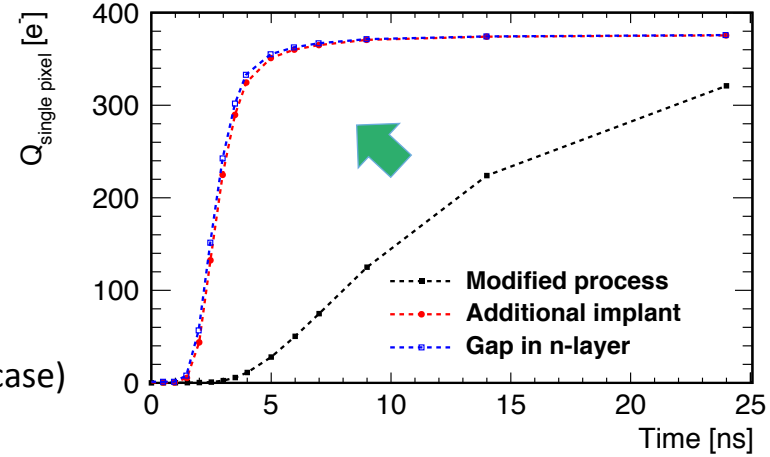
Standard, not fully depleted (ALPIDE)

Not fully depleted at low reverse bias

Depletion at higher reverse bias (MALTA1, MONOPIX)

Further improvements by influencing the lateral field

Hit in the pixel corner (= worst case)



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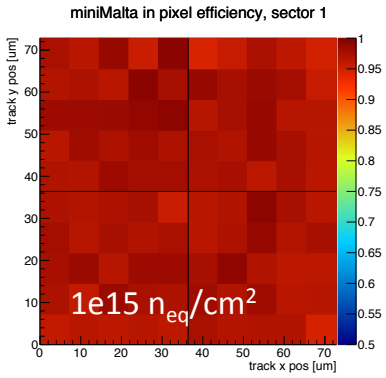

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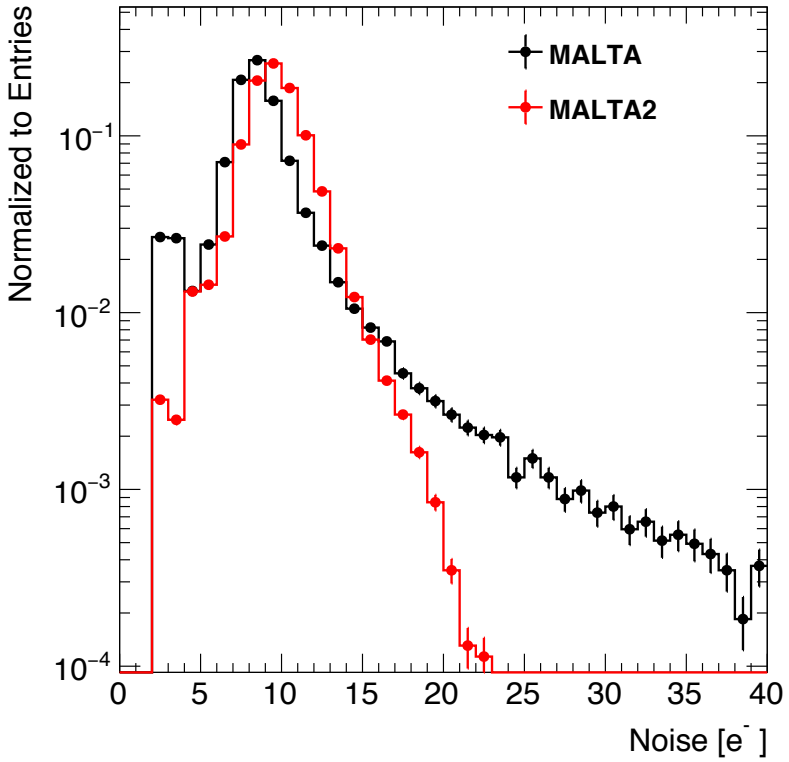
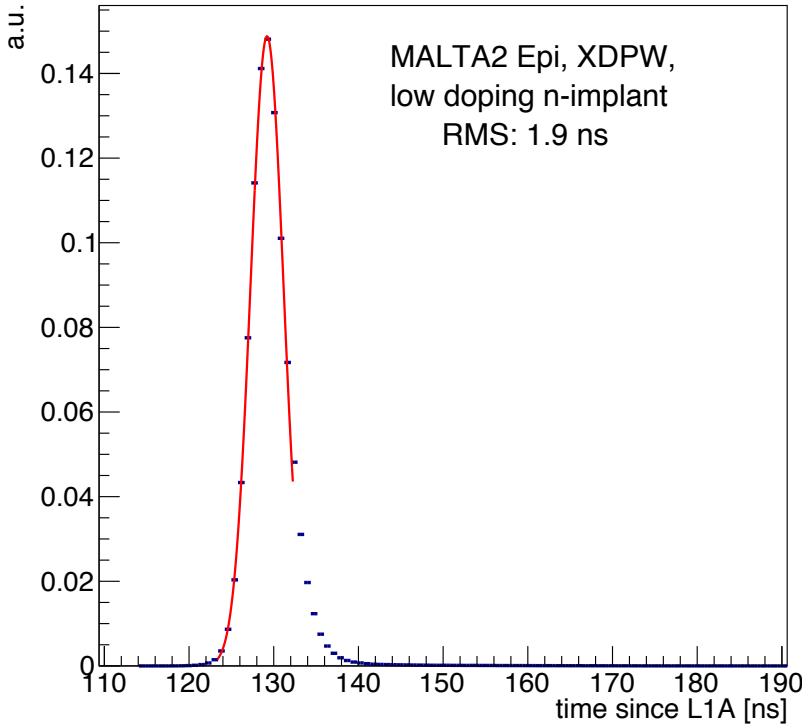
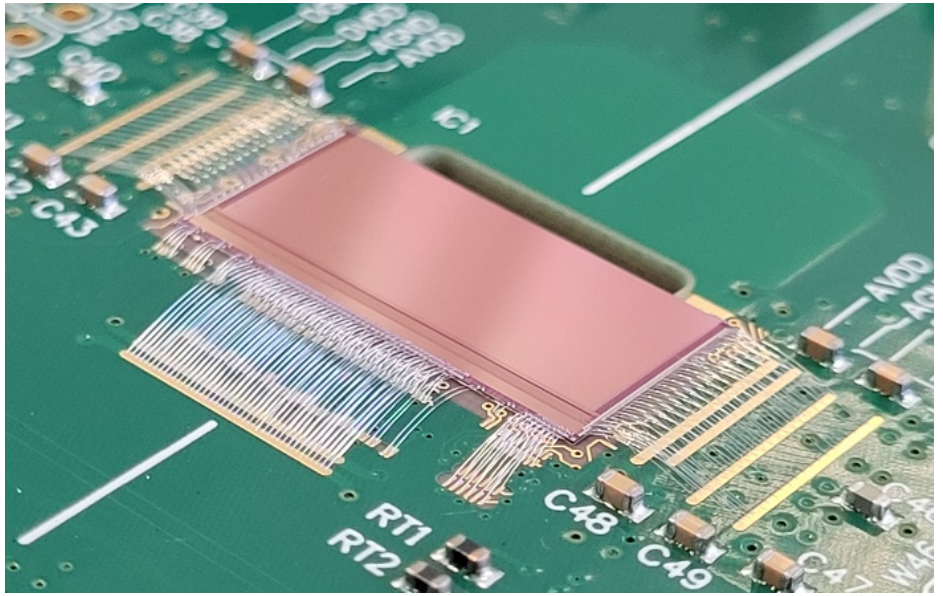
S. Kawahito et al., Sensors 18(1) (2017) 27, https://doi.org/10.3390/s18010027
L. Pancheri et al., PIXEL 2018, https://doi.org/10.3390/s18010027
C. Kenney et al. NIM A (1994) 258-265, IEEE TNS 41 (6) (1994), IEEE TNS 46 (4) (1999)

MALTA2: improved front end





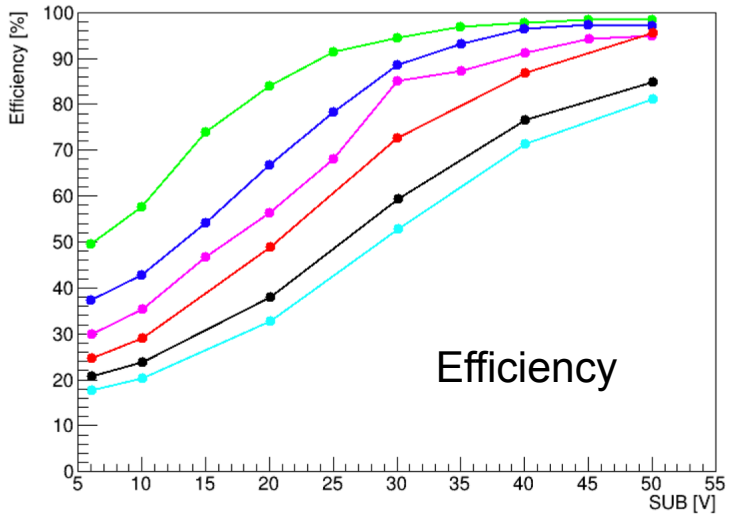


M. Van Rijnbach et al. https://doi.org/10.1088/1748-0221/17/04/C04034
Leblanc et al., https://doi.org/10.1109/TNS.2022.3170729
F. Piro et al. https://doi.org/10.1109/TNS.2022.3170729

- Significant reduction of 1/f noise: opens operation at thresholds around 100 e- and better timing resolution
- Continued testing of radiation tolerance with MALTA and MALTA2
- Development of telescope with MALTA M. Van Rijnbach et al. tBTTB 2022,

High resistivity Czochralski material

Increased signal due to depletion layer extending deeper into the bulk material



IDB/ITHR 120/20

IDB/ITHR 120/40

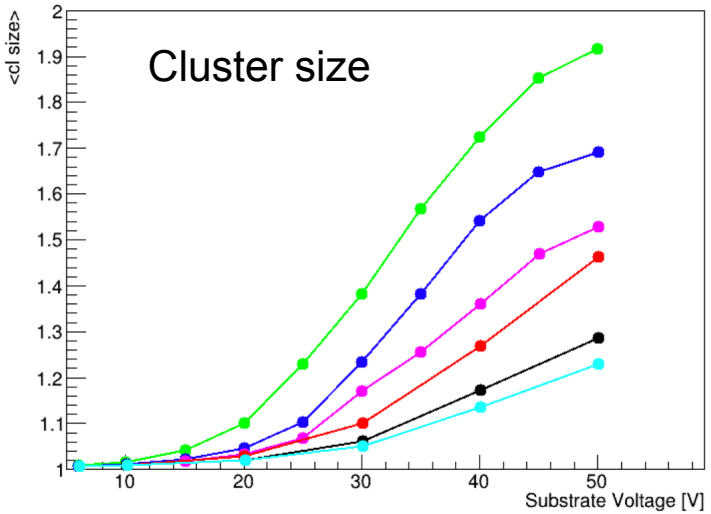
IDB/ITHR 120/60

IDB/ITHR 120/80

IDB/ITHR 120/100

IDB/ITHR 120/120

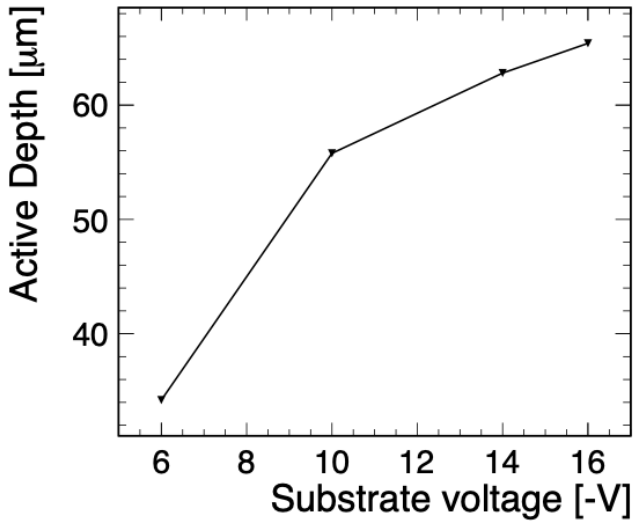
$2\ 10^{15}\ n_{eq}/cm^2$



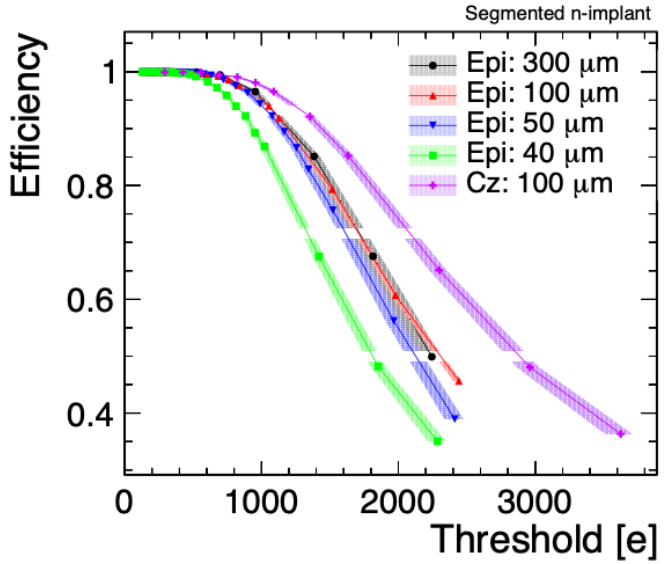
MALTA

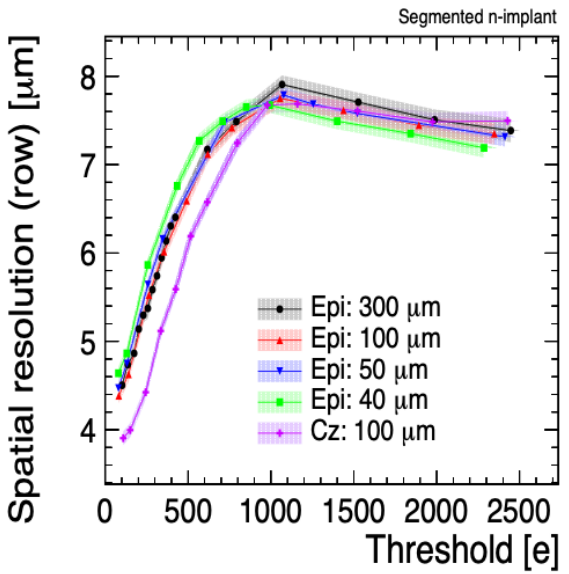
More margin at larger fluencies, higher cluster size

See also H. Pernegger et al, Vertex 2022



K. Dort et al. submitted to NIMA



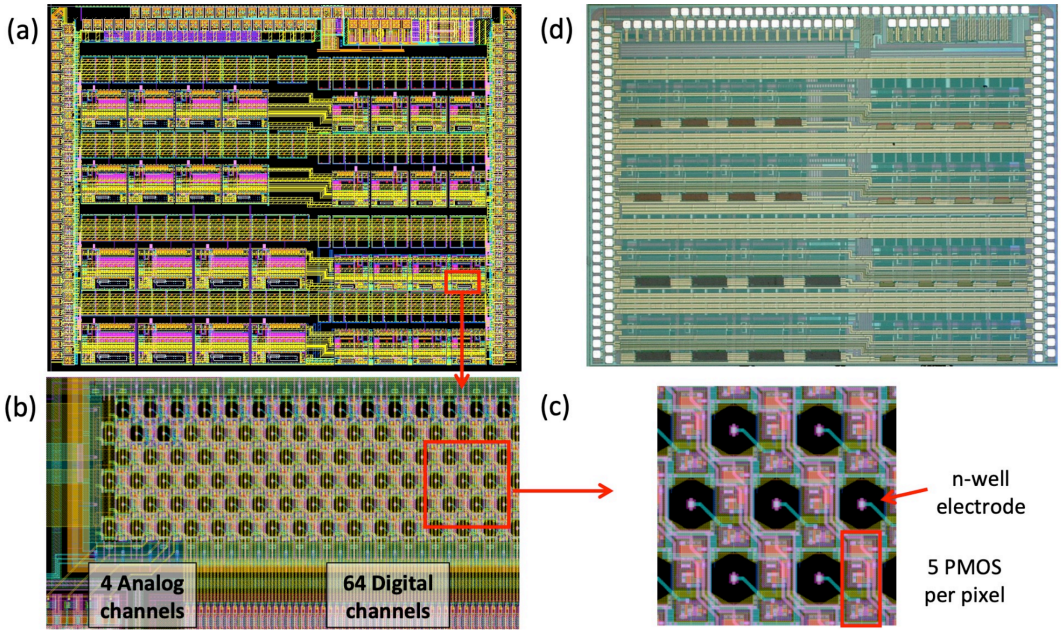


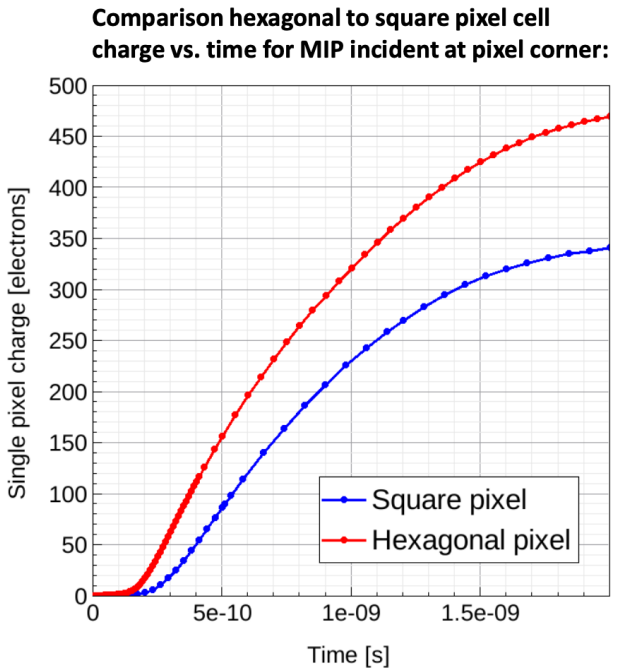
CLICTD

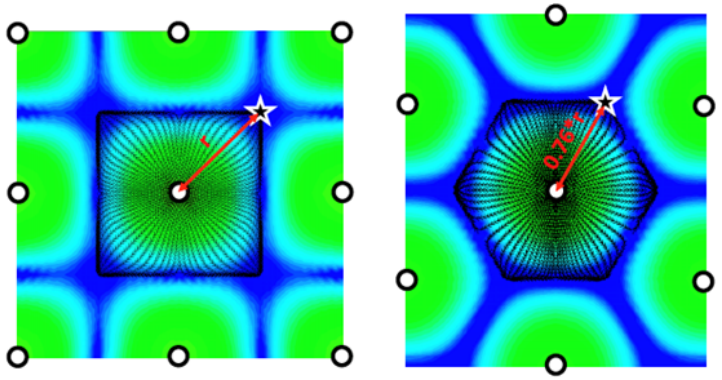
larger efficiency window

better position resolution at low charge thresholds

FASTPIX ATTRACT project: ^{90}Sr Risetime distributions







Reduction of the minimal distance between collection electrodes while maintaining area for circuitry

T. Kugathasan et al., https://doi.org/10.1016/j.nima.2020.164461 (ATTRACT: INFN, Ritsumeikan University and CERN)

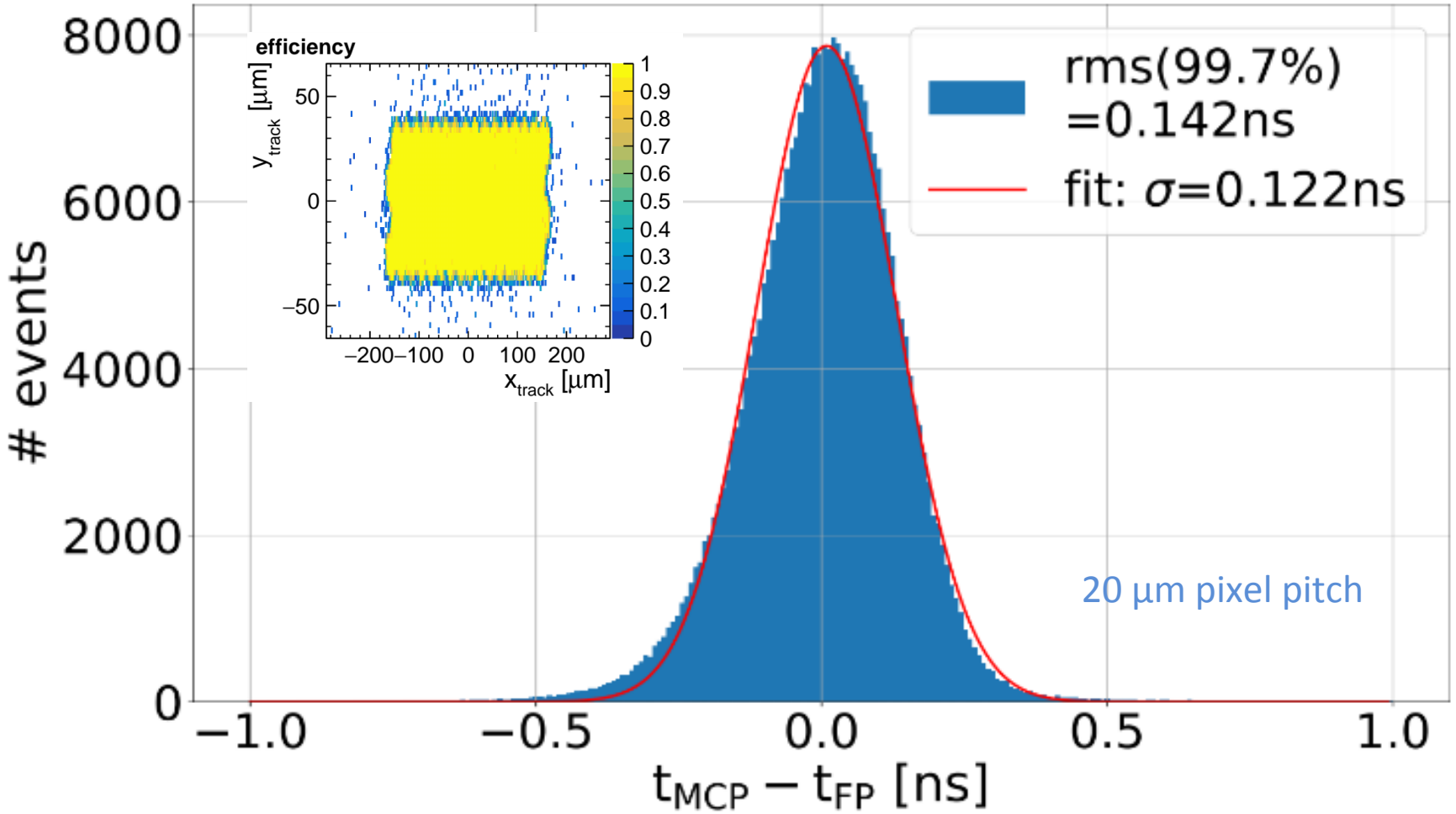
Direct relation between charge collection and process variant (TowerJazz 180nm)

Significant impact even at very small pixel pitch

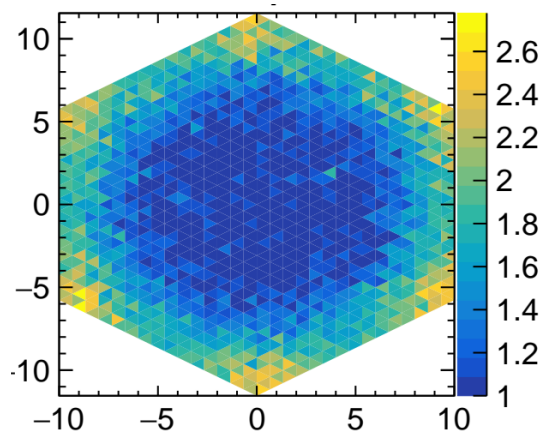
Hexagonal pixels

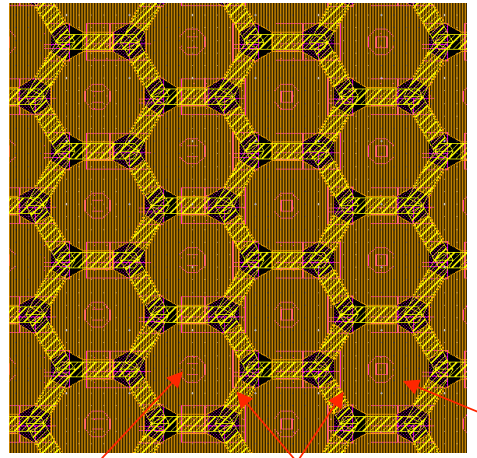
- better approximation of a circle
- charge sharing in the corners between 3 pixels instead of 4 -> more margin
- collection electrodes on hexagonal grid, circuit to remain on Manhattan layout

FASTPIX: sensor optimization for hexagonal pixels



Cluster size





- 8.66, 10, 15 and 20 µm pixel pitch
- Time resolution better than 150 ps at full efficiency, TOT corrected

https://www.mdpi.com/2410-390X/6/1/13

J. Braach, E. Buschmann, D. Dannheim, K. Dort, T. Kugathasan, M. Munker, M. Vicente

FASTPIX started as an ATTRACT project funded by the EC Grant Agreement 777222, with INFN, Ritsumeikan U. and CERN

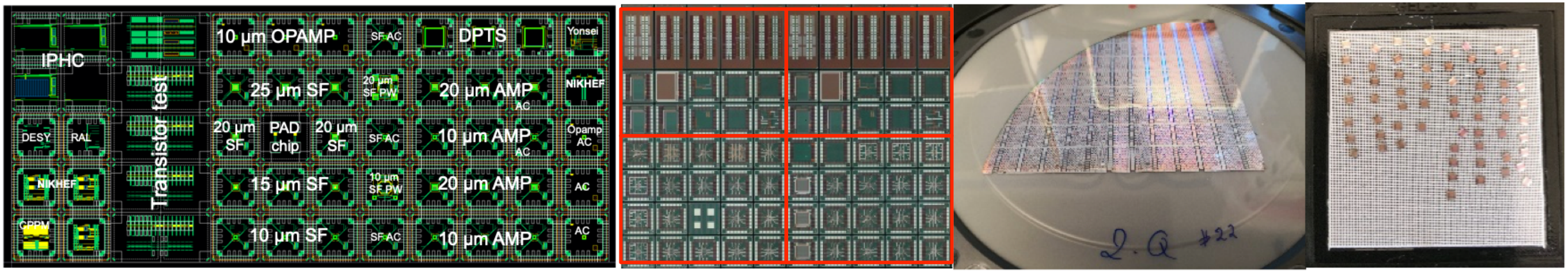
Moving to deeper submicron CMOS (CERN EP RD WP1.2)

First technology selected: TPSCo 65 nm ISC

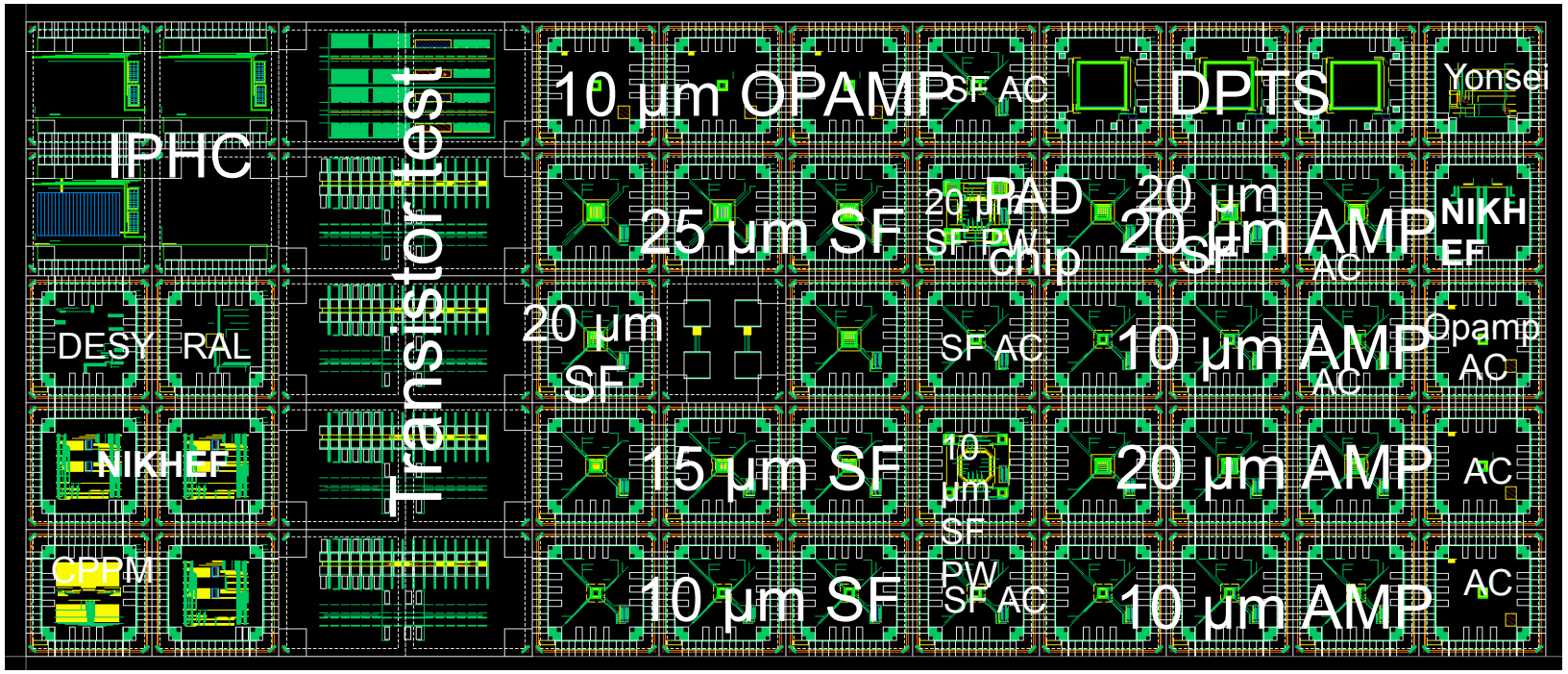
- TPSCo (joint venture TJ & Panasonic): several 65 nm flavors: high density logic, RF, and imaging (ISC)
- ISC preferred: 2D stitching experience, special sensor features, different starting materials, lower defect densities, etc
- Initially 5 metal layers, now 7 metals
- NDA (M. Campbell, L. Pocha & M. Ayass) for participating groups
- Finance Committee approval for stitched runs

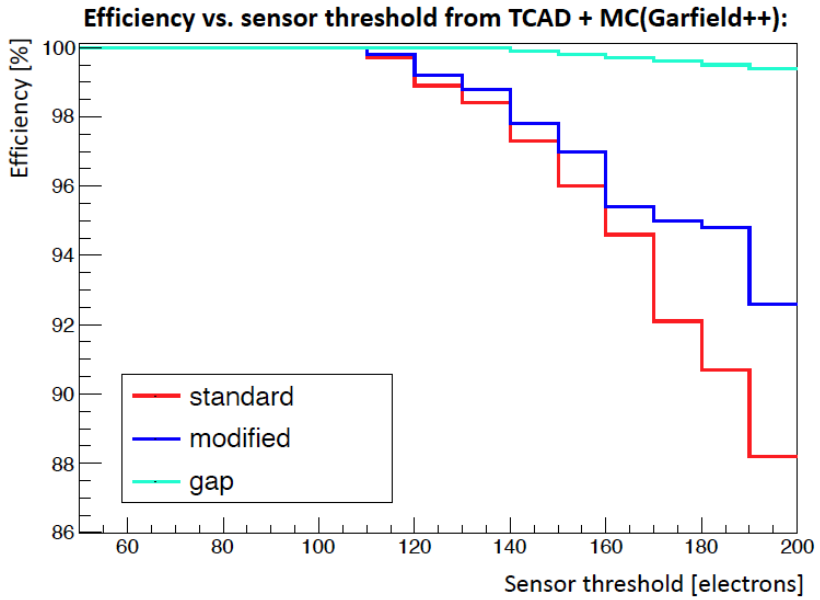
First submission: Multi Layer per Reticle MLR1 details in Gianluca's presentation

- Significant contribution from outside groups (from ALICE but not only) to design and test (!), also financially
- Many test chips of 1.5 x 1.5 cm^2 or twice that size.
- GDS submitted Dec 1, 2020, chips ready to test, Sept, 2021



CERN EP-RD WP1.2 TPSCo 65 nm





Jan Hasenbichler

- IPHC: rolling shutter larger matrices, DESY: pixel test structure (using charge amplifier with Krummenacher feedback, RAL: LVDS/CML receiver/driver, NIKHEF: bandgap, T-sensor, VCO, CPPM: ring-oscillators, Yonsei: amplifier structures
- Significant effort from participating institutes, also financially
- Transistor test structures, analog pixel (4x4 matrix) test matrices in several versions (in collaboration with IPHC with special amplifier), digital pixel test matrix (DPTS) (32x32), pad structure for assembly testing.
- Converged with 4 splits of 3 wafers, back from foundry beginning of June
- Process modifications even more needed due to thinner epitaxial layer, similar results as on 180nm process

MAIN RESULTS MLR1 65 nm

See also A. Kluge's presentation

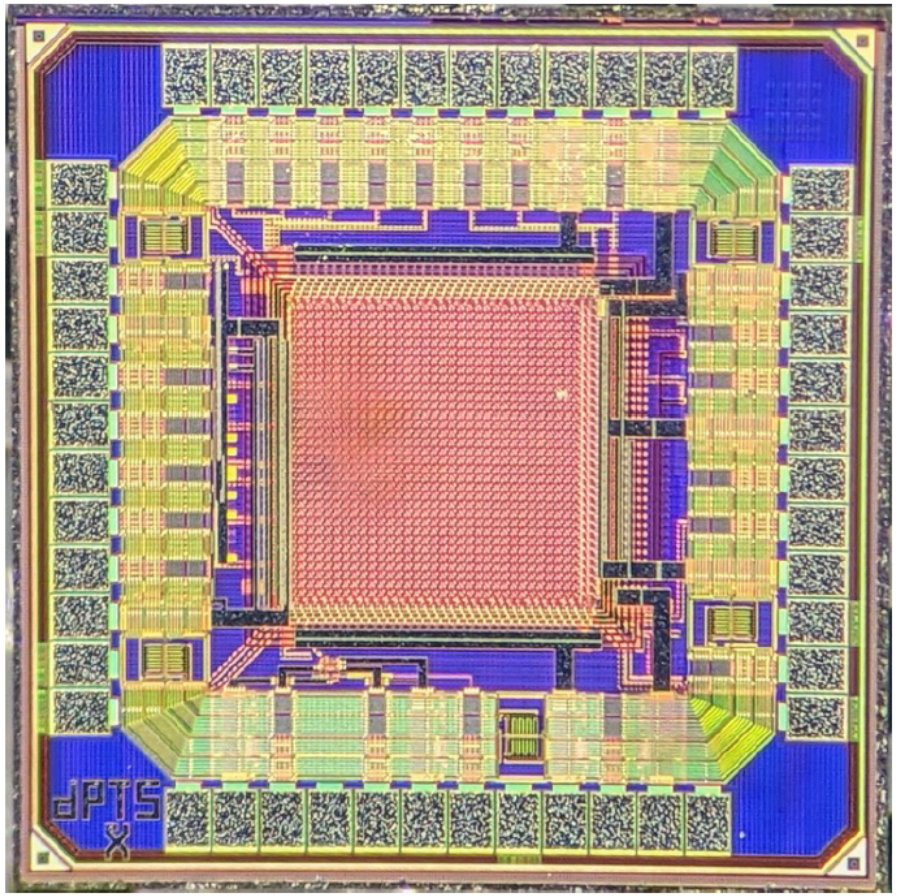
EP R&D

Functionality

- Fully efficient sensor, analog front end, digital readout chain in 15 x 15 µm^2 pixel (DPTS) including sensor optimization
- Sensor optimization clearly accelerates charge collection
- Frontend tunable from 10 nA to 5 µA (power – time resolution tradeoff)
- Measurements at 100 nA, time resolution ~7.5 ns

Radiation effects

- Single event upset cross-section according to expectations
- Circuit radiation tolerance TID in line with other 65 nm technologies
- Sensor radiation tolerance NIEL: analysis in progress:
  - ~ 99% efficiency after 1e15 n_{eq}/cm^2 and 10 Mrad at room temperature
  - higher fluencies to be investigated, also at lower temperature



Building knowledge about this technology for general interest

- Very significant contribution from the ALICE experiment
- Towards full technology validation for our applications

Next submission Stitched Engineering Run ER1

- Learning about stitching and continue learning about the technology

Fully in line with ECFA RD Goals

The R&D on MAPS will combine multiple strands that can build on common features, either gradually in time or in parallel, linking also with the further developments in microelectronics:

- MAPS for small-pixel trackers in sub-micron node(s) for smaller pixels pitch and stitching process for large area sensors to reach ultimate precision and radiation length in vertex detectors;

  DPTS 15 µm pixel pitch, stitched devices in ER1 18 µm and 22.5 µm

- MAPS for small-pixel trackers with radiation-hard cell designs and high hit-rate capability (sufficient charge collection after 10^{15} n_{eq}/cm^2 to 10^{16} n_{eq}/cm^2 non-ionising energy loss (NIEL), single event upsets (SEU) and single event effects (SEE) tolerant and power-optimised logic, concepts for high data volumes handling on a sensor);

  DPTS 10^{15} n_{eq}/cm^2 at room temperature, samples with higher fluencies are investigated

  circuit total ionizing radiation tolerance and SEU cross-sections in line with other deep submicron CMOS

- MAPS designs to reach ultimate timing precision in different processes;

  FASTPIX < 150 ps with small collection electrode in 180nm, expected better in 65 nm, being confirmed

- MAPS with reduced granularity and very low power consumption in very large area detectors for tracking and calorimetry applications.

  DPTS 10 − 1000 nA, sensor variant with gap designed to maintain efficiency for larger pixel pitches

Stitched sensor: challenges

Power consumption: only considering the matrix, pixel size 200 μm^2 (~ 15 µm pixel pitch on a hexagonal grid) 1nA/pixel = 0.5 mW/cm^2

Dynamic hit-rate related power density proportional to column height (28 cm, on average 14 cm x CV^2) and hit rate

- Avoid distribution of a clock to every pixel (150 – 200 mW/cm^2 for 40 MHz)

Static leakage not negligible at all, analog power determined by sensor Q/C (slow front end ~10-20 nA)

Power distribution:

- Additional thick metal(s) for power distribution to contain voltage drop, otherwise 10's of $mV/mW/cm^2$
- Power regulation for uniformity
- Beyond 50 mW/cm^2 :
  - Power pads no longer only at the bottom, or
  - on-chip serial powering,

    interesting even for lower hit rates, for a single point connection of power/data/slow control

    1mW/cm^2 corresponds to 280 mA…

Yield:

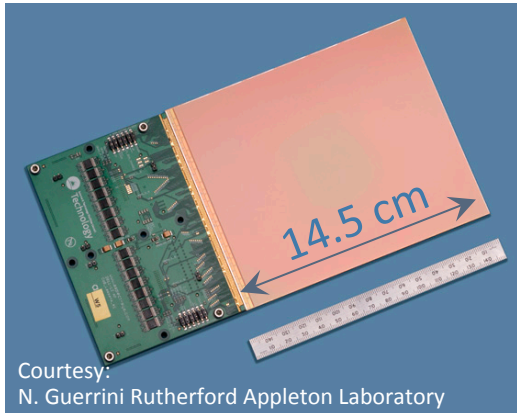
- Conservative stitching rules represent a significant area penalty, need to find ways to regain density
- Power regulation for uniformity but also segmented with current limitation to protect against shorts

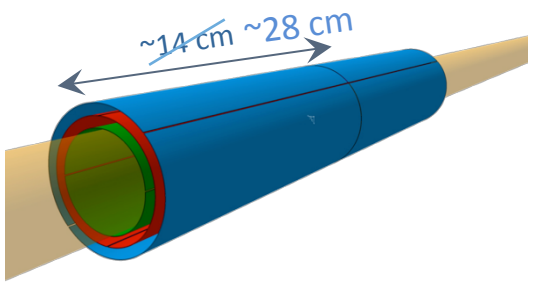
Very large chip:

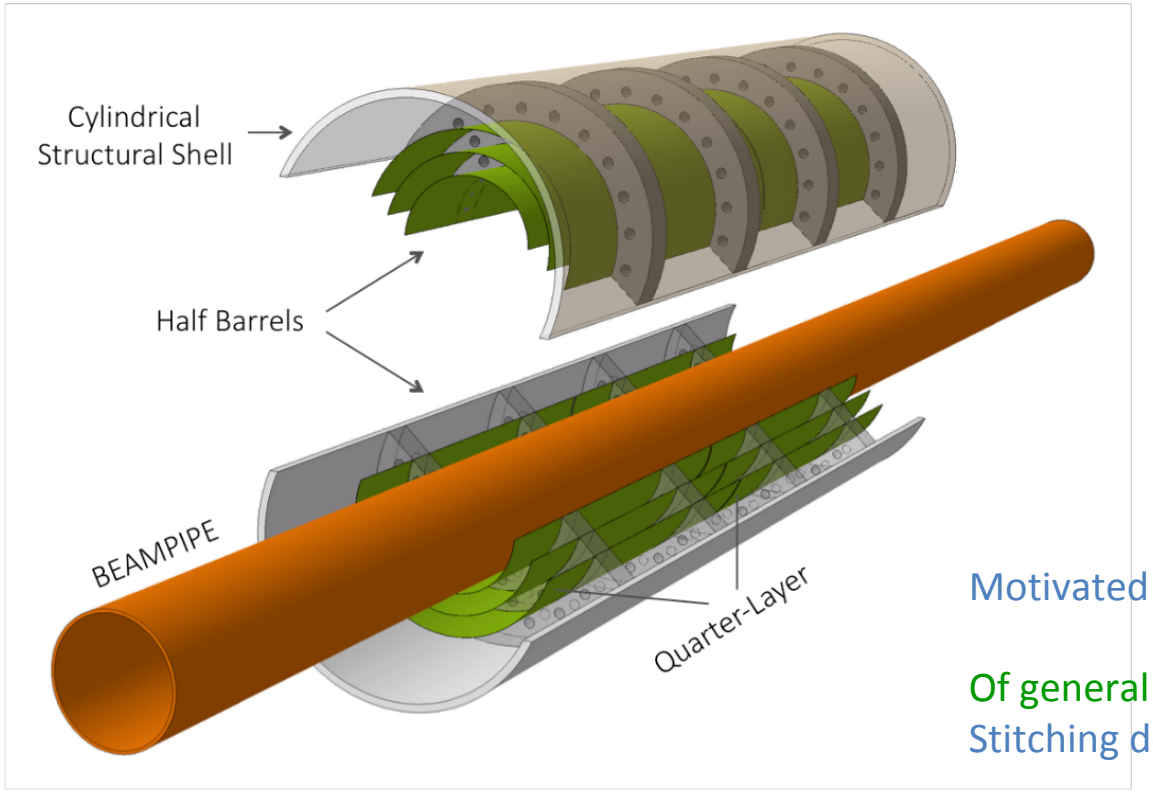
- One column ~ 2^{14} pixels, extract hit info with limited number of lines
- Need digital on-top design and verification

Stitching for better integration, lower mass and constructing larger areas

Exploiting flexible nature of thin silicon and stitching







Truly cylindrical vertex detector
New ultra light barrel in LS3 0.05% X/X0 per layer
ALICE-PUBLIC-2018-013

ALICE ITS3 upgrade
see A. Kluge's presentation

Motivated by lower material budget

Of general interest to cover large areas
Stitching details and bending

-

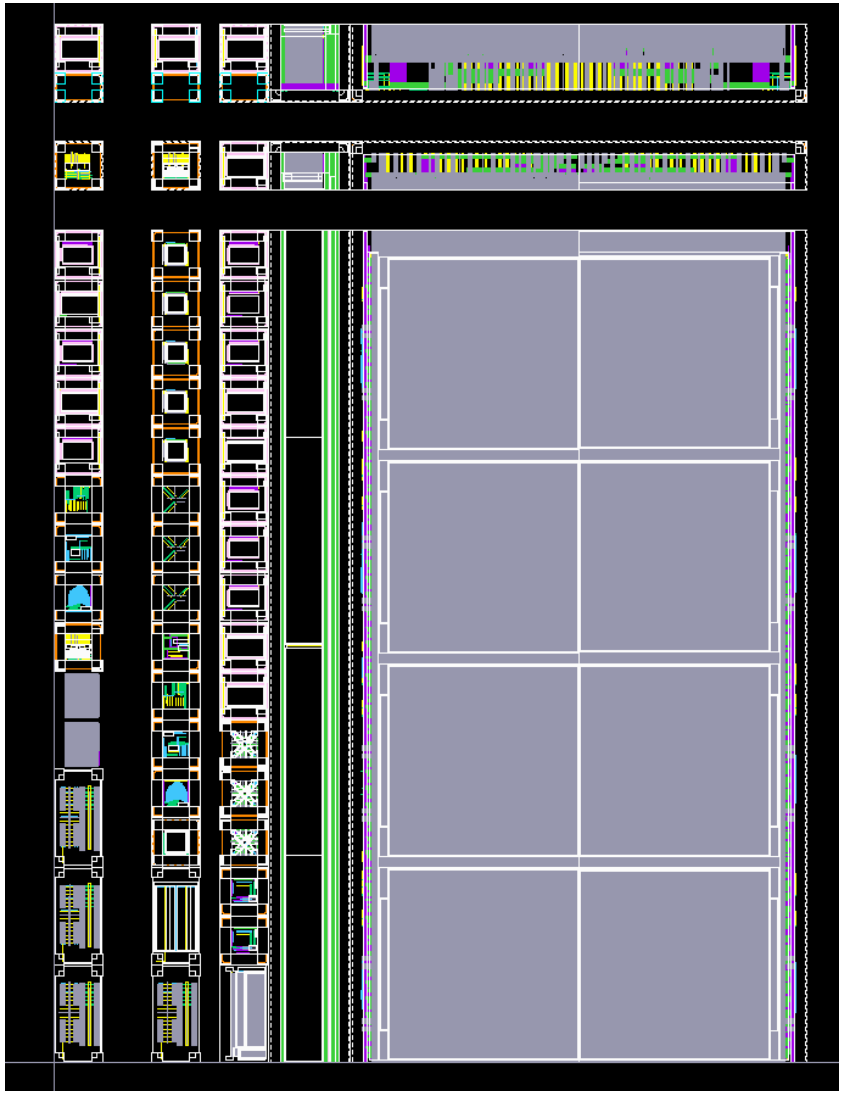
Work under the assumption of a wafer-scale sensor
~28 x 10 cm^2, to be revised if needed

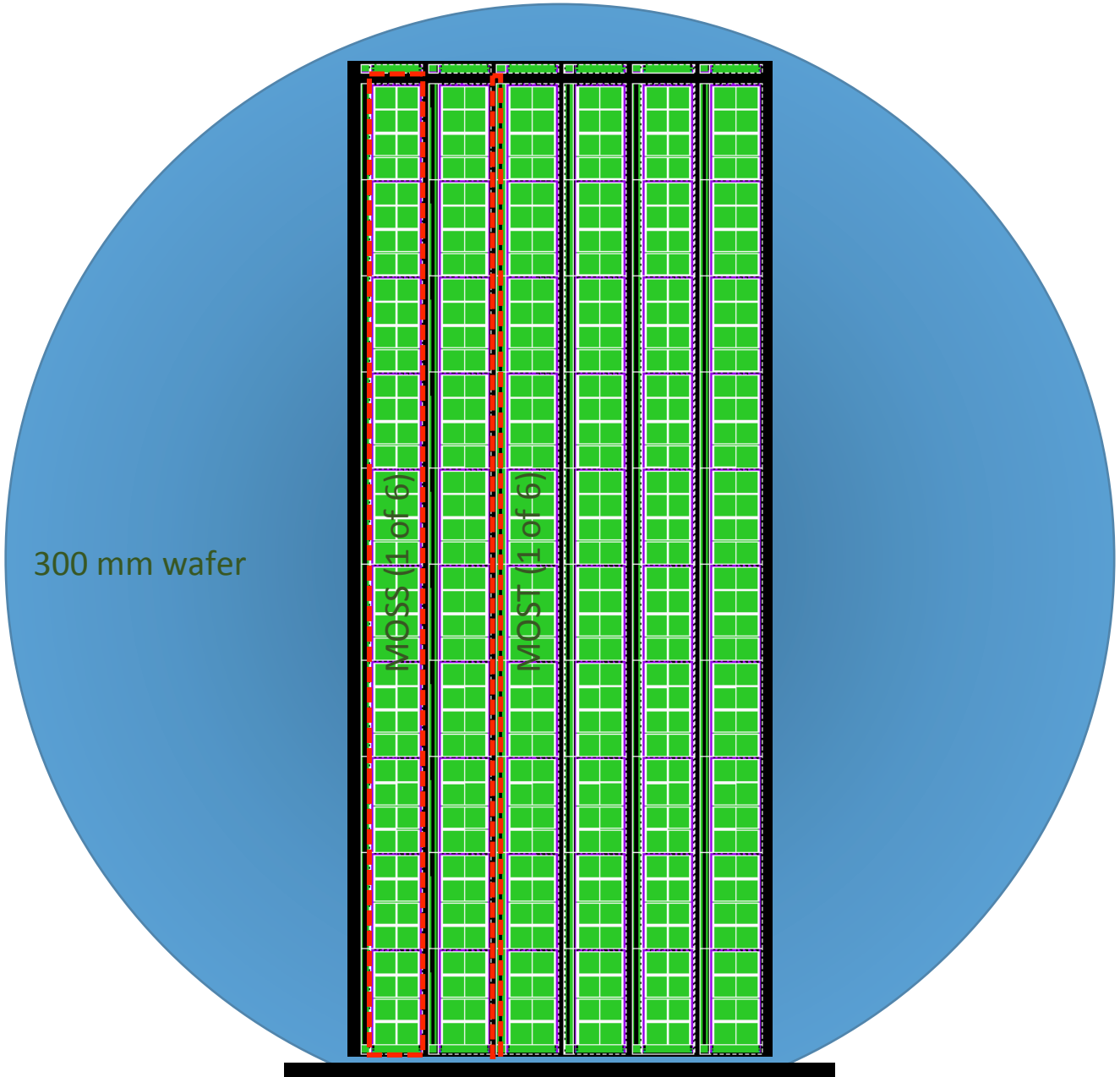
Power budget ~ 20 mW/cm^2 for ~2.5 $Mhit/cm^2/s$

ER1 Submission (together with ALICE)

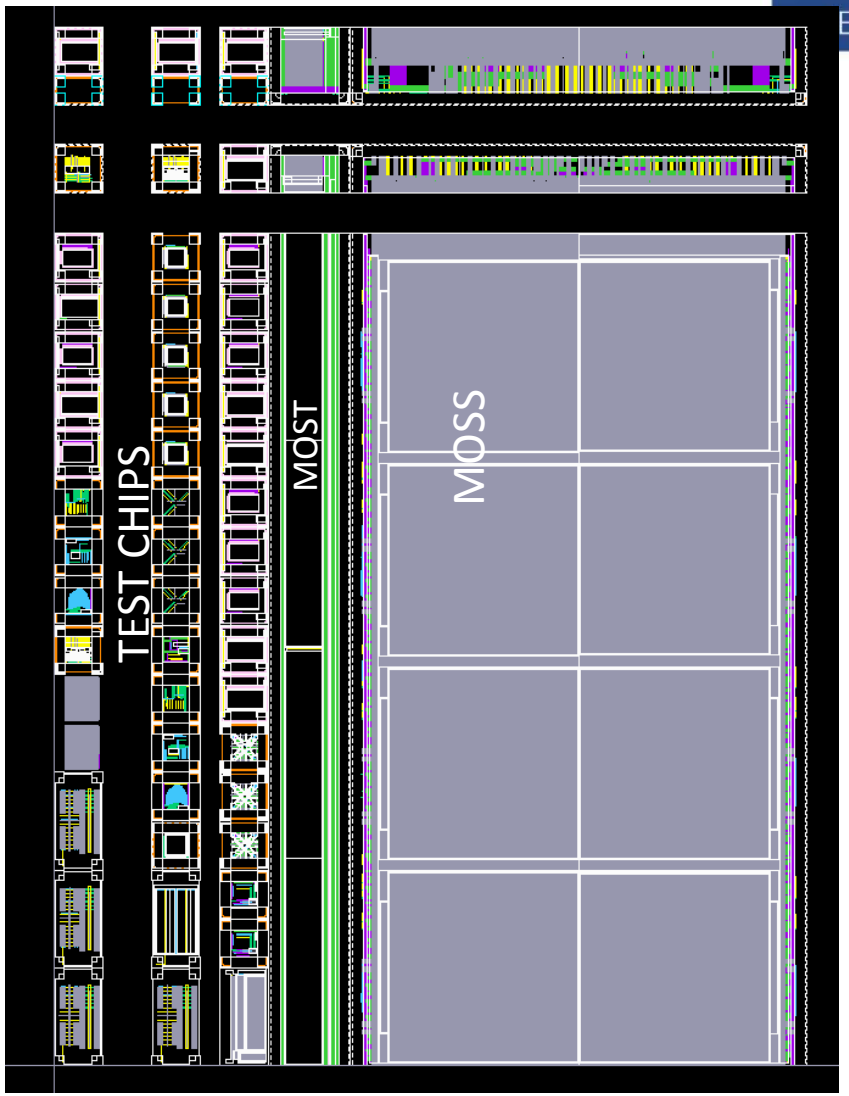
- Learn and prove **stitching**
- Two large *stitched* sensor chips (MOSS, MOST)
- Multiple small *Test Chips*
  - Pixel and Circuit Prototypes
  - Fast Serial Links
- Technology and Support
  - New metal stack, new I/O libraries, new PDKs
  - Specific features of kits and libraries

Design Reticle





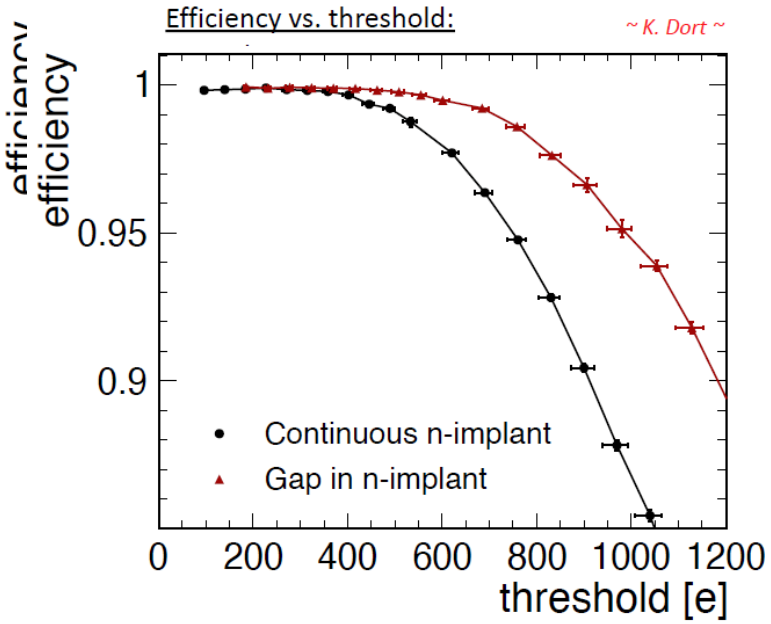
6 MOSS and 6 MOST per Wafer

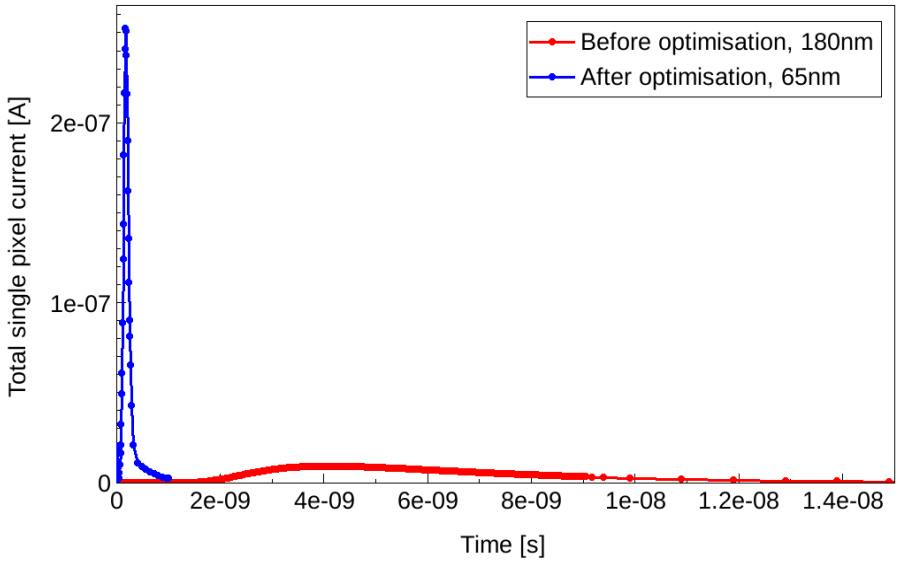


51 instances of Test Chips per Reticle

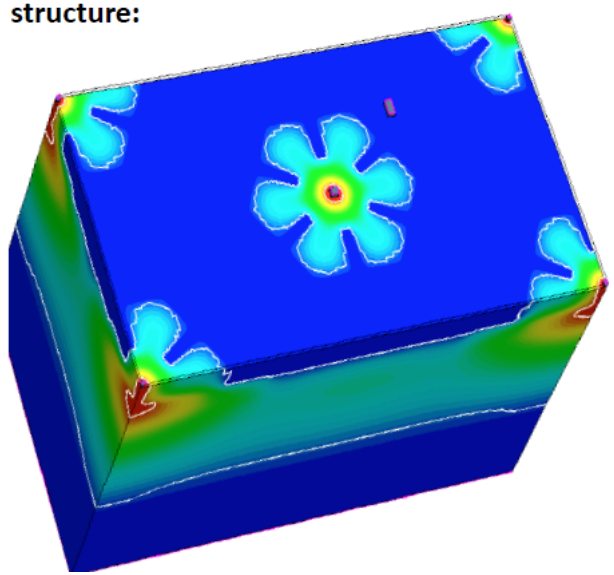
Process optimizations for small collection electrode

arXiv:2102.04025





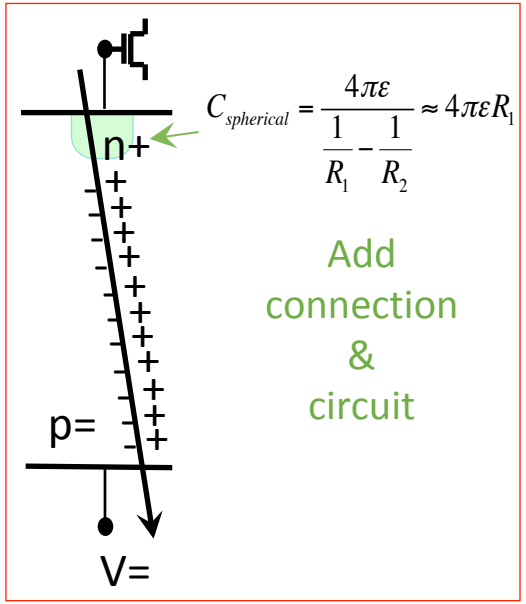
Example of complex 3D TCAD structure:



- Efficiency improvement is not only simulated but also measured, even before irradiation (see top left: efficient operating window is almost doubled)
- The optimization over different pixel pitches and flavors, and technologies has improved the timing by several orders of magnitude. Simulations of even more complex structures bring peak-to-peak variations in the order of 50 ps at the moment
- These techniques have now been applied to several chips, and technologies and are generally applicable.

See M. Muenker's CERN EP detector seminar

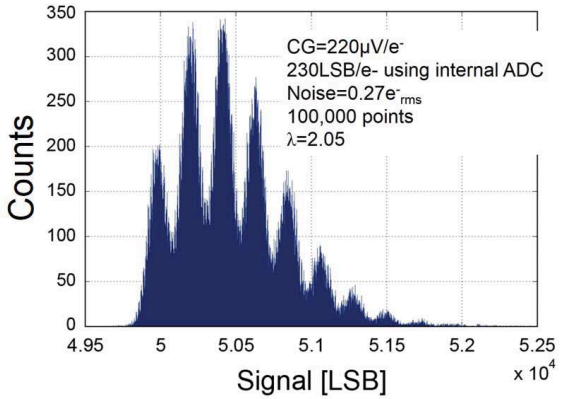
Analog power consumption ~ $(Q/C)^{-2}$ (NIM A 731 (2013) 125)



$$C_{spherical} = \frac{4\pi\varepsilon}{\frac{1}{R_1} - \frac{1}{R_2}} \approx 4\pi\varepsilon R_1$$

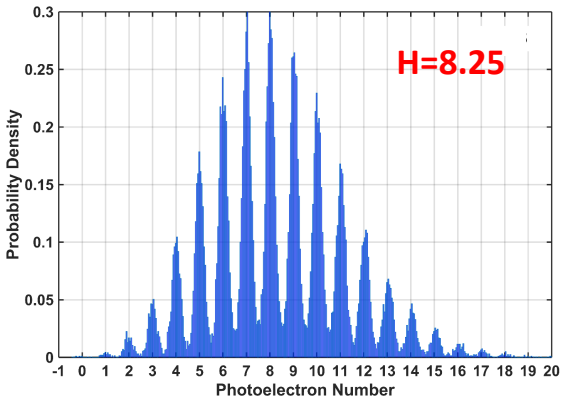
Add connection & circuit

M.W. Seo and S. Kawahito EDL 2015



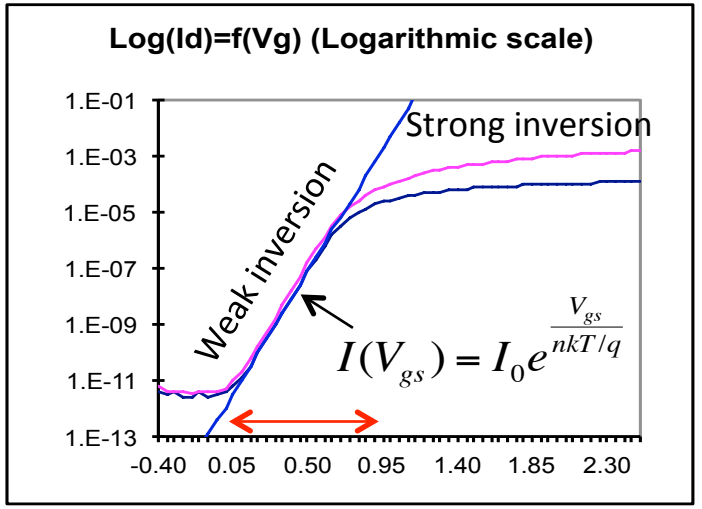
220 μV/e⁻ in 0.11 μm, C=0.73 fF

Ma, Masoodian, Wang, Fossum 2017



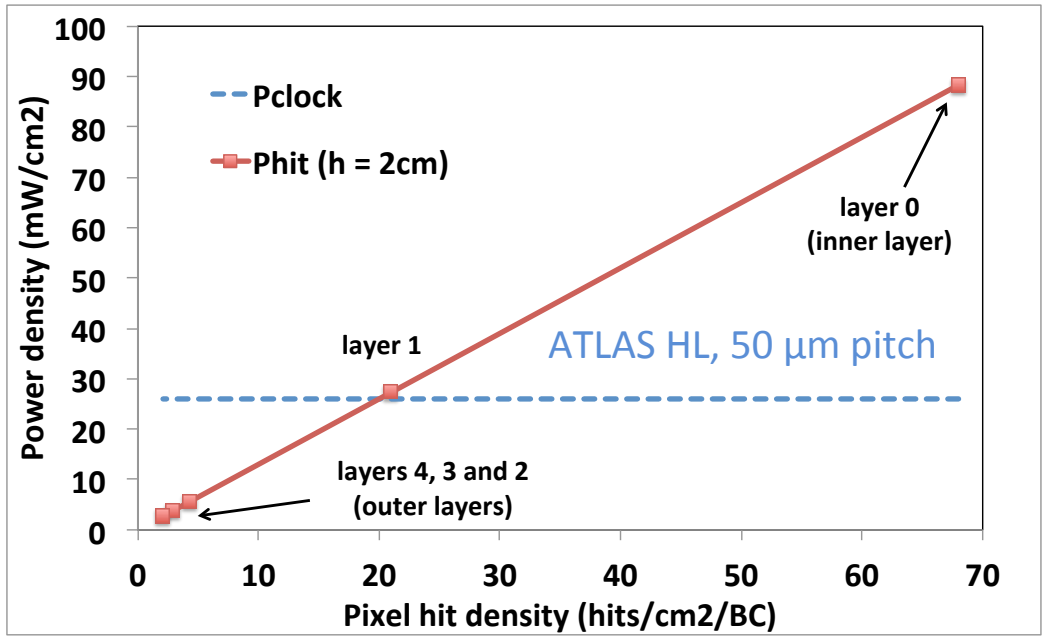
350 μV/e⁻ in 45 nm, C=0.46 fF

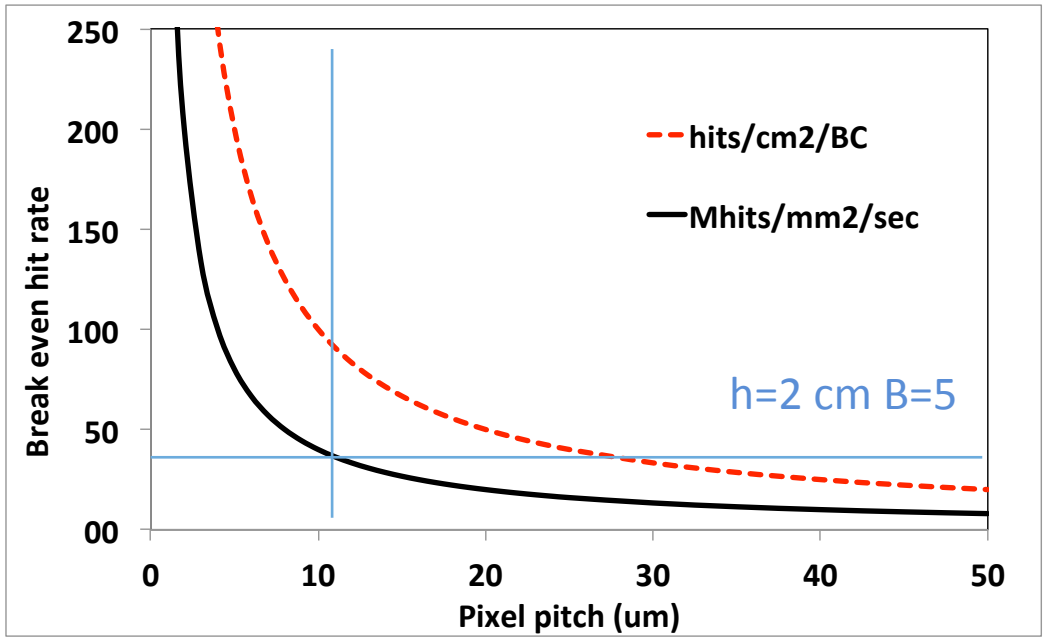
Non-linearity in weak inversion



- Q/C several 10's of mV in 180 nm
- "Conventional" approach
  - ITS3 estimate ~ 10-15 nW front end for about 10 mW/cm² (ALPIDE in 180nm ~ 40 nW), 5x area reduction
  - Increase power and speed for better timing, μW for < 1 ns F. Piro
- Reduce capacitance further, using:
  - tricks from imaging technology, at present not yet explored?
    - now very conventional nwell collection electrode…
    - Still need to extract signal charge from underneath the readout circuit !
  - deeper submicron: 2500 e- to switch inverter in 65 nm, 850 e- in 28 nm, 100 e- in 5 nm A. Marchioro 2019 CERN EP seminar
- Holy Grail: For Q/C > 400 mV, analog power consumption goes to zero.

Digital power consumption





Energy to transfer 1 bit to the periphery (assume line toggle, not step):

1 cm line at 1.8 V = CV^2 = 2 pF x $(1.8\ V)^2$ = **6.5 pJ** Lower VDD in deep submicron = 2 pF x $(1\ V)^2$ = **2 pJ**

Caveat: 2pF/cm can increase depending on line load…

- Defines break-even hit hit rate, where power for the clock = power to transfer hits to the periphery (h is column height, p is pixel pitch, B is number of bits transmitted/hit): $R_{/BC} = (hpB)^{-1}$
- At pitches < 12-13 µm should not distribute the clock over the pixel matrix, even at HL-LHC ATLAS inner pixel
- Break-even decreases with column height but very often rate is lower as well

Off-detector transmission:

ISSCC 2013 / SESSION 2 / ULTRA-HIGH-SPEE

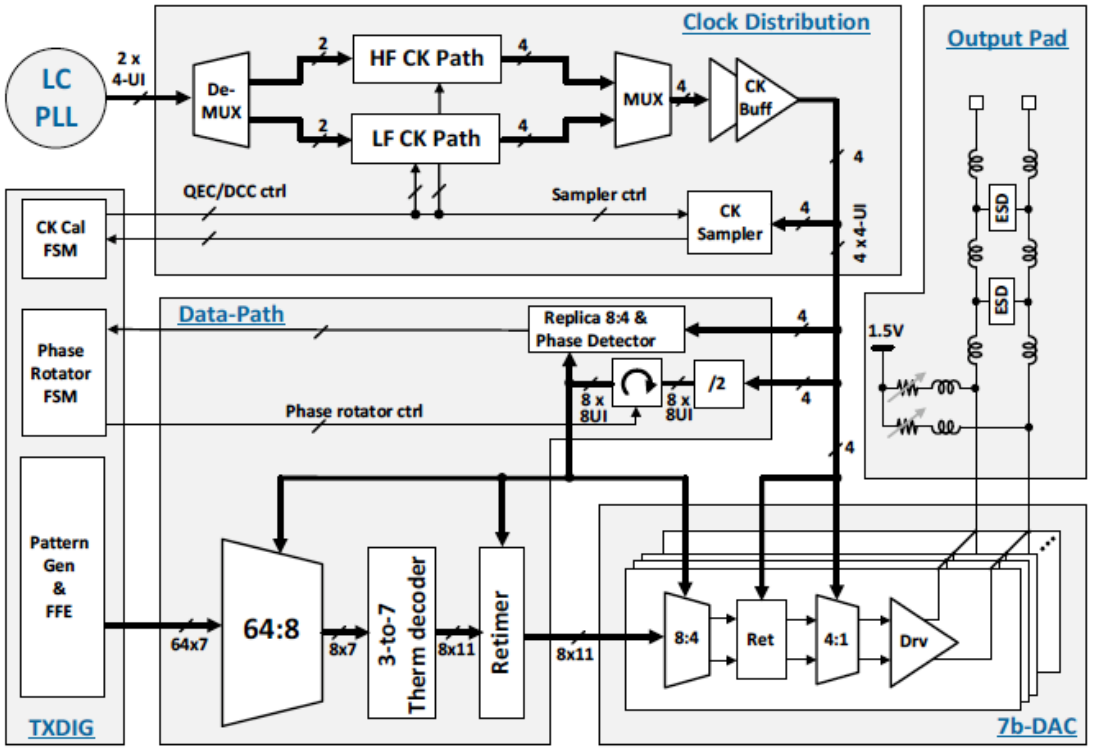
2.6 A 32-to-48Gb/s Serializing Transmitter Using Multiphase Sampling in 65nm CMOS

Amr Amin Hafez, Ming-Shuan Chen, Chih-Kong Ken Yang

University of California, Los Angeles, CA

Block	Power (mW)	Fraction (%)
VCO	26.6	30.2
Divider Chain	18	20.5
Buffer/PFD/CP	2	2.3
Predriver/Driver	26.4	30
Serializer	15	17
Total	88	100

INTEL, ISSCC2021, 224Gbps, PAM-4, 1.7 pJ/bit, 10 nm technology



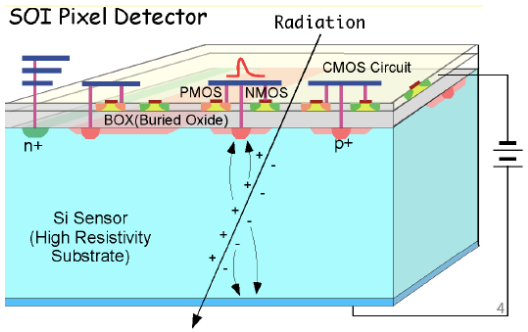
State of the art: a few mW/Gbps, already earlier but also now at much higher bandwidths

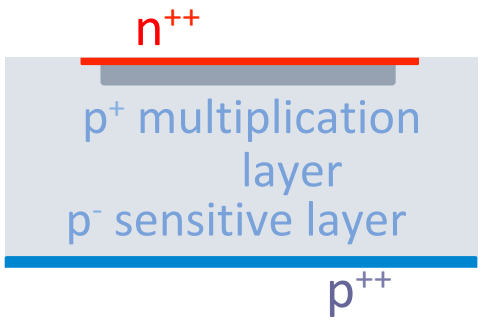
Significant circuit complexity

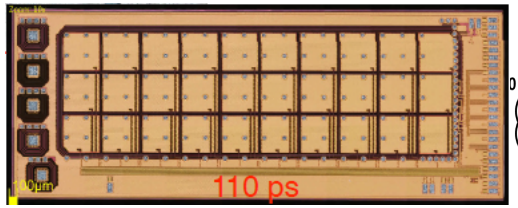
For HEP important penalty for SEU robustness due to triplication/larger devices…

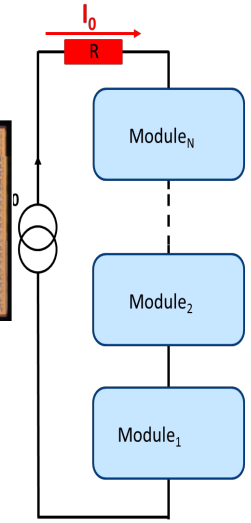
Important: data concentration, physical volume for material budget, and technology

Some other developments

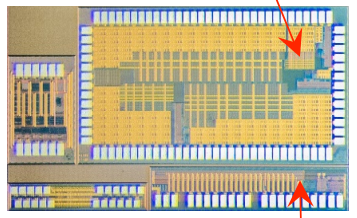








Regulator



Charge Pump

SOI sensors

LAPIS 0.2 µm Y. Arai et al.

- Impressive technology development with excellent Q/C
- Large user base
- Some freedom on sensor material
- BOX causes reduced radiation tolerance, several measures for improvement

Low gain Avalanche Diodes (LGAD)

N. Cartiglia et al.

- Charge gain in Si
- ps timing for thin sensors
- Radiation damage mitigation under study

NIM A730 (2013) 226-231, NIM A831 (2016) 18-23

NIM A796 (2015) 141-148, NIM A845 (2017) 47-51

W. Riegler & G. Aglieri: 2017 JINST 12 P11017 "Time resolution of Si detectors"

See also other presentations

TT-PET

G. Iacobucci et al.

- SiGe readout + TDC
- Down to 50 ps
- Picosecond avalanche detector to do even better

arxiv:1908.09709
JINST 14 (2019) P02009,
JINST 14 (2019) P07013
JINST 13 (2017) P02015,
JINST 11 (2016) P03011,
arxiv:1812.00788
arxiv:1811.12381

Serial power

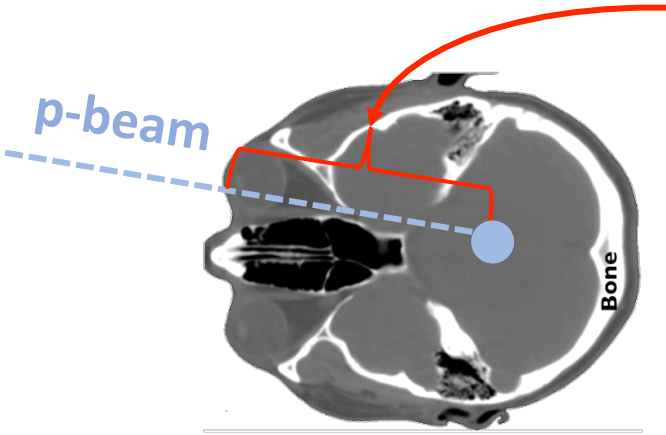
M. Karagounis et al. for hybrid sensors

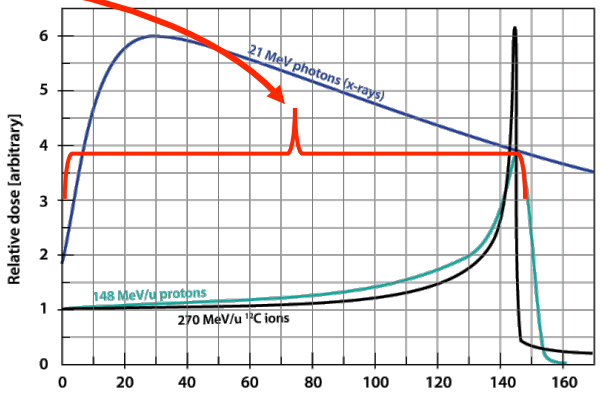
- Connecting sensors in series saves power cabling
- Requires regulation
- Charge pump for sensor bias

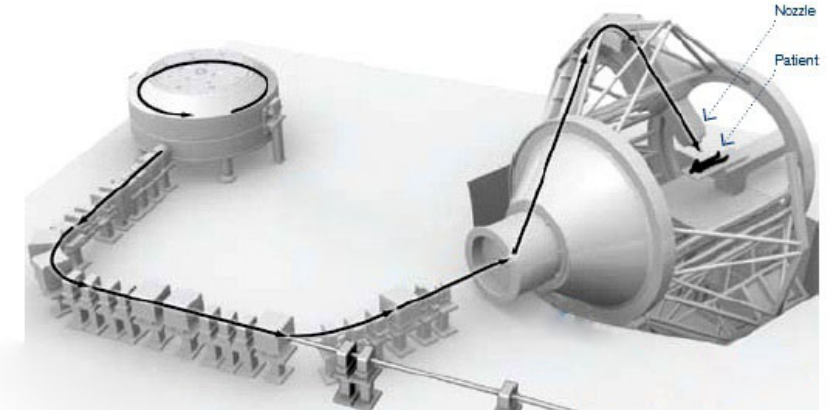
S. Bhat, A. Habib et al PIXEL 2018 (for CMOS sensors)

From medical imaging to medical tracking: Proton therapy and proton CT

Energy tuning proton beam better than 0.5 % requires proton CT rather than X-ray CT (too poor tissue density resolution)

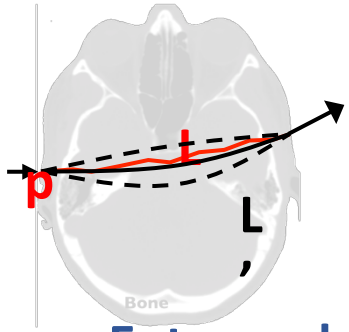






courtesy of P.Giubilato

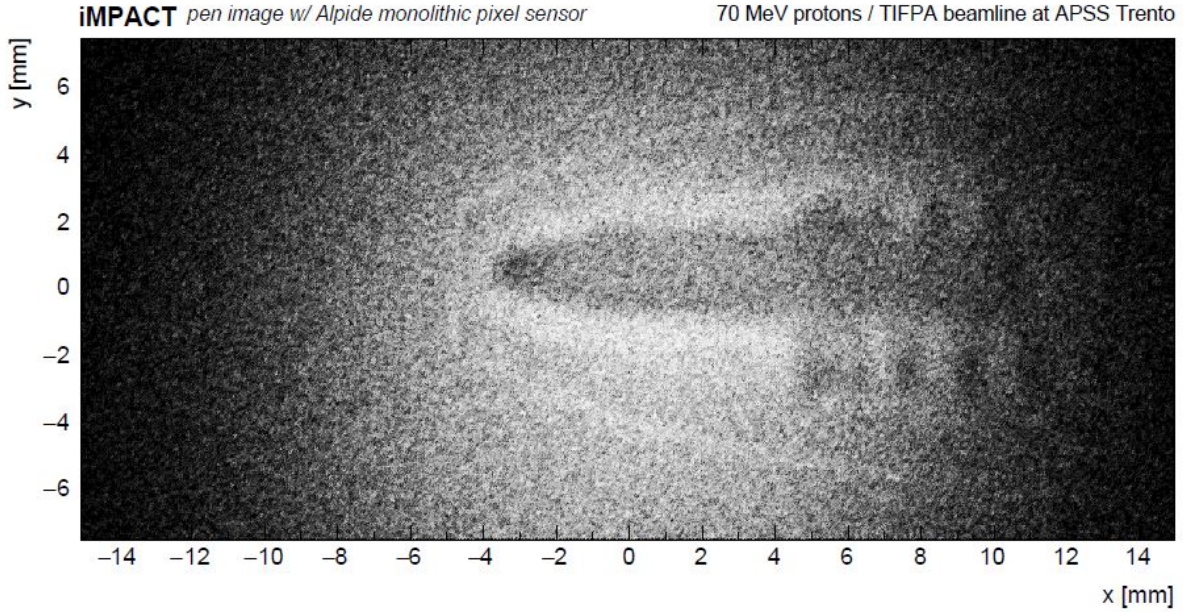
Proton true trajectory



Energy measurement

Entry and exit points + angle

Most Likely Path calculation



Demonstration with ALPIDE chip

Need at least 10^9 proton tracks (entry and exit + most likely path) and 10s of minutes with state of the art detectors.

Gaining time requires detectors which do not yet exist

Concluding remarks

After years of R&D monolithic sensors for HEP move to CMOS MAPS in mainstream CMOS technology, but requirements for HEP are not completely identical to those for visible light imaging, and some technology flexibility can still be beneficial.

Circuit radiation tolerance as for standard CMOS, which naturally evolved towards significant tolerance with some caveats.

Sensor radiation tolerance, precision timing and improved efficiency can be obtained from optimization for fast charge collection using techniques based on general principles applicable to different technologies. Large collection electrode sensors provide extreme radiation tolerance and more uniform sensor timing but exhibit large input capacitance.

Decreasing technology feature size or special imaging sensor features can increase the voltage excursion on a small collection electrode and ultimately reduce analog front end power to zero and allow precision timing.

Hybrid vs Monolithic distinction is becoming more vague:

2D integration combined with stitching will bring us a long way. 3D could help for the most challenging applications.

Feasibility studies on stitched devices will determine the size of the sensors we will design in the future and whether and to what extent we can profit from unbeatable wafer-scale integration. (production volume is in the outer layers, we need to be prepared for volume test/acceptance/monitoring)

Concluding remarks

A Monolithic Active Pixel Sensor or MAPS is a complex circuit with extra constraints: sensor bias, coupling into the sensor, …

- The increasing complexity of the sensors and the chips we design require evolution towards digital-on-top design techniques with increasing verification effort (cfr F. Faccio and A. Rivetti's presentations).
- Need team of expert chip designers, complemented with device/TCAD/Monte Carlo experts for sensor optimization and simulation. It takes years to train people for this activity and our community needs to do efforts to sufficiently preserve critical mass and know-how for this activity.

Large area pixel sensors are enabling devices for many cutting edge research fields and practical applications like tracking in HEP, medical imaging, space-borne instruments, etc, illustrated by the interest in chips like ALPIDE and others but also by other successful developments like Medipix/Timepix

MAPS are one of the few areas where production volume even within HEP would not be negligible, but where our community can have an impact not only on the quality of its own measurements, but also on society in general, and which we should try to exploit to enable access to the most advanced technologies.

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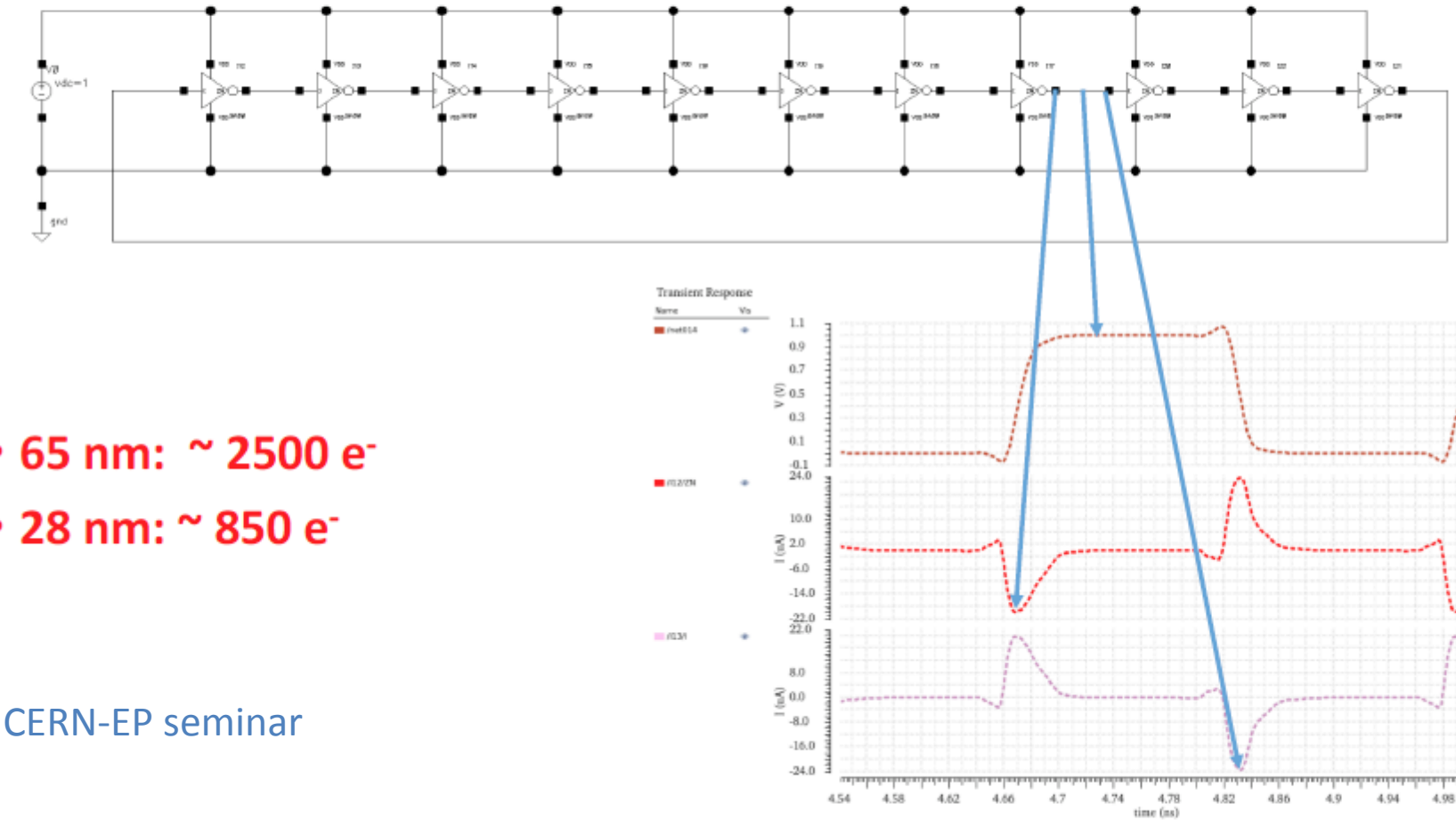
THANK YOU !

How many electrons are needed to switch a logic gate ?



- **65 nm: ~ 2500 e⁻**
- **28 nm: ~ 850 e⁻**

A. Marchioro, 2019 CERN-EP seminar