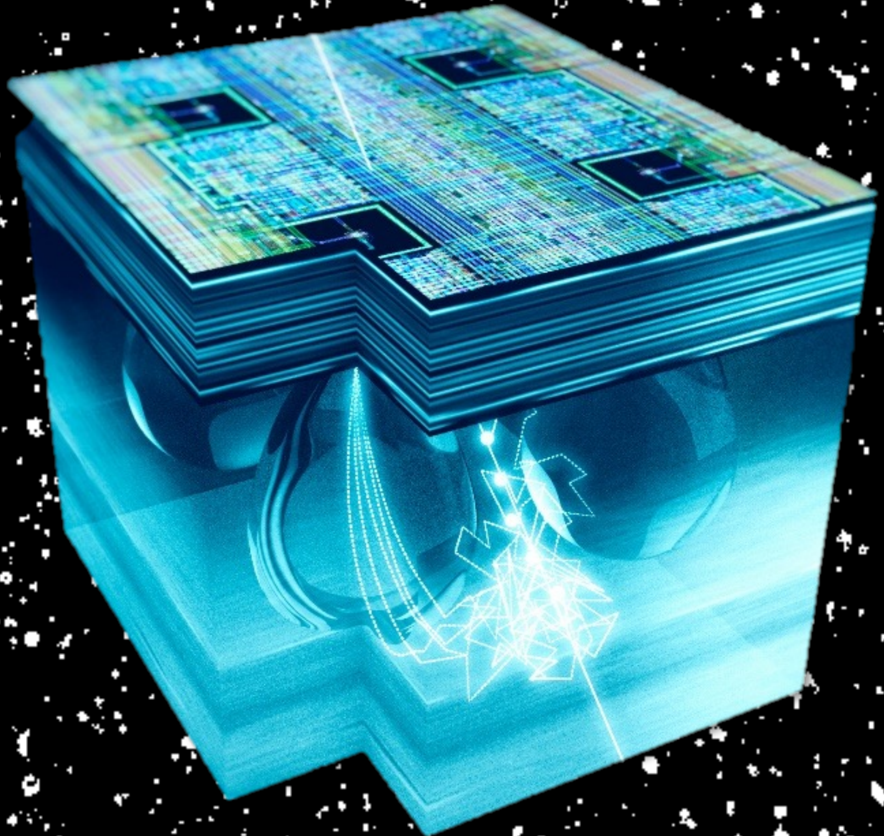
CMOS Monolithic Active Pixel Sensors



ALPIDE prototype: 200 MeV protons at PSI

Walter Snoeys

16th Pisa meeting on Avanced Detectors, La Biodola, Elba, May 30th, 2024

walter.snoeys@cern.ch

Acknowledgements

- ICFA and the selection committee
- Marc Winter and Renato Turchetta for their key contribution, friendly contacts over these many years, and nice continued collaboration with IPHC and STFC.
- KULeuven, integrated accelerometer: L. Reynaert, B. Puers, W. Sansen (1943 – 2024)
- Stanford U.: S. Parker, C. Kenney, J. Segal, J. Plummer, G. Rosseel, C. H. Aw … and BAEF fellowship
- Colleagues from CERN & the ESE group, the ALICE ITS2 &3 upgrade, ATLAS ITk, CLIC, EP R&D WP1.2 … and the foundries !
  - Hybrid pixels: M. Campbell and E. Heijne, E. Cantatore, R. Dinapoli, L. Scharfetter … and WA97, NA57, ALICE, LHCb
  - TOTEM and VFAT: K. Eggert, E. Radermacher, A. Scribano, V. Avati, M. Deile, P. Aspell, G. Antchev, E. Oliveri, N. Turini …
  - C4i – Mind & collaboration with the Haute Savoie Dept: H. Mugnier, J. Rousset, S. Pothier, JM Thenard, D. Lajust, …

  Monolithic: T. Kugathasan, G. Aglieri, M. Munker
  - LePIX (IBM 90nm): A. Marchioro, P. Giubilato, S. Mattiazzo, D. Pantano, A. Potenza, A. Rivetti …
  - ALICE ITS2 & 3 : L. Musa, M. Mager, F. Reidt, W. Riegler, A. Kluge, C. Hu, C. Colledani, …
  - ATLAS Itk & Stream: H. Pernegger, P. Riedler, P. Pangaud, M. Barbero, P. Schwemling, N. Wermes, G. Iacobucci, V. Dao, …
  - CLIC and FASTPIX: D. Dannheim, K. Dort, J. Braach, E. Buschmann, …
  - EP R&D WP1.2: P. Leitao, G. Ripamonti, G. Borghello, C. Lemoine, S. Emiliani, S. Bugiel, L. Ceccone, F. Piro …
  - EP and ESE Management
- My family, my parents and my wife

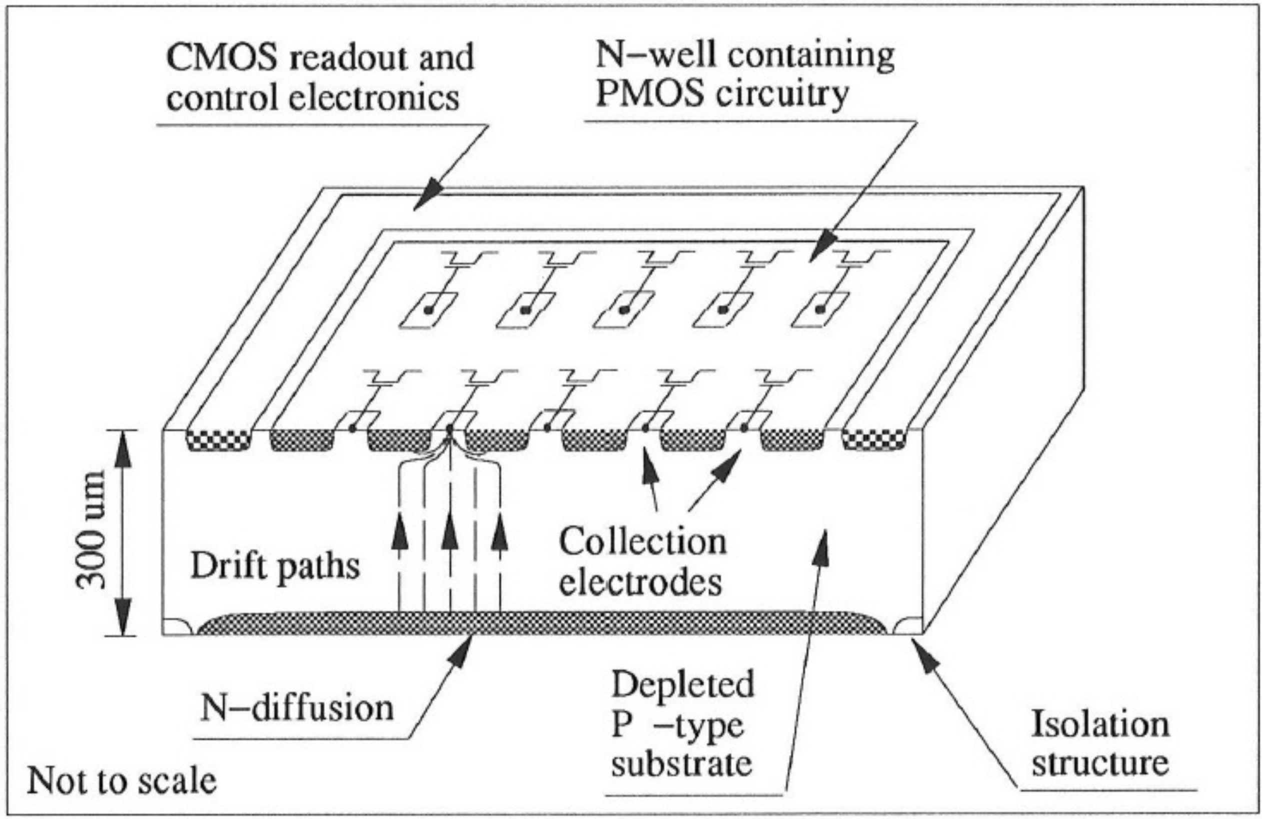
and many, many others !!

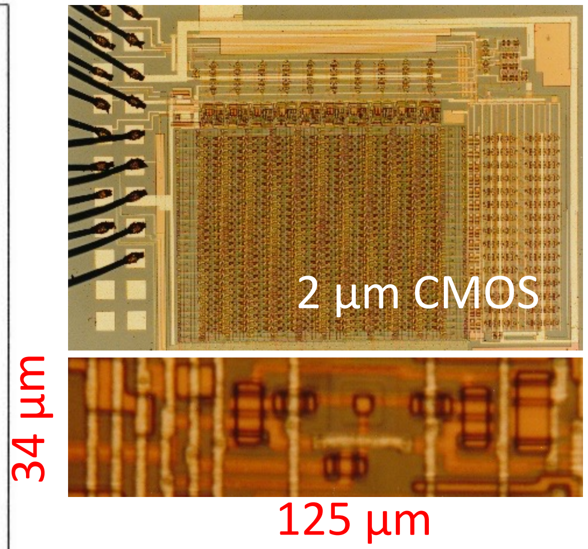
walter.snoeys@cern.ch

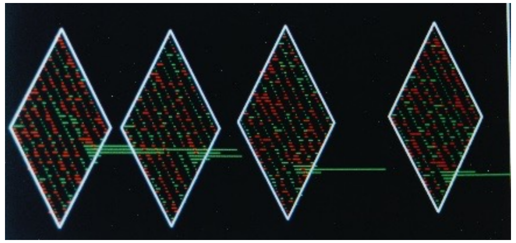
A monolithic detector for high energy physics (PhD thesis 1992), CMOS with double sided processing

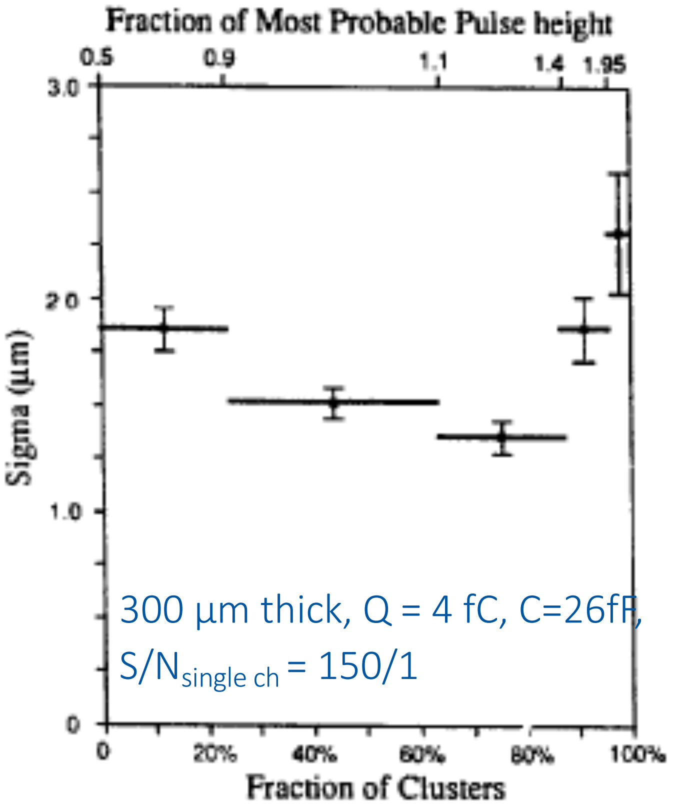
Stanford University 1987-1992, and the University of Hawaii

First year funded by a fellowship from the Belgian American Educational Foundation.



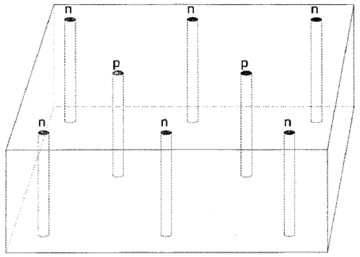






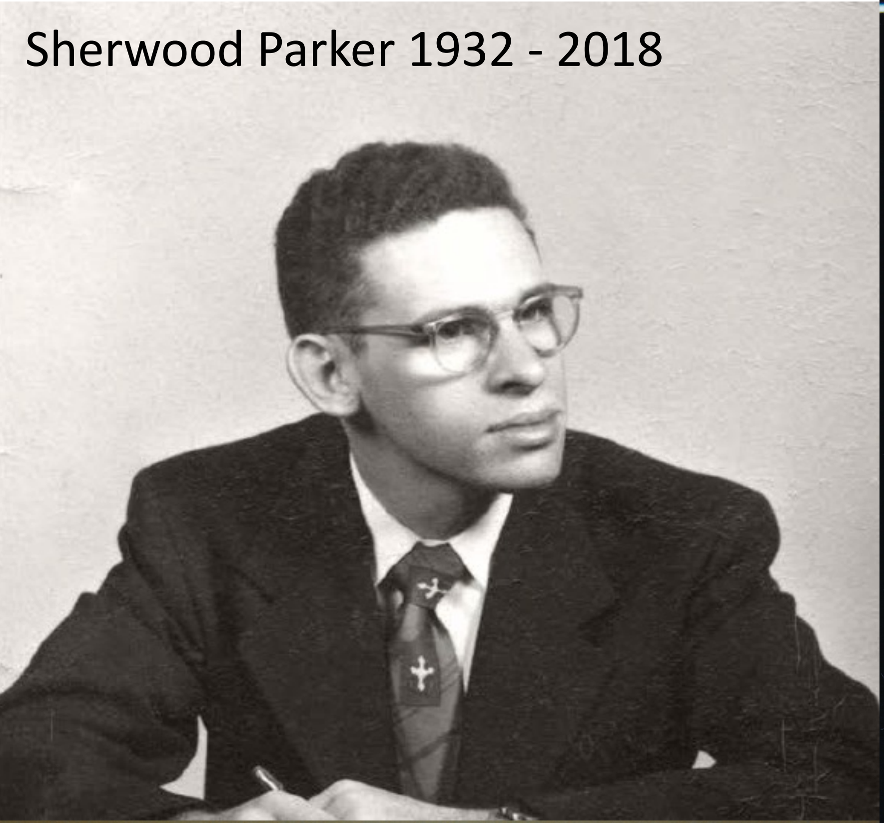
300 µm thick, Q = 4 fC, C=26fF, $S/N_{\text{single ch}}$ = 150/1

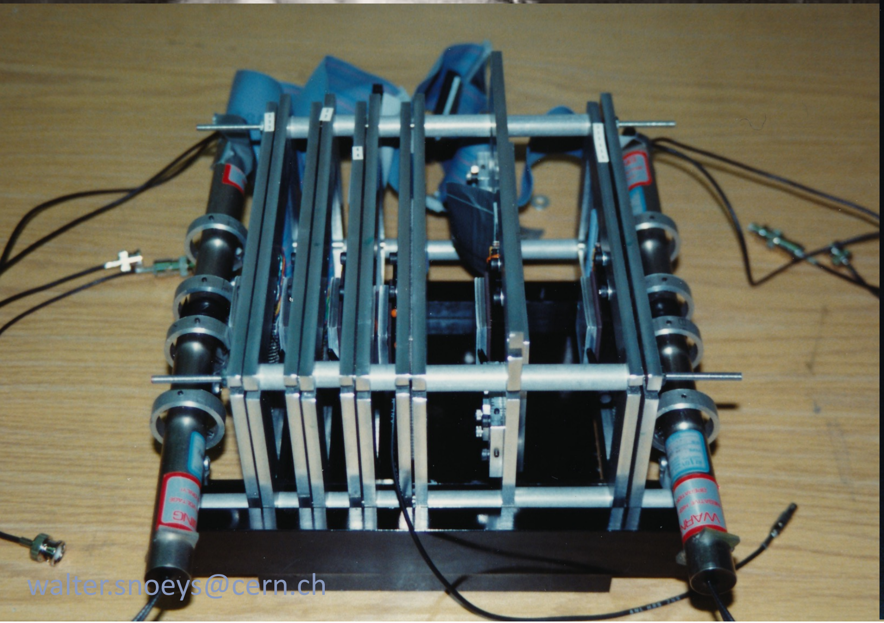
- Separation of junction from small collection electrode
- Better than 2 µm position resolution even at 34 µm pitch due to good S/N
- Improved back side trench isolation led to sensors with 3D electrodes (S.Parker, J. Segal) →



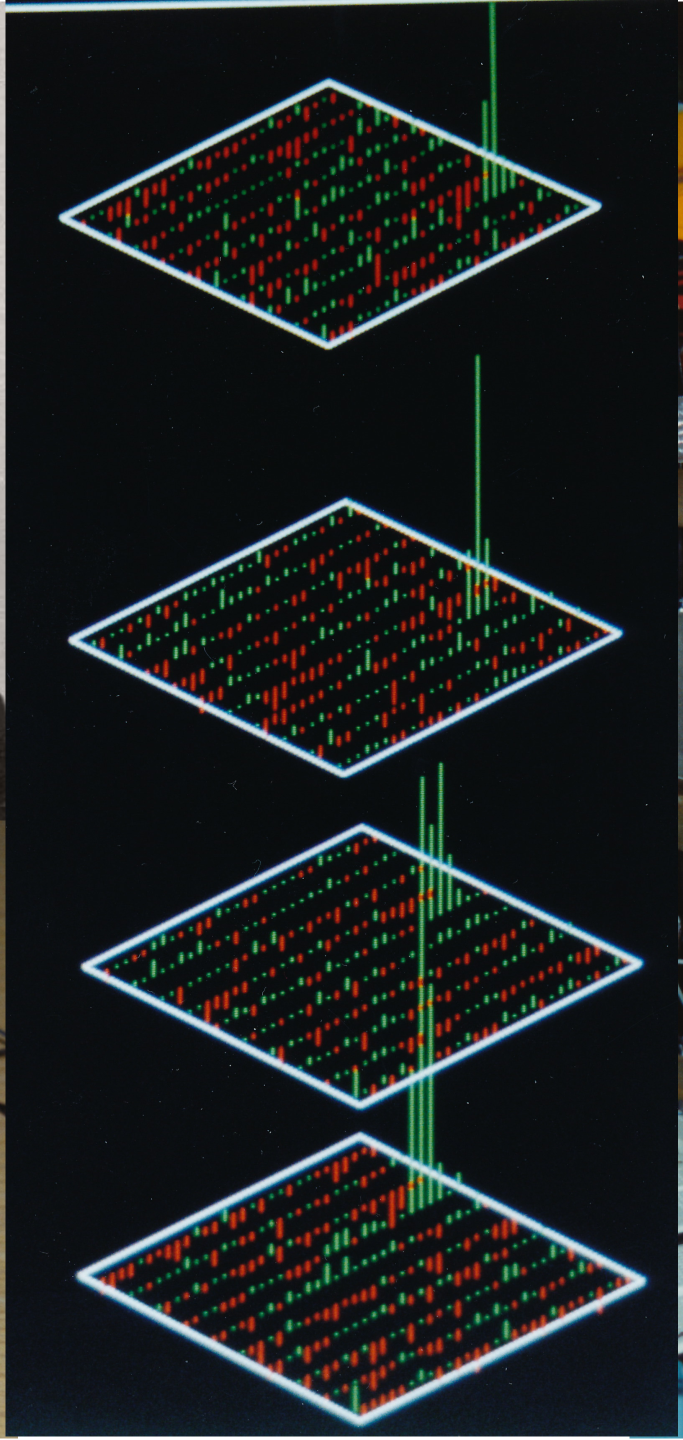
C. Kenney, S. Parker, J. Plummer, J. Segal, W. Snoeys et al. NIM A (1994) 258-265, IEEE TNS 41 (6) (1994), IEEE TNS 46 (4) (1999)

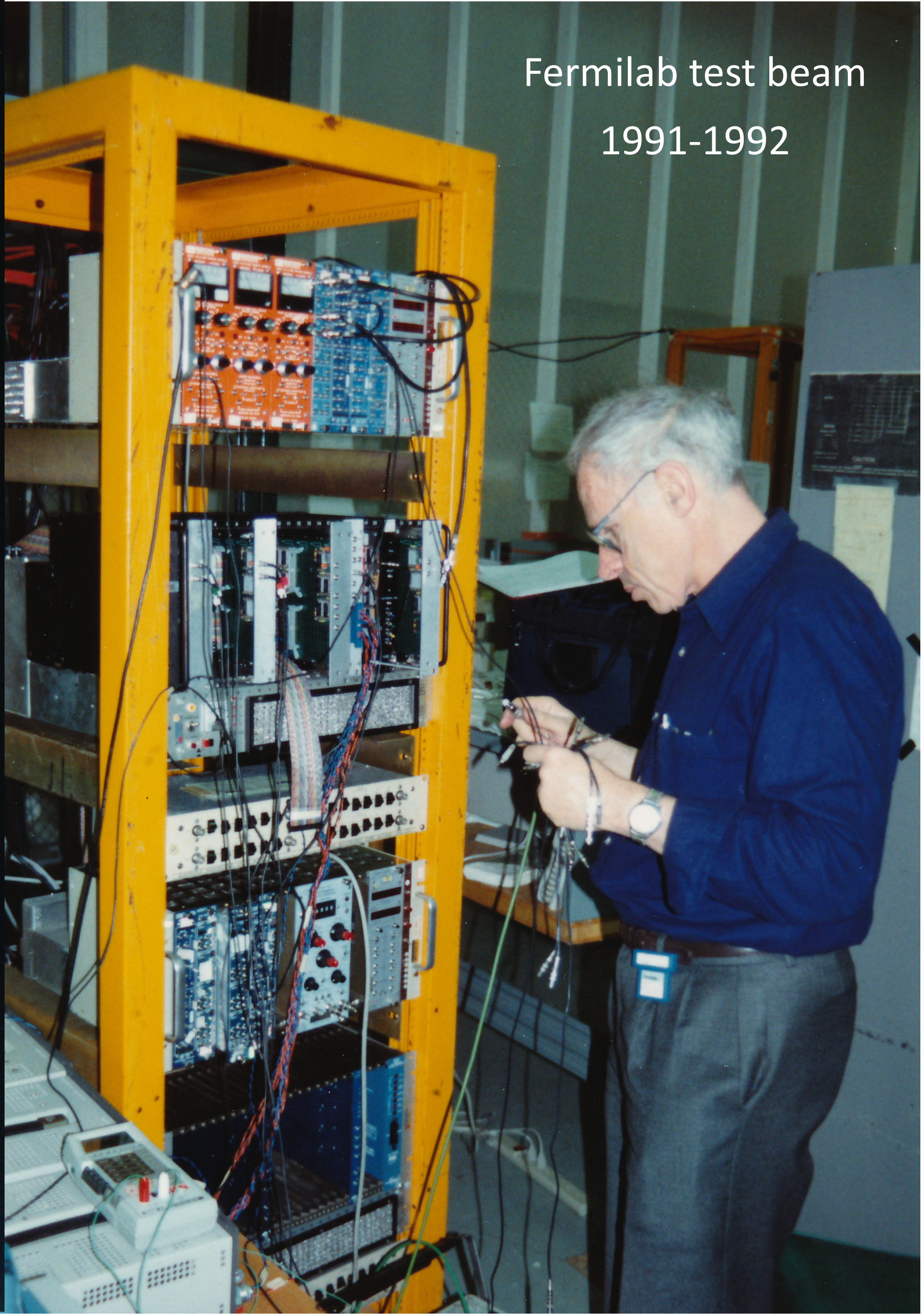
Sherwood Parker 1932 - 2018





walter.snoeys@cern.ch

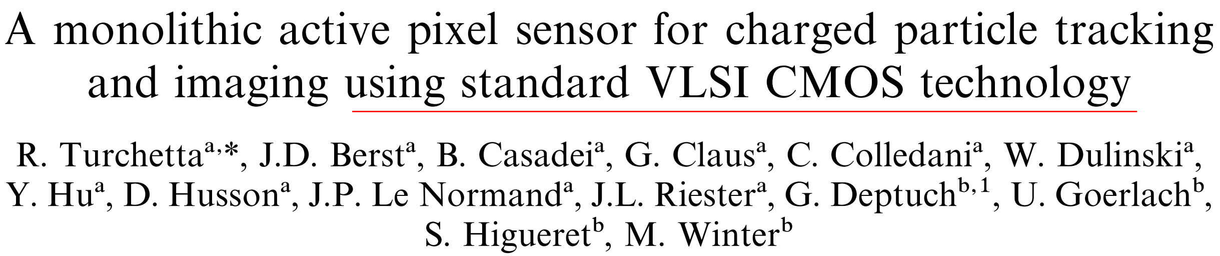




Fermilab test beam

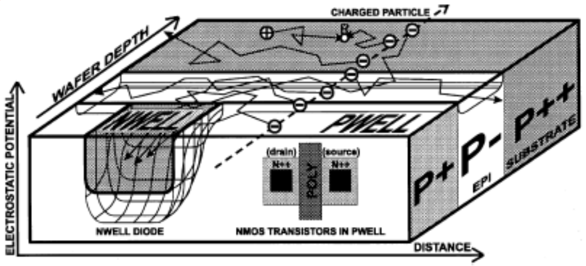
1991-1992

KEY ENABLERS: Mimosa series – IPHC Strasbourg - Move to standard CMOS



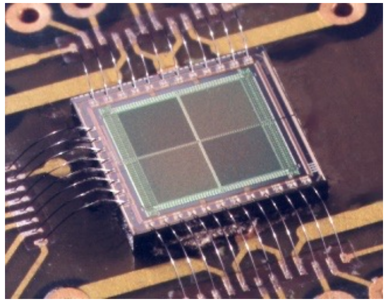
A monolithic active pixel sensor for charged particle tracking and imaging using standard VLSI CMOS technology

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]



NIM A 458 (2001) 677-689

Mimosa1 – 1999
AMS 0.6 µm

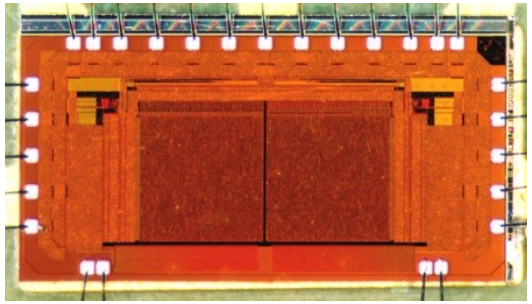


20µm pixel

Mimosa2 – 2000
MIETEC 0.35 µm

20µm pixel

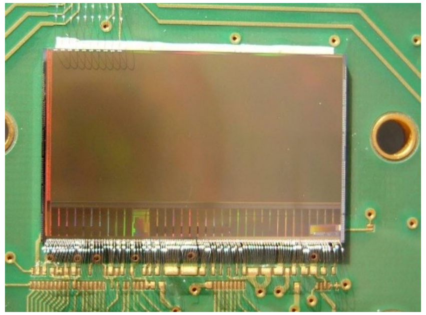
Mimosa3 – 2001
IBM 0.25 µm



8µm pixel

....

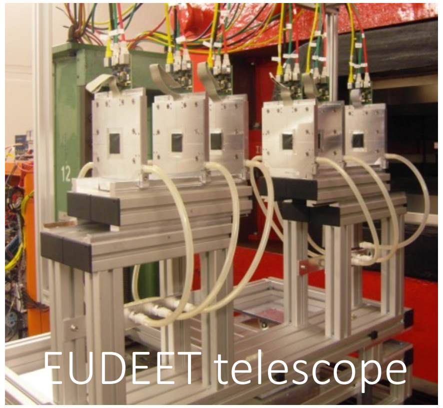
Mimosa26 – 2008
AMS 0.35 µm



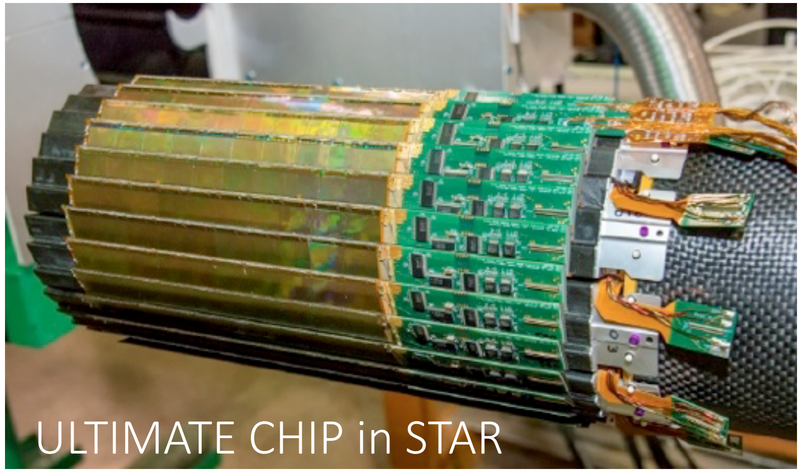
18.4 µm pixel

....

Mimosa26 – 2008 in the EUDET Telescope,

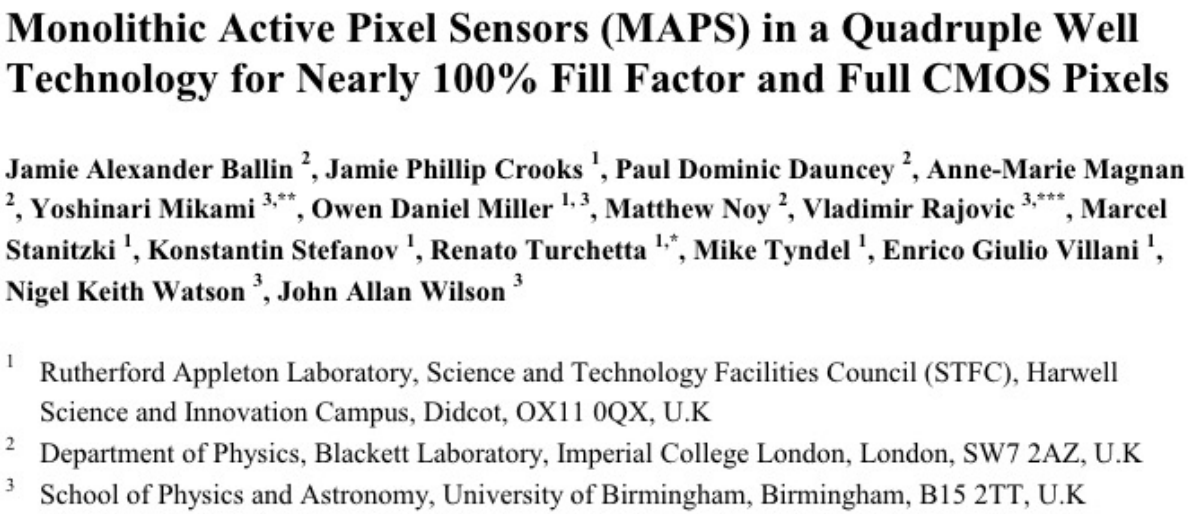


First use of MAPS in HEP



KEY ENABLERS: The INMAPS process: STFC development, in collaboration with TowerJazz: a game changer

Additional deep p-well implant allows full CMOS in the pixel and 100 % fill factor



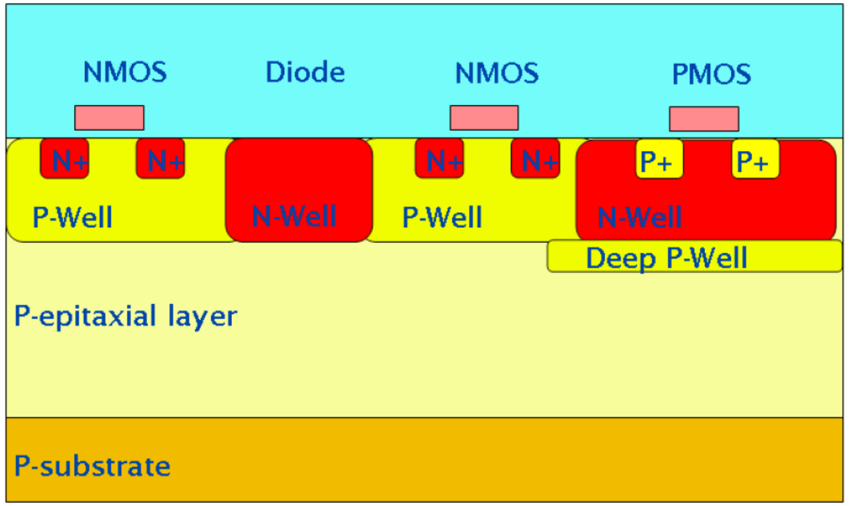
Monolithic Active Pixel Sensors (MAPS) in a Quadruple Well Technology for Nearly 100% Fill Factor and Full CMOS Pixels

Jamie Alexander Ballin [2], Jamie Phillip Crooks [1], Paul Dominic Dauncey [2], Anne-Marie Magnan [2], Yoshinari Mikami [3,], Owen Daniel Miller [1,3], Matthew Noy [2], Vladimir Rajovic [3,***], Marcel Stanitzki [1], Konstantin Stefanov [1], Renato Turchetta [1,*], Mike Tyndel [1], Enrico Giulio Villani [1], Nigel Keith Watson [3], John Allan Wilson [3]**

[1] Rutherford Appleton Laboratory, Science and Technology Facilities Council (STFC), Harwell Science and Innovation Campus, Didcot, OX11 0QX, U.K

[2] Department of Physics, Blackett Laboratory, Imperial College London, London, SW7 2AZ, U.K

[3] School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, U.K

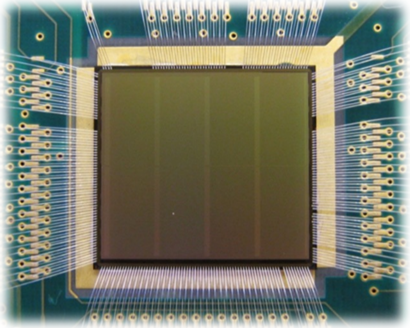


Sensors 2008 (8) 5336, DOI:10.3390/s8095336

courtesy of STFC

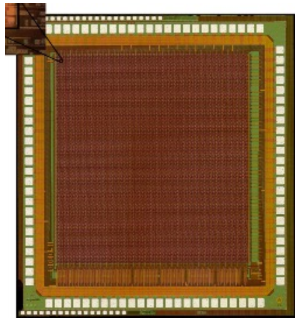
New generation of CMOS sensors for scientific applications in TowerJazz CIS 180nm

TPAC
ILC ECAL (CALICE)



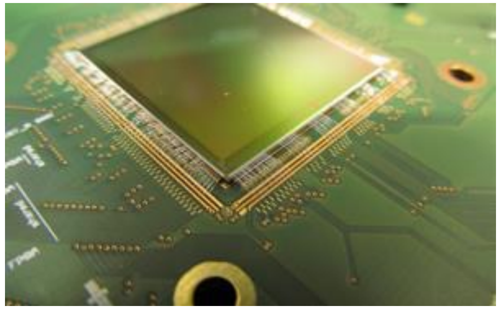
50μm pixel

DECAL
Calorimetry



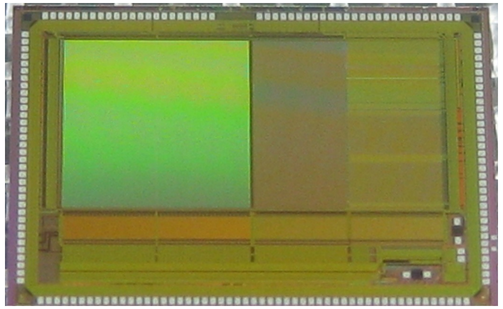
50μm pixel

PIMMS
TOF mass spectroscopy

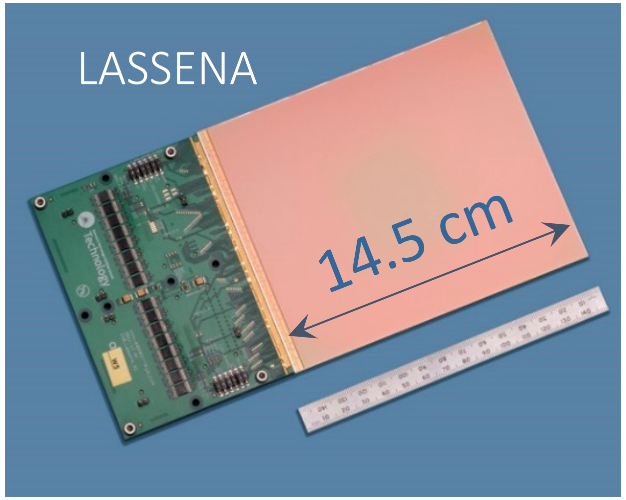


70μm pixel

CHERWELL
Calorimetry/Tracking



48 μm x 96 μm pixel

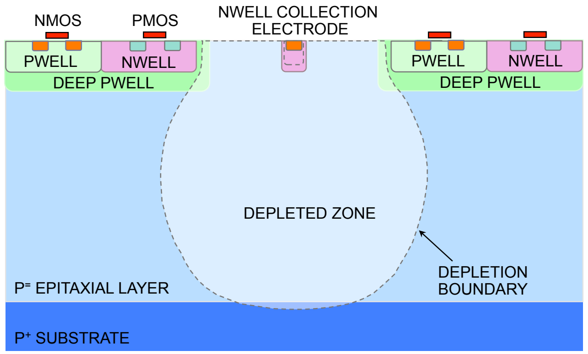


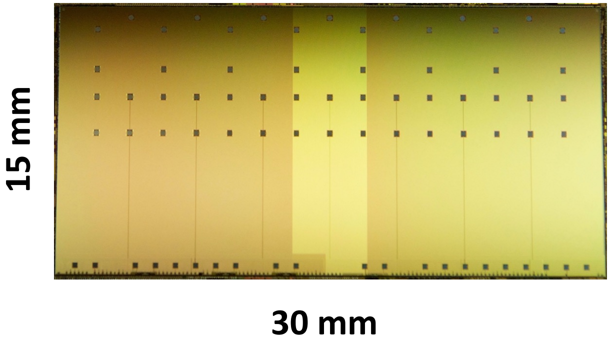
50μm pixel, waferscale

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

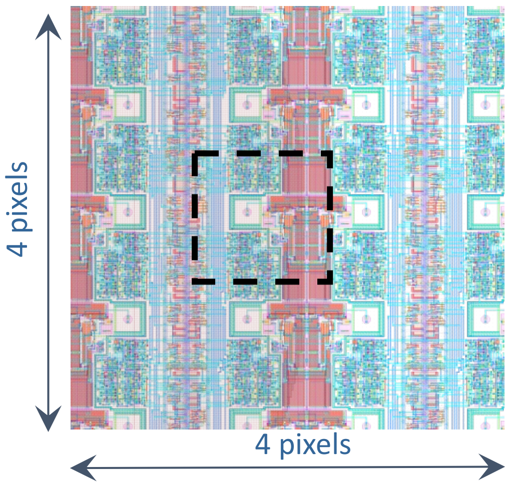
L. Musa et al.: The ALICE ITS2 and the ALPIDE chip in the TJ 180nm INMAPS process

Also used for other applications

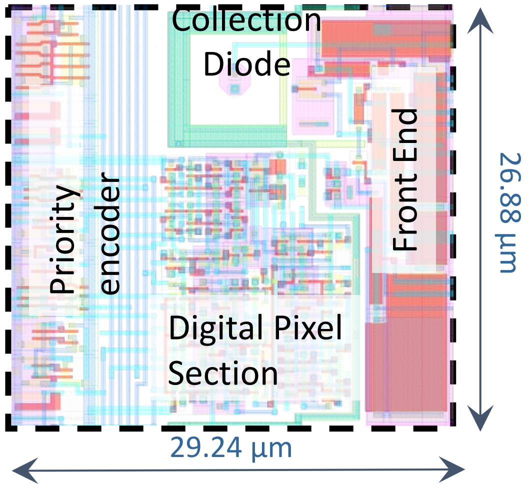




Matrix layout

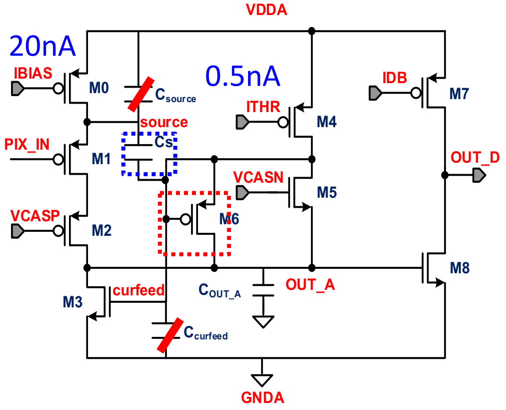


Pixel layout



Zero-suppressed readout, no hits no digital power

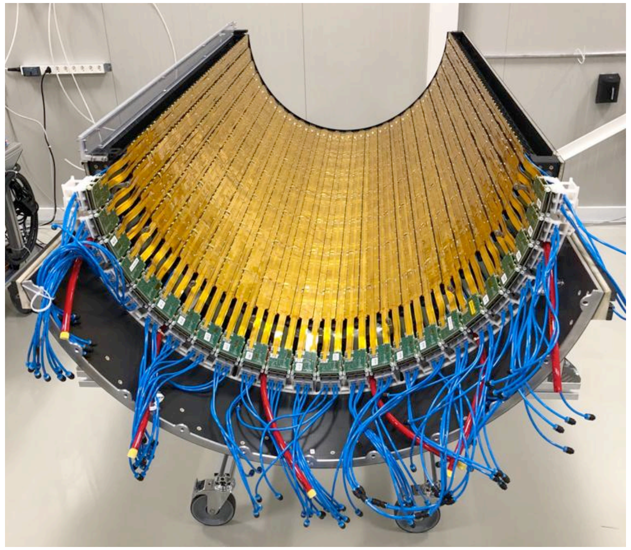
G. Aglieri et al. NIM A 845 (2017) 583-587



40 nW continuously active front end

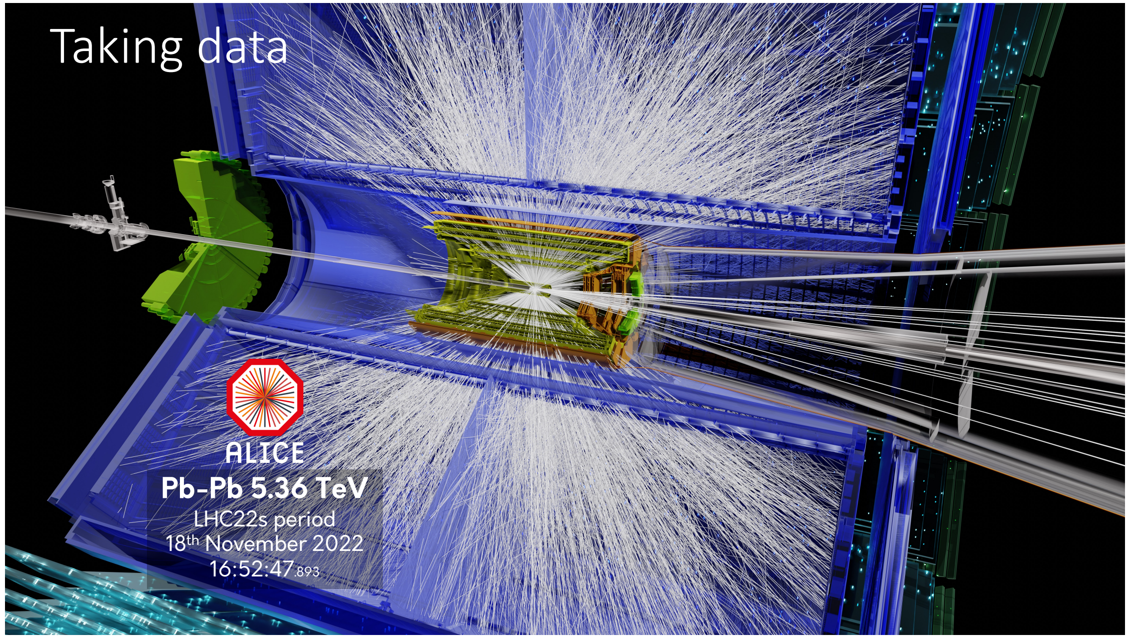
D. Kim et al.

DOI 10.1088/1748-0221/11/02/C02042



Half outer barrel (layer 6)

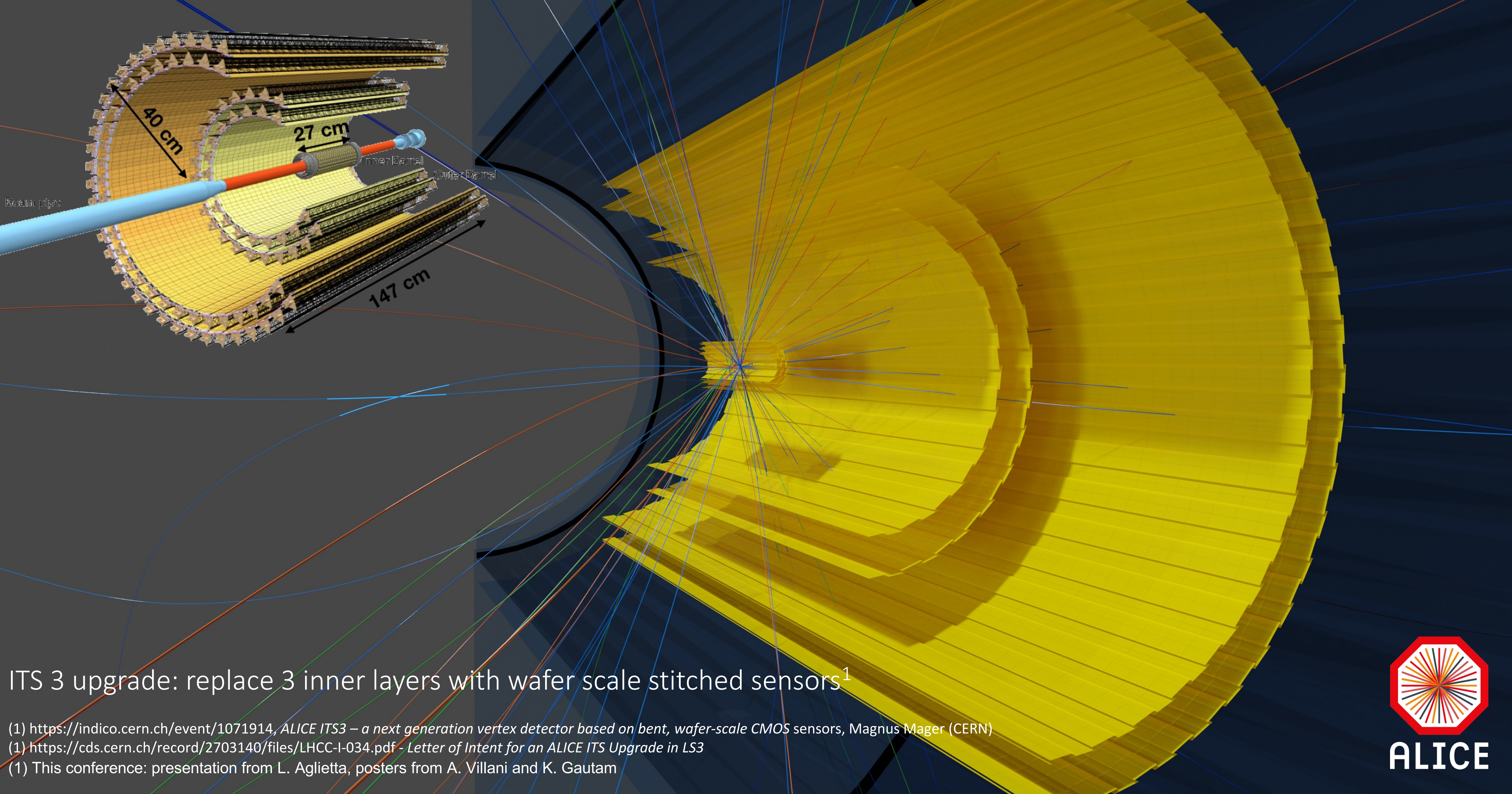
~ 2.47 Gpixels covering ~ 2 m^2 sensitive area



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

ALICE Inner Tracker System 2 (ITS2) taking data

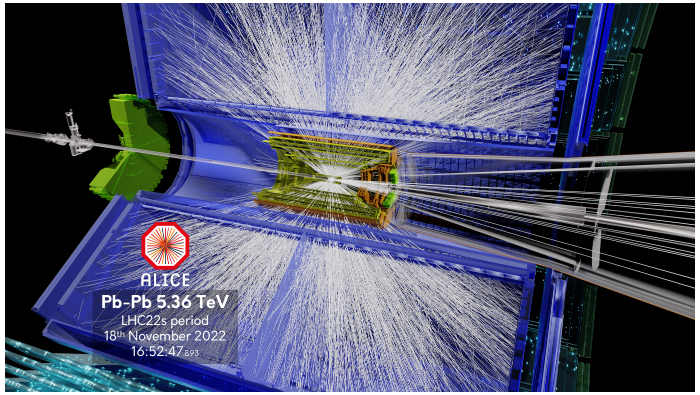


ITS 3 upgrade: replace 3 inner layers with wafer scale stitched sensors[1]

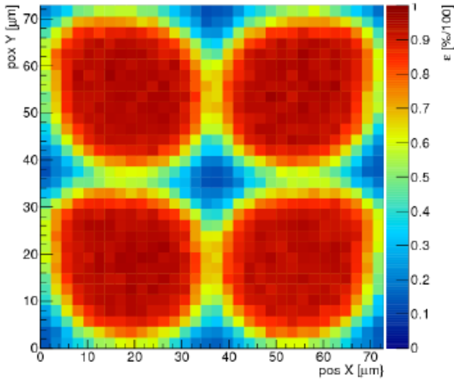
(1) https://indico.cern.ch/event/1071914, *ALICE ITS3 – a next generation vertex detector based on bent, wafer-scale CMOS* sensors, Magnus Mager (CERN)
(1) https://cds.cern.ch/record/2703140/files/LHCC-I-034.pdf - *Letter of Intent for an ALICE ITS Upgrade in LS3*
(1) This conference: presentation from L. Aglietta, posters from A. Villani and K. Gautam

Pixel optimization for better margin: move junction away from the collection electrode for full depletion: Better time resolution, radiation hardness and … efficiency, especially for thin sensors

in 180 nm

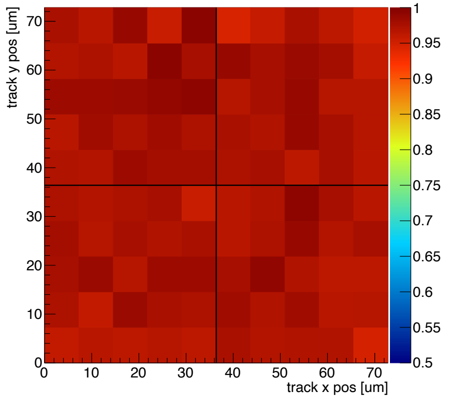


ALPIDE and ITS2 in ALICE (10 m^2)

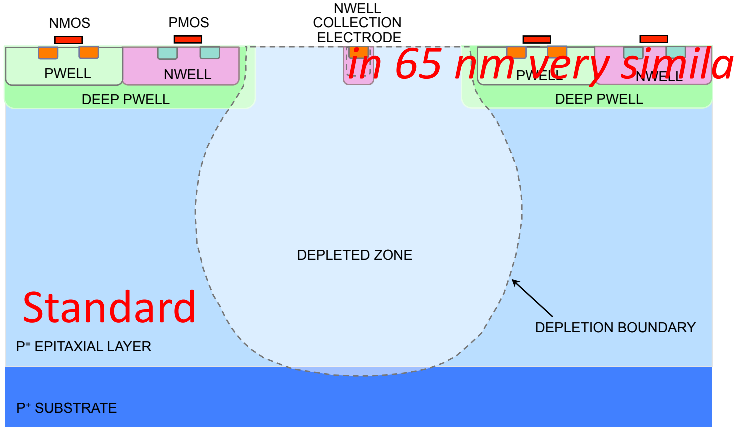


E. Schioppa et al, VCI 2019

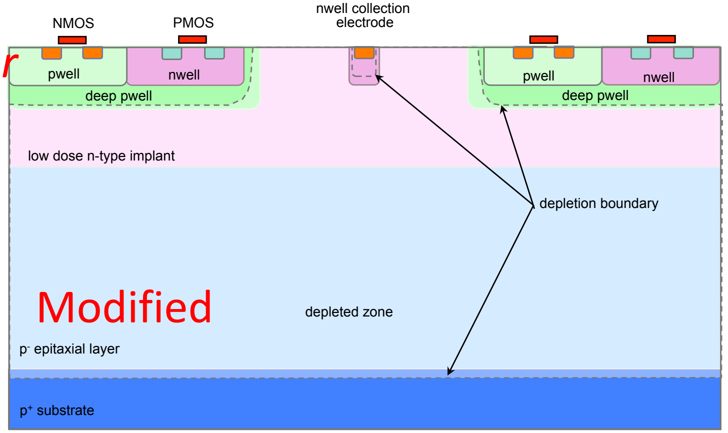
efficiency loss at $\sim 10^{15}\ n_{eq}/cm^2$



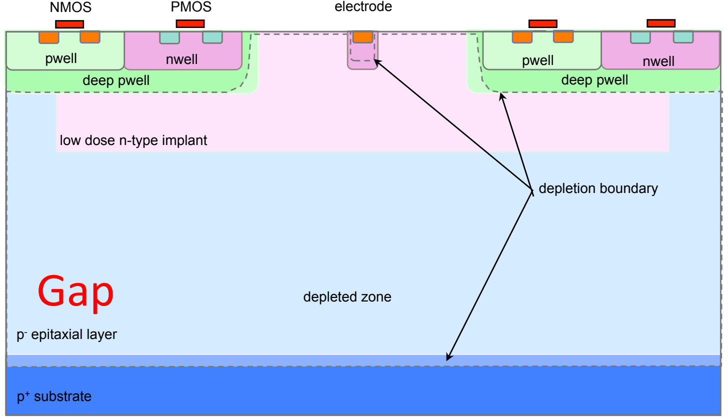
H. Pernegger et al., Hiroshima 2019,
M. Dyndal *et al* 2020 *JINST* **15** P0200



in 65 nm very similar



M. Munker et al.
https://doi.org/10.1016/j.nima.2017.07.046 (180nm)



https://iopscience.iop.org/article/10.1088/1748-0221/14/05/C05013
(180nm)

Charge collection speed →

← Charge sharing

DOI: https://doi.org/10.22323/1.420.0001 (65nm)

65 nm very similar, profited significantly from 10 years experience in 180 nm

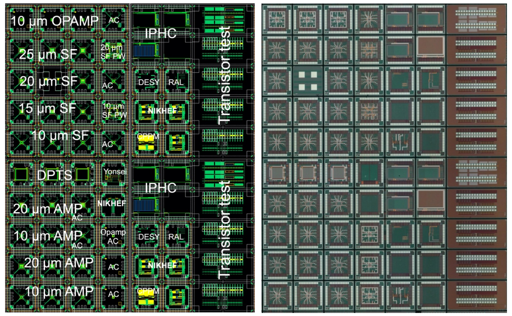
EP R&D WP1.2 with a very significant contribution from ALICE ITS3 team (large measurement team 40-50 people)

One slide on runs in 65 nm (MLR1, ER1 and ER2)

See presentation from L. Aglietta, posters from A. Villani and K. Gautam
Last EP R&D report: https://cds.cern.ch/record/2891650
ITS3 TDR: https://cds.cern.ch/record/2890181?ln=en

MLR1: Dec 2020: 1.5 x 1.5 mm^2 test chips

qualification of TPSCo 65 nm for HEP

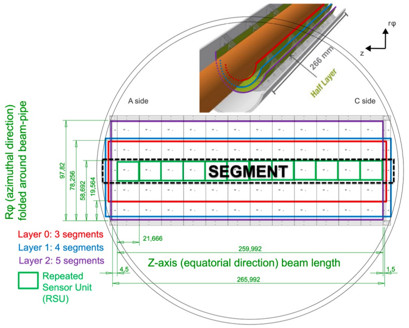


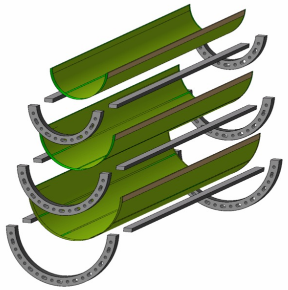
- Fully efficient at RT before and after 10^{15} n_{eq}/cm^2
- Sensor time resolution ~ 70 ps (10 µm pitch)
- Investigating path to tolerance to higher irradiation levels and lower input capacitance

(C. Lemoine *et al* 2024 *JINST* **19** C02033)

ER2: MOSAIX: Fall 2024:

First full prototype for ALICE ITS3





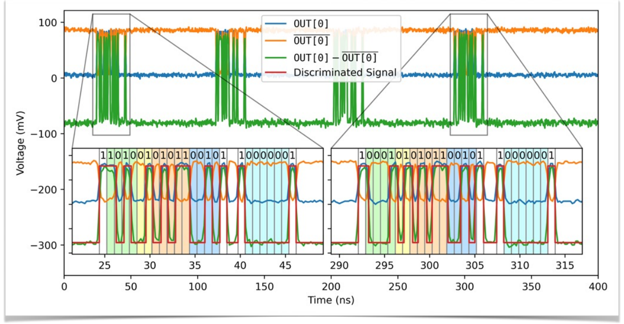
ER1: Dec 2022:

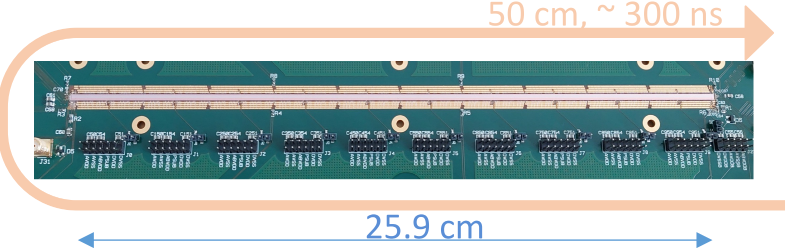
Learning about stitching

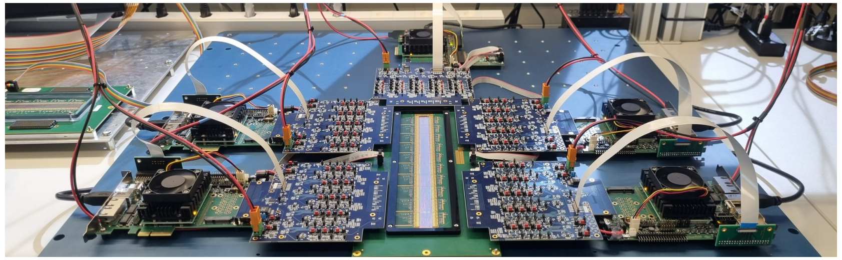
Two stitched sensors with 10 repeated units:
Both functional, learnings to be included in ER2

MOST (25.9 cm x 0.25 cm):

- 18 µm pitch, very densely designed pixel matrix
- Global power distribution + conservatively designed highly granular power switches to switch off faulty parts
- Asynchronous, hit-driven readout, low power consumption + timing information
- Pulsing signal and output signals at the end of the chip, round trip more than 50 cm, ~ 300 ns, with ~800 repeaters, all 256 signal lines functional



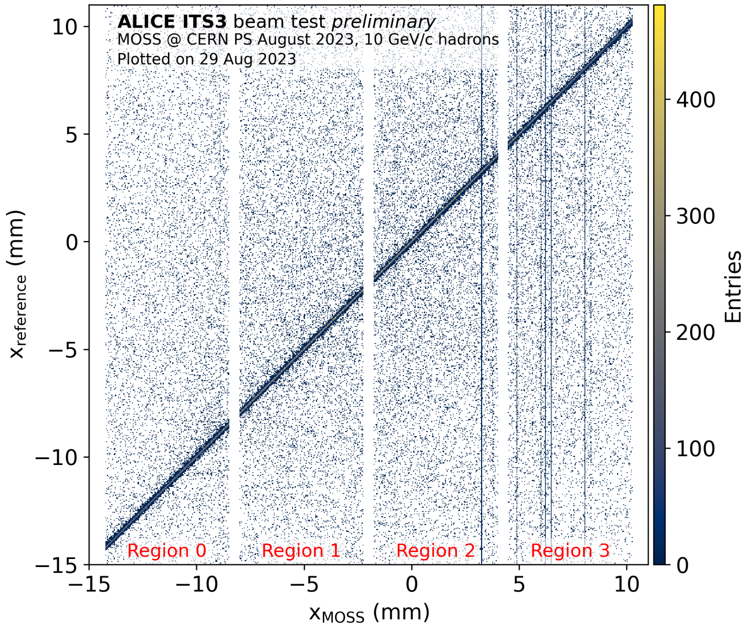




MOSS (25.9 cm x 1.4 cm):

- Top half 22.5 µm pitch, bottom half 18 µm pitch
- Each half powered completely independently with 4 conservatively designed submatrices -> many power domains
- Synchronous readout

Hit x-coordinate correlation between MOSS and reference ALPIDE telescope



walter.snoeys@cern.ch

CONCLUSIONS and OUTLOOK

- Key contributions of Marc Winter and Renato Turchetta helped us to move monolithic sensors for HEP to CMOS MAPS in mainstream CMOS technology with complex full CMOS in-pixel circuitry, and to design the ALICE ITS2 detector with 10 m^2 of ALPIDE chips presently taking data.

- 10 years of experience with 180 nm enabled fast qualification of the 65 nm technology for HEP and the exploration of wafer-scale sensors for ITS3, opening perspectives for other projects like ALICE3. Some foundry flexibility has allowed greatly improved sensor timing, radiation tolerance and operating margin based on general principles applicable to different technologies.

- The increasing complexity of Monolithic Active Pixel Sensors requires digital-on-top design techniques and verification by a team of expert chip designers, and sensor optimization and simulation by device/TCAD/Monte Carlo experts. Our community needs to preserve critical mass and know-how, and to concentrate resources exploiting convergence in sensor requirements for different future HEP applications.

- Large area pixel detectors are enabling devices for cutting edge research fields and practical applications in HEP, medical imaging, space-borne instruments, etc, illustrated by the interest in chips like ALPIDE, some of the examples mentioned by Renato and Marc, and other developments like Medipix/Timepix.

walter.snoeys@cern.ch

CONCLUSIONS and OUTLOOK

- 3D wafer stacking now allows the connection of a readout wafer to a detector wafer, and deliver the fully finished diced assemblies to the customer. This reduces the distinction with hybrid sensors, but provides opportunities well beyond with multiple connections within each pixel and stacking of even more than two wafers.

- Unprecedented integration in electronics systems continues to be driven by the computation needs of AI. Stitching and wafer stacking brings pixel pitches around 10 um within reach. The circuitry on a monolithic sensor allows the mitigation of local, otherwise fatal defects for large, even wafer-scale sensors. Efficient volume test, assembly, and mounting, together with significant progress towards lower power densities and on-chip resistive drops, will be enablers for large area detectors, and this for practically all applications in HEP.

- CMOS monolithic sensors will become widely applied in HEP, in tracking, calorimetry and timing detectors. Non-negligible MAPS production volumes within HEP should allow our community to impact not only the quality of its own measurements, but also society in general, with access to the most advanced technologies.

THANK YOU !

walter.snoeys@cern.ch