RD50 activities

Pierre Barrillon (CPPM) with contributions from G. Calderini (LPNHE), A. Lounis (IJCLab) and P. Pangaud (CPPM)

Mercredi 19 octobre 2022

RD50 introduction

- The R&D collaboration *Radiation hard semiconductor devices for high luminosity colliders* was proposed in 2001 and approved in 2002 as RD50.
- Diverse expertise:
  - Solid state physics
  - Interaction of radiation with matter
  - Electronics and ASIC design
  - Sensor design
  - Experimental HEP


CERN, 31 May 2018

RD50

RD50 Prolongation Request

– May 2018 –

The RD50 Collaboration

- Program extended in 2018 (2018-2023 5 years work plan)
  - Main targets: HL-LHC & FCC
  - Sensing up to extreme radiation fluences (10^{17} n_{eq} cm^{-2} and above):
    - Characterization of sensor behavior (current, temperature dependence, annealing effects, signal measurements)
    - Microscopic defects investigation to the new damage regime
  - Extended models for describing sensor performances up to these extreme fluences:
    - Insertion of extreme damage effects in TCAD semiconductor simulation software
    - Parametric description of operation parameters (signal, trapping, current) as a function of fluence and temperature.
  - Investigation of new structures and enhancement of their potential (LGAD, small area 3D, HV-CMOS).

The RD50 Collaboration

- RD50: 66 *institutes and 430 members*

51 European institutes

Austria (HEPHY), **Belarus** (Minsk), **Czech Republic** (Prague (3x)), **Finland** (Helsinki, Lappeenranta), **France (Marseille, Paris, Orsay)**, **Germany** (Bonn, Dortmund, Freiburg, Göttingen, Hamburg (Uni & DESY), Karlsruhe, Munich (MPI & MPG HLL)), **Greece** (Demokritos), **Italy** (Bari, Perugia, Pisa, Trento, Torino), **Croatia** (Zagreb), **Lithuania** (Vilnius), **Montenegro** (Montenegro), **Netherlands** (NIKHEF), **Poland** (Krakow), **Romania** (Bucharest), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona(3x), Santander, Sevilla (2x), Valencia), **Switzerland** (CERN, PSI, Zurich), **United Kingdom** (Birmingham, Glasgow, Lancaster, Liverpool, Oxford, Manchester, RAL)

8 North-American institutes

Canada (Ottawa), **USA** (BNL, Brown Uni, Fermilab, LBNL, New Mexico, Santa Cruz, Syracuse)

7 Asian institutes

China (Beijing-IHEP, Dalian, Hefei, Jilin, Shanghai), **India** (Delhi), **Israel** (Tel Aviv)

Full member list: www.cern.ch/rd50

Organizational Structure / Work Program

Covering all fields of semiconductor detectors exposed to radiation

Co-Spokespersons
Gianluigi Casse (Liverpool University, UK & FBK-CMM, Trento, Italy) and *Michael Moll* (CERN EP-DT)

Targeting new solid-state detector technologies including high precision 4D detectors

Defect / Material Characterization
Ioana Pintilie
(NIMP Bucharest)

- Characterization of microscopic properties of standard-, defect engineered and new materials; pre- and post- irradiation
- DLTS, TSC, ….
- **SIMS, SR, …**
- NIEL (calculations)
- Cluster and point defects
- Boron related defects
- SiC/GaN based detectors

Detector Characterization
Eckhart Fretwurst
(Hamburg University)

- **Characterization of test structures (IV, CV, CCE, TCT,.)**
- Development and testing of defect engineered devices
- EPI, MCZ and other materials
- NIEL (experimental)
- Device modeling
- Operational conditions
- Common irradiations
- Very high radiation fluences
- Wafer procurement (M.Moll)
- Acceptor removal (Kramberger)
- TCAD modeling (J.Schwandt)

New Structures
Giulio Pellegrini
(CNM Barcelona)

- 3D detectors
- **Thin detectors**
- Cost effective solutions
- Other new structures
- Detectors with internal gain
- **LGAD:Low Gain Avalanche Det.**
- Deep Depleted Avalanche Det.
- Slim Edges
- LGAD (S.Hidalgo)
- **HVCMOS (E. Vilella)**

Full Detector Systems
Gregor Kramberger
(Ljubljana University)

- LHC-like tests
- Links to HEP (LHC P2, FCC)
- Links electronics R&D
- Low rho strips
- Sensor readout (Caribou,Alibava)
- Comparison:
  - pad-mini-full detectors
  - different producers
- **Radiation Damage in HEP detectors**
- Timing detectors
- Test beams (M.Bomben & G.Casse)

Collaboration Board Chair & Deputy: G.Kramberger (Ljubljana) & Daniel Münstermann (Lancaster), Conference committee: U.Parzefall (Freiburg)
CERN contact: M.Moll (EP-DT), Secretary: V.Wedlake (EP-DT), Budget holder: M.Moll & M.Glaser (EP-DT) , EXSO: R.Costanzi (EP-DT)

Highlighted IN2P3 contributions

IN2P3 in RD50

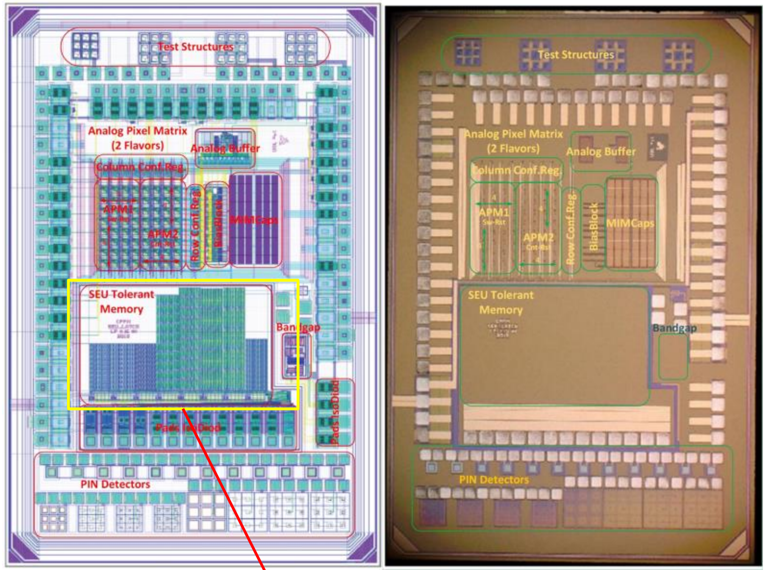
- 3 IN2P3 laboratories are members of RD50: **CPPM (2018), IJCLab (initialy LAL - 2009) and LPNHE (2012)**.
- All the researchers and engineers involved on the activities related to RD50 work mainly on the ATLAS ITk pixel upgrade
- The activities within RD50 are diverse and dependent of the opportunities and availabilities
- CPPM is involved on HV-CMOS with the participations to two MPW runs in Lfoundry technology
- IJCLab is involved in doping profile studies and measurements as well as simulation
- LPNHE is involved in sensors (thin, active edge) studies and tests, micro-channel cooling and Anisotropic Conductive Films connection.

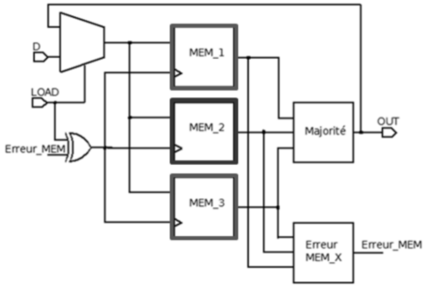
CPPM activities

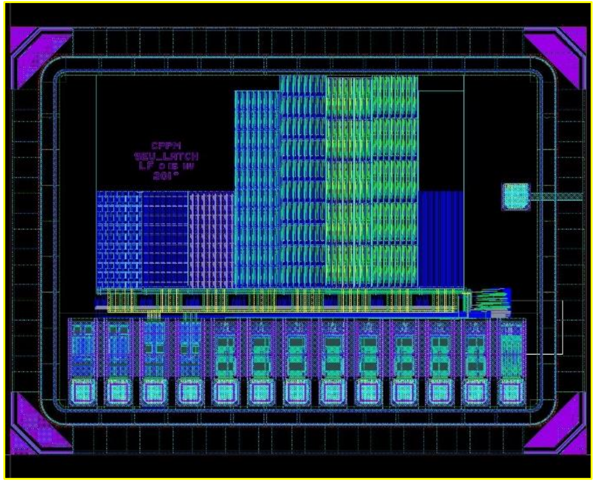
- Joining RD50 was an opportunity for the CPPM group to continue its work on HV-CMOS chip design in LF technology.

- Participation in **MPW2 run** (2019-2020) with the submission of SEU tolerant memories and an analog buffer.

- SEU tolerant memories 8 columns of different flavors of memory:
  - Col1 with standard cell
  - Col2 with DICE cell (full custom)
  - Col3 with enhanced DICE cell (full custom)
  - Col4 with TRL and standard cells
  - Col5 with TRL and DICE cell (full custom)
  - Col6 with TRL and standard cell with split latch
  - Col7 with TRL and DICE cell (full custom) with split latch
  - Col8 with SRAM



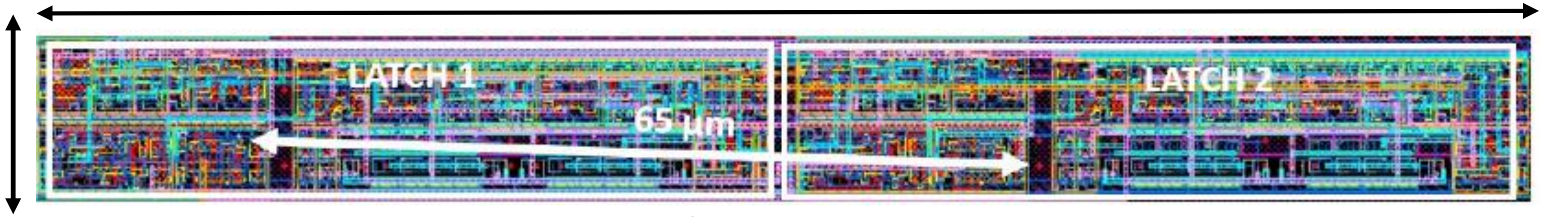




Block size : ~1600µ (Pad limited) x 1200µ (Core Limited)

TRL

115 µm

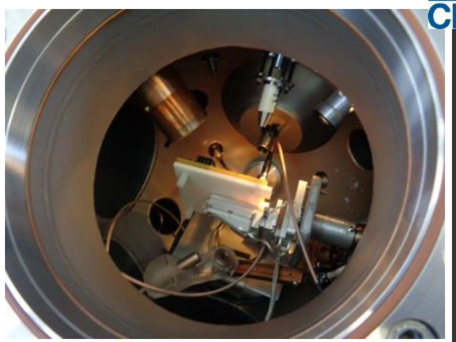


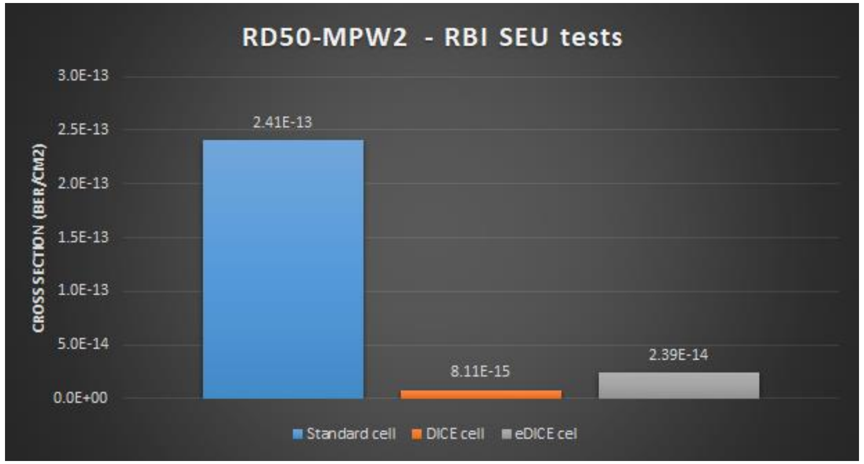
Split latches

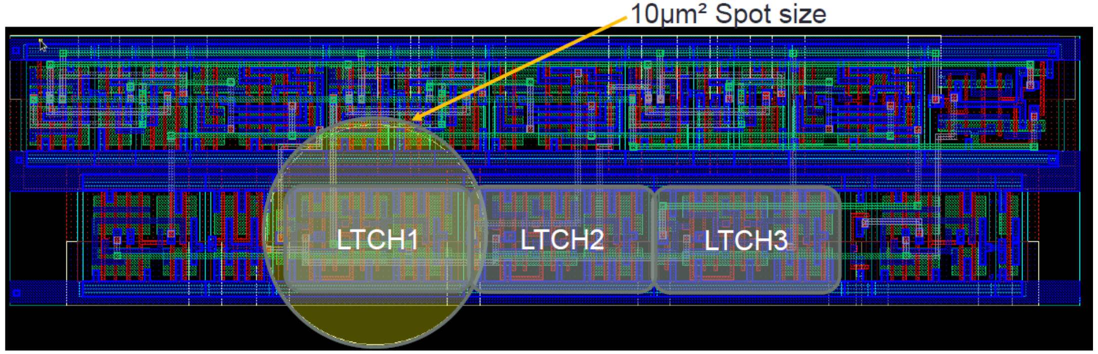
From **Patrick Pangaud**

CPPM activities

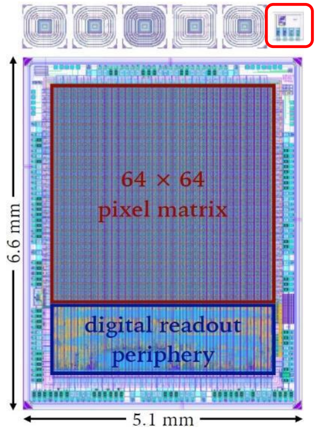
- SEU tolerant memories were tested at GANIL and RBI (Zagreb) in 2021.
- Results showed that the LF technology is robust to irradiation. Only the single latches had SEUs. Dice cells are 30 times more tolerant than the standard cells (2.4e-13 vs 8e-15 cm2).
- The triplicated cells didn't exhibit any SEUs. More exposition time needed (GANIL) and the RBI beam size was too small to hit two latches at the same time.



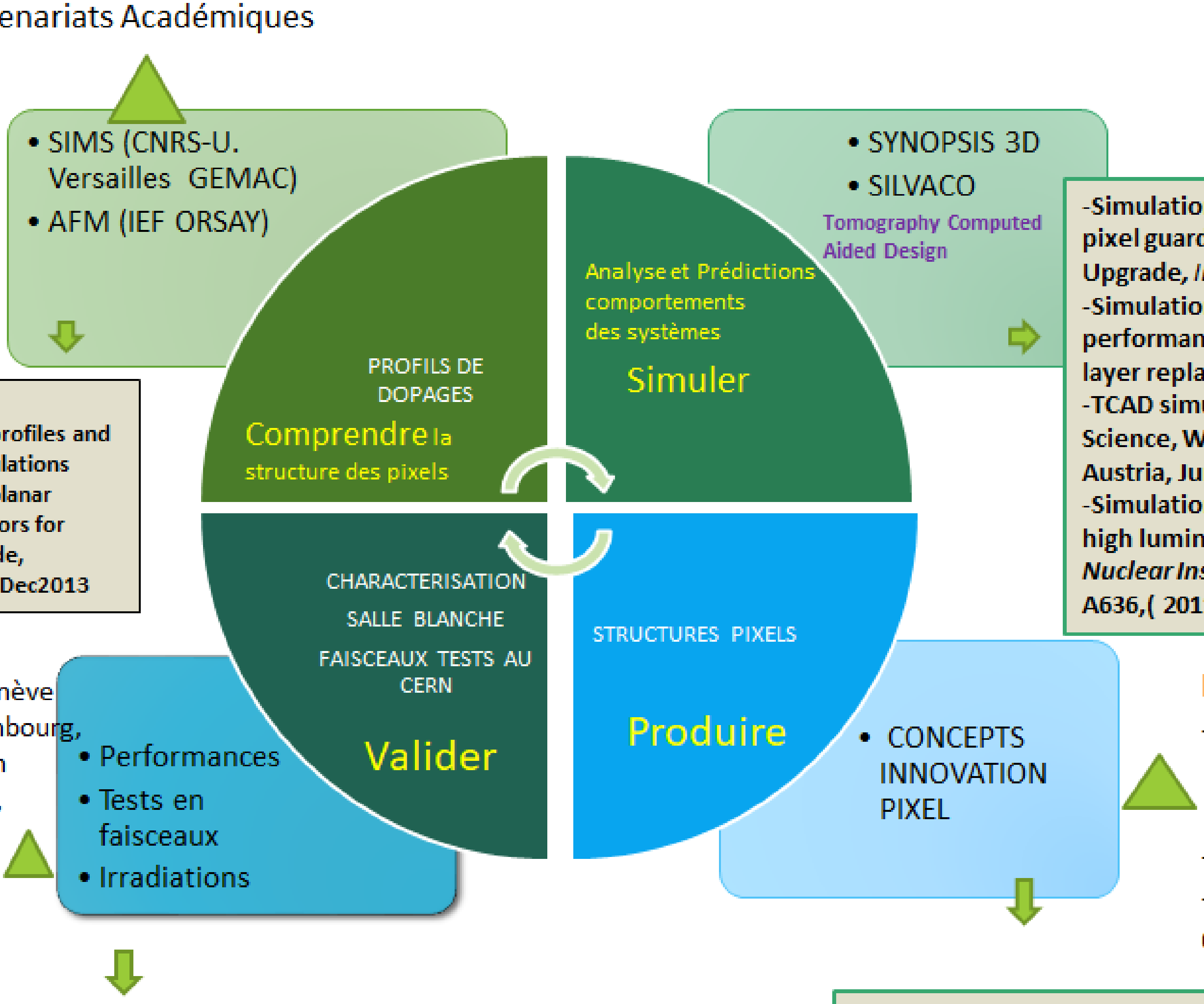


- Participation in **MPW3 run** (2021-2022) with the submission of a bandgap (correction with respect to the one submitted with LF-Monopix2). Chip expected shortly at CPPM for characterization, temperature and irradiation (Rx) tests.
- See also talk by M. Barbero on DICE



From **Patrick Pangaud**

IJCLab activities



- Doping profiles and TCAD simulations of ATLAS planar pixel sensors for IBL upgrade, ATL-COM, Dec2013

CERN, Genève
DESY Hambourg,
PSI, Zurich
Karlsrhue,

-Simulation of radiation damage effects on planar pixel guard ring structure for Atlas Inner Detector Upgrade, *IEEE Trans. Nucl.Sci.*, Dec 2009,
-Simulation of guard ring influence on the performance of ATLAS pixel detectors for inner layer replacement : *J. Instrum.* 4 (2009) P03025
-TCAD simulation of planar pixel sensors, Procee. Science, Workshop Vertex detectors, Vertex 2011, Austria, June 19th-24th.
-Simulations of planar pixel sensors for the ATLAS high luminosity upgrade,
Nuclear Instruments and Methods in Physics A636,(2011)S37

Partenariats Industriels
- MPI-CiS Institut für Mikrosensorik gGmbH (Erfurt, Germany) ,
- LETI Grenoble, France
- VTT Technical Research Center of Finland,

-Development of novel n+-in-p silicon planar pixel sensors for HL-LHC, Nucl.Instrum.Meth. A699 (2013) 72-77.

- Evaluation of novel KEK/HPK n-in-p pixel sensors for ATLAS upgrade with testbeam, Nucl.Instrum.Meth. A699 (2013) 78-83.

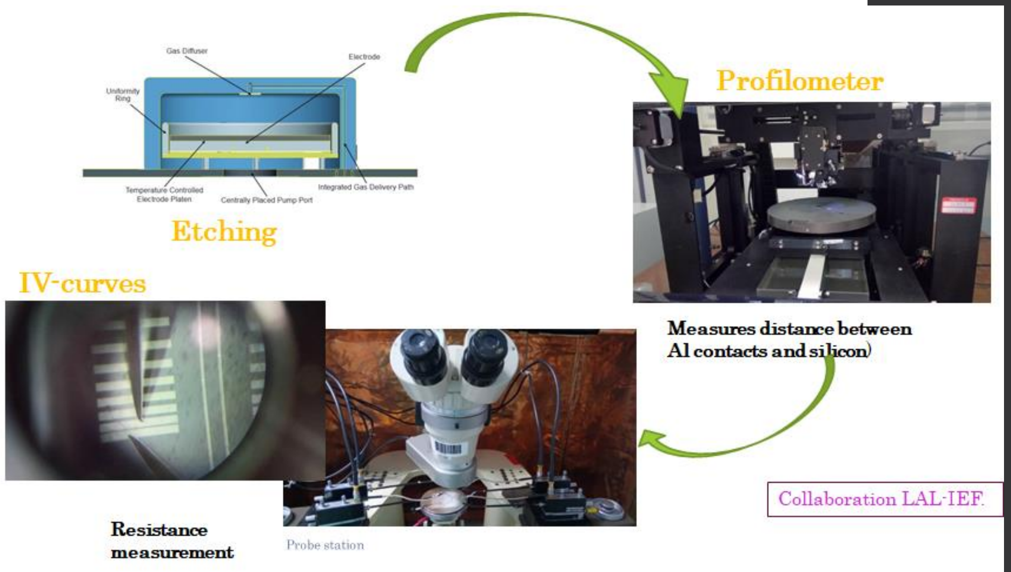
-TCAD simulations of planar pixel sensors, invited speaker,
The 20th Anniversary International Workshop on Vertex Detectors – Vertex 2011 conférence, Rust, Lake Neusiedl, Austria (June 19 – 24, 2011)

-Leading edge of the technological developments of Planar Pixel Sensors and prospects for ATLAS HL-LHC, IEEE seoul 2013, proceedings, 22 Nov. 2013.

From **Abdenour Lounis**

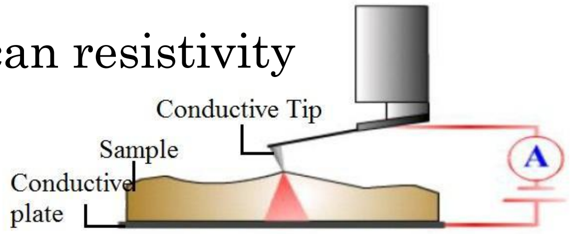
IJCLab activities

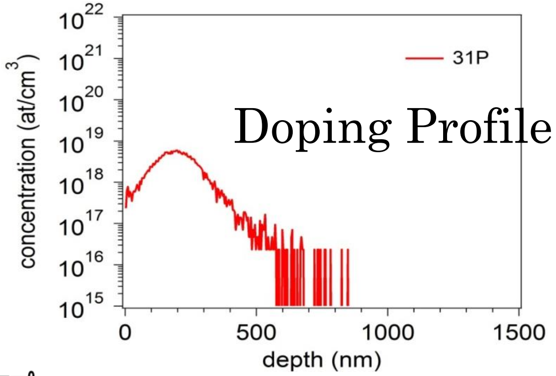
- Doping profile measurement in collaboration with Institut d'Electronique Fondamentale Orsay (IEF):
  - **Measuring sheet resistances by Transmission Line Method**: Four points probe are used (2 for I, 2 for V) to determine the sheet resistance of a layer while minimizing effects of contact resistance.
  - Four wafers with special geometry have been produced **in CNM (Barcelona)**, with both Phosphorus and Boron implantation.



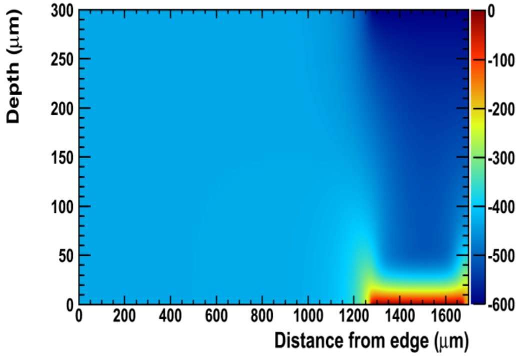
- Measurement of the doping profile in LGAD:
  - Secondary Ion Mass Spectroscopy (SIMS)
  - X-Ray Photoelectric Spectroscopy (XPS, ESCA)
  - Spreading Resistance Profiling (SRP)
  - Scanning Spreading Resistance Microscopy (SSRM)

Scan resistivity





- Simulations:
  - 3D Simulations
  - Migrating from SILVACO TCAD to Synopsys
  - Both process simulation and irradiation model integration

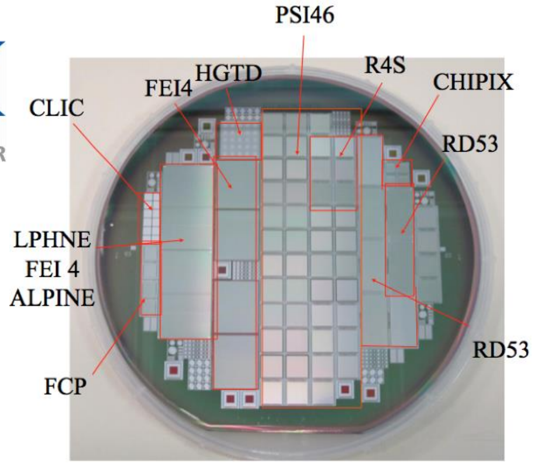


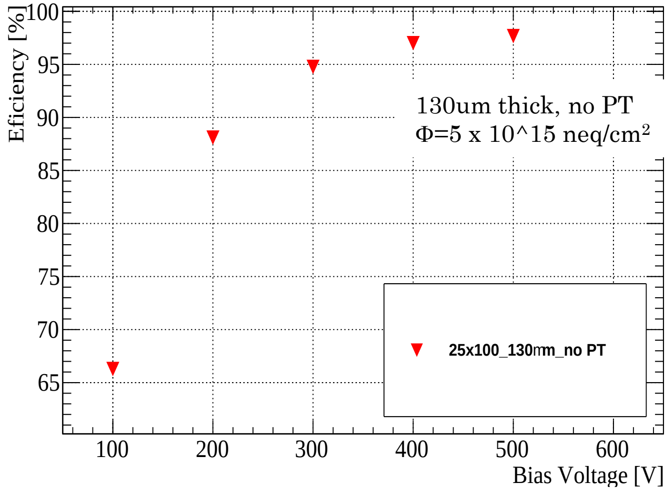
Pixel Voltage simulation (600V - 5 x$10^{15} n_{eq} cm^{-2}$)

From **Abdenour Lounis**

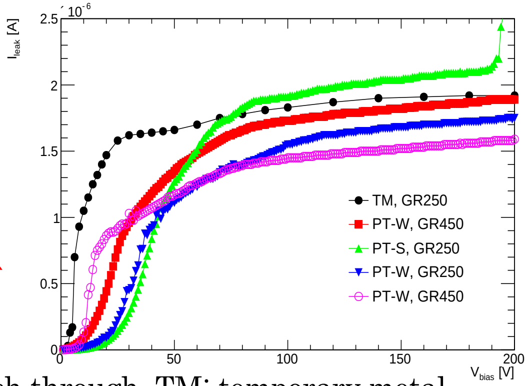
LPNHE activities

- **Planar pixel productions with FBK (2018)**: 6” 100-130 µm thick n-on-p INFN ATLAS/CMS project Active Edge:
  - RD53a compatible sensors + many other designs
  - Significant hit efficiency even in proximity of the trench edge: >50% at 10µm distance
  - **Breakdown typically larger than 200V**
  - Characterization at test-beams **after irradiation Hit-efficiency above 97%**





- **Standard edge (2019) – ATLAS Inner Tracker (ITk) oriented**:
  - Single RD53a sensors, Double RD53a, Quad ITk sensors
  - Breakdown voltage before irradiation typically larger than 200V
  - Depletion voltage in the 10-15V (for 100µm) and 20-30V range (for 150 µm)
  - Sensors of 100 and 150µm **tested at DESY after irradiation** (2.10^{15} and 5.10^{15} neq)
  - Even at a fluence of 5.10^{15} neq/cm^2, the **hit efficiency reaches a value above 97%** (the ITk standard for that dose) already at Vbias < 250V
  - **Characterization of 50µm thick sensors** with different bias network structures and guard ring regions. Beam tests and irradiation.
  - Typical depletion voltage of the order of 20V with a couple of sensors at 40V
  - More results in the back-up slides

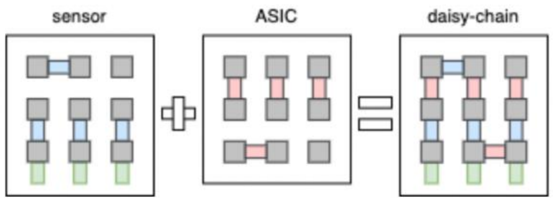


PT: punch through, TM: temporary metal

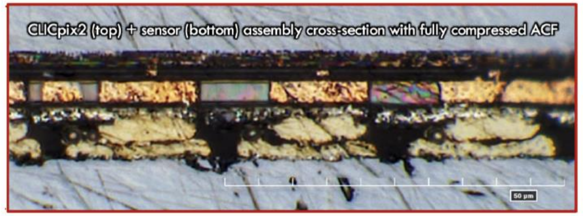
From **Giovanni Calderini**

LPNHE activities

- Production of conductive chains to test performance of bump bonding (standard solder technologies and Anisotropic Conductive Films):
  - Principle of **conductive chains**: a long conductive line is subdivided into segments deposited following an alternating pattern on the surface of two facing dies. After flip-chip bonding the sequence of segments reconstructs the full line.
  - Layout features the pad structure of existing chips (RD53, Timepix3, CLICpix2)
  - **Anisotropic conductive films** can also be used as interconnection technique. Application potentially important also from the cost point of view since Bump-bonding represent a significant fraction of the hybridization cost of pixel modules



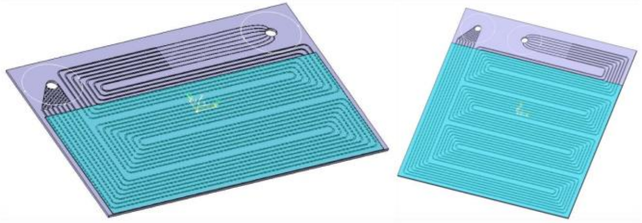
Cross section through CLICpix2 ACF assembly



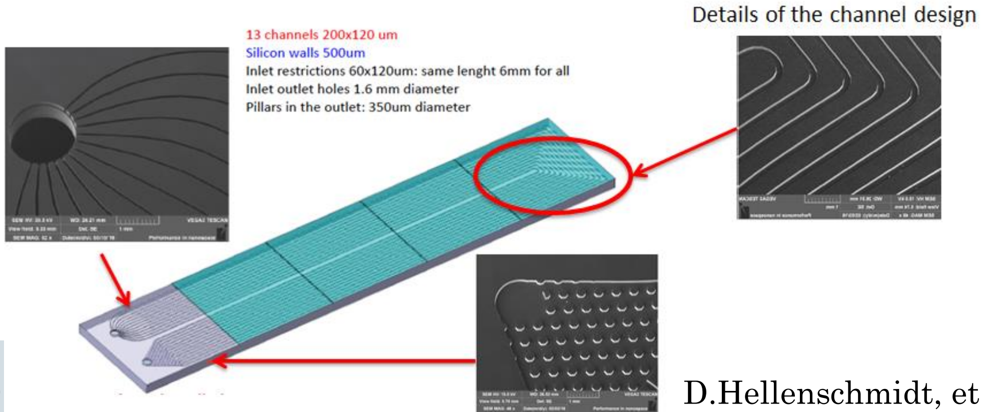
- **Micro-channels design** (see also talk by R. Kossakowski):
  - The goal is to reduce the fraction of x/x0 brought by the services
  - Develop cooling blocks for our silicon modules
  - Develop structures able to study the evaporative behavior of CO_2 in channels and compare with models
  - Prototypes produced by LPNHE with FBK and IEF Orsay

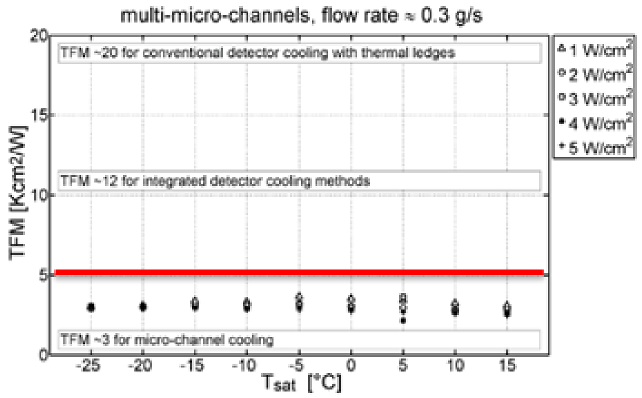
"Snake" design microchannel cooling unit size

Design	Width [mm]	Height [mm]
Single	30.0	30.0
Double	30.0	41.3
Quad	42.4	48.0



FONDAZIONE BRUNO KESSLER





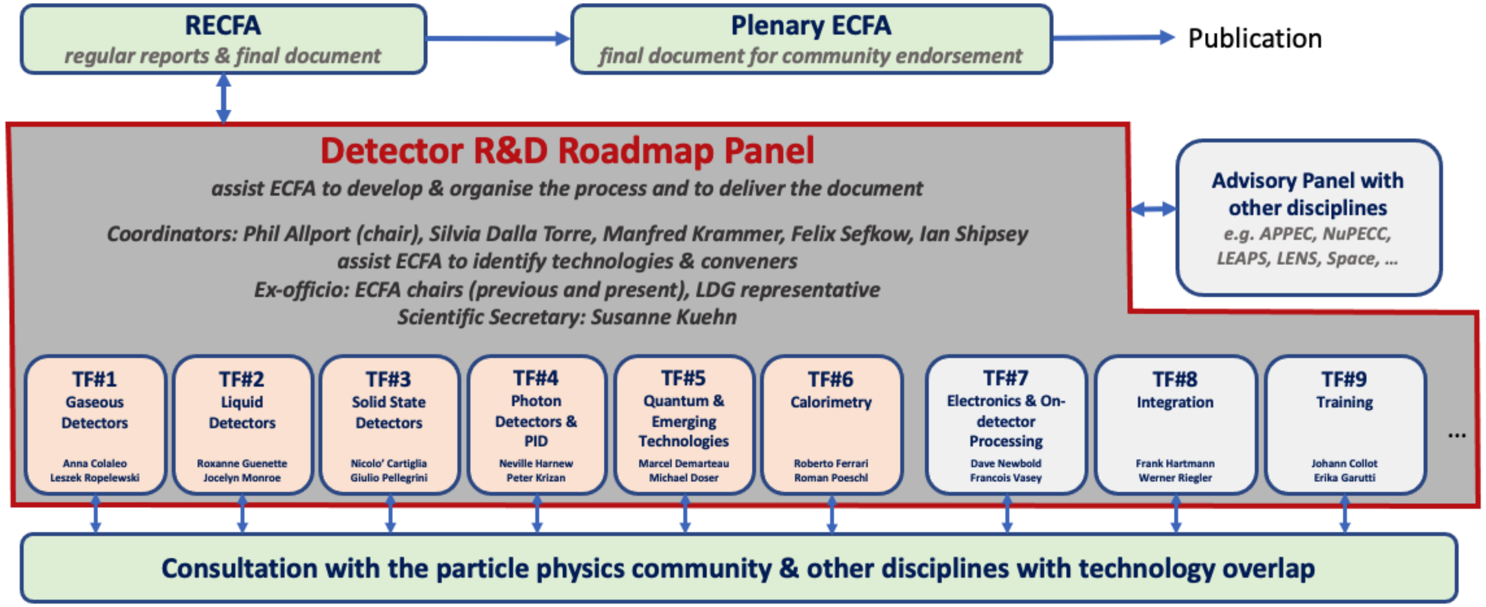
D.Hellenschmidt, et al, Nucl. Instrum. Meth. A 958 (2020) 162535

From **Giovanni Calderini**

Conclusions

- CPPM, IJCLab and LPNHE are members of RD50 since several years and have contributed to diverse studies linked to the pixel detector design. Mainly:
  - HV-CMOS development (SEU tolerant memories, bandgap)
  - Doping profile
  - Sensor studies
  - Anisotropic conductive films
  - Micro-channels cooling

- With the ECFA roadmap, RD50 will end (end of 2023) but activities will continue within the DRDTs



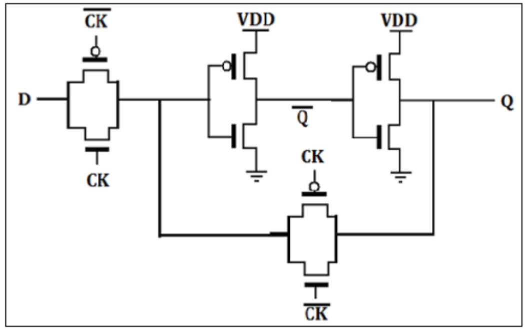
BACK-UP

Glossary

- LGAD: Low Gain Avalanche Detector
- MPW: Multi Project Wafer
- DICE: Dual Interlocked Storage Cell
- TRL: Triple Redundancy Latches ou Technical Readiness Level
- TCAD: Technology Computer Aided Design
- TFM: Thermal Figure of Merite

Latch(s) description

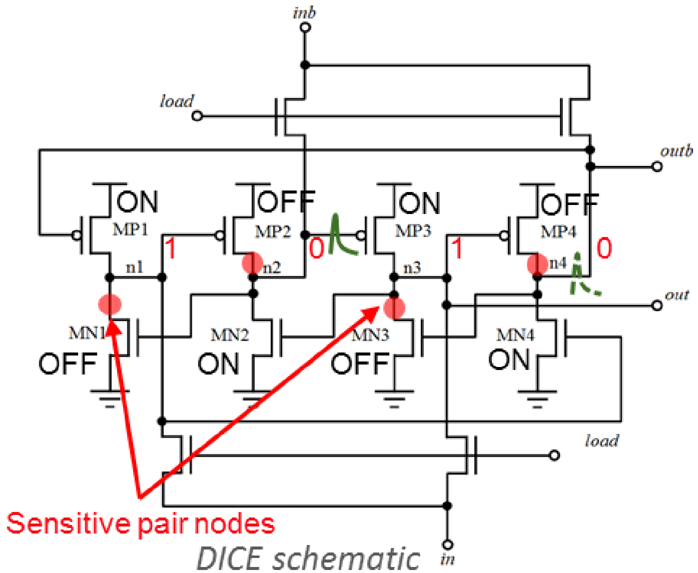
- Standard cell "DF_X2"
  from the "lf15adlvt9s" library



- DICE "Dual Interlocked Storage Cell"
  (full custom cell)

- DICE latch structure is based on the conventional cross coupled inverters:
  - The charges deposited by a ionising particle strike one node can't be propagated due to the stability of this architecture.
  - If 2 sensitive nodes (corresponding to the OFF transistors drain area) are affected simultaneously, the immunity is lost and the DICE latch is upset

- Enhanced DICE "Dual Interlocked Storage Cell"
  (full custom cell)
  - The distance between the 2 sensitive nodes (corresponding to the OFF transistors drain area) is bigger to increase the immunity

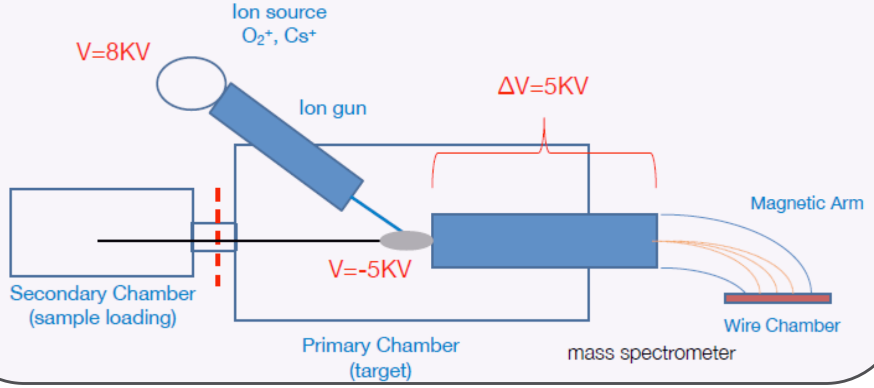


DICE schematic
(example of a stored data = 1)

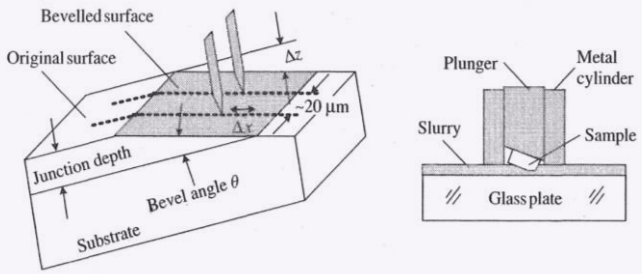
… developments over the years on this activity

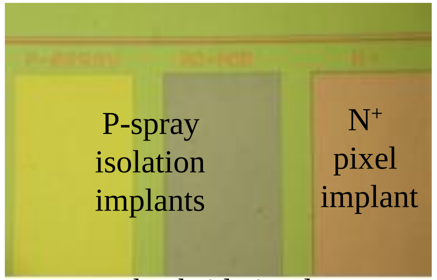
- Two main experimental methods are used to measure dopant profiles:
  - Secondary Ion Mass Spectrometry (SIMS) – GEMaC - CNRS, eng. F. Jomard, collaboration since 2009
    - determines the total dopant profile (dopant concentration [at.cm^{-3}] vs depth [nm])
  - Spreading Resistance Profiling (SRP) – EAG metrology lab, U.K.
    - determines the carriers density profiles (carrier concentration [cm^{-3}] vs depth [nm])

SIMS



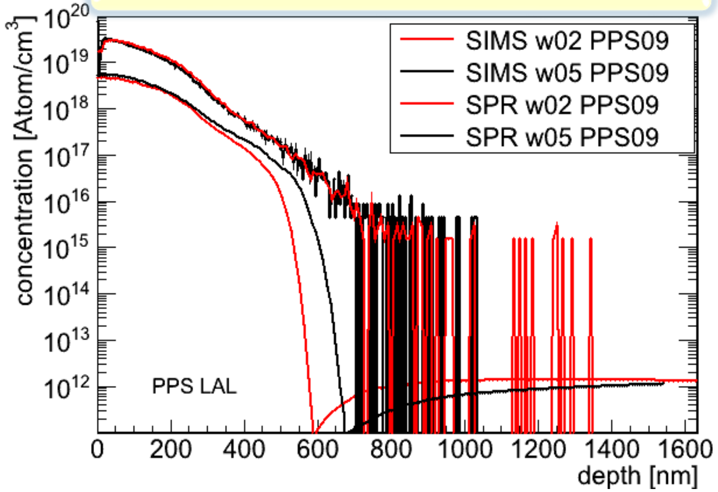
SRP



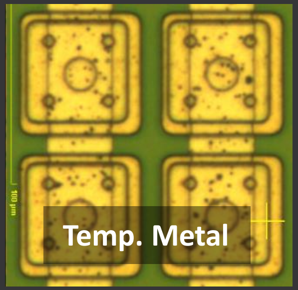


p+ backside implant

P+ (boron) backside, run n-in-n 2009

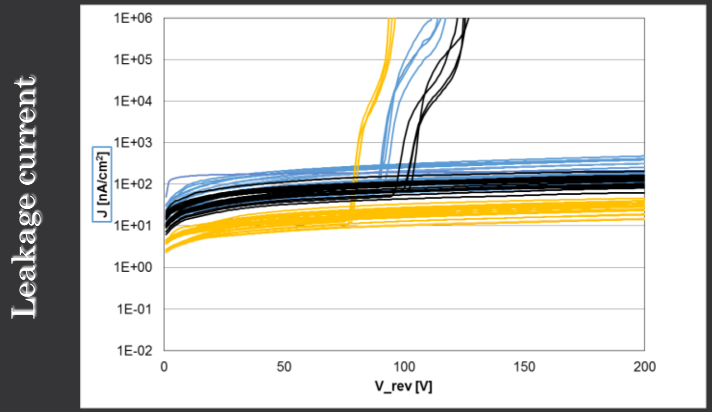


Sensors with different bias networks



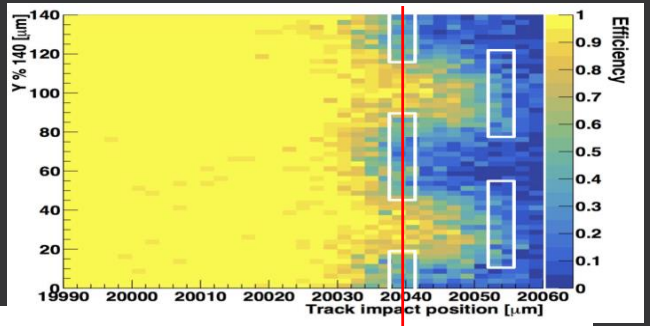
Temporary Metal
Punch-Trough
- Straight
- Wiggled

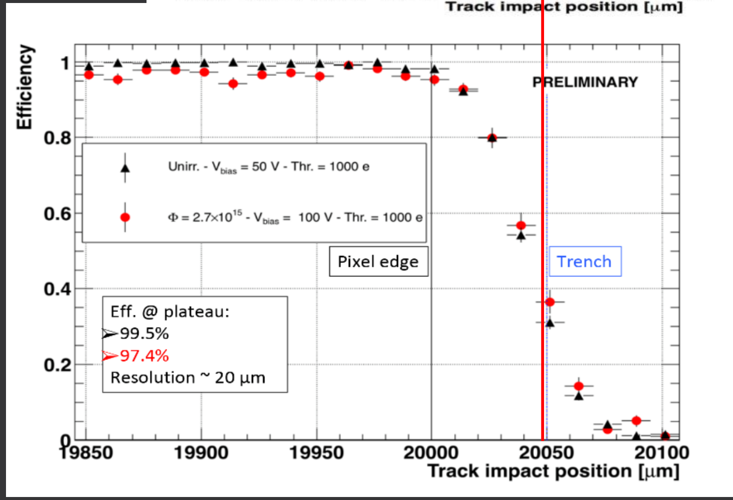
Breakdown typically larger than 200V



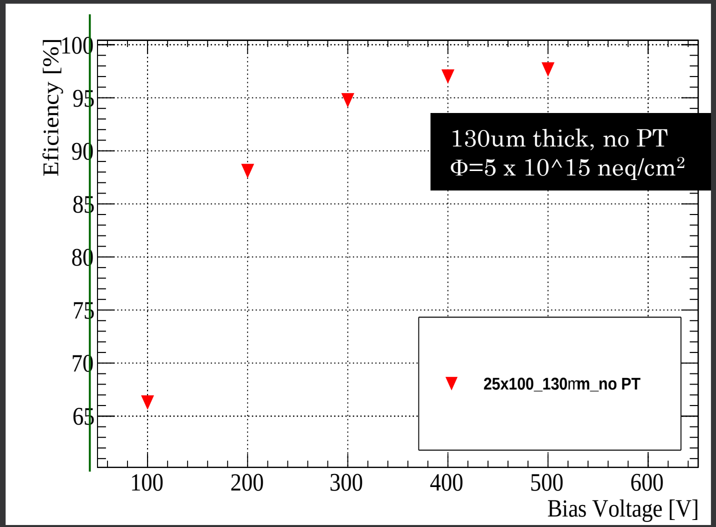
Very aggressive design:
0-1-2 guard rings (0-1 for active edge)
Distance from pixel to trench: 60 to 80 μm

Significant hit efficiency even in proximity of the trench edge: >50% at 10μm distance





Characterization at test-beams after irradiation
Hit-efficiency well above 97%



Characterisation of 100/150 μm thick sensors

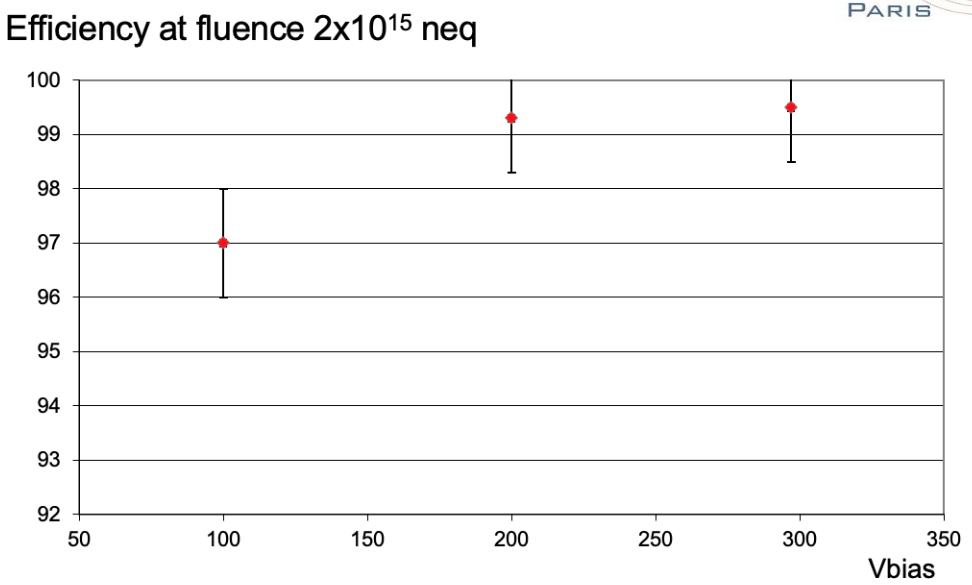
Tested at DESY after irradiation
- 2 x 10^15
- 5 x 10^15

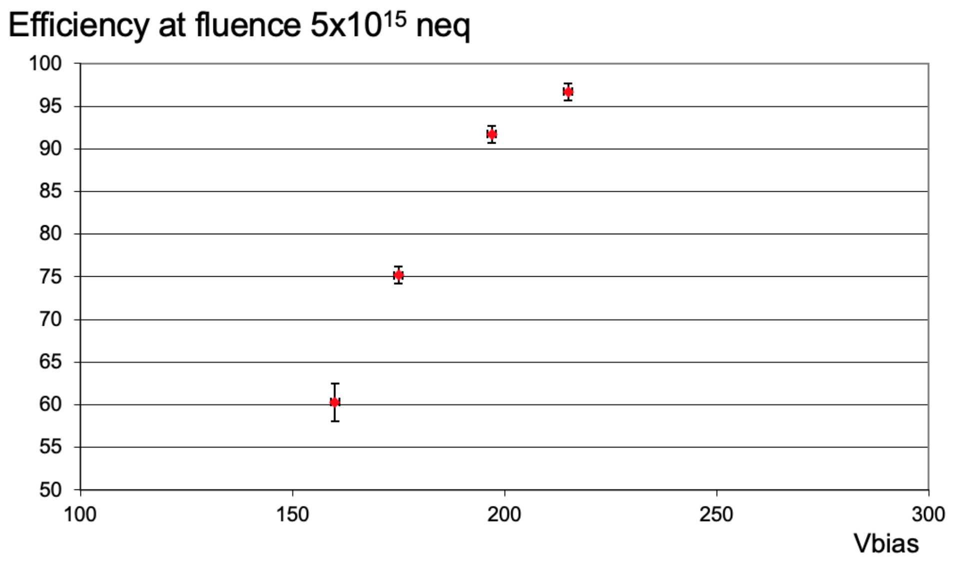
Lack of time has prevented to apply parylene protection for HV
- HV limited to 400V after irradiation

During the runs at $5x10^{15}$ neq/cm^2 a cooling problem had a large impact on the leakage current of all the tested modules.
The effective Vbias was significantly different from the provided tension due
to some voltage drop in resistances

The effective Vbias has been carefully evaluated

Even at a fluence of $5x10^{15}$ neq/cm^2, the hit efficiency reaches a value well above 97% (the ITk standard for that dose)
already at (effective) Vbias < 250V

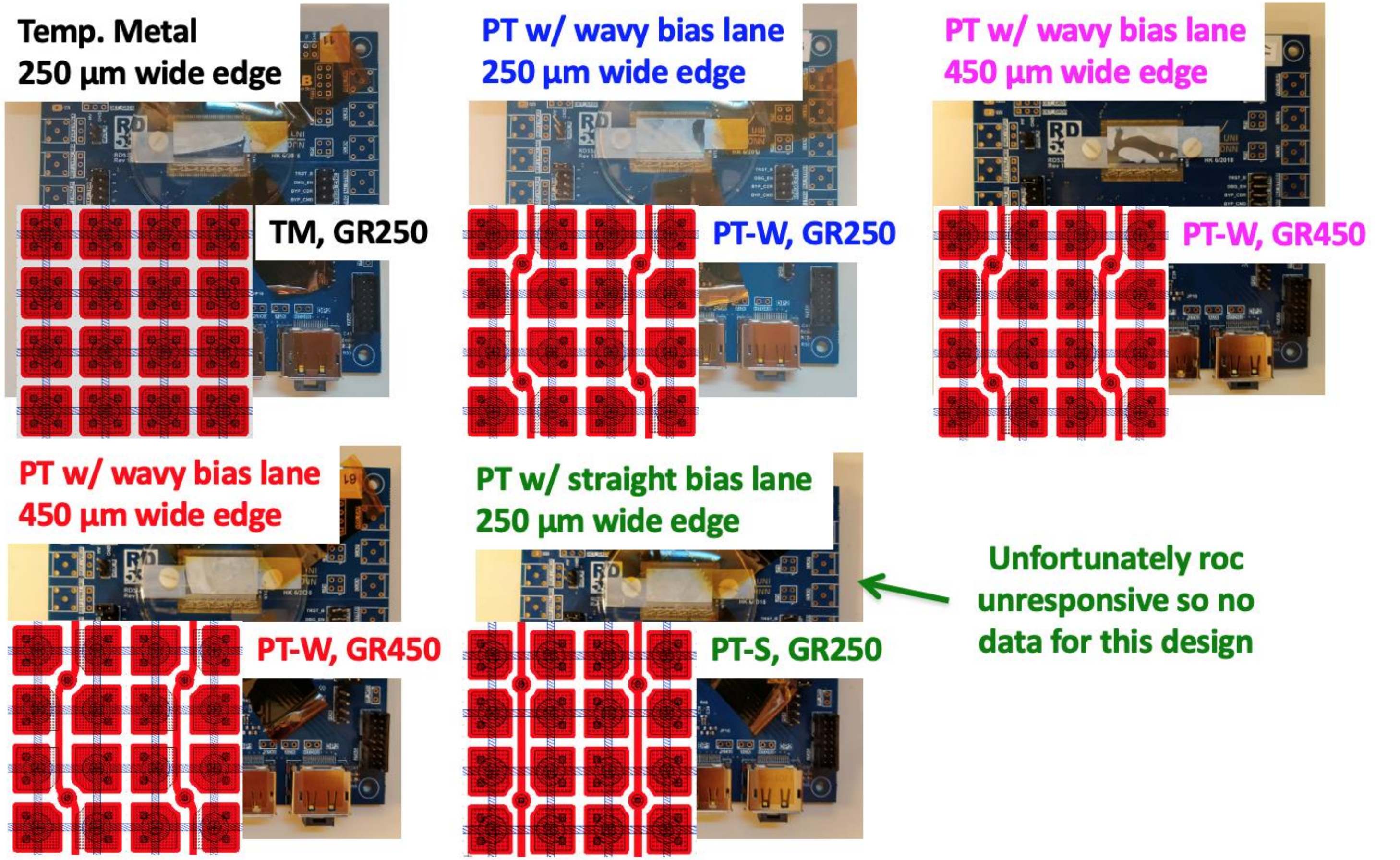




Characterisation of 50 μm thick sensors

The lower threshold achievable with the RD53A FE chip allowed to design and produce thinner sensors

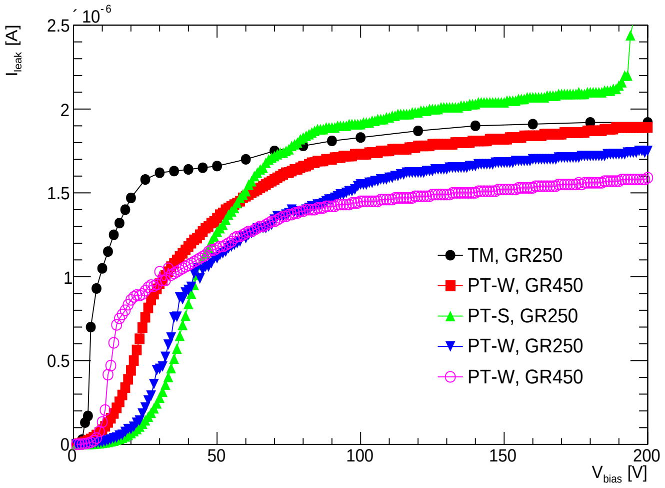
Five modules of 50μm thickness with different bias network structure and guard ring region were tested on beam and have been now irradiated. Unfortunately one is not working, data available from the remaining four

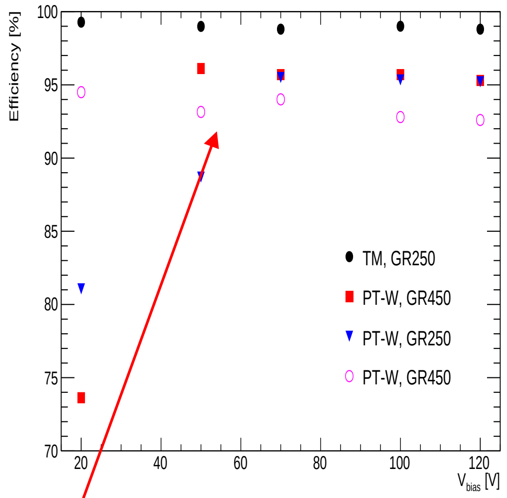


Characterisation of 50 µm thick sensors

LPNHE PARIS

Typical depletion voltage of the order of 20V with a couple of sensors at 40V (rather high values, reason for this still under investigation)



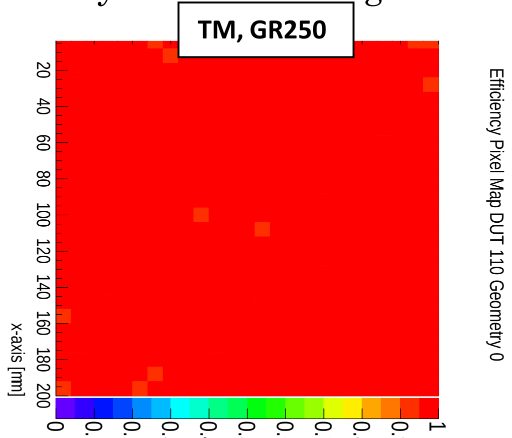


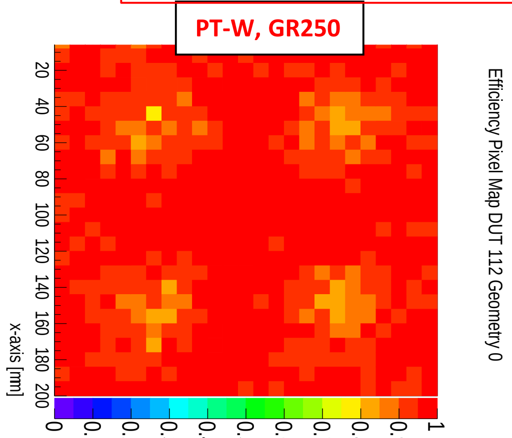
Effect of PT biasing network more evident wrt 100/150 µm (for tracks at normal angle)

Efficiency for Temporary Metal is stable around 99% even at very low bias voltage

Devices with PT networks lose a few % due to the inefficient regions of the bias dots / lines

Hit-eff. folded in a 4x4 pixel map





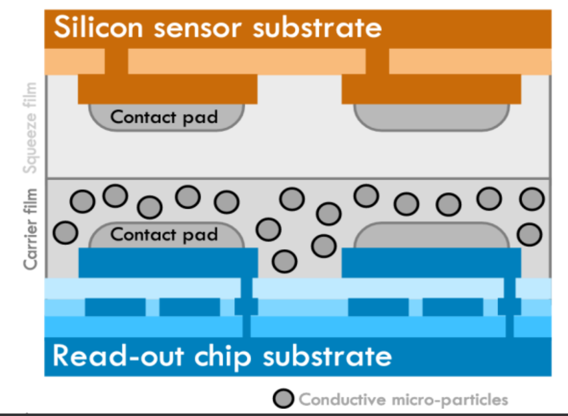
Sensors have been irradiated up to 5×10^{15} neq/cm^2 but test-beam characterization has not been possible yet due to COVID.

That will happen soon, stay tuned

Goal is to use to study ACF connections

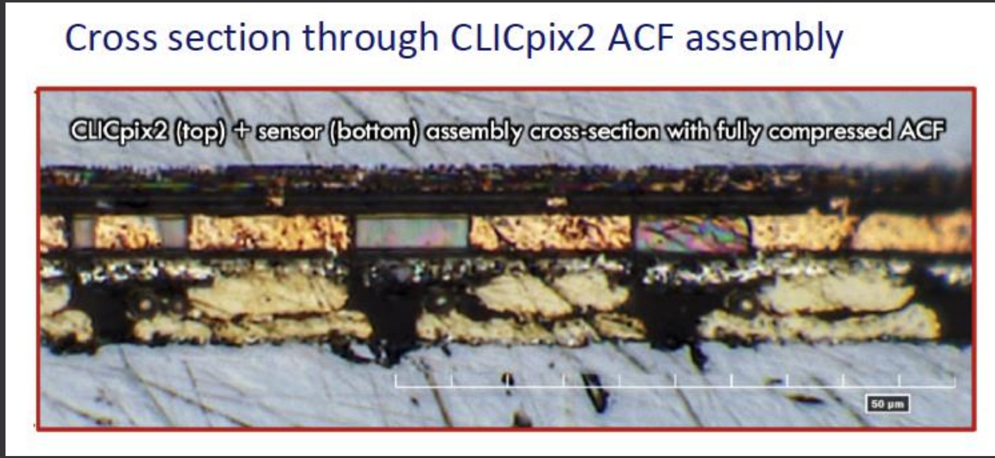
Anisotropic conductive films can also be used as interconnection technique

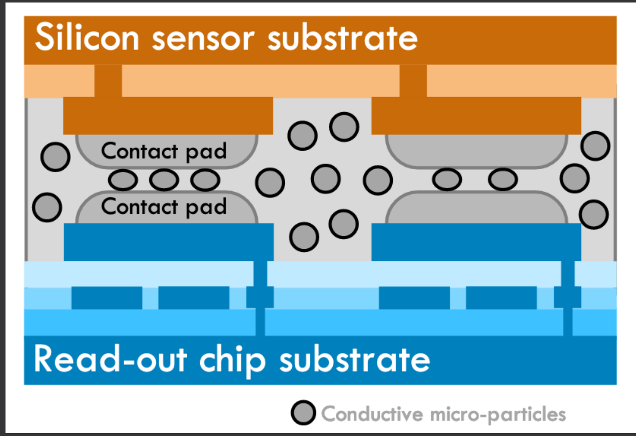
Application potentially important also from the cost point of view



Bump-bonding represent a significant fraction of the hybridization cost of pixel modules

Development is also part of AIDAinnova proposal in the hybrid detectors Working Package





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