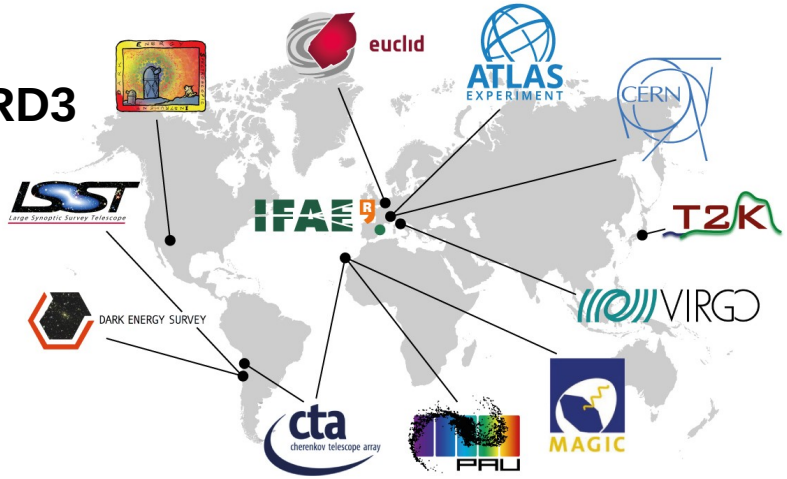
Instrumentation Activities at IFAE on DRD3

S. Terzo, M. Chmeissani and S. Grinstein

for the IFAE Solid State Detectors Group

- IFAE conducts research on:
  - High-energy physics, astrophysics, and cosmology
  - Applied and medical physics and quantum technologies
- Related to the DRD initiative, IFAE is active in:
  - QT, led by **P. Forn** (DRD5)
  - Neutrino Physcis led by **T. Lux** (DRD1, 2, 6…),
  - Solid State detectors (ST, MC & SG) (DRD3 and DRD7)
- In this talk:
  - Briefly will present activities and plans on **DRD3**



Spanish Instrumentation Meeting
6-7 March 2023 at CNM

IFAE Institut de Física d'Altes Energies

One Slide Overview

- **Tile Calorimeter** *(led by I. Korolkov)*
  - IFAE fabricated part of the ATLAS TileCal (Tile Calorimeter)
  - For HL-LHC: production of housing for new front-end electronics (mini-drawers)
    - In-kind contribution to ATLAS, being delivered on time (mostly done)
- **Pixel Detector**
  - Past: production of modules for IBL and AFP (current ATLAS system)
  - For HL-LHC: 3D sensors at CNM and assembly of innermost pixel modules (IFAE)
    - 3D sensors being produced at CNM (delay due to CR upgrade)
    - IFAE assembly qualification stage 1 and 2 done
    - Pre-production end 2023: target linear triplets (innermost modules)
- **Timing with Silicon**
  - Past: qualification of LGAD for ATLAS timing detector (HGTD)
  - HL-LHC: LGAD sensors (from CNM) and hybridization & module assembly (IFAE)
    - HGTD LGAD sensor qualification run on-going at CNM
    - Hybridization and assembly at IFAE of first full modules completed
    - Pre-production to start early 2024: target 10% of modules
- **Solid state detectors R&D**
  - In the context of RD50 and various projects working on DMAPS, Medical, timing, radiation hard sensors and new materials

ITk 3D Sensors and Module Assembly

S. Terzo
J. Carlotto
P. Fernandez
E. Peregrina
J. Piñol

- IFAE will assemble **3D modules for the innermost pixel layer** of ATLAS
  - Built on the experience of IBL and AFP
- Multi-stage **qualification process** on-going
  - Dummy silicon and process/tooling qualification ☑
  - RD53A (planar) module qualification/testing ☑
  - ITkPixV1.1 module qualification/testing (on-going) ☐
  - Assembly with final chips ☐
- In parallel, studying the **performance and limits** of the technology

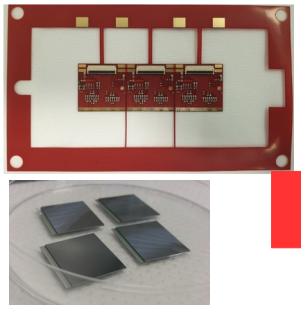
frontiers

Novel 3D pixel sensors for the upgrade of the ATLAS Inner Tracker

Stefano Terzo [1,*], Maurizio Boscardin [2], Juan Carlotto [1], Gian-Franco Dalla Betta [3,4], Giovanni Darbo [5], Ole Dorholt [6], Francesco Ficorella [2], Giuseppe Gariano [5], Claudia Gemme [5], Giulia Giannini [1], Sebastian Grinstein [1,7], Andreas Heggelund [6], Simon Huiberts [8], Angela Kok [9], Ozhan Koybasi [9], Alessandro Lapertosa [5,10], Magne Elk Lauritzen [8], Maria Manna [11], Roberto Mendicino [2,3,4], Hideyuki Oide [5], Giulio Pellegrini [11], Marco Povoli [9], David Quirion [11], Ole Myren Rohne [6], Sabina Ronchin [2], Heidi Sandaker [6], Md. Arif Abdulla Samy [3,4], Bjarne Stugu [8], and Leonardo Vannoli, [5,10]

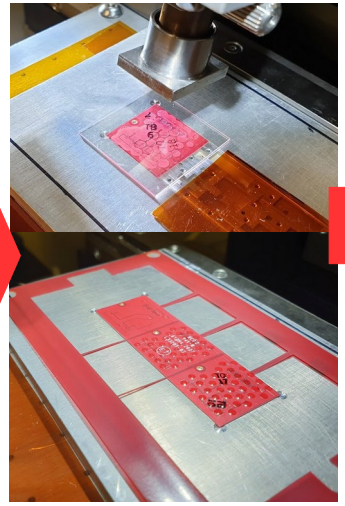
[1] *Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology (BIST), Barcelona, Spain*
[2] *Fondazione Bruno Kessler (FBK), Trento, Italy*
[3] *Trento Institute for Fundamental Physics and Applications (TIFPA), Trento, Italy*

https://doi.org/10.3389/fphy.2021.624668

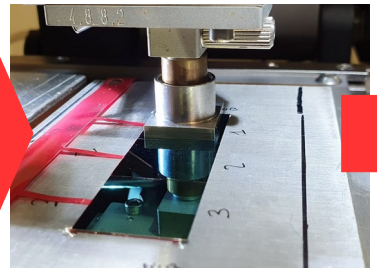


Bare module and flex

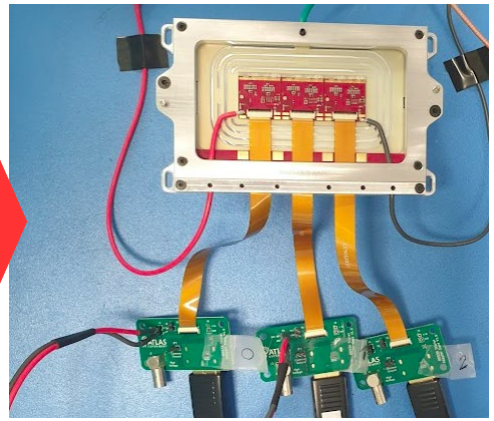
Initial metrology



Glue deposition



Placing and glue drying



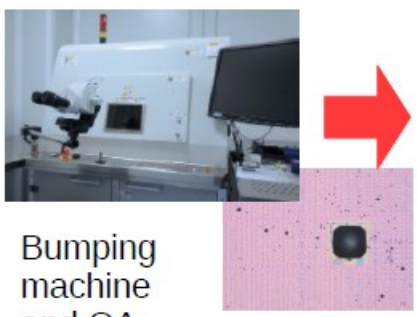
Triplet testing

IFAE will assemble ~150 triplet modules

HGTD: Module Development

- **H**igh **G**ranularity **T**iming **D**etector: consists of 4 layers of LGAD silicon sensors
  Improve pile-up rejection in forward region by using track **timing** information
  - **Sensor** performance studies and qualification
    - https://doi.org/10.1088/1748-0221/17/09/C09021
  - **ASIC** design (R. Casanova led digital part of full size chip)
  - Defined and qualified **hybridization** process
  - **Module assembly** of first prototypes for demonstrator

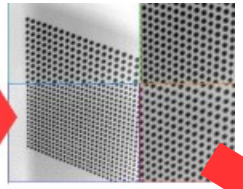
V. Gautam
L. Castillo
S. Terzo
R. Casanova
M. Chmeissani
S. Grinstein



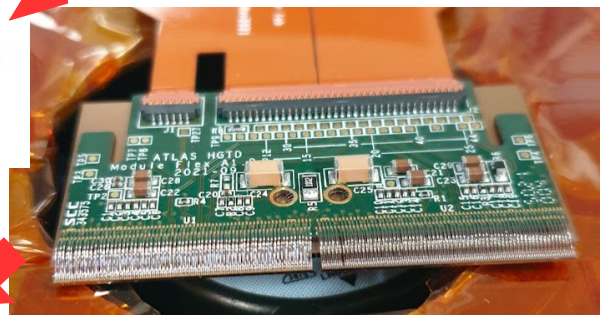
Bumping machine and QA

Reflow

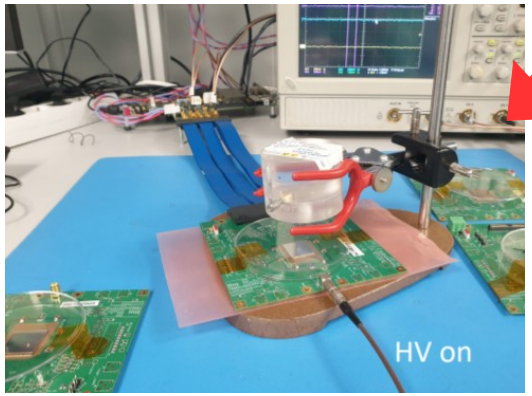
Flip-chip/bump-bonding

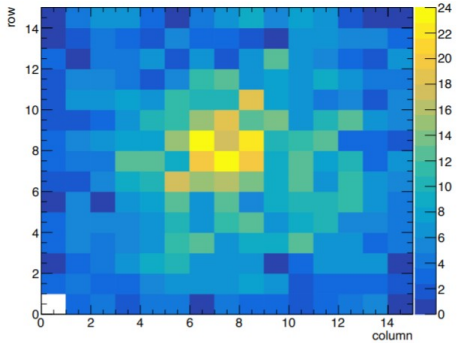


X-ray inspection (QA)



Module prototypes for HGTD demonstrator program being finalized



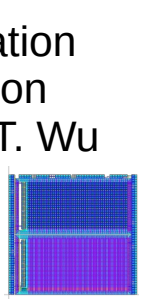
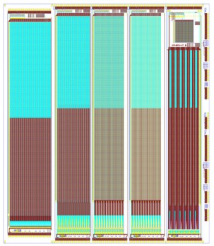
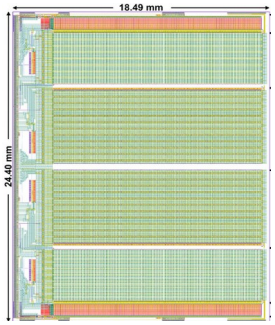


Functionality verification

Detector R&D

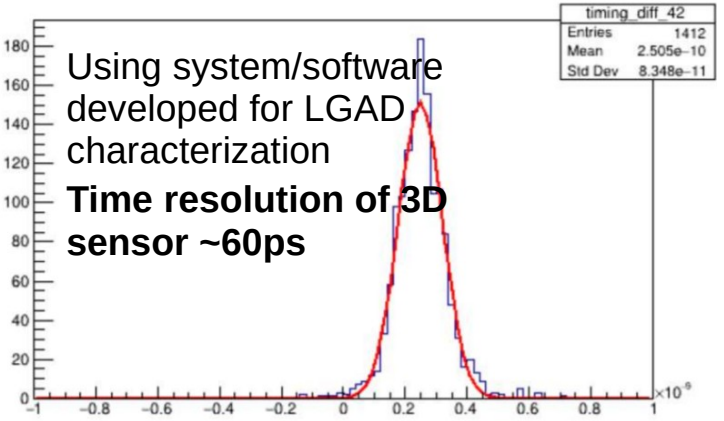
Some DMAPS by IFAE et al.

- **DMAPS** devices explored for ATLAS pixel upgrade
  - IFAE led chip design of early devices & device characterization
  - Full testing cycle: design, readout, irradiation characterization
    - Publication: S. Terzo et al., JINST 14 P02016 (2019), T. Wu et al., JINST 16 P09020 (2021), ...
  - Now activities centered around RD50 and AIDAinnova

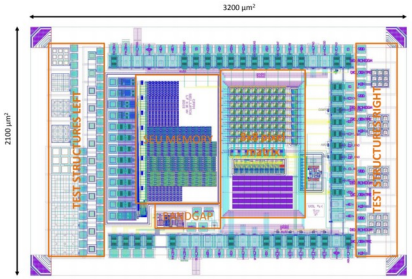
LF2 *LF ATLAS Pix* *H35Demo*

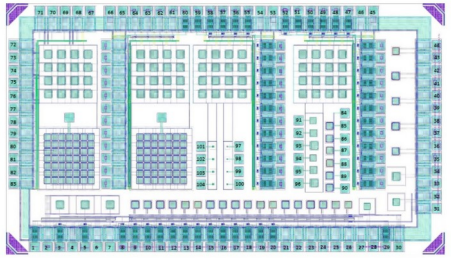
- On-going studies of **3D sensors for timing and extreme fluencies**
  - 3D technology promising for FCC fluence levels while providing a decent timing performance
  - Activity in the context of RD50 and AIDAinnova



- **LGAD sensors for timing and soft x-ray detection**
  - In HEP challenge is improve radiation hardness
  - Project with CNM to explore LGADs coupled with Timepix4 (soft x-ray detection - SOFTPIX)

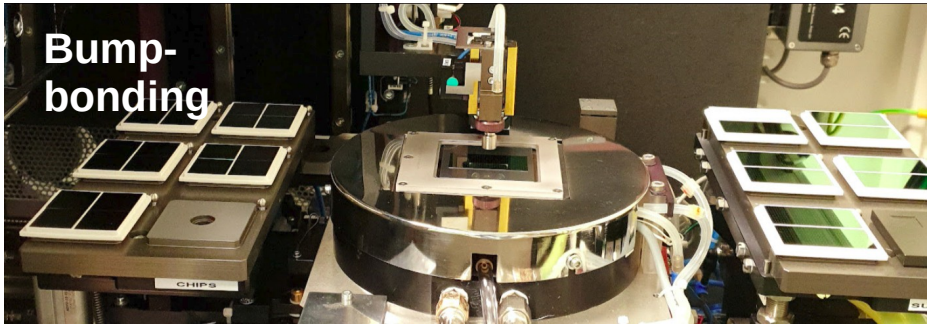
- **Other R&D**
  - Exploring various applications in medical and other realms
    - SPADs for neuro-monitoring
    - 2D materials for MIP detection

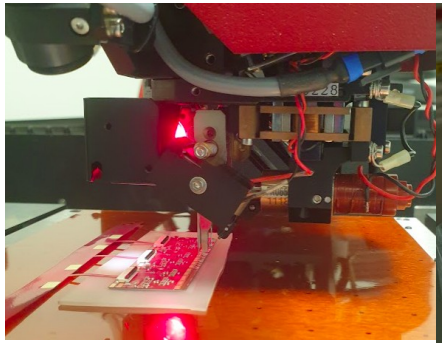

SPADs 2019

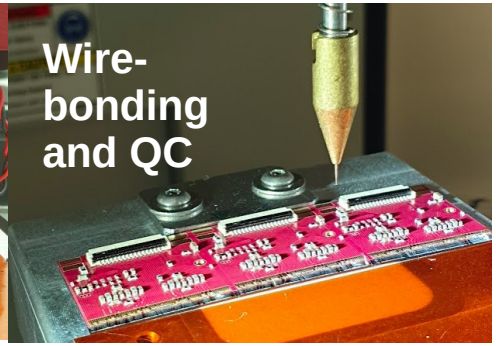

SPADs 2020

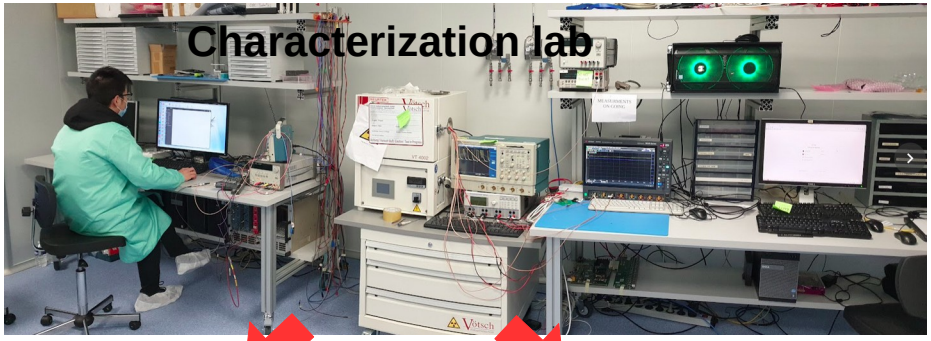
Infrastructure at IFAE

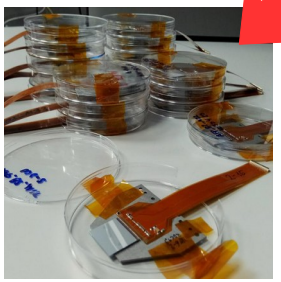
- **Full assembly line at IFAE clean rooms**
- **Hybridization**:
  - Bump deposition
  - Flip-chip
  - Reflow oven
  - Inspection (x-ray)
- **Assembly**:
  - Pick and place
  - Metrology
  - Wire-bonding
  - Pull and shear
- **Characterization**:
  - Many setups...
  - TCT, climate chambers, probe station, Timing with Sr90, ITk and HGTD readout systems, etc
- **Expertise**:
  - Productions for ATLAS (IBL, AFP, ITk, HGTD), medical, etc
  - Productions for other institutions/experiments



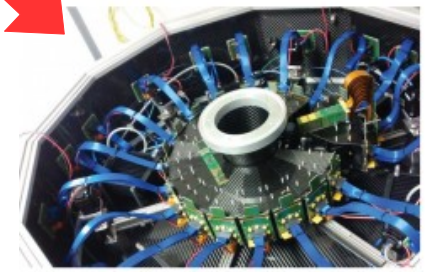








ATLAS module productions



High resolution PET (EU funded)

ATLAS Pixel: Person-power

- S. Grinstein (ICREA)
- S. Terzo (IFAE)
- M. Chmeissani (IFAE)
- R. Casanova (IFAE Chip design engineer)
- P. Fernandez (BdP)
- L. Castillo (CERN PJAS, now ProBIST)
- M. Kolstein (IFAE)

- C. Puigdengoles (Eng., readout system/firmware support)
- J. Garcia (Eng., microelectronics device assembly)
- E. Peregrina (technician)

- Y. Gan (Co-PhD student with CCNU/China)
- V. Gautam (PhD student – PreBIST)
- *J. Carlotto (PhD student – FPI MINECO)*
- *J. Piñol (PhD student)*
- *N. Kakoty (PhD student to start in May)*

July 2022 (some people missing)

- **In terms of FTEs (estimated):**

Researchers	11 (6 senior + 5 PhD students)
Engineers	1
Technicians	1

Group Publications and Positions

2020			
1	Maria Manna, Chiara Grieco, Sebastian Grinstein, Salvador Hidalgo, Giulio Pellegrini, David Quirion, Stefano Terzo	First characterisation of 3D pixel detectors irradiated at extreme fluences	Nucl. Instrum. Methods Phys. Res. Sec A, Volume 979, 1 November 2020, 164458
2	R. Casanova and T. Wu	A Monitoring 12-bits Fully Differential Second Order Incremental Delta Sigma Converter ADC for TimePIx4	Proceedings of Science
3	L. Castillo García	A High-Granularity Timing Detector for the Phase-II upgrade of the ATLAS Calorimeter system: detector concept, description, R&D and beam test results	2020 JINST 15 C09047
4	Stefano Terzo, Sebastian Grinstein, Maria Manna, Giulio Pellegrini, David Quirion	A new generation of radiation hard 3D pixel sensors for the ATLAS upgrade	Nucl.Instrum.Meth.A
2021			
1	S. Terzo, M. Boscardin, J. Carlotto, G.-F. Dalla Betta, G. Darbo, O. Dorholt, F. Ficorella, G. Gariano, C. Gemme, G. Giannini, S. Grinstein, A. Heggelund, S. Huiberts, A. Kok, O. Koybasi, A. Lapertosa, M. E. Lauritzen, M. Manna, R. Mendicino, H. Oide, G. Pellegrini, M. Povoli, D. Quirion, O. M. Rohne, S. Ronchin, H. Sandaker, Md. A. Samy, B. Stugu, L. Vannoli	Novel 3D pixel sensors for the upgrade of the ATLAS Inner Tracker	Front. Phys.
2	T. Wu et. al, (T. Wu,W. Wei, S. Grinstein, R. Casanova, Y. Zhang, X. Wei, J. Dong, L. Zhang, X. Li, Z. Liang, J. Guimaraes da Costa, W. Lu, L. Li, J. Wang, R. Zheng, P. Yang and G. Huang)	The TaichuPix1: a monolithic active pixel sensor with fast in-pixel readout electronics for the CEPC vertex detector	2021 JINST 16 P09020
3	S. Terzo on behalf of the ATLAS Collaboration	ATLAS ITk pixel detector overview	PoS ICHEP2020 (2021)
2022			
1	L. Castillo García, E. L. Gkougkousis, C. Grieco, S. Grinstein	Characterization of Irradiated Boron, Carbon-Enriched and Gallium Si-on-Si Wafer Low Gain Avalanche Detectors	Instruments 2022, 6(1), 2
2	C. Grieco, L. Castillo García, A. Doblas Moreno, E.L. Gkougkousis, S. Grinstein, S. Hidalgo, N. Moffat, G. Pellegrini and J. Villegas Dominguez	Overview of CNM LGAD results: boron Si-on-Si and epitaxial wafers	2022 JINST 17 C09021
3	J.I. Carlotto, P. Fernandez-Martinez, S. Terzo, J.T. Gonzalez, S. Grinstein	Characterization of the first RD53A triplet modules assembled at IFAE	JINST 17 (2022) 10, C10018
4	Stefano Terzo, Juan Carlotto, Sebastian Grinstein, Maria Manna, Giulio Pellegrini, David Quirion	Performance of radiation hard 3D pixel sensors for the upgrade of the ATLAS Inner Tracker	J.Phys.Conf.Ser. 2374 (2022) 1, 012168
5	E - L Gkougkousis, L. Castillo Garcia, S. Grinstein and V. Coco	Comprehensive technology study of radiation hard LGADs	2022 J. Phys.: Conf. Ser. 2374 012175
6	V. Gautam, R. Casanova, S. Terzo and S. Grinstein	Development of single photon avalanche detectors for NIR light detection	JINST 17 C12019

Only publications with 1st author from IFAE, about 5 publications/yr

Current leadership positions:

- S. Terzo: ITk Pixel sensor co-coordinator
- L. Castillo: HGTD test-beam co-coordinator, HGTD Speakers committee
- S. Grinstein: HGTD deputy Project Leader, HGTD modules co-coordinator, AIDAinnova WP5 co-convener, BIST Research Committee and ATLAS PMO sub-committee

Summary

- IFAE has been working on **detector R&D, advancing key technologies**
- Focus always of implementing new technologies on **detector construction**
  - IBL, AFP, and now ITk and HGTD
- The **main objective** of the activities in the next years is the successful **delivery of key detector systems to ATLAS** for the HL_LHC
  - Innermost tracking **modules (ITk-Pixel)** and **timing modules (HGTD)**
  - Target is to make **in-kind contributions** (with sensors, hybridization and assembly in/from Spain)

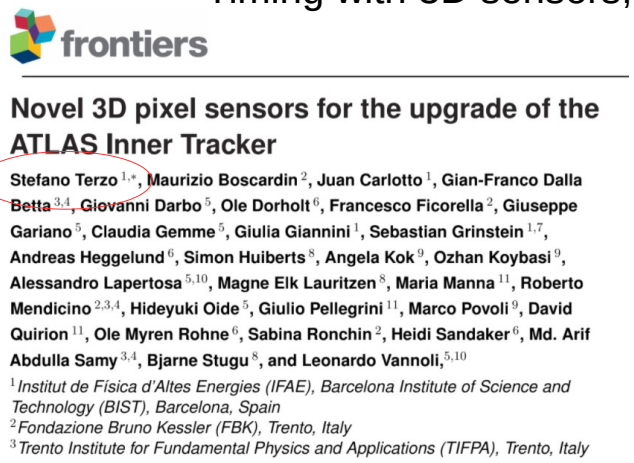
- **Towards Detector R&D (DRD3)**
  - DMAPS (FPN, RD50 and AIDAinnova) for tracking and timing [3.1]
  - Timing with LGADs (challenge is increase radiation hardness) [3.2]
  - Tracking and timing with 3D sensors (FPN and AIDAinnova) [3.3]
  - Hybridization [3.4]
  - New materials (BIST-ICN2 and CNM) [5.1 and 5.2] and in context of QT (P. Forn)
  - ASIC development towards 4D tracking (hybrid and monolithic) [7.3]
- IFAE eager to continue to **develop new solutions and implement them in the future upgrades or new HEP detectors**

Back Up Slides

3D Sensor Activities

- **Sensors for innermost pixel layer of ITk**
  - Radiation hardness to 1E16 neq/cm2 (replace inner layer once, due to ASIC)
  - CNM 3D sensor qualification done, **in-kind** contribution accepted (200 kCHF)
- First pre-production batch from CNM failed (June 2021)
  - New pre-productionon-going (delayed due to clean room upgrade)
- In parallel we continue exploring the **limits of the 3D sensor technology**
  - Further irradiations, characterization and beam tests (beyond HL-LHC)
    - Timing with 3D sensors, irradiations at ultra-high fluence,...

S. Terzo
J. Carlotto
D. Vazquez
M. Manna



frontiers

1

Novel 3D pixel sensors for the upgrade of the ATLAS Inner Tracker

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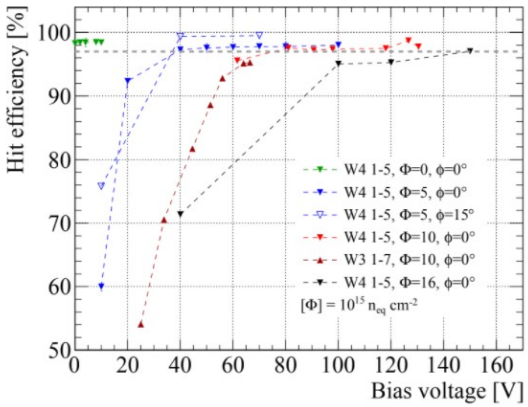
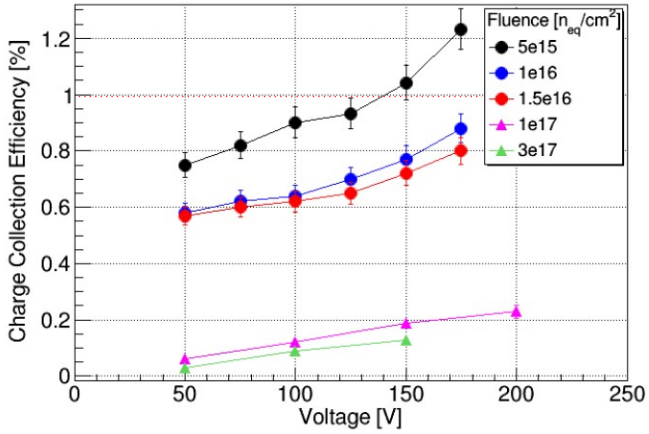
[3] *Trento Institute for Fundamental Physics and Applications (TIFPA), Trento, Italy*





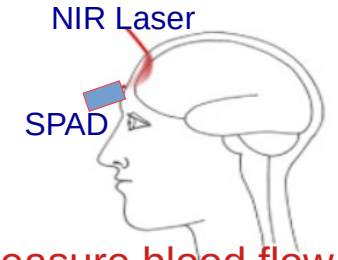
Review paper of 3D sensors for HL-LHC

Beyond HL-LHC
- Lab characterization and beam-test
- Charge collection studies with diode-like structures

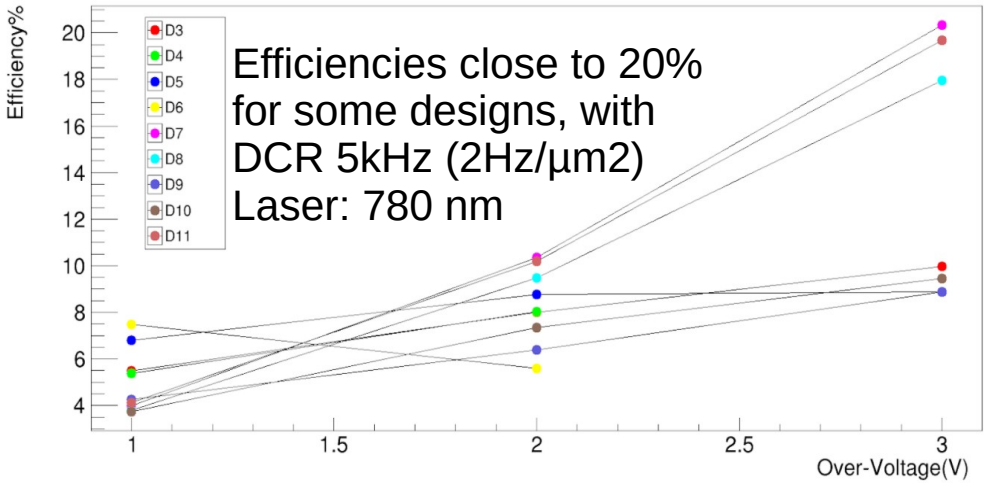
Non-ATLAS Activities: SPADs for Neuromonitoring

V. Gautam
S. Terzo
R. Casanova
E. Peregrina
C. Puigdengoles

- Project to develop **CMOS SPADs** for neuromonitoring building on **DMAPS** experience
- Carried out with **ICFO** (Catalan Photonics Inst) in the context of BIST (Barcelona Inst of Science and Tech)
- Received seed IGNITE grant and followed up with award
  - Moderate funds, but plan to search for other opportunities
  - Impacted by Covid-19, ramping activities recently

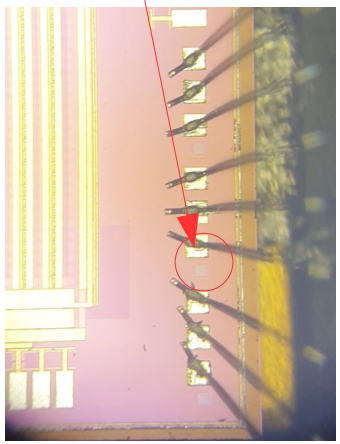


Measure blood flow from scattered IR light

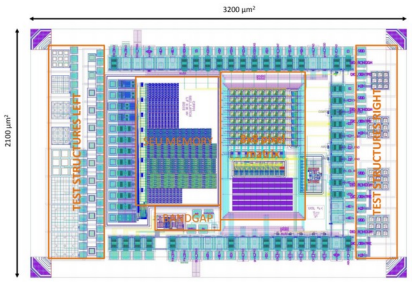


Efficiencies close to 20% for some designs, with DCR 5kHz (2Hz/µm2)
Laser: 780 nm

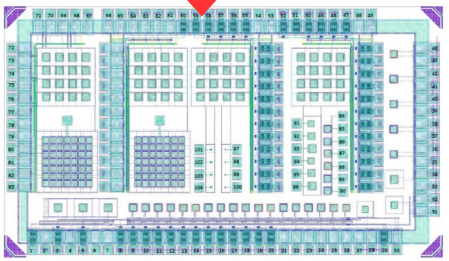
50x50 µm² APD



APDs mounted for readout



SPADs 2019



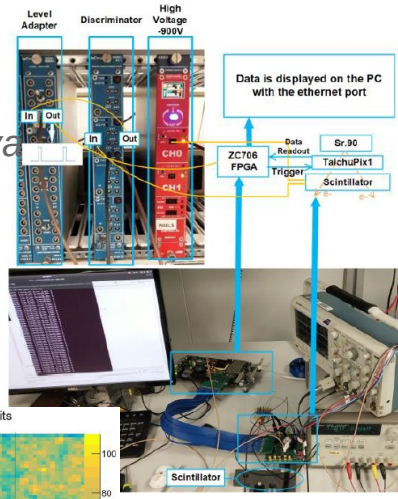
SPADs 2020

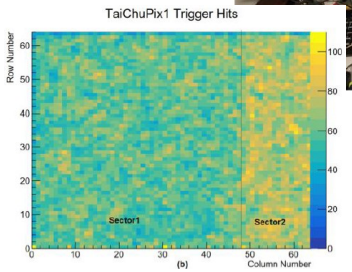
- Encouraging **preliminary** results, work on-going
- **Specific SPADs** received mid 2020, starting characterization work now
- *IR sensors: many bioimaging applications*

Non-ALTAS Activities: DMAPS and 2D Materials

- **DMAPS are the future of HEP** (for moderate fluences)
  - Builds from initial ATLAS DMAPS effort (H35demo...)
  - IFAE participating in R&D of CEPC Vertex detector
  - CEPC target a small pixel size, fast monolithic device, 2nd prototype partially designed at IFAE
  - Paper submitted to JINST *(T. Wu et al)*
- Also DMAPS activities within **RD50** and **AIDA (EU)**
  - MPW demonstrator design (RC) and characterization

T. Wu
R. Casanova
S. Terzo

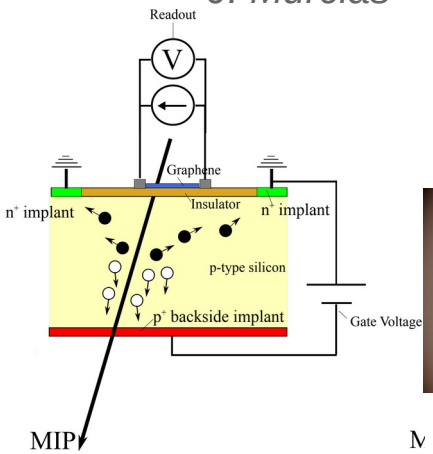


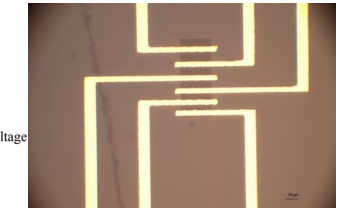


Sr90 tests of Taichupix1

- **2D Material for MIP detection (2DETMIPS)**
  - Small BIST-funded project with ICN2 (Nano-tech institute next to IFAE) *and CNM*
  - Explore particle detection with Graphene FET
  - Characterization at IFAE of first prototypes built at ICN2 (CVD Graphene) and CNM (Epitaxial Graphene)
  - David M. master thesis (UB) under preparation, to be defended in July

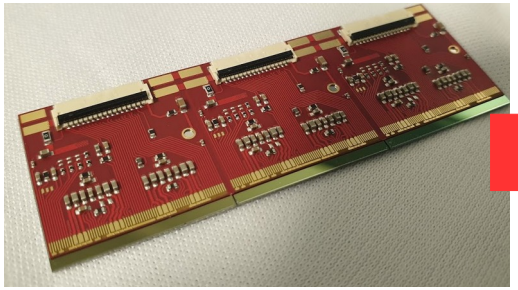
D. Muradas
S. Terzo
J. Murcias





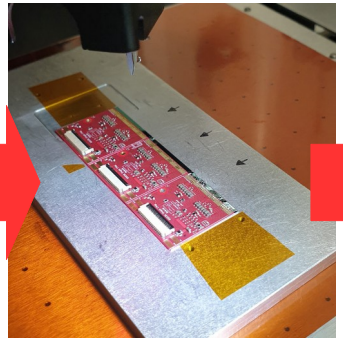
ITk 3D Module Assembly

J. Carlotto
P. Fernandez
E. Peregrina
J. Garcia



Triplet

Metrology



Wire-bonding

Pull-test

Requirements

- **Dimensions**
  - Overall size limit (to 61.3 mm + 40 µm – 110 µm)
  - Inter gap > 50 µm, align edges to 25 µm
  - Module thickness
- **Glue**
  - Glue thickness (to ~ 40 ± 20 µm)
  - Glue weight to 5 mg/bare module
  - Glue coverage (>80%)
  - No overflow to pads of chuck
- **Wire-bonding**
  - Average > 8 g (min 5 g)
  - Breaks at heel

OK, but marginal results, identified problems with flex

*Last week **built first dummy triplet** up to specifications (!!)*, next two in coming weeks

- *Working in **close collaboration with Italian and Norwegian** clusters (together with IFAE, the 3 groups on inner-layer assembly)*
- *Project delay wrt to last review (expected to finish 1st step qualification in ~mid 2020)*
- *Note: Hybridization activities in back-up slide*

AFP: ATLAS Forward Protons

- **Full assembly line of IFAE** was used to built the AFP tracker modules for the AFP silicon tracker (2016, 2017 and 2019, total in-kind contribution of 160kCHF
- *Also used for ITk, HGTD and CMOS module assembly*

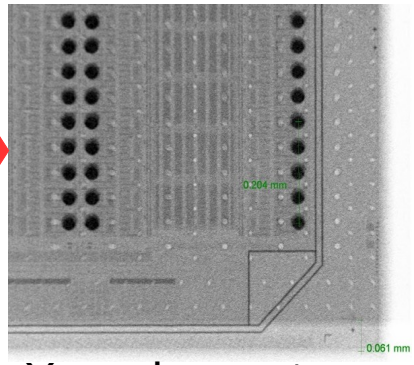
S. Grinstein et al., JINST 12 (2017) C01086

FEI4 readout chip and 3D sensor

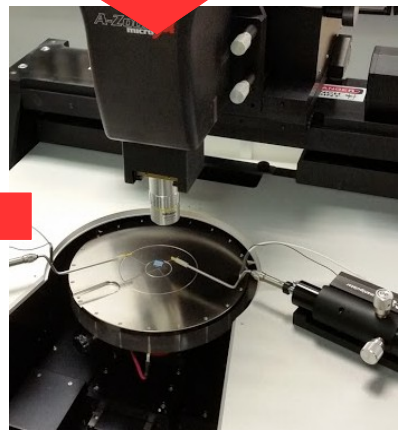
I. Lopez, F. Forster
J. Garcia, E. Peregrina
M. Chmeissani

Flip-chip

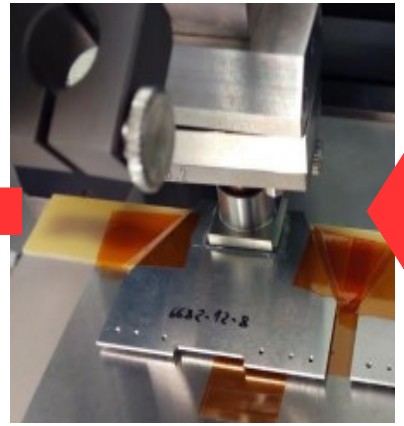
Reflow



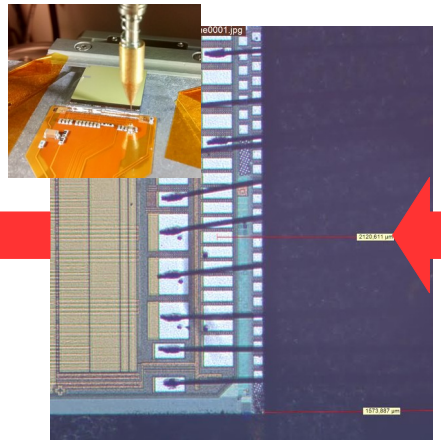
X-ray inspect



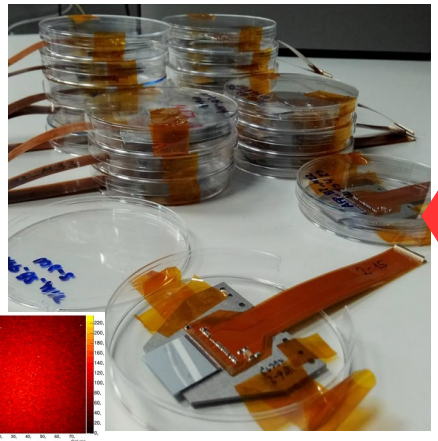
Probe



Glue



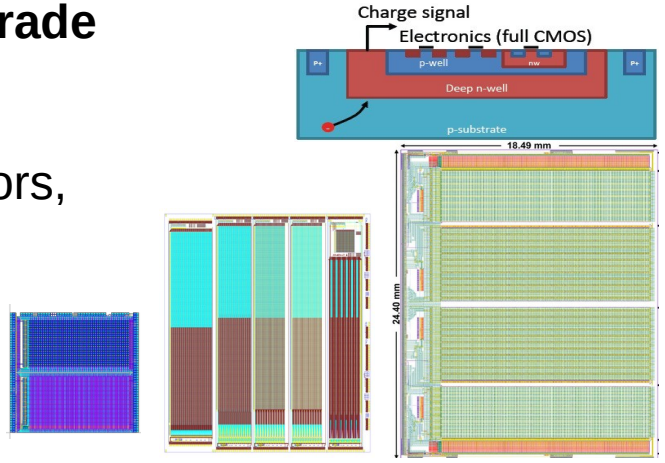
Wire-bond and pull test



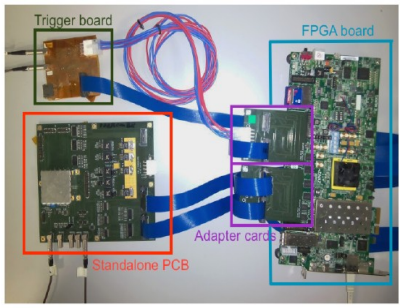
QA of final modules!

Depleted-MAPS for ATLAS ITk

- **Depleted-CMOS** devices explored for ATLAS pixel **upgrade**
  - Basic idea is deep n-well that collects charge
  - Standard CMOS (HV) fabrication process
  - Many options, monolithic/hybrid, small/large fill factors, fabrication sites...
- IFAE expertise in chip design & device characterization
  - Activities focused on **monolithic devices**
  - Early results from IFAE
    - Full testing cycle: design, readout, irradiation characterization
    - Publication *S. Terzo et al., JINST 14 P02016 (2019)* *R. Casanova*

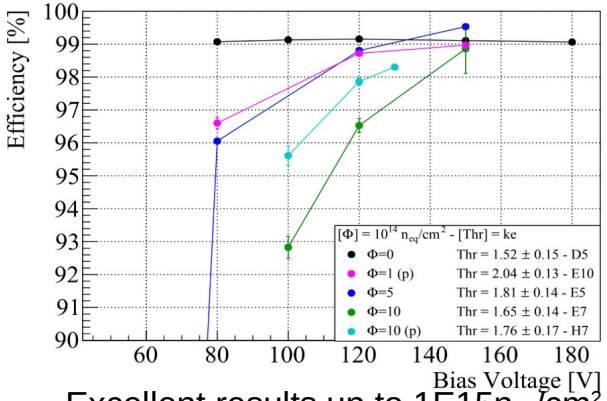


LF2 *LF ATLAS Pix* *H35Demo*



IFAE readout system
C. Puigdengoles

DESY Beam tests



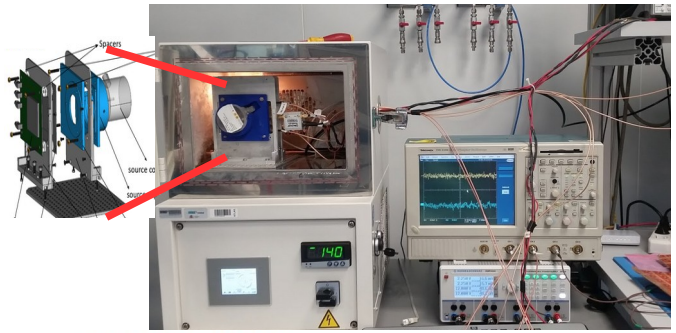
Excellent results up to 1E15n_{eq}/cm^2

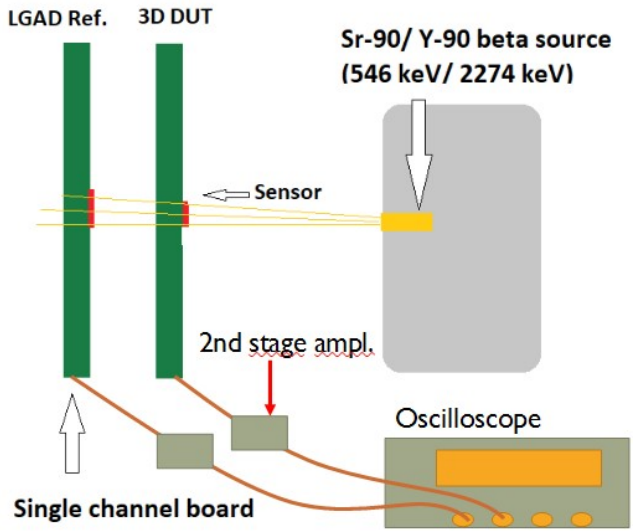
Due to schedule constrains ATLAS dropped DMAPS option early in 2019

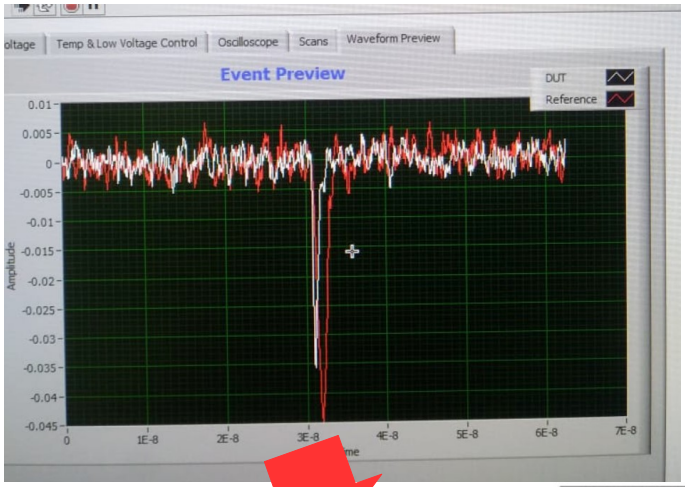
3D Sensor Activities: Timing

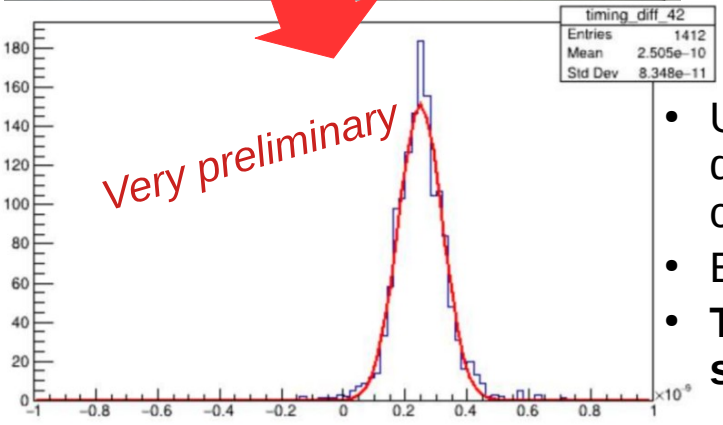
G. Petrogiannis
P. Fernandez
E. Gkoukousis
C. Griecco

- On-going studies of **3D sensors for timing**
  - 3D best radiation hard technology
  - Short distance between electrodes… natural to study timing performance
  - Activity in the context of RD50 and AIDAinnova *(future hadron colliders...)*







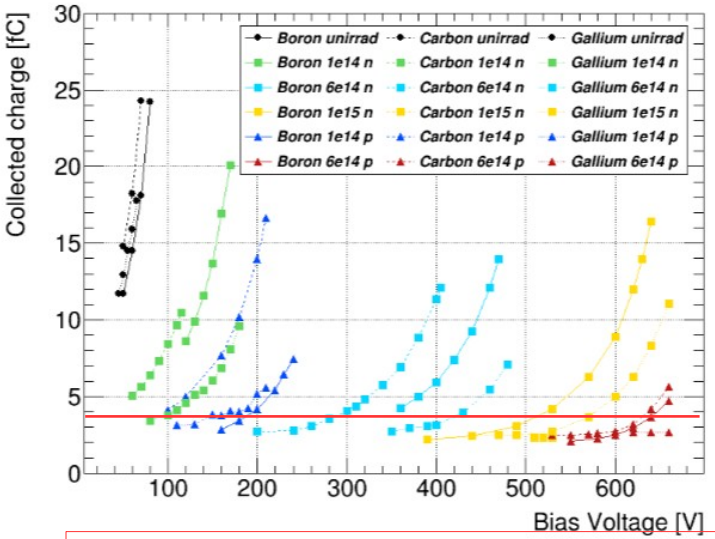


3D sensor in these studies is a single cell (50x50 um2), low rate, now buying a stronger source

- Using system/software developed for LGAD characterization
- Bias voltage 10V
- **Time resolution of 3D sensor ~60ps**

Timing Activities: Sensor Development

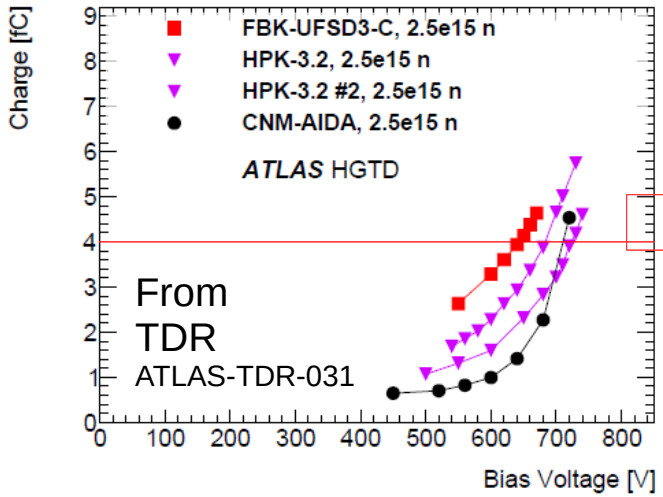
- LGAD sensors for HGTD required to provide Q=4fC after 2.5E15neq/cm2
- Studying performance of sensors in beam tests and lab
- Capability of LGAD sensors from CNM (invented technology) already demonstrated (results in TDR)
- Feasibility to operate sensors at large HV bias remains a challenge
  - Solution: C-infusion to lower HV

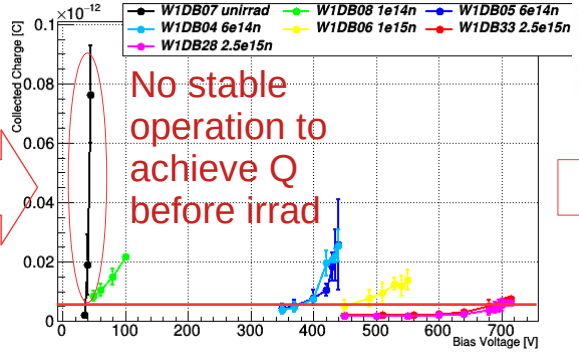


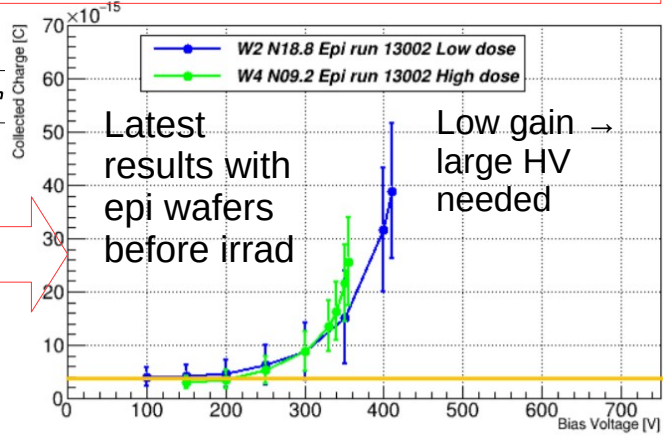
C. Grieco, L. Castillo, V. Gkougkousis

Investigation of B, Ga and C devices

Note: sensor size reduced from 15x30 to **15x15** pads of 1.3x1.3 mm2 (→ improve yield)





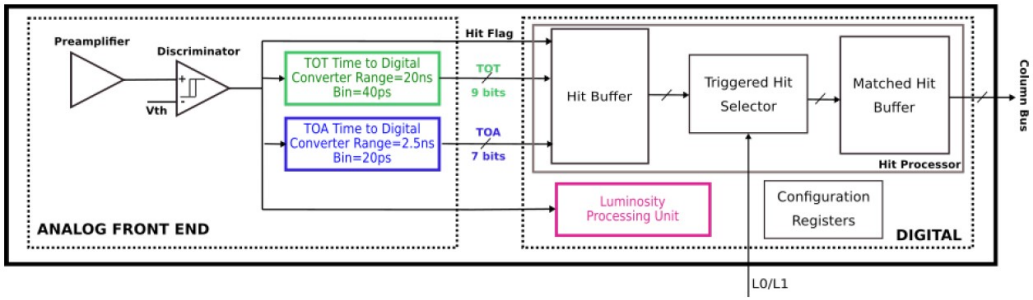


Full size sensors productions (for qualification) on-going at CNM, including C-infused wafers

HGTD Front-End Chip: ALTIROC2

- Large (2x2cm2) ASIC to achieve demanding time performance, rad tolerance 1.4MGy TID
- Large pad (1.3x1.3 mm2) allows in-"pixel" TDC implementation
- Amplifier + discriminator + TDC (TOA and ToT for time-walk correction)

R. Casanova

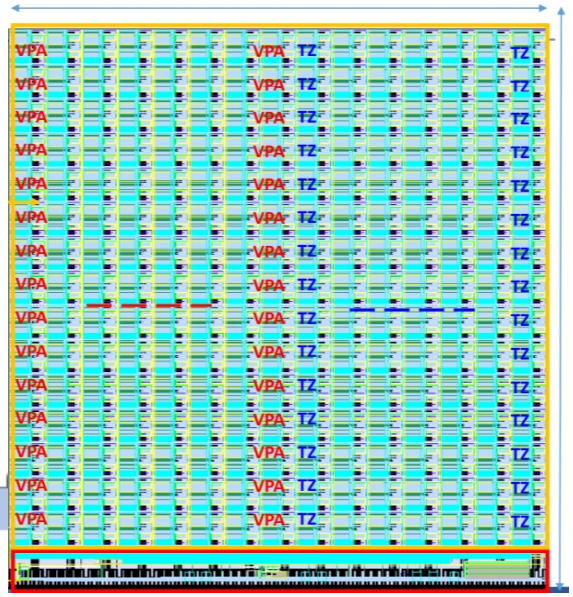


Target is **20 ps jitter contribution** (achieved for ALTIROC1)

- Challenging architecture (several clks distributed in a large chip)
- IFAE led the design of the **digital part** of ALTRIOC2
  - Also big effort on chip **verification**
  - Submitted in 11th May 2020 (expected end of Aug)
- Now working on **readout-system** (w/C. Puigdengoles) and designing **ALTIROC3**

2 cm

ALTIROC2: TMSC CMOS 130 nm



2.2 cm