RD Collaboration on
3D Sensors and Micro-Fabricated Systems

Cinzia Da Vià, the University of Manchester, UK

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- Objectives
- State of the art
- Challenges
- Synergies
- Deliverables and Milestones
- Organization
- Collaboration
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3D Sensors & MicroFab Systems

Introduction

- We held a workshop last November at CERN to explore common features amongst 3D sensors, Micro-cooling and integration in the use of Micro-Fabrication

- The participation was good as well as the spontaneous interaction amongst the participants so we agreed together to explore the possibility to formally collaborate

Today :

- we would like to present our plans and explain why we believe this could be beneficial for the LHC Experiments Upgrade program

- ask the LHCC approval to run an RD study for 5 years to achieve our goals

LHC Upgrade Program benefits and RD Objectives

We would like to join efforts with colleagues within LHC experiments and with processing facilities to explore :

- The next generation of 3D sensors (fully compatible with existing and future ROCs) for HL-LHC environments (ATLAS, CMS, TOTEM *)
- Micro-cooling for effective thermal management:
  ATLAS, NA62, ALICE, LHCb
- Low mass integration and simulation: ALL the above

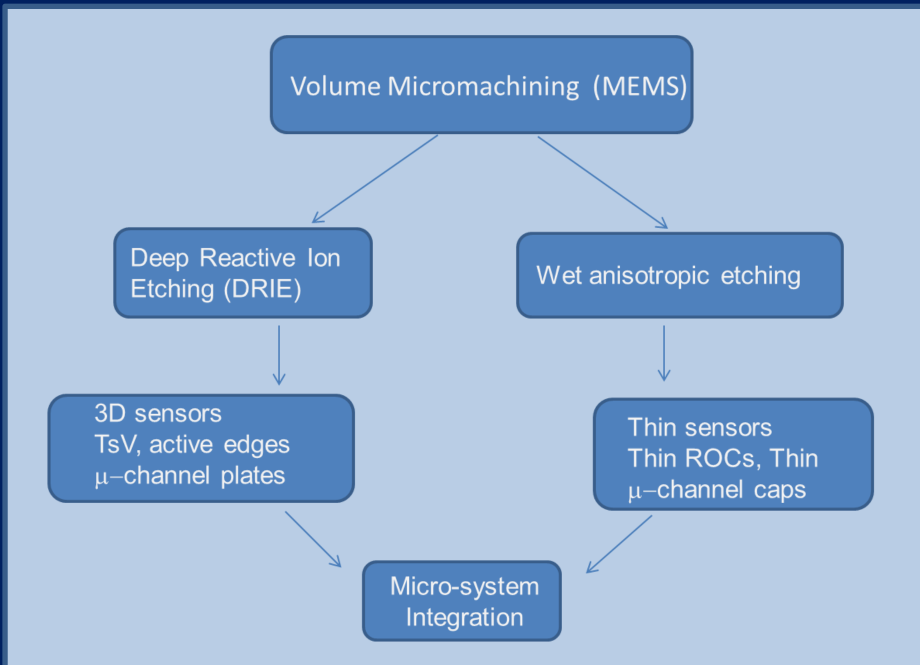
And effectively concentrate human, financial and intellectual efforts amongst ourselves and the facilities which already applied micro-fabrication and integration in HEP to reach reliable answers in time for decisions for LHC upgrades production.

So we are NOT aiming at "generic R&D" but at focused work towards solutions of practical problems on realistic system demonstrators for specific experiment environments where RELIABILITY as well as functionality is assessed using Micro-Fabrication as a main common tool

*interested, will discuss within Coll. Board in June

Micro-Fabrication and processing facilities

In Micro-fabrication, used mainly for Micro-Electro Mechanical System, the process is performed 3-dimensionally within the silicon volume

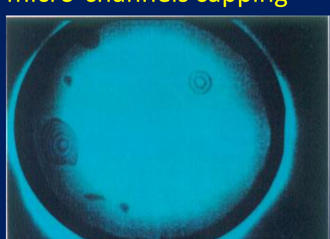


This project gathers 7 major facilities with proven skills to perform all the required processing and integration steps of the proposed program

Together we believe we can solve "faster" and "cheaper" technological and production challenges

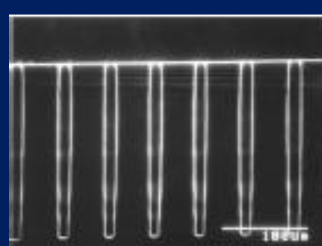
Potential technology transfer to other fields

Wafer bonding
mechanical stability
Active edge 3D sensors
Thin electronics
micro-channels capping



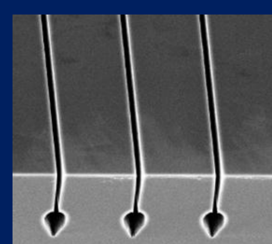
CIS-Stanford

3D electrodes and
active edges single side
3D double side sensors



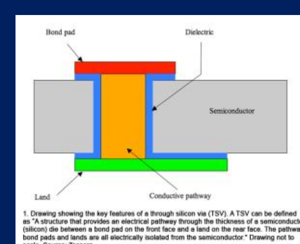
CNM

Embedded
micro-challels



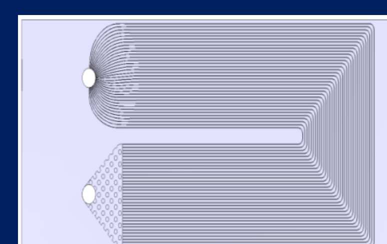
FBK-Pisa

Integration , TsV



IZM-CSEM-LETI

Superficial micro-channels



EPFL-CERN-LHCb

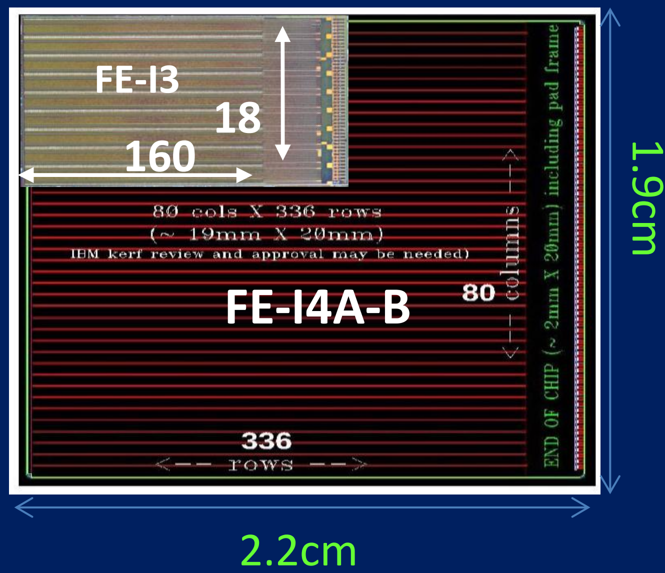
State of the Art -1 http://cerncourier.com/cws/article/cern/49691 May 2012

3D for the ATLAS IBL by the 3DATLAS R&D Collaboration
25% of the total IBL modules: within specs and on schedule

NIMA 694 (2012) 321–330

3DATLAS RD Collaboration:

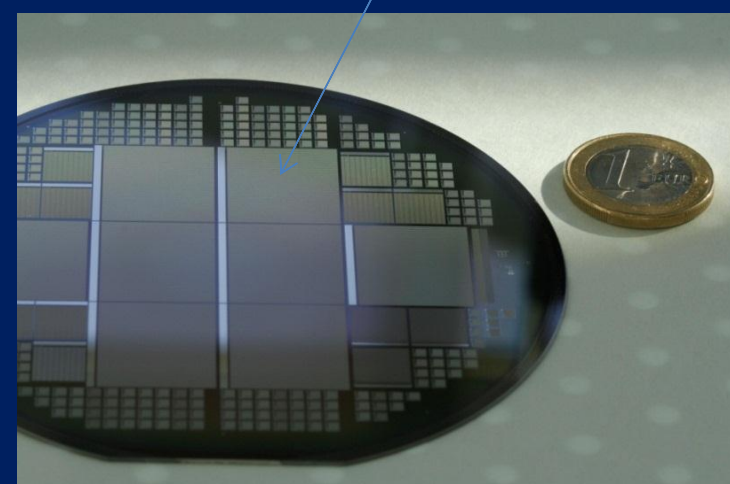
18 Institutions
5 Processing Fabrication Facilities



4+1 runs were completed in February and October 2012 by CNM (Barcelona, Spain) and FBK (Trento, Italy) with double side process with >350 good chips, more than 100 wafers and an yield exceeding 60% fulfilling the following:

Sensor specifications for IBL:
- Qualify to $5x10^{15}$ n_{eq}
- max. power dissipation: 200 mW/cm² at -15 C
- tracking efficiency > 98%.

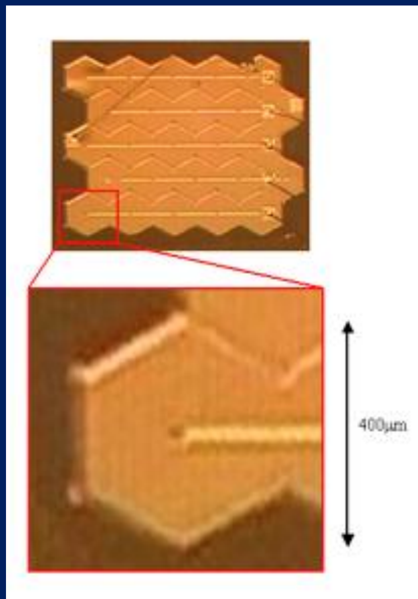
The key to this success is the consequence of the unusual interaction with processing facilities and a change of their industrial practice to COLLABORATE rather than COMPETE towards a common goal. 3D is now considered a mature technology

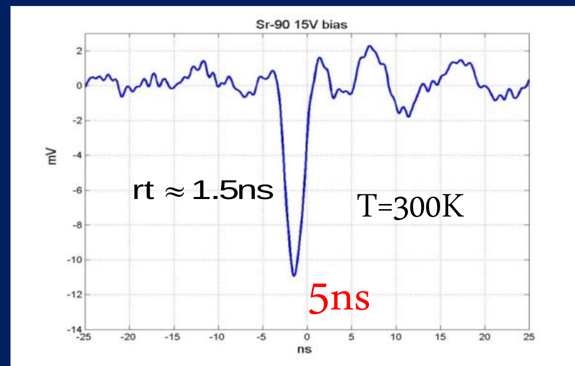


Different 3D structures

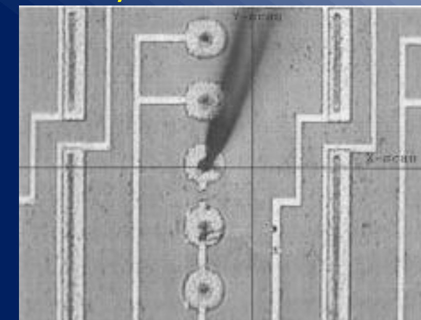
http://cerncourier.com/cws/article/cern/28790 Jan 2003

S. Parker et al., Increased speed: 3D silicon sensors. Fast current amplifiers, IEEE Trans. Nucl. Sci. 2011; 58:404-417

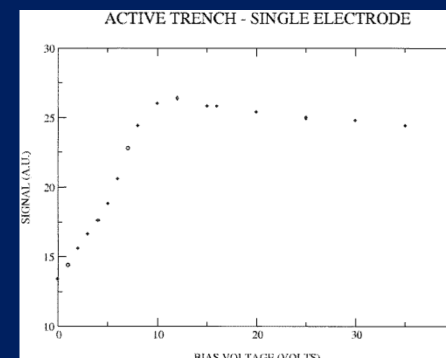




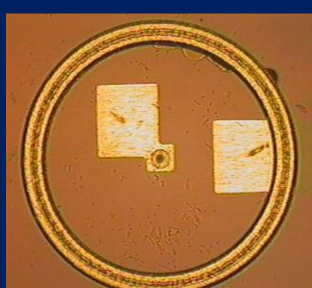
Combination of trenches and cylindrical electrodes

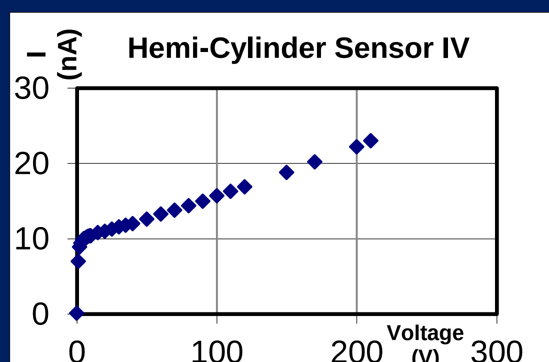


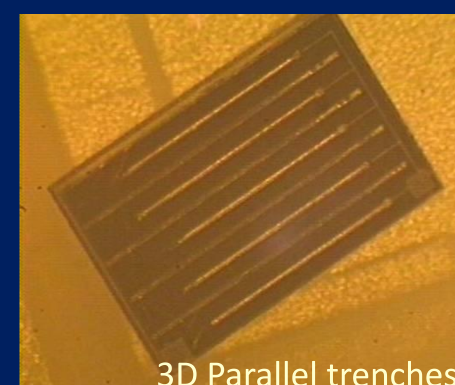
Hexagonal or parallel trench shapes for enhanced speed



This will be used for Micro-dosimetry







3D Parallel trenches

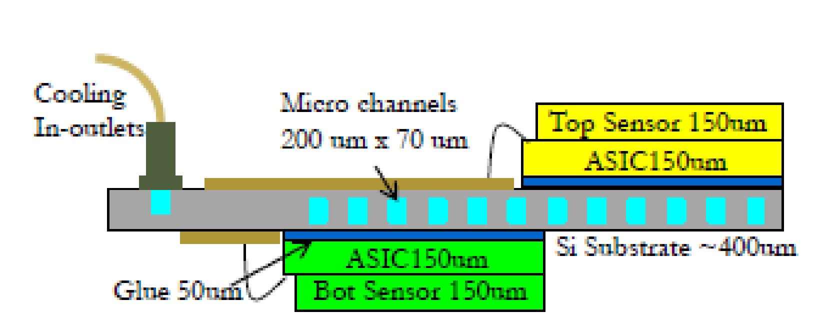
C. Kenney et al. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 48, NO. 6, DECEMBER 2001

Dual readout—strip/pixel systems Cinzia Da Via , Sherwood Parker et al. NIMA A 594 (2008) 7– 12

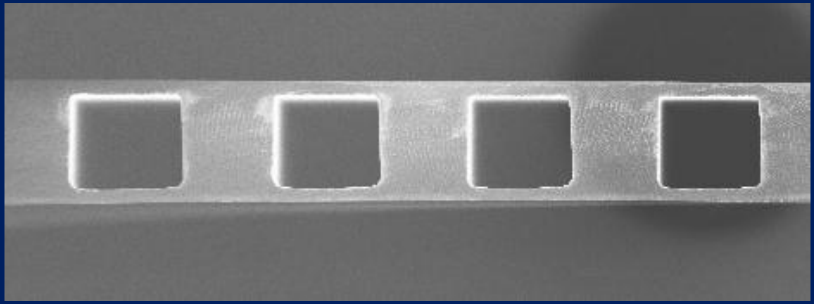
Dual readout: 3D direct/induced-signals pixel systems , Sherwood Parker, et al. NIMA A 594 (2008) 332–338

State of the Art-2 Micro-cooling

Pioneering work for HEP within CERN PH-DT



LHCb system layout. J. Buytaert, Pixel2012



- Cooling device based on the ATLAS design
- Pressure tests > 100bar

❖ Explored since a while in microprocessor industry

Cooling channel is integrated in the substrate:

❖ Can customize the routing of channels to run exactly under the heat sources.

Many parallel channels:

❖ large liquid-to-substrate heat exchange surface.

Low mass :

❖ No extra 'bulky' thermal interface required between cooling channel and substrate.

No heat flows in the substrate plane:

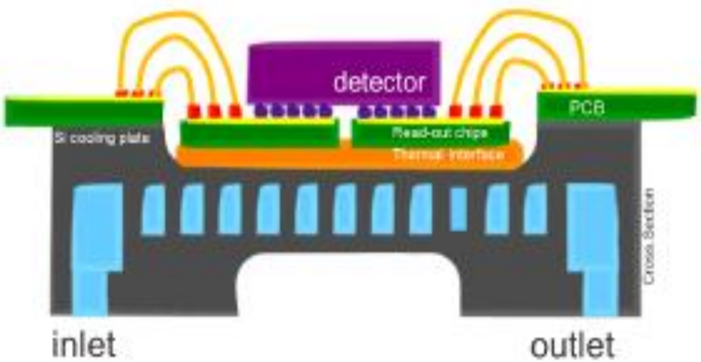
❖ Small thermal gradients across the module.

All material is silicon :

❖ No mechanical stress due to CTE mismatch.

Pioneering experiments using micro-cooling in collaboration with CERN PH-DT use C_6F_{14} and C_4F_{10} with less aggressive geometrical constraints

NA62 Gigatracker



- Cooling requirements
  - minimize material below detector
  - detector area: 60 x 27 mm
  - T on Si detector: -20°C ÷ 5°C
  - ΔT over detector: 6°C
  - Heat dissipation by read-out chips:
    - 4 W/cm^2 in the periphery (Digital)
    - 0.5 W/cm^2 in the center (Analog)
    - total 48 W
  - thin silicon plate (130 μm)
  - C_6F_{14} liquid (8bar)

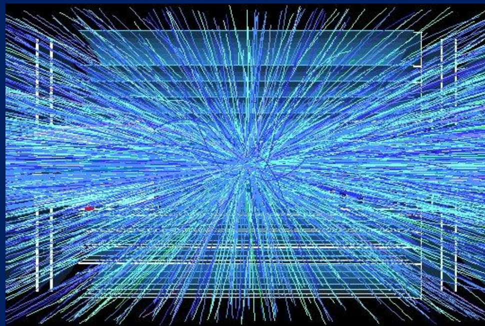
Decision taken to use u-channels in experiment!

ALICE upgrade pixels

- cooling μ-channels only under asics.
- no material under sensor
- Total heat dissipation 21W.
- T sensor ~ +20C
- Evaporative C_4F_{10}
- Pressure 2 bar

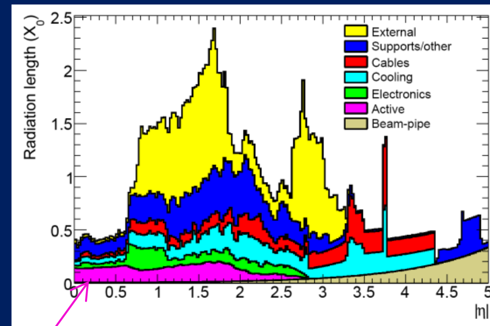
Slide courtesy of Jan Buytaert LHCb

The ultimate challenge: HL-LHC Vertex detectors



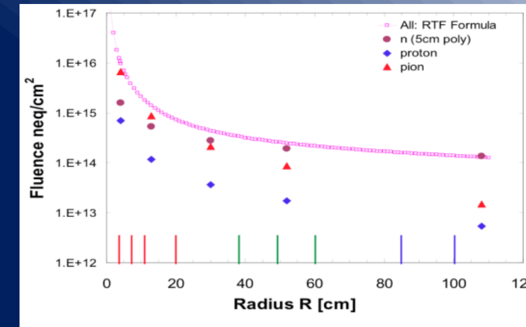
Precision reconstruction

Needs the signal over threshold



Material budget

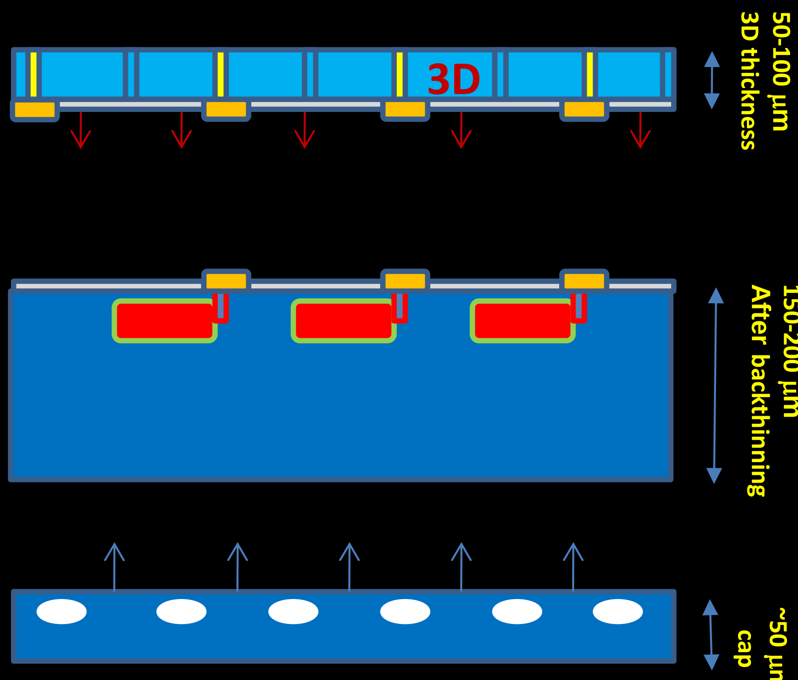
is not the sensor



Radiation tolerance

and power budget

A possible solution: a modular microsystem with one or all the following



- Thin (or thick) 3D silicon sensor (..) modules with active edges
- Interconnected with thinned ROCs and novel micro-electrical elements
- Low mass embedded micro-cooling for efficient thermal management -Reliable materials and connectors

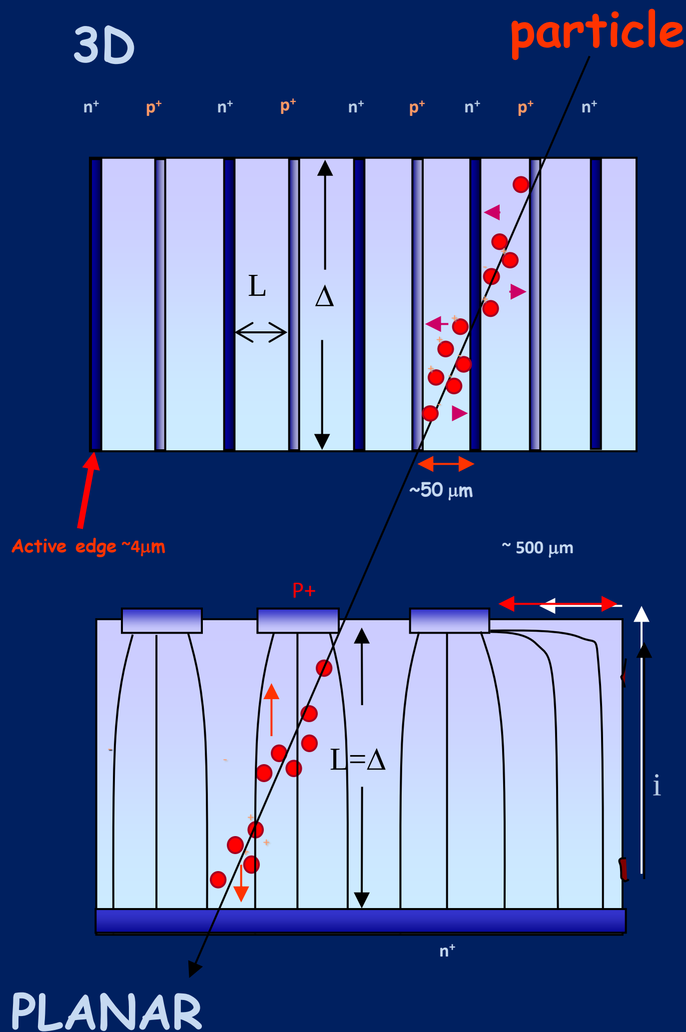
3D is the a possible choice for HL-LHC

because it's "geometrically" radiation hard at low V_{bias} (hence low power)

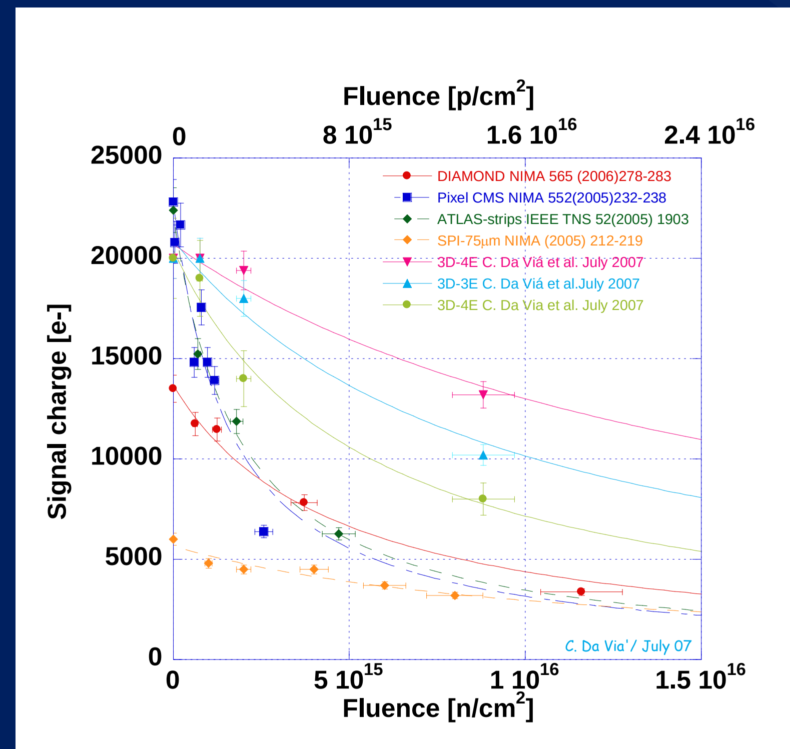
$$\frac{dS}{dt} = q\frac{dV_W}{dx}\frac{dx}{dt}\exp\left(-\frac{x}{\lambda}\right)$$

$$S = \frac{\lambda}{L}\left[1-\exp\left(-\frac{x}{\lambda}\right)\right]$$

$$\lambda = v_D \cdot \tau$$



3D 4E
3D 3E
3D 2E
Diamond
Thick Si
Thin Si



C. Da Via et al. NIM A 603 (2009) 319–324

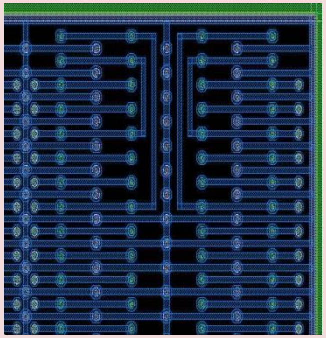
How much signal for 3D at HL-LHC fluences?

λ = τ × v

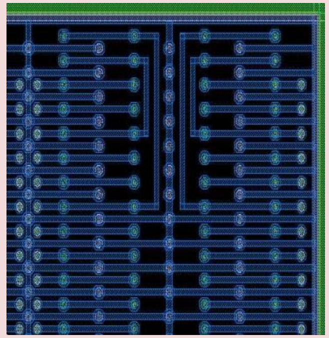
Drift length | Trapping time | Drift Velocity (saturated)

$$S = \frac{\lambda}{L}\left[1 - \exp\left(-\frac{L}{\lambda}\right)\right]$$

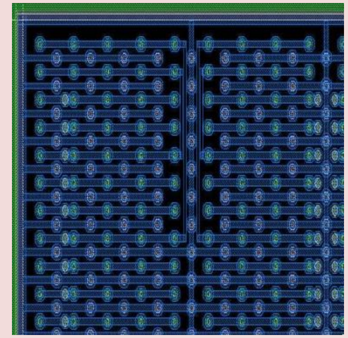
L= Inter-Electrode Spacing



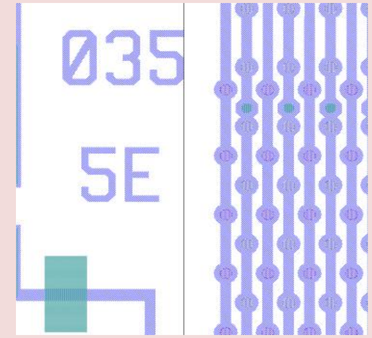
2E = 103um



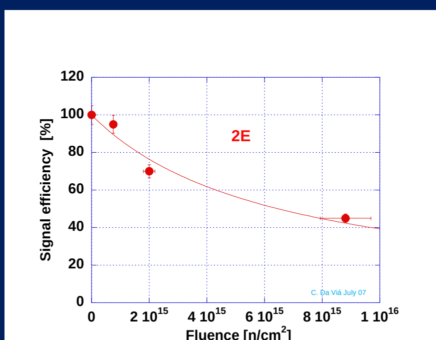
3E= 71um (IBL DESIGN)

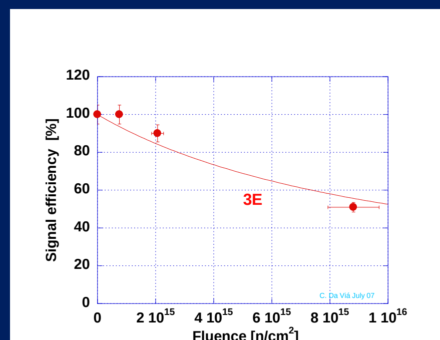


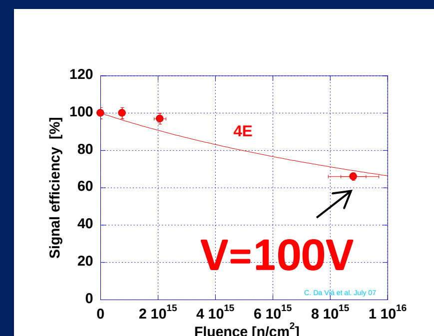
4E= 56um HL

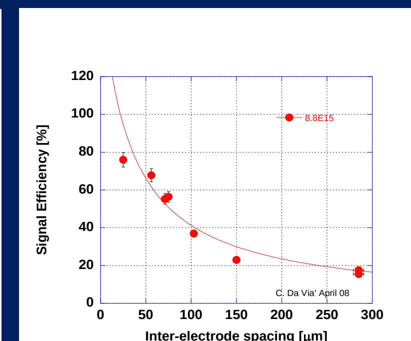


5E= 47um









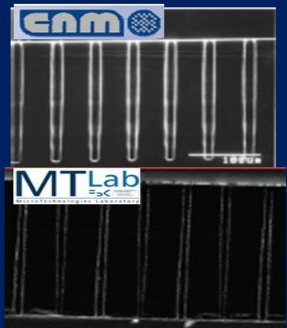
At 9×10^{15} ncm $^{-2}$ And biases below 200V

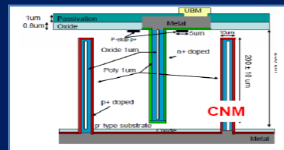
L=IES [um]	105	71-IBL	56-HL	47
Signal Efficiency [%]	45	51	66	68
Charge 50um [e-]	1800	2040	2640	2720
Charge 100um [e-]	3200	4080	5280	5440
Charge 200um[e-]	6400	8160	10560	10880

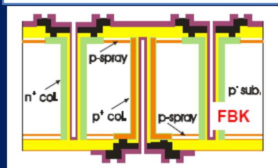
Nucl. Instrum. Meth. A 603 (2009) 319-324

Synergies with LHC experiments:

- ATLAS 3D IBL wafers have CMS sensors in the floor-plan







The Stanford Nanofabrication Facility
SINTEF
ITC
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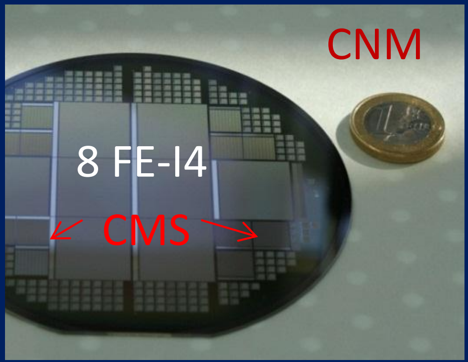
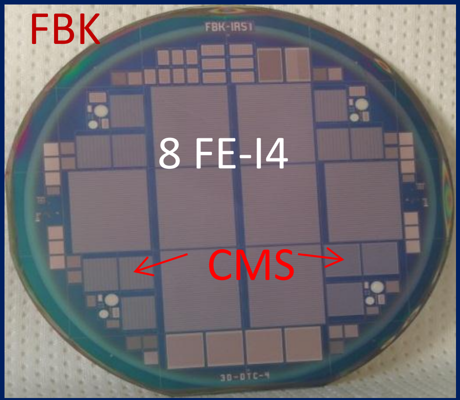
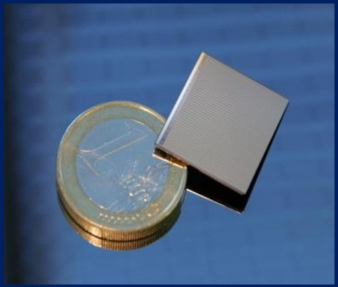
FONDAZIONE BRUNO KESSLER
CNM



Also SINTEF and Stanford completed active edge runs with the same floor-plan





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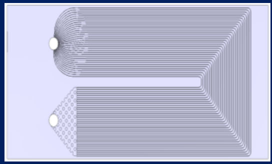
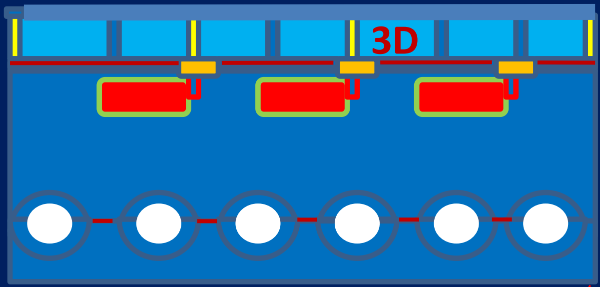
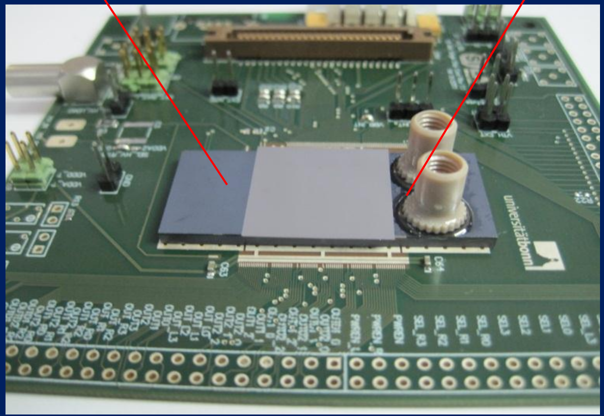
- ATLAS CNM 3D sensor bump-bonded to a 100μm thinned FE-I4 readout chip At IZM mounted on a LHCb "snake' μ-cooling plate







Deliverables

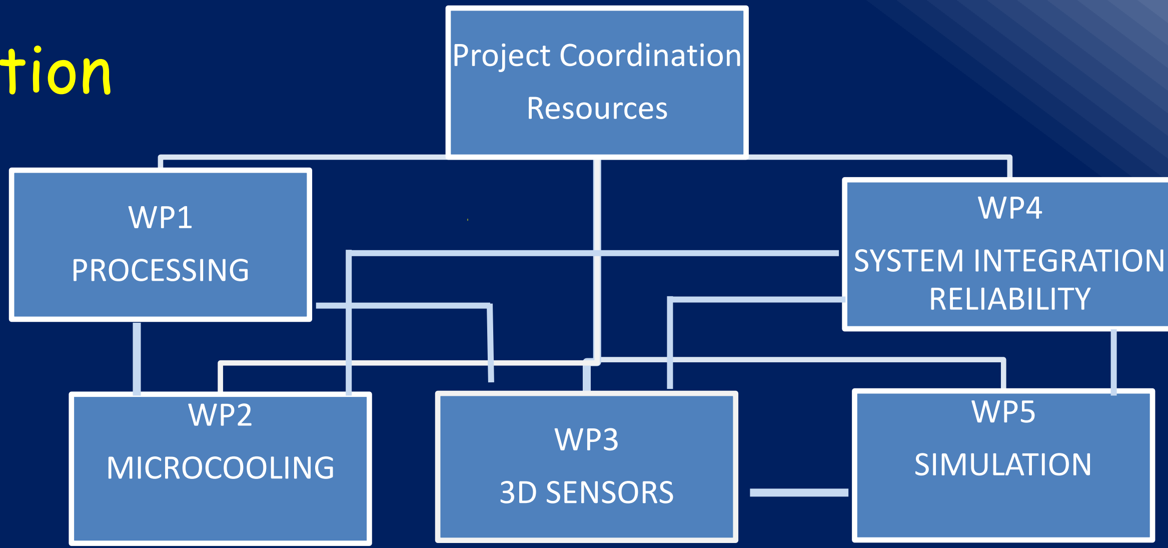
Objective	Deliverables description
A new generation of 3D sensors with active edges	-Multi project Fabrication of thin and thick active edge sensors prototypes at facilities -Integration with existing ATLAS and CMS CMOS pixel chips. -Tests of thin sensors with alternative reversible wafer-bonding
Micro-channels for effective on-chip thermal management	-Micro-channel prototypes compatible with each participating experiment's detector module requirements suitable for microfluidic and pressure characterization. -Tests with available connectors -Study of new connectors
System Reliability studies	Electrical and microfluidic connectors soldering joints, cables, organic components (glues, polyimides, cable-protections) validation after thermal and irradiation stresses.
Single system component and full system simulation	Simulations of sensors (before and after irradiation), microfluidic modeling, thermo-mechanical support modeling, Geant4 simulation of the microsystem in the experiment environment

Milestones over five years

	Description of Work	Start and End Dates
Milestone 1	-Module demonstrators for externally accessible detectors with existing sensors (NA62, ALICE, LHCb) -3D sensors fabrication with HL-LHC IES and novel active edges on 200um substrate -Simulation of novel 3D sensors performance Report	**2014-2015**
Milestone 2	-Connectors definition and reliability demonstration for key components for large detectors area -3D sensors fabrication with HL-LHC on thin substrate. -Support wafer removal validation results -First reliability study results on existing demonstrators -Microfluidic simulation for large area demonstrators Report	**2015-2016**
Milestone 3	-Low mass demonstrators for large area vertex trackers -Simulation of the low mass demonstrators physics performance -Reliability study and test beam of irradiated demonstrators Report	**2016-2017**
Milestone 4	-Preparation of final report with the specification of demonstrators for Large area experiments	**2018**

We are asking for financial support for processing, space for tests and visitors and beam-time periods

Organization



WP1. PROCESSING: Fabrication of 3D sensors, wafer thinning and bonding, active edges, novel structures, fabrication of micro-channels

WP2. MICROCOOLING: micro-channel design, setup and testing, micro-connectors procurement, design and evaluation.

WP3. 3D SENSORS: Design of thin and thick single and double side 3D chips. Modules testing in laboratory and beam experiments.

WP4. SYSTEM INTEGRATION AND RELIABILITY: mechanical and connectivity. Mechanical, structural and radiation reliability tests. Risk analysis.

WP5. SIMULATION: Sensors, Microfluidic, Mechanical, System, Physics.

Periodic WP meetings are foreseen for project monitoring as well as yearly general meetings, review and reports

Collaboration

Institutes

1. **Bergen** (Heidi Sandaker, Bjarne Stugu) **(ATLAS)**
2. **Bari** (Vito Manzari, Giuseppe Eguenio Bruno, Cosimo Pastore) **(ALICE)**
3. **Cosenza** (Anna Mastroberardino, Giuseppe Cocorullo, Felice Crupi, Marco Schioppa, GianCarlo Susinno)
4. **Glasgow** (Richard Bates) **(ATLAS)**
5. **Gottingen** (Jens Weingarten, Arnulf Quadt, Joern Grosse-Knetter, Julia Rieger) **(ATLAS)**
6. **Hawaii** (Sherwood Parker) **(ATLAS)**
7. **IFAE Barcelona** (Sebastian Grinstein, Andrea Micelli, Ivan Lopez) **(ATLAS)**
8. **Manchester** (C. Da Vià, Chris Parkes, Joleen Pater, Vladislav Tyzhnevyi; Stefano Di Capua, Steve Watts) **(ATLAS, LHCb)**
9. **MPI Munich** (H-G Moser) Late expression
10. **Oslo** (Ole Rohne) **(ATLAS)**
11. **Oxford** (Malcolm John) **(LHCb)**
12. **Prague** (Stanislav Pospisil, Tomas Slavicek) **(ATLAS)**
13. **Purdue** (Daniela Bortoletto, Mayur Bubna, Alex Krzywda, Mayra Cervantes, Richard Brosius, Gino Bolla, Petra Merkel, Ian Shipsey, Kaushik Roy) **(CMS)**
14. **Seattle (Washington Uni)** (Shih-Chieh Hsu) **ATLAS**
15. **SLAC** (Chris Kenney, Philippe Grenier, Jasmine Hasi, Dong Su) **(ATLAS)**
16. **Stony Brook** (Dmitri Tsibichev) **(ATLAS)**
17. **Torino** (Flavio Marchetto, Nicolo Cartiglia, Roberta Arcidiacono) **(NA62),**
18. **Trento** (GianFranco Dalla Betta, Lucio Pancheri, Marco Povoli, Roberto Mendicino, Alberto Quaranta)
19. **Udine** (Mario Paolo Giordani, Marina Cobal)

Processing Facilities

CNM (Giulio Pellegrini, Manuel Lozano, Celeste Fleta, Miguel Ullan, Salvador Hidalgo, Virginia Greco, David Quirion), *Barcelona, Spain*

FBK (Maurizio Boscardin, Alvise Bagolini, Francesca Mattedi, Sabina Ronchin, Pierluigi Bellutti, Paolo Conci, Stefano Girardi, Nicola Zorzi, Gabriele Giacomini, Claudio Piemonte)

CSEM (Aurelie Pezous, Patrick Albert, Olivier Dubochet) ,

SINTEF (Angela Kok, Thor-Erik Hansen)

IZM (Thomas Fritszch, Oswin Erhmann)

CEA-LETI (Eric Rouchouze, Jean Francois Tessier, Yann Lamy),

NSF/SLAC (Chris Kenney, Jasmine Hasi) Stanford Nano Fabrication Facility, Palo Alto California USA

More groups have expressed interest to join .
Their request will be considered later this year if the proposal will receive positive recommendation by this committee

Summary

- In this RD collaboration we would like to join efforts and skills to solve problems for HL-LHC experiments upgrades using micro-fabrication
- We aim to build demonstrators for relevant testing at future realistic experimental conditions by a dedicated and not a generic work activity
- Seven Top Processing Facilities joined the project: this has proven to be the key for a rapid solution of technological problems
- Several groups and facilities in this proposal have industrialized 3D sensors and had them included in the first detector upgrade at the LHC, the ATLAS IBL, after a stringent review process. Thanks to that 3D is now considered a 'mature' technology and being considered for pixel upgrades in various experiments.

We are therefore asking this committee to give this collaboration an opportunity to capitalize on this experience so this sensor technology can be brought to the next level.

Together with micro-system prototypes we aim at gathering the relevant reliability and production information in time for decisions at experiments

We believe that having this done as a CERN RD is the best platform to unify effort amongst and for CERN-LHC experiments