Electronics for Particle Physics in Perugia

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Outline

- ✓ Introduction: electronics background.
- ✓ The CMS (Compact Muon Solenoid) experiment:
  - the Silicon Strip Tracker: R&D, Opto-Hybrid and Construction;
  - the Phase-2 65nm Pixel Read-Out chip.
- ✓ The NA48 & NA62 experiments.
- ✓ The AMS-02 (Alpha Magnetic Spectrometer) experiment:
  - the tracker power supply & thermal control system.
- ✓ The R&D (INFN CSN5) experiments:
  - RAPS, RAPSODIA, VIPIX, RAPID,…
- ✓ Conclusions.

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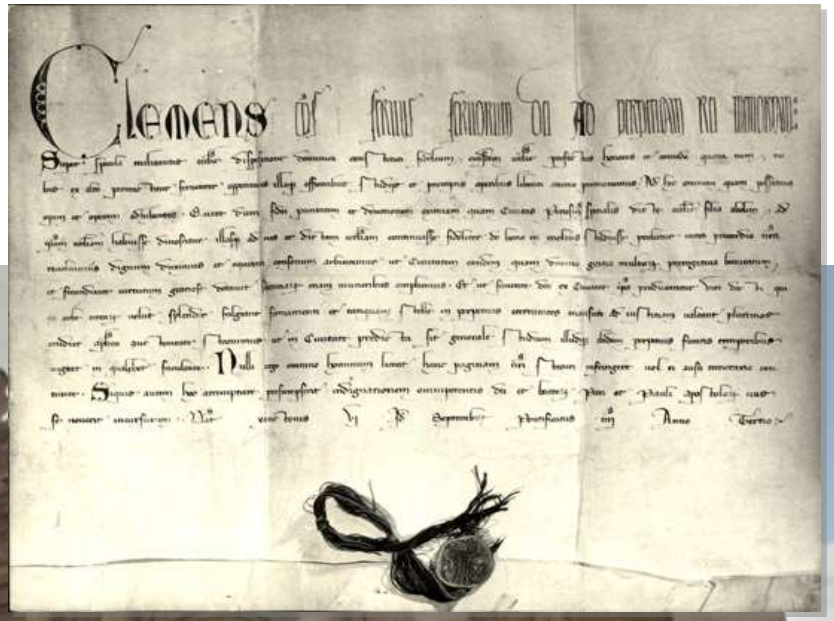
The University of Perugia

- ✓ The University of Perugia is one of the most ancient universities in Italy
  1308 - Pope Clemente V Founding Papal Bull



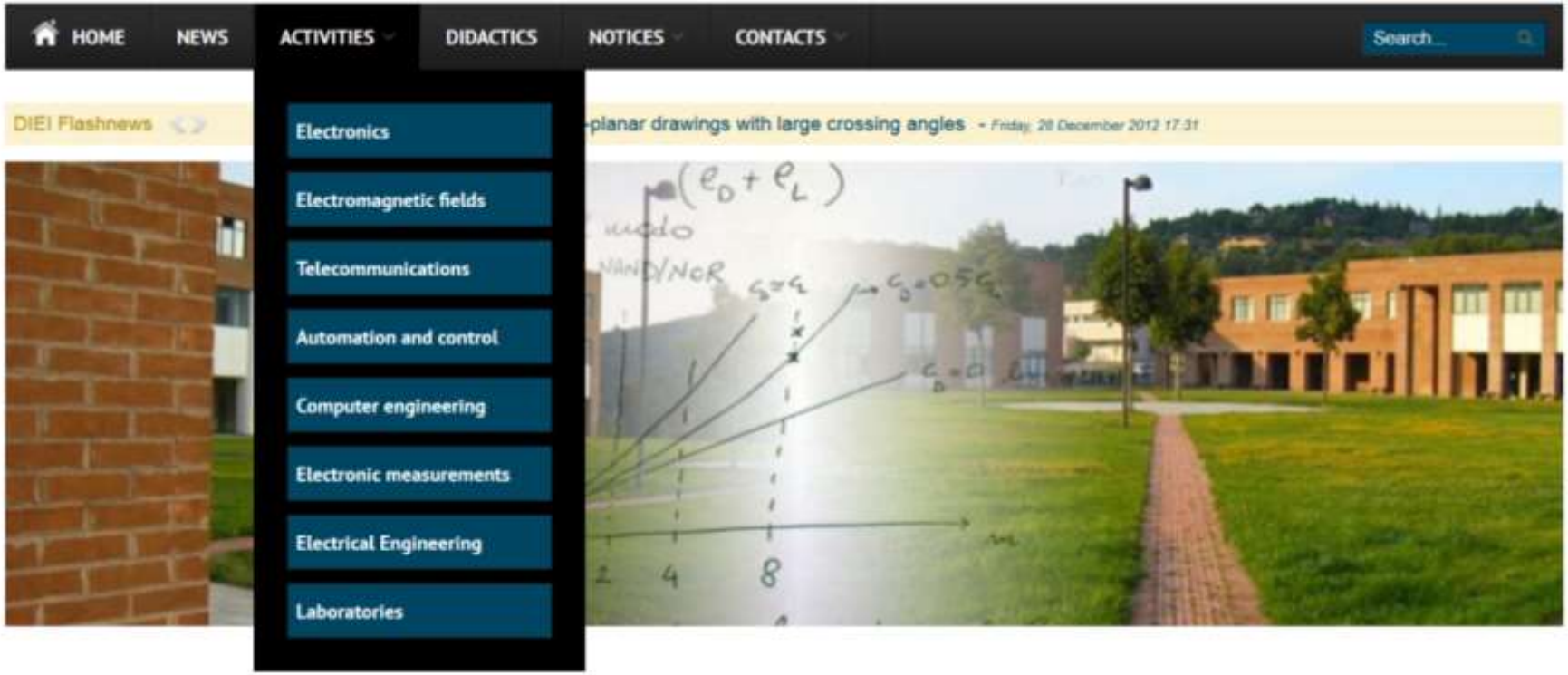
The Faculty of Engineering

The Faculty of Engineering of the University of Perugia was founded in August 1986, featuring three main areas:

- ✓ Civil Engineering (1987/1988)
- ✓ Electronics Engineering (1987/1988).
- ✓ Mechanics Engineering (1988/89).

The DIEI

The Department of Electronics Engineering and Information (DIEI) is one of the main Departments of the Faculty of Engineering (www.diei.unipg.it)



Electronics activities at DIEI

Sensors, Circuits & Systems - This activity focuses on the design and test of CMOS Active Pixel Sensors integrated in VLSI sub-micrometer and vertical scale (3D-IC) technologies, on the development of a multi-channel analog front end for brain-computer interfaces (BCI), on a Lab-on-Chip (LoC) for viral infection diagnosis as well as on a real time dosimeter for Interventional Radiology.

Devices and technology - Activities are devoted to physical modeling and numerical analysis of semiconductor devices, to the study of thermal properties of micro electro mechanical systems and to the Silicon on Diamond (SoD) technology for radiation sensor and biomedical applications.

High Frequency - Activities in this branch are about RFID systems, RF Integrated circuits (RFIC), Front End design for telecommunication, telemetry and radiometers, System in Package (SiP) and interconnections. Most recently, specific attention has been devoted to solutions for Internet of Things (IoT) applications.

"Green Electronics" - Organic devices and low cost recyclable materials (mostly paper) are adopted here to develop circuits using inkjet printing as well as adhesive copper tape. Design approaches suitable for Wide Area Electronics (WAE) applications are being carried on, among them: chipless RFID tags, Harmonic RFID systems and Systems in Package on Paper (SiPoP).

Main electronics competences

- ✓ The electronics know-how originates from the confluence of different research lines:
  - modeling and design of smart sensors
  - CMOS analog and mixed-signal VLSI design
  - microcontroller based microsystems
- ✓ In order to increase the innovation potential in circuit design, the field of interest has progressively been extended, e.g. to digital circuits for telecom applications.
- ✓ When applicable, results obtained in modeling and circuit design techniques are translated into specific CAD tools as a subset of the main CAD environment of the lab.
- ✓ Suitable electronics "substrate" for particle physics applications…

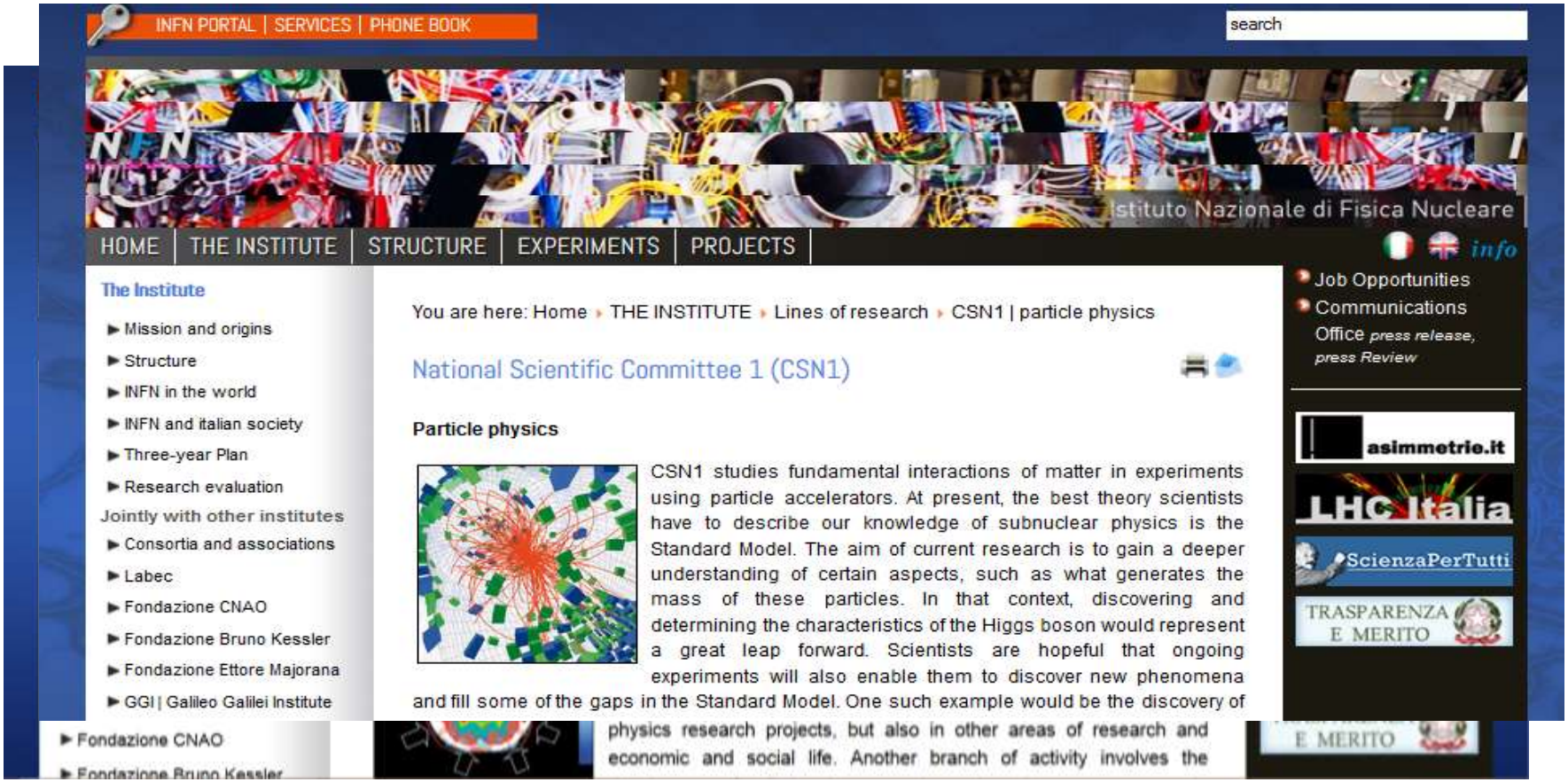
The Department of Physics

The Department of Physics of the University of Perugia.
(www.fisica.unipg.it/dip/)

The INFN

The Italian Institute of Nuclear Physics (Section of Perugia).

www.infn.it -> www.pg.infn.it



INFN & University of Perugia Background

- ✓ About two decades of collaborations.
- ✓ Very fruitful interactions.
- ✓ Know-how sharing of between physicists and engineers: modeling, simulation, design, fabrication and test.
- ✓ Potential applications:

  …

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Perugia past contributions to CMS

- ✓ The CMS Tracker activity was established in 1994 by G. Mantovani and G.M. Bilei. The group participated to all phases of CMS Tracker from its conception, R&D, construction, integration commissioning and data taking. Main interests in R&D activities were:
- ✓ Developments of Rad Hard Silicon Sensors (participation to RD48 and later RD50):
  - modeling of silicon strip detector and simulation of radiation damage effects;
  - irradiation of silicon devices with neutrons at ENEA in Rome and lab tests, comparison with simulations;
  - participation to several test beams with irradiated sensors.
- ✓ Developments of Analog Optical link for Front-End Readout (participation to RD23):
  - participation to the development of Laser Driver and PLL;
  - development and qualification of analog Opto-Hybrid system.

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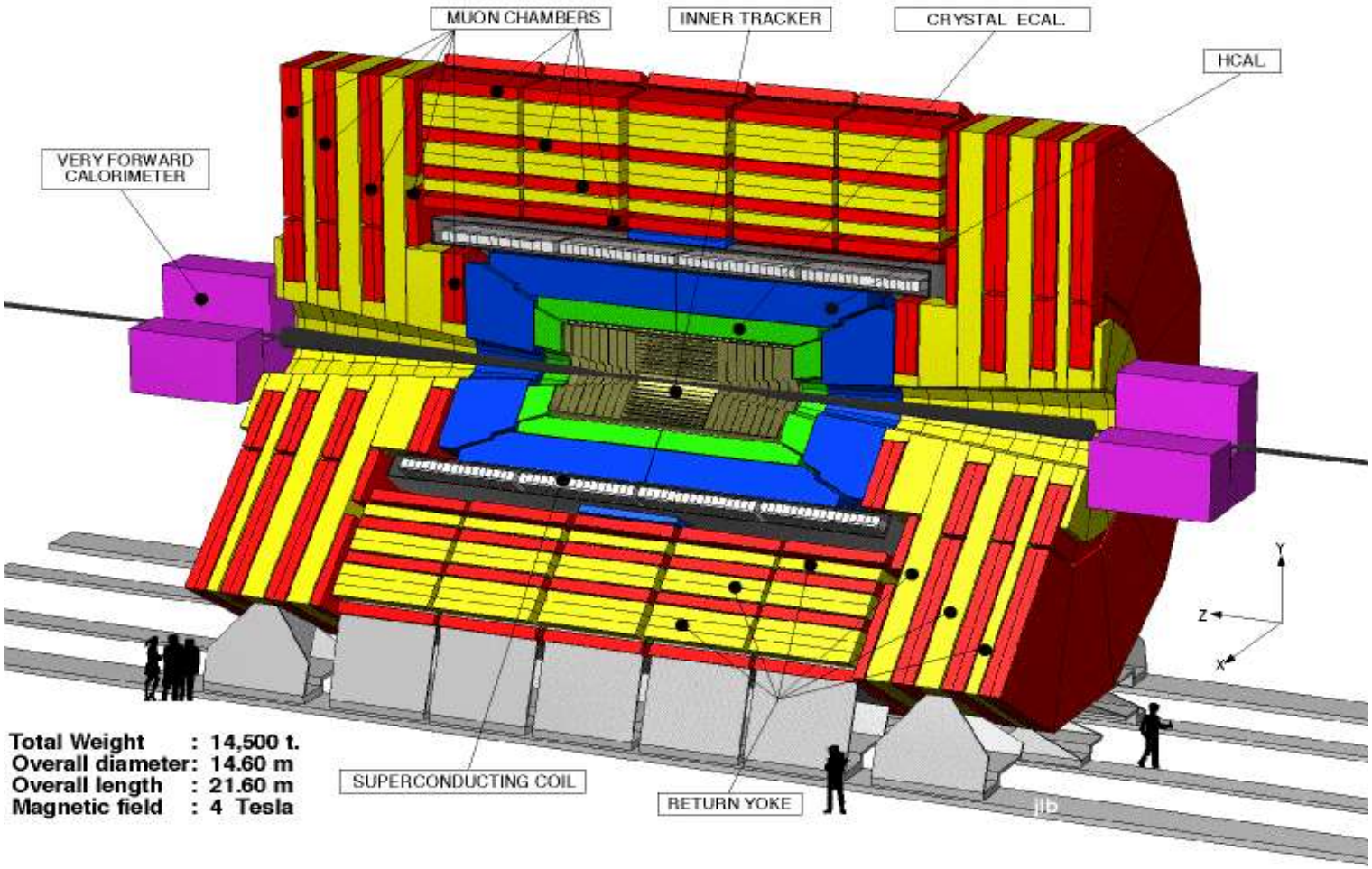
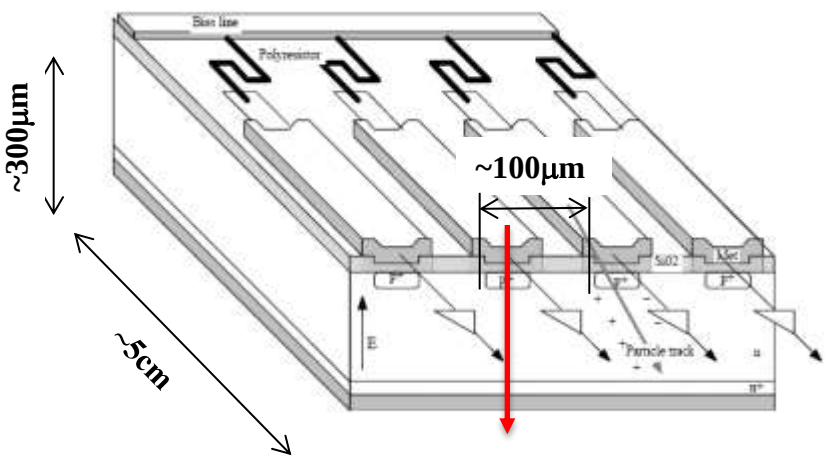
The CMS experiment

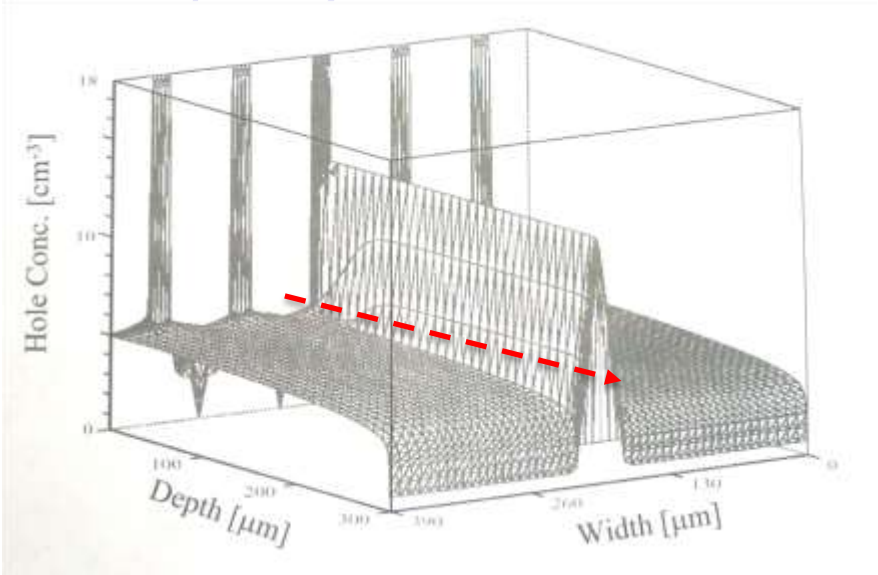


✓ What does this have to deal with (micro)electronics?

The CMS Si Microstrip Tracker

- ✓ Numerical analysis and physical modelling of semiconductor devices.
- ✓ Technological CAD tool specialization to the analysis/design of NON conventional microelectronics devices (particle sensors):
  - macroscopic dimensions, microscopic details;
  - low doped substrates $N_D=10^{12}cm^{-3}$ (high resistivity kΩ·cm);
  - high voltages - V_{BIAS} 300V and more;
  - high electric fields (charge collection by drift).





Particle Detectors Device Level Simulation

- ✓ Numerical analysis and physical modelling of semiconductor devices.
- ✓ Modeling of ionizing particle / silicon substrates interaction at device level.

$$\nabla \cdot \left(-\varepsilon_s \nabla \varphi\right) = q\left(N_D^+ - N_A^- + p - n\right)$$

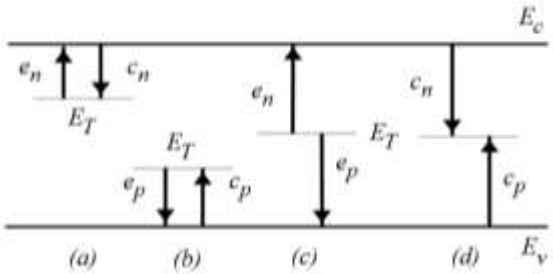
$$\frac{\partial n}{\partial t} - \frac{1}{q}\nabla \cdot \vec{J}_n = G - R + G^{rad}$$

$$\frac{\partial p}{\partial t} + \frac{1}{q}\nabla \cdot \vec{J}_p = G - R + G^{rad}$$

- ✓ The G^{rad} term can be distributed in time and space, according to the spatial discretization scheme (Box Integration Method) and the numerical solving algorithms (HFIELDS tool – University of Bologna)

Particle Detectors Device Level Simulation (2)

- ✓ Numerical modeling of radiation damage in semiconductor detectors:
  - radiation induced G^{rad} term;
  - deep-level recombination centers (traps);
  - explicit contribution of the trapped charges to the charge density.



$$\nabla \cdot \left(-\varepsilon_s \nabla \varphi\right) = q\left(N_D^+ - N_A^- + p - n + p_d - n_a\right)$$

- ✓ Continuity equations for both free and trapped charges.

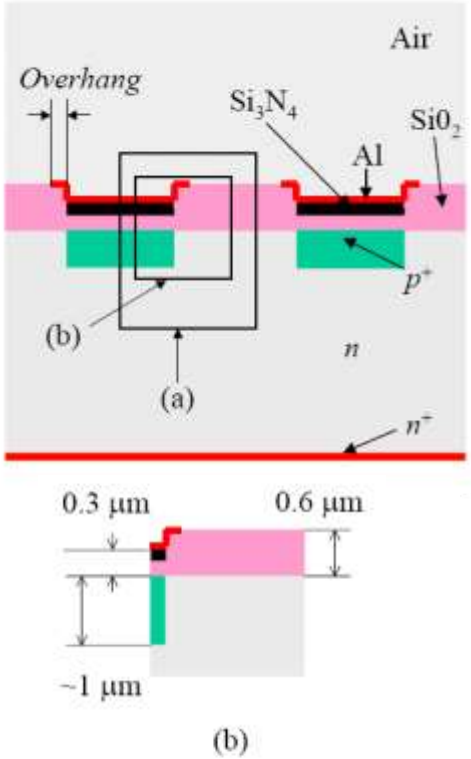
$$\frac{\partial n}{\partial t} - \frac{1}{q}\nabla \cdot \vec{J}_n = -U_n \qquad \frac{\partial n_a}{\partial t} - \frac{1}{q}\nabla \cdot \vec{J}_{na} = -U_{na}$$

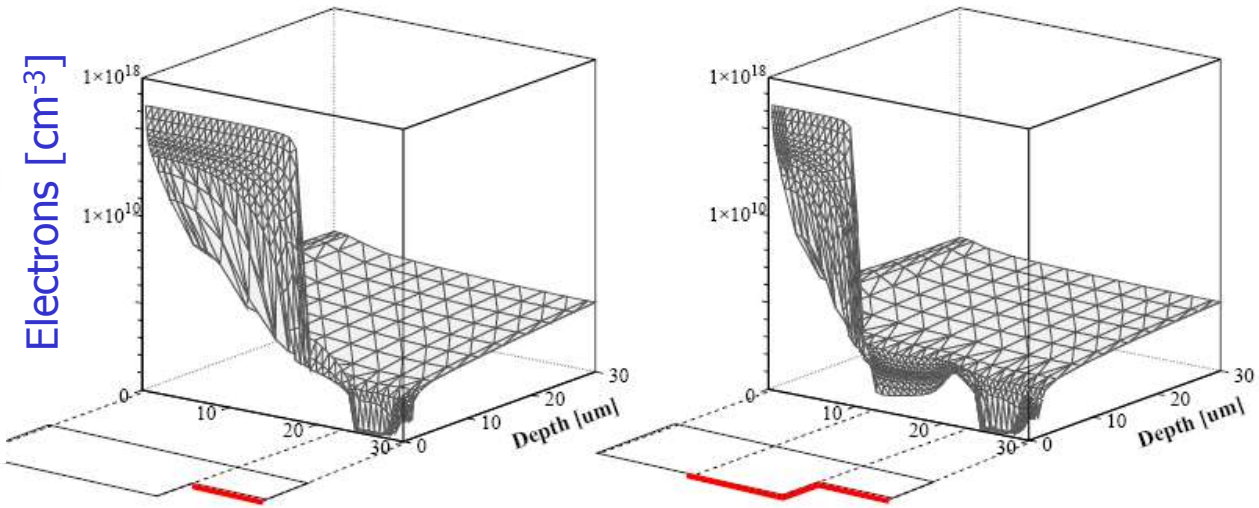
$$\frac{\partial p}{\partial t} + \frac{1}{q}\nabla \cdot \vec{J}_p = -U_p \qquad \frac{\partial p_d}{\partial t} + \frac{1}{q}\nabla \cdot \vec{J}_{pd} = -U_{pd}$$

CMS Si Tracker technology options

- ✓ Geometry and fabrication technology optimization of the Si microstrip detector of the CMS experiment:
  - substrate resistivity options.
  - metal contact geometry.

Metal overhang effect on the electrons distribution at the Si/SiO_2 interface.





- ✓ The obtained results contributed to the definition of the specifications of the CMS tracker.

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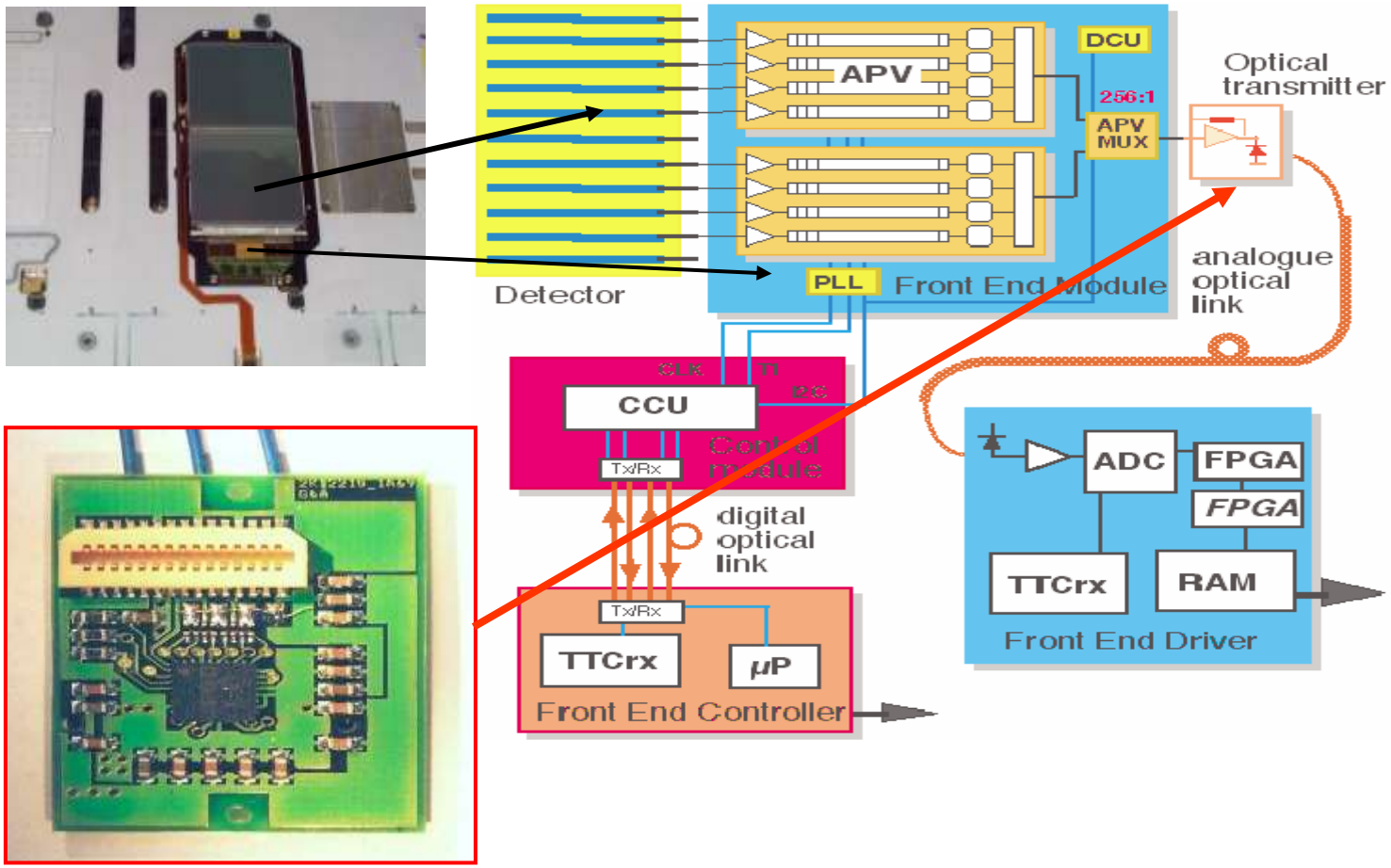
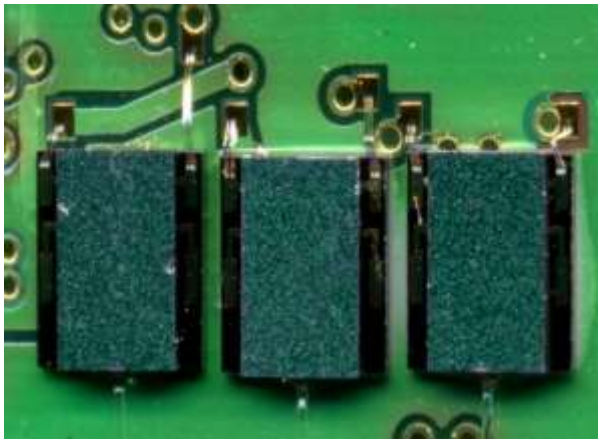
The CMS Opto-Hybrid System

- ✓ The Opto-Hybrid project for the inner barrel & disks of the CMS tracker.



The CMS Opto-Hybrid System (2)

- ✓ Laser diodes interconnected to the substrate by means of wire-bonding.



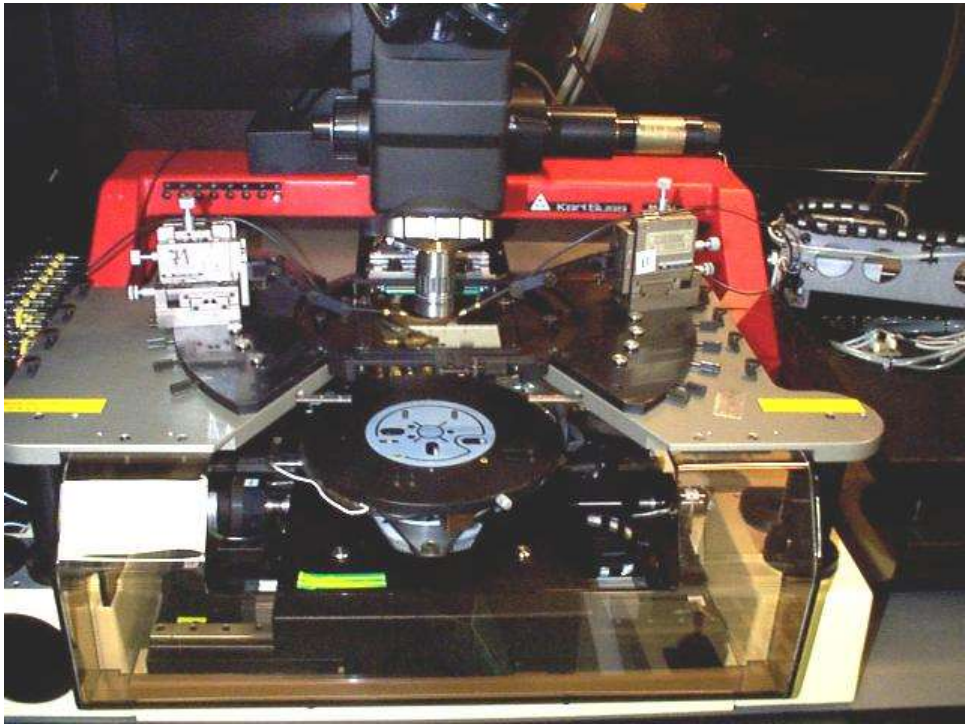
- ✓ Due to serious abrasions of optical fibers buffer discovered at the beginning of the production, all the diodes (100%) have been tested before mounting.
- ✓ In Perugia between 2003 and 2004:
  - ✓ more than 8000 diodes have been tested.
  - ✓ 4290 modules for the inner barrel have been successfully developed, with an yield of 98.2%.

INFN PG Clean Room

	Clean Room "A"	Clean Room"B"
Specs:	ISO 4 (FED 209D M 5,5)	ISO 2 (FED 209D M 3,5)
T range:	± 1°C	± 1°C
Umidity:	± 5%	± 5%
Flux:	M 3,5 n° 4-dim 120x60 cm	M 3,5 n° 1-dim 200x60 cm

INFN PG Clean Room (2)

Bonding Delvotec.



SUSS PA 200 Semi-Automatic Prober.

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CMS Tracker construction and integration

- ✓ The CMS group was heavily involved in the construction of the CMS Strip Tracker in Perugia. The main activities carried out during the construction were:
  - quality assurance of silicon strip sensors (20% of total silicon strip sensors);
  - silicon strip inner barrel module assembly and testing (50% of Inner Barrel);
  - development and construction of analog optical hybrid for the inner barrel (100% of the inner barrel).

- ✓ Later on, the CMS group was involved at CERN for the Integration, Commissioning and Data taking of Tracker.

CMS Tracker construction and integration (2)

- ✓ Half of Tracker Inner barrel modules assembled in Perugia.
- ✓ Perugia was one of the 6 CMS silicon module assembly centers.

- CF Support, Si Sensors and Hybrids automatic assembled.
- Glue automatically dispensed.
- Accuracy of mounting ~ 5μm.

Aerotech AGS 10,000 gantry positioning system Assembly platform (individual for each module type).

CMS Perugia Tracker future activities

- ✓ New Pixel detector for Phase-1 to be installed in 2016-17
  - Contribution to the construction of Pixel modules.
- ✓ Future developments for the new Silicon Tracker at HL LHC:
  - contribution to RD53 for the design of a new Pixel Read-Out Chip electronics in 65nm CMOS;
  - contribution to R&D for the development of Track Trigger back-end electronics based on Associative Memories.

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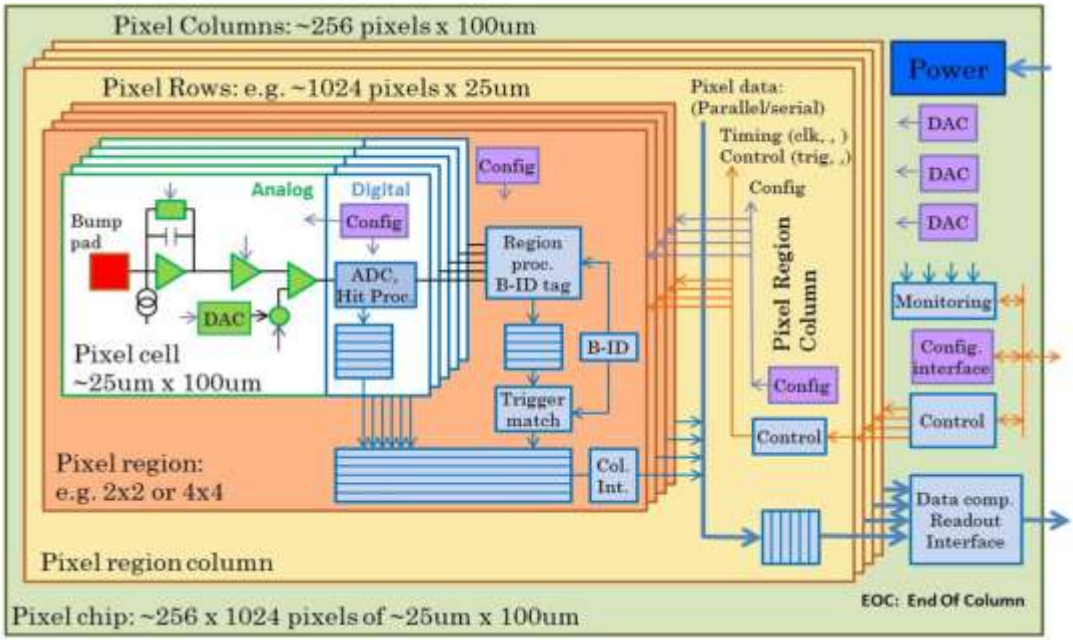
The CMS Phase-2 Pixel Read-Out chip

- ✓ The CMS (Compact Muon Solenoid) hybrid pixel detector is one of the large general purpose experiments at the LHC (Large Hadron Collider) located at CERN.
- ✓ For its Phase-2 upgrade not only will the luminosity and pileup drastically increase (5×10^{34} $cm^{-1}s^{-1}$), but also the trigger rates will necessarily increase as the experiment will grapple with triggering on high pileup events.
- ✓ Critical design challenges on the IC design:
  - smaller pixels to resolve tracks in boosted jets;
  - much higher hit rates (1GHz/cm^2);
  - unprecedented radiation levels (10 MGy);
  - much higher output bandwidth;
  - large IC format with low power consumption.
- ✓ Adoption of a 65nm CMOS technology.

Activity on Pixel Detector Upgrade

- ✓ **CERN RD53** collaboration**: "***Development of pixel readout integrated circuits for extreme rate and radiation"* between the ATLAS and CMS experiments.
- ✓ Collaboration organized by Institute Board (IB) with technical work done in specialized Working Groups (WG)…



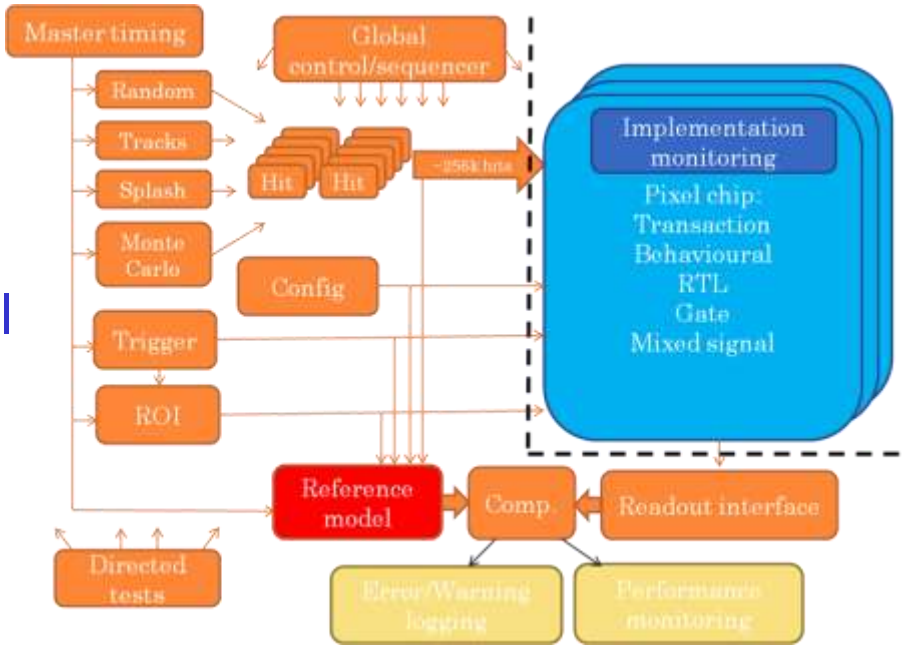
WG	Domain
WG1	Radiation test/qualification
	Coordinated Test and qualification of 65nm for 10rad TID and10[15] neu/cm2 Extensive radiation tests and report. Transistor simulation model after radiation Expertise on radiation effects in 65nm
WG2	Design Methodology/tools
	Integration of analog in large digital design Design and verification methodology for very large chips Design methodology for low power design/synthesis Clock distribution and optimization.
WG3	Simulation/verification framework
	System Verilog simulation and Verification framework Optimization of global architecture/pixel regions/pixel cells
WG4	I/O + (Standard cell)
	Development of rad hard IO (and standard) cells Make available to collaboration
WG5	Analog design /analog front-end
	Define detailed requirements to analog front-end and digitization Evaluate different approaches Make analog front-end block(s) available to collaboration
WG6	IP blocks
	Definition of required building blocks: PLL, references , ADC, DAC, power conversion, LDO, , Distribute design work Coordinate implementation and test/verification work Make cells available to collaboration

Thanks to Jorgen CHRISTIANSEN CERN/PH-ESE

Activity on Pixel Detector Upgrade (2)

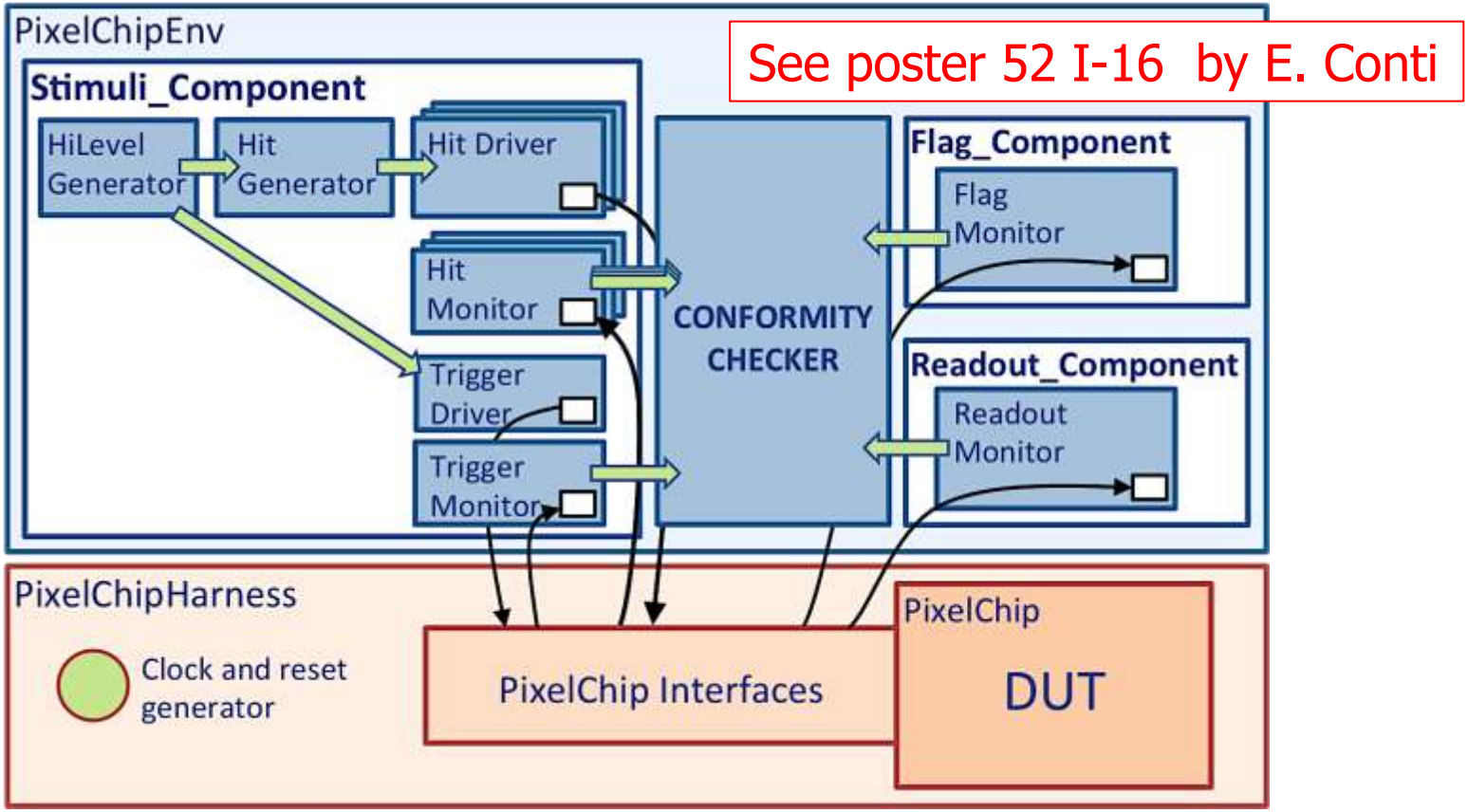
- ✓ WG3: "Simulation Testbench" Goals:
  - definition/evaluation of requirements for next generation pixel chips;
  - system performance evaluation for different pixel architectures;
  - pixel architecture optimization based on pixel grouping (validation of statistical study).

- ✓ Behavioral description of a pixel chip and implementation of a standardized and reusable simulation and verification environment.



PG Activity on Pixel Detector Upgrade

- ✓ *SystemVerilog* class-based verification environment
- ✓ Testbench standardization into a verification environment based on Universal Verification Methodology (UVM)



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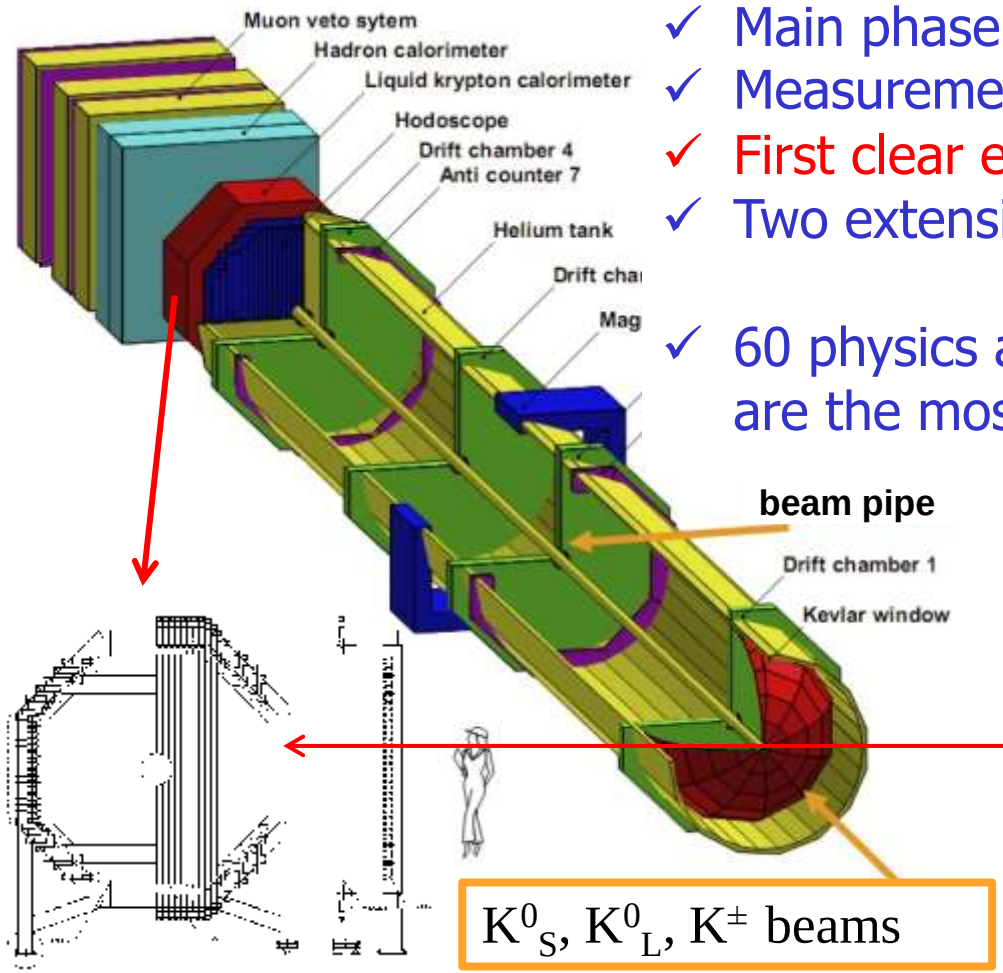
The NA48 experiment

- ✓ To study neutral and charged kaons



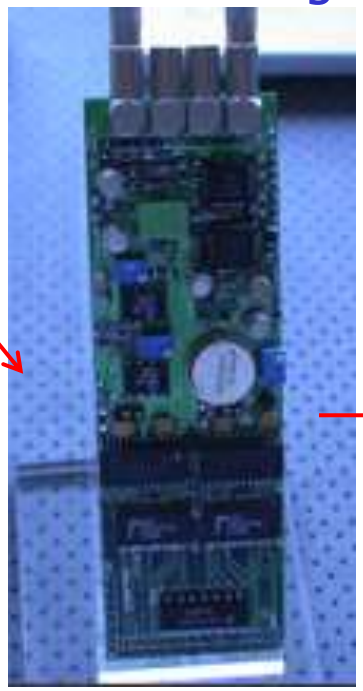
K^0_S, K^0_L, $K^\pm$ beams

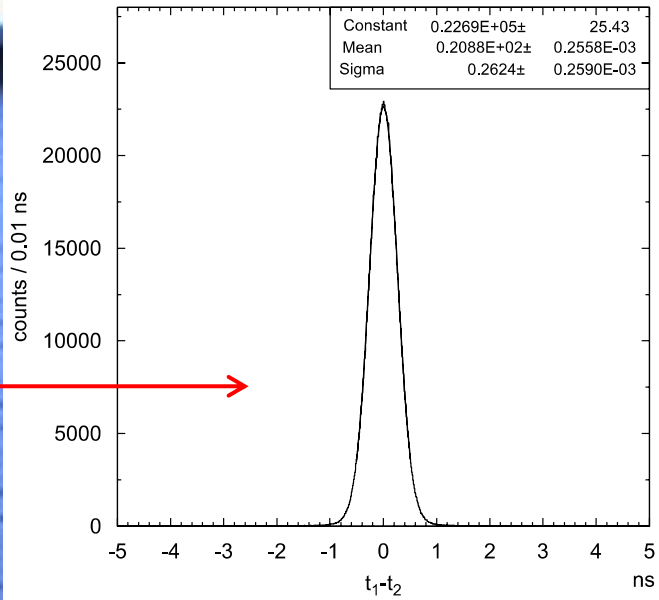
- ✓ Main phase from 1995 to 2001:
- ✓ Measurement of Re(ε'/ε)=$(14.7 \pm 2.2) \times 10^{-4}$
- ✓ First clear evidence of direct CP violation!
- ✓ Two extensions: - NA48/1 (2002, K^0_S)
  - NA48/2 (2003-2004, $K^\pm$)
- ✓ 60 physics articles, many measurements are the most precise in the field.

- ✓ The Perugia group was responsible for the design, construction and operation of:
  - the charged and neutral Hodoscopes (scintillator detectors);
  - The charged pre-trigger.

The NA48 electronics PG contributions

- ✓ Daughter boards of the PMBs (Pipeline Memory Board, developed by Cagliari), three different types of daughter boards, working at 40 MHz:
  - the 'ADC/TDC', which provided sub-nanosecond timing and pulse height (10 bits) information for scintillator signals (charged and neutral hodoscopes, large and small angle anti-counters);
  - the 'pattern unit', to store digital data produced by external, trigger related, sources;
  - the 'counter' that allowed data counts to be associated with an event.



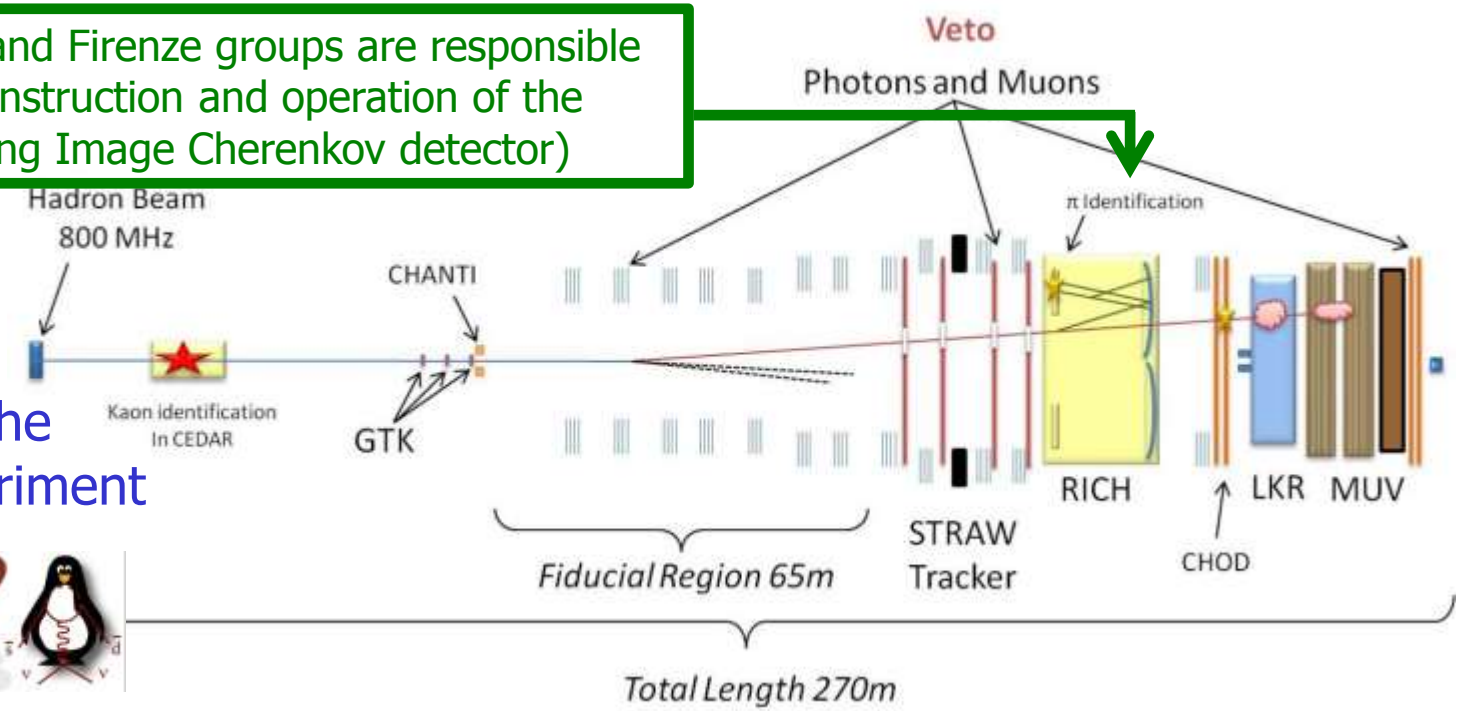


Time difference between two vertical slabs.

The NA62 experiment

- ✓ First phase (2007-2008): measurement of the ratio $R_K = BR(K^+ \to e\nu)/BR(K^+ \to \mu\nu)$ exploiting the NA48 detector ➡ $R_K = (2.488 \pm 0.010) \times 10^{-5}$ (Phys. Lett. B 719 (2013) 326-336)
- ✓ Main phase (2014-201x): measurement of Branching Ratio of the decay $K^+ \to \pi^+ \nu\nu$ (Test of Standard Model complementary to direct searches)

Perugia and Firenze groups are responsible of the construction and operation of the RICH (Ring Image Cherenkov detector)

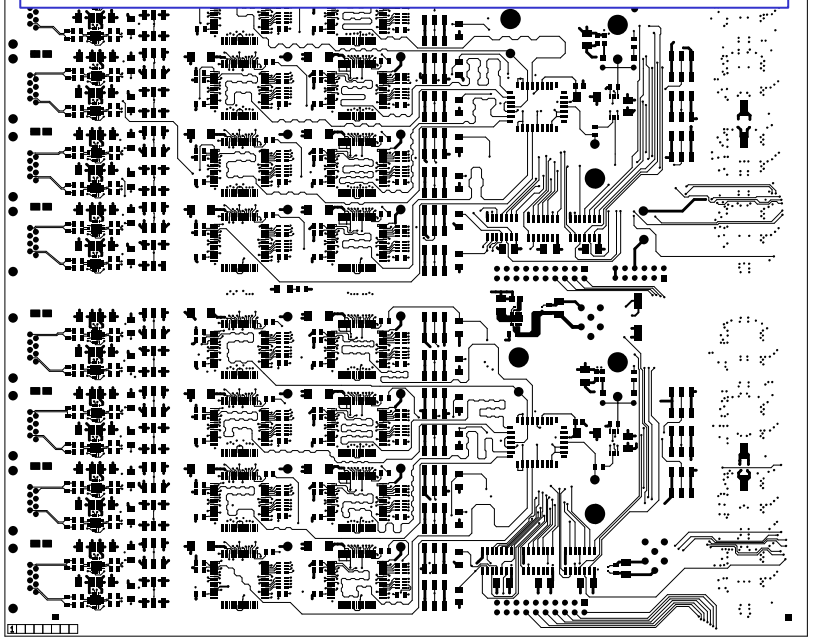


Layout of the NA62 experiment

The NA62 electronics PG contributions

- ✓ NA62 will use a unique readout scheme for almost all sub-detectors based on the TEL62 boards developed by Pisa group (see talk given by B. Angelucci).
- ✓ Perugia is responsible for the RICH Trigger & DAQ and currently is writing the part of the firmware concerning the generation of the L0 trigger primitive.
- ✓ Perugia group is also responsible for the design, production and test of the TELDES daughter board (to be plugged on TEL62) that will be used on the chain generating the L0 trigger primitives from the Electromagnetic Calorimeter. (see posters by S. Venditti and N. De Simone)

Teldes schematic (layer 1 of 8)



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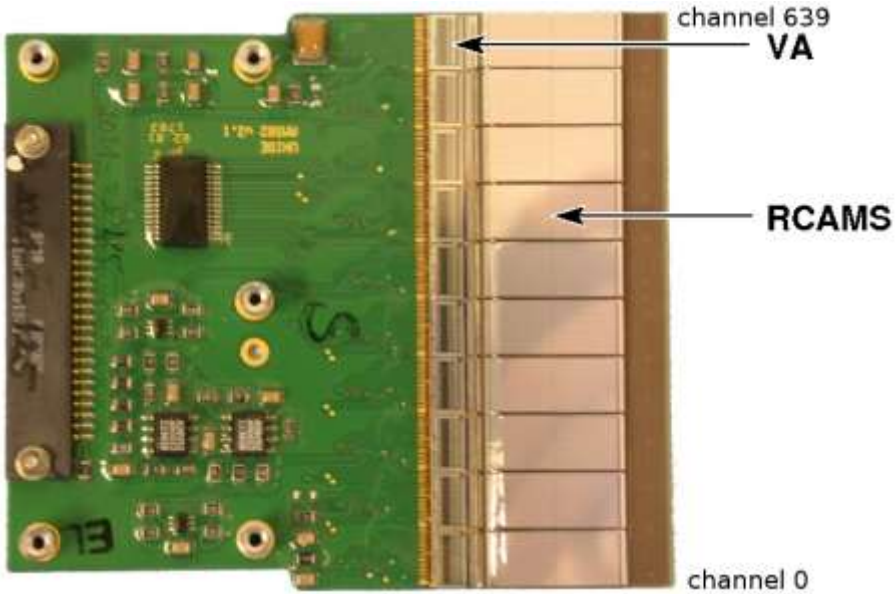
The AMS-02 experiment

- ✓ The Alpha Magnetic Spectrometer (AMS) experiment has as physics goals the search for anti-nuclei, dark matter and strangelets, the measurement of the cosmic ray primary spectrum, the measurement of the cosmic ray trapped component around 350 km of altitude and the observation of diffuse and source-emitted gamma rays.

- ✓ The tracking system of the AMS-02 instrument is built from silicon detectors. Each elemental detector is a double-sided silicon detector having dimensions 40×70mm and 300μm thickness.

The AMS-02 Si strip readout

✓ The VA64HDR9A chip (3072 in-use chips)



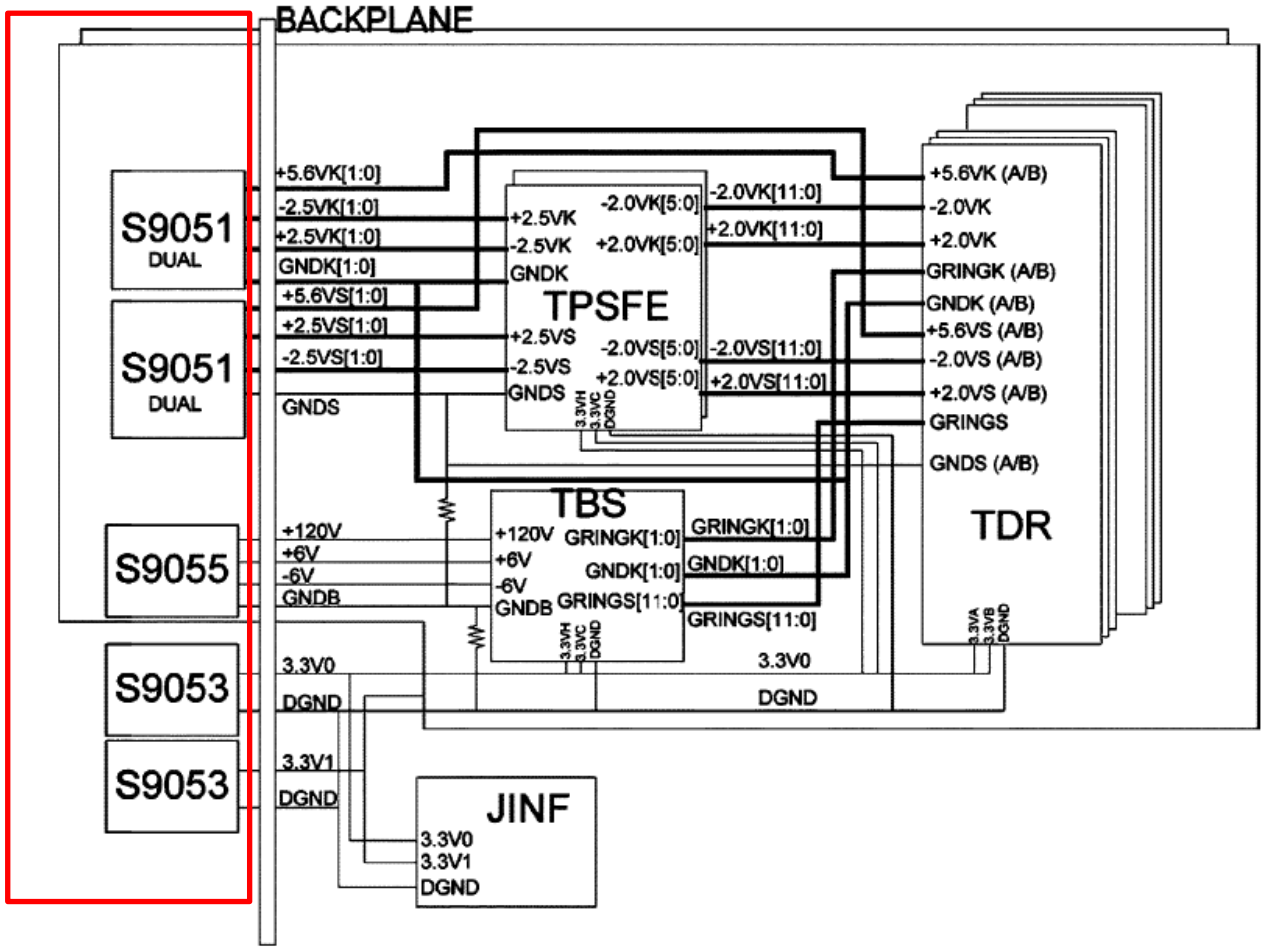
Parameter	VA64HDR9A	VA140
Noise, Cd=50pF (eRMS)	520	430
DNR	+100fC,-200fC	±200fC
Power cons. (mW/channel)	0.8	0.29
Peaking time (μs)	5	6.5
SEL thrshd (MeV·cm^2/mg)	22	21-22

The AMS-02 power supply system

- ✓ The power supply system of the AMS tracker detector is divided into 8 sub-units; each subunit takes power from one 28 VDC output of the PDS (Power Distribution System) common for the entire apparatus.
- ✓ Each subunit is composed by:
  - a TPD (Tracker Power Distributor) that contains DC-DC converters, input filter and an interface board with the slow control system;
  - a crate which hosts linear regulator board (for bias generation and for powering the front-end electronics), readout cards (TDR tracker data reduction) and the interface with the main slow control and data collection system (called JINF).

The AMS-02 power supply system (2)

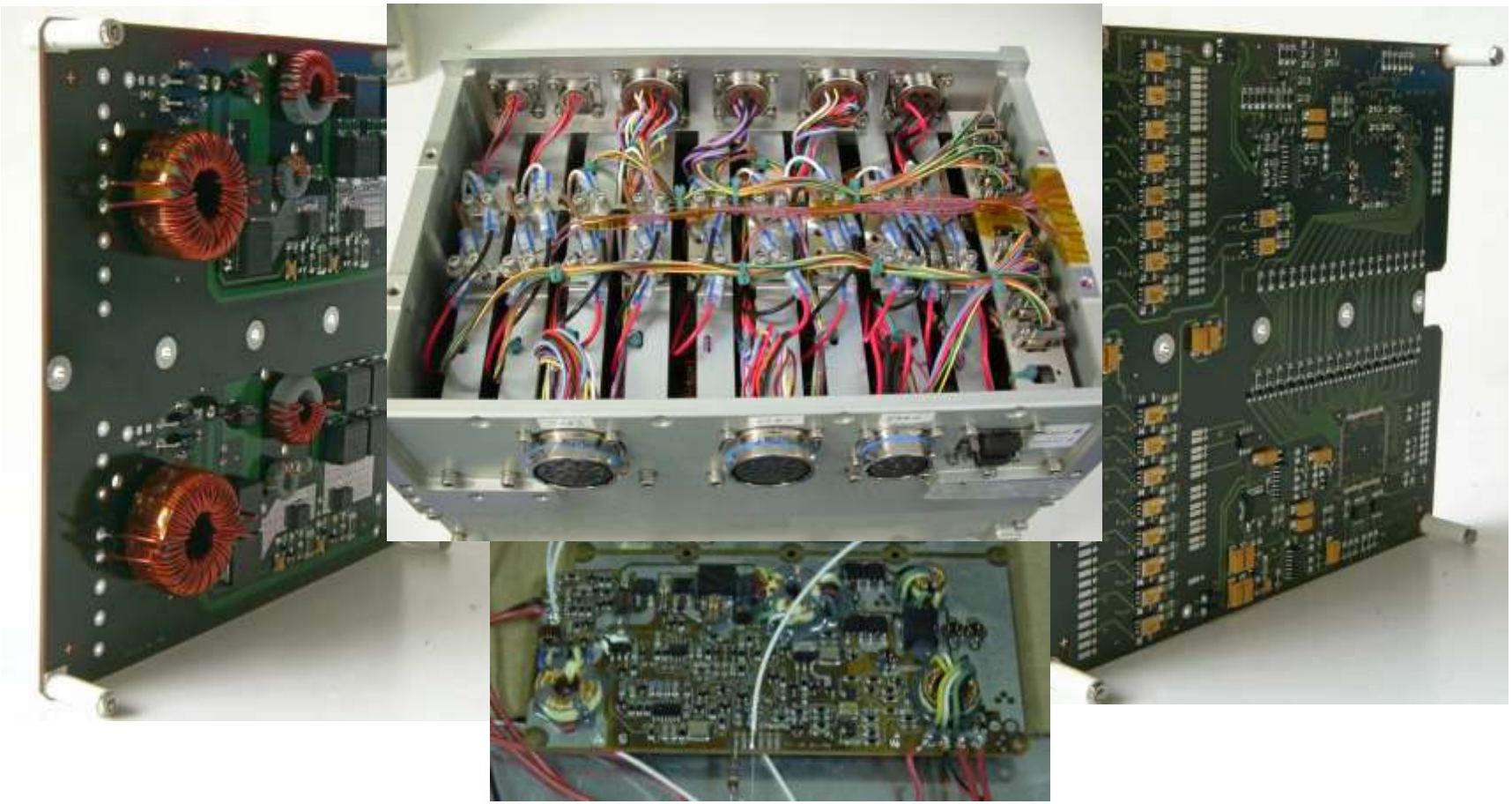
✓ Block diagram of power supply system electronics sub-unit.



The AMS-02 TPD (Tracker Power Distributor)

The dual input filter (S9011B)

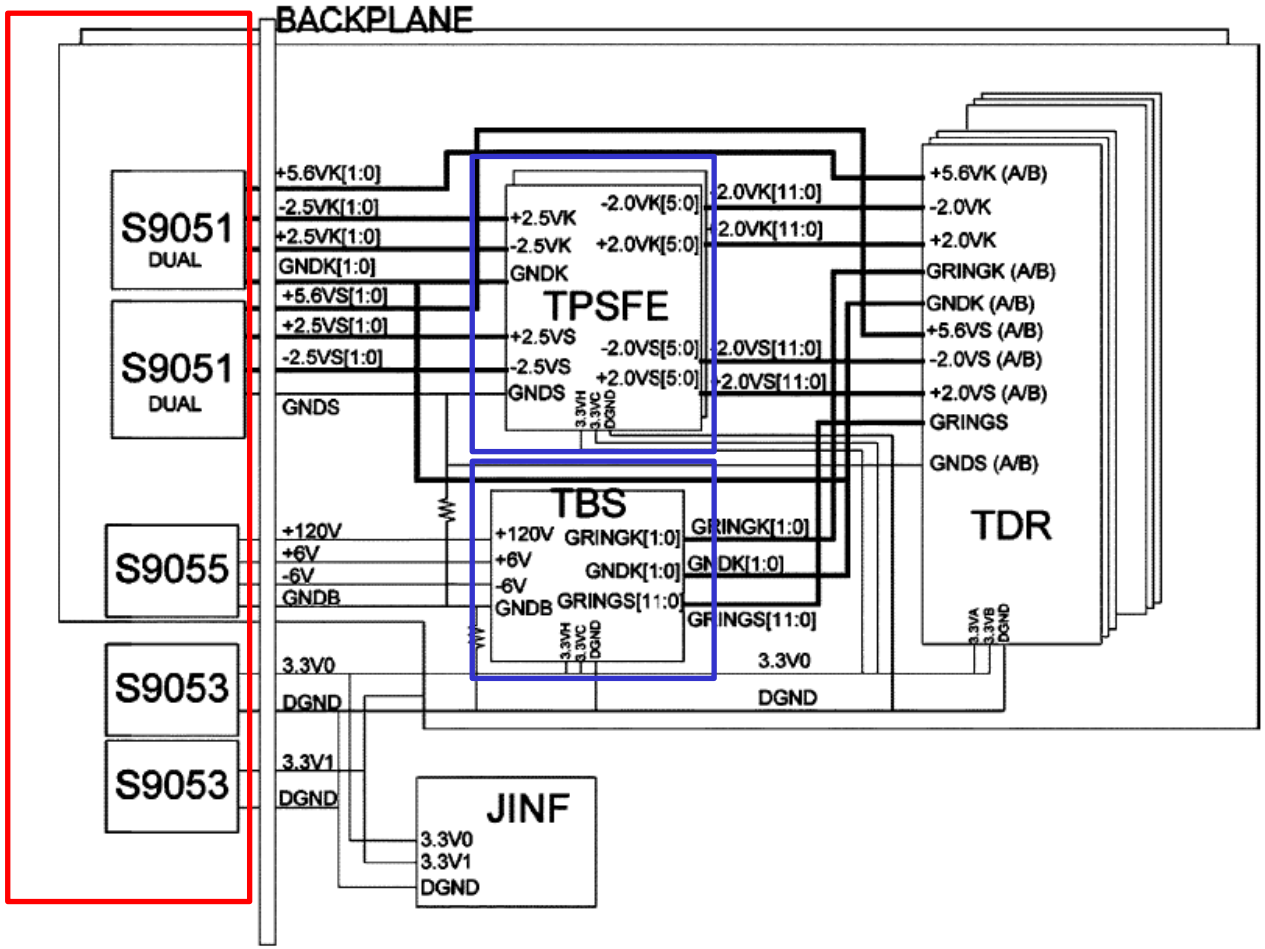
The interface board (S9011AT)



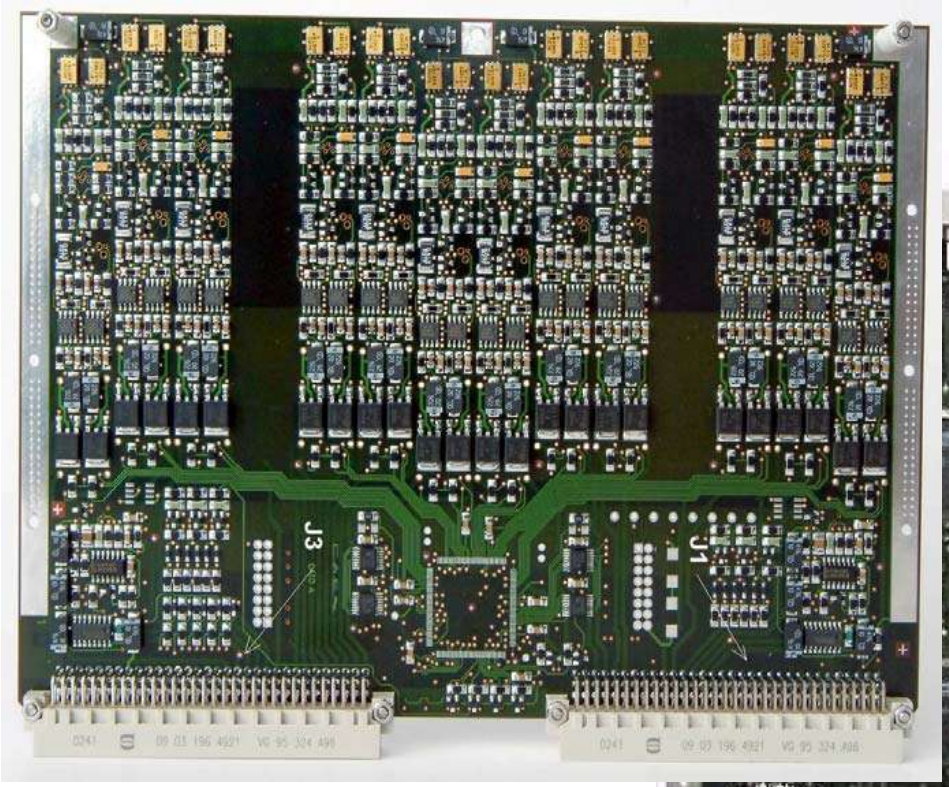
The DC-DC converter

The AMS-02 power supply system (2)

✓ Block diagram of a tracker electronics sub-unit.

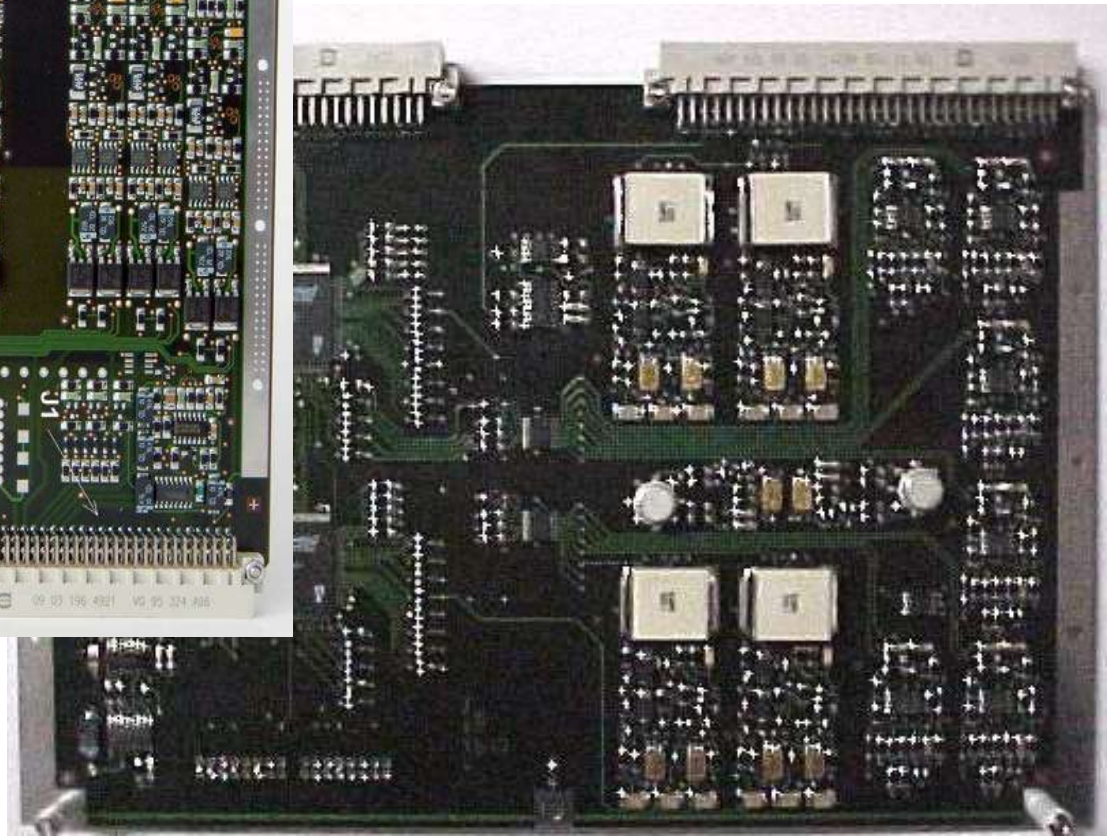


The AMS-02 crate



The Tracker Power Supply Front-End (TPSFE)

The linear regulator for the bias (TBS)

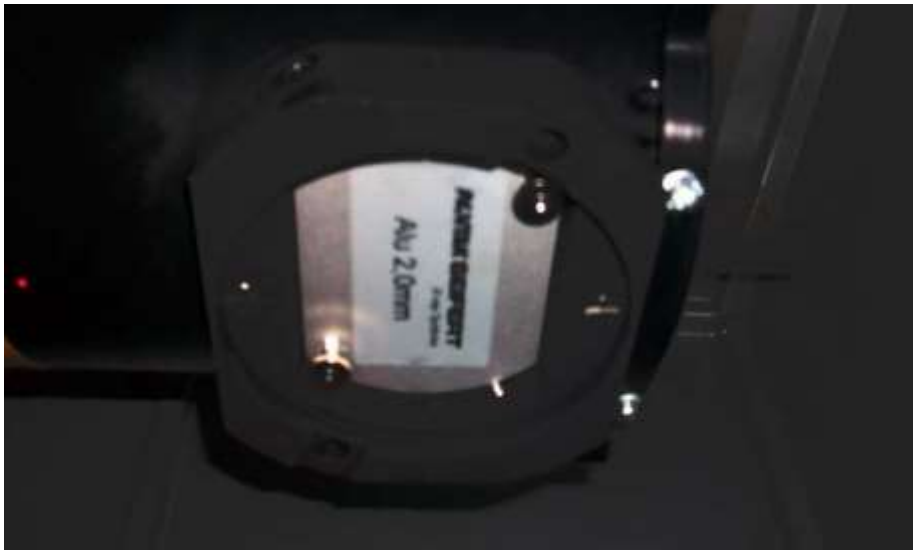


The AMS-02 power supply system test

- ✓ The qualification tests:
  - the radiation tests.
  - the thermo-vacuum test;
  - the thermo-mechanical test;
  - the EMI/EMC test.

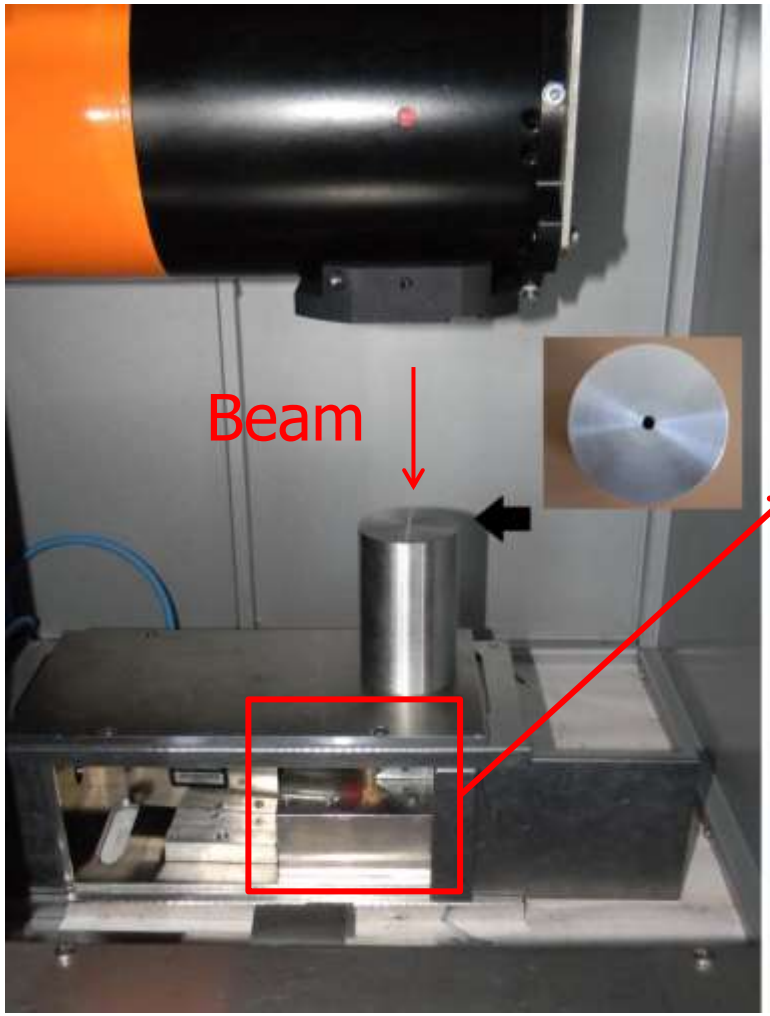
INFN PG Setup test X-ray tube

- ✓ 900 W (200 kV max) tube designed for radiation damage studies.



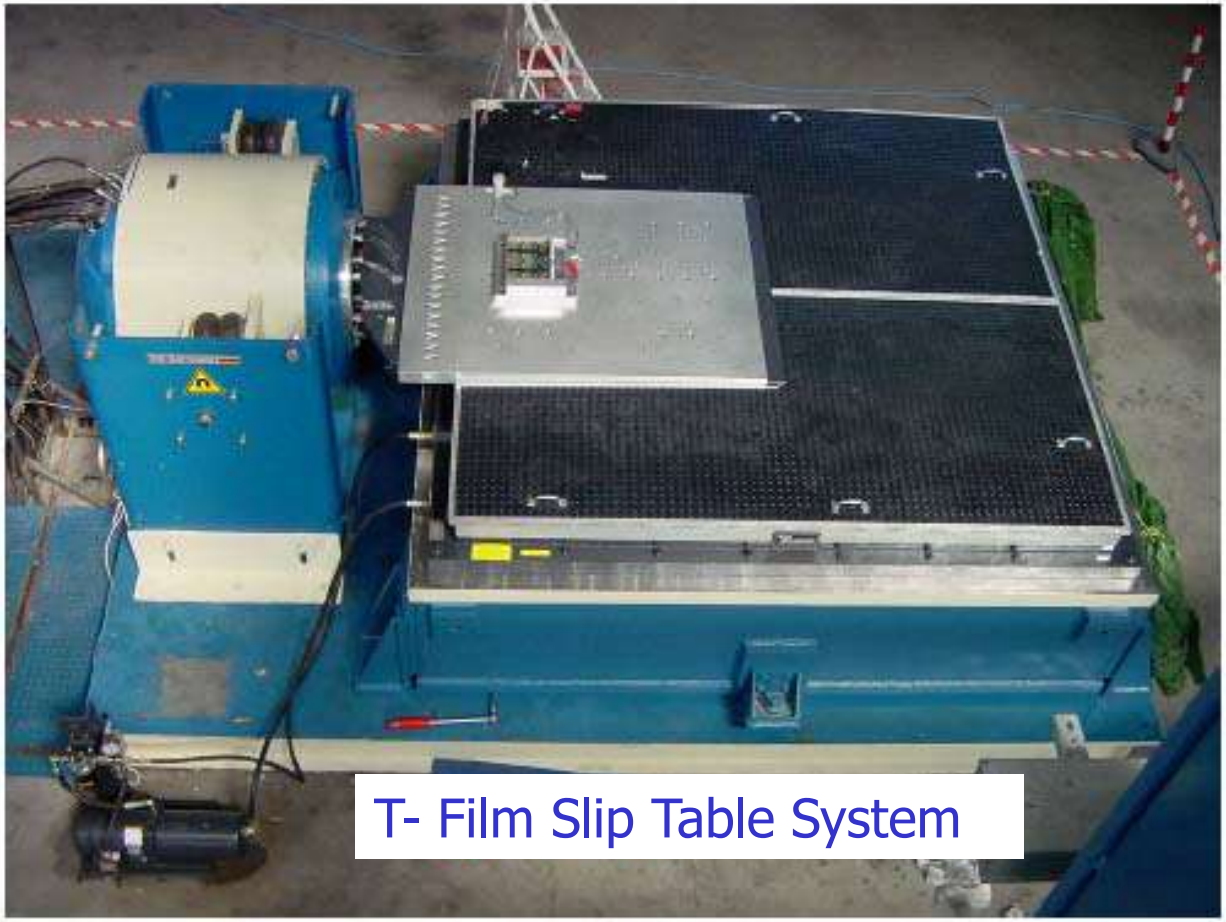
INFN PG Setup test X-ray tube (2)

- ✓ Target and collimator customization.



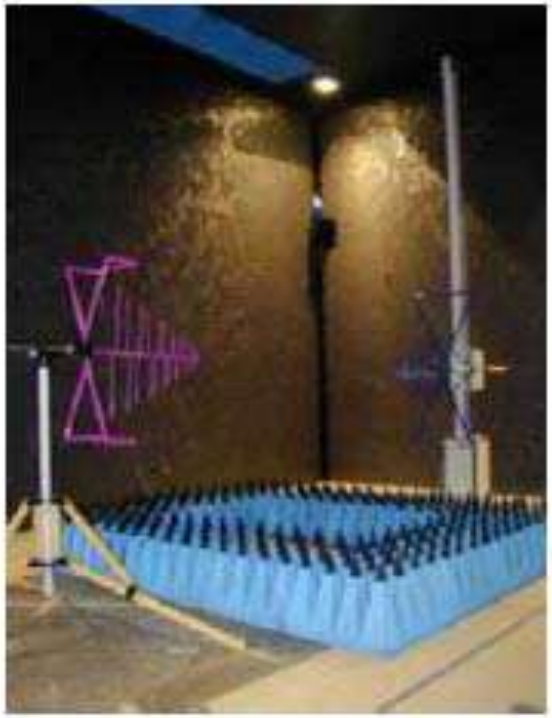
The AMS-02 power supply system test (2)

✓ The Thermo-Mechanical Test



The AMS-02 power supply system test (3)

- ✓ Electromagnetic Compatibility (EMC) / Electromagnetic Interference (EMI) testing have been performed to ensure that product will perform properly when subjected to the electromagnetic environment in which it is expected to operate.



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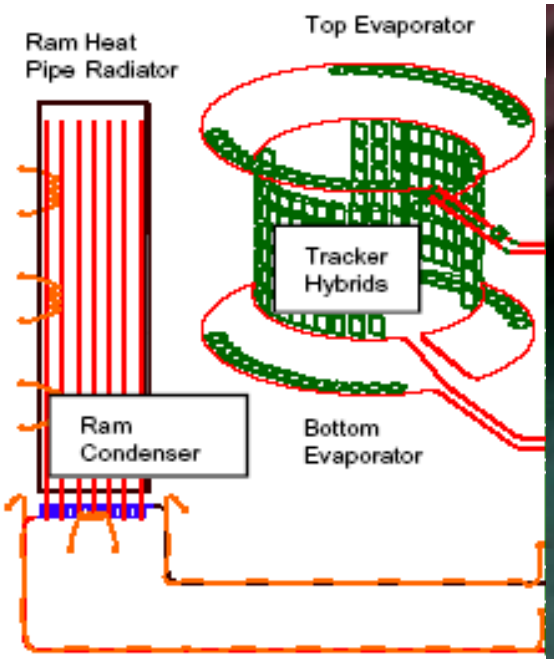
- ✓ The AMS-02 (Alpha Magnetic Spectrometer) experiment:
  - the tracker power supply & thermal control system.
- ✓ The R&D (INFN CSN5) experiments:
  - RAPS, RAPSODIA, VIPIX, RAPID,…
- ✓ Conclusions.

The AMS-02 Tracker Thermal Control System

- ✓ The AMS-02 Tracker Thermal Control System (TTCS) is a carbon dioxide two-phase cooling system developed by NIKHEF (The Netherlands), Geneva University (Suisse), INFN Perugia (Italy), Sun Yat Sen University Guangzhou (China) and NLR (The Netherlands).
- ✓ Its objective is to provide accurate temperature control of AMS Tracker front-end.
- ✓ The tracker cooling system may be viewed as a set of different sensors and actuators which are necessary for bringing the tracker detector to a uniform temperature at which it can operate properly.

The AMS-02 TTCE System

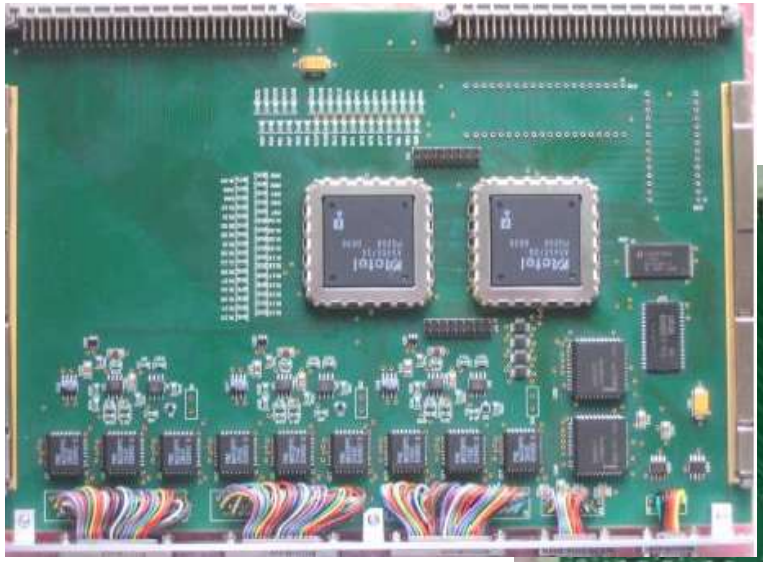
- ✓ The Tracker Thermal Control Electronics (TTCE)



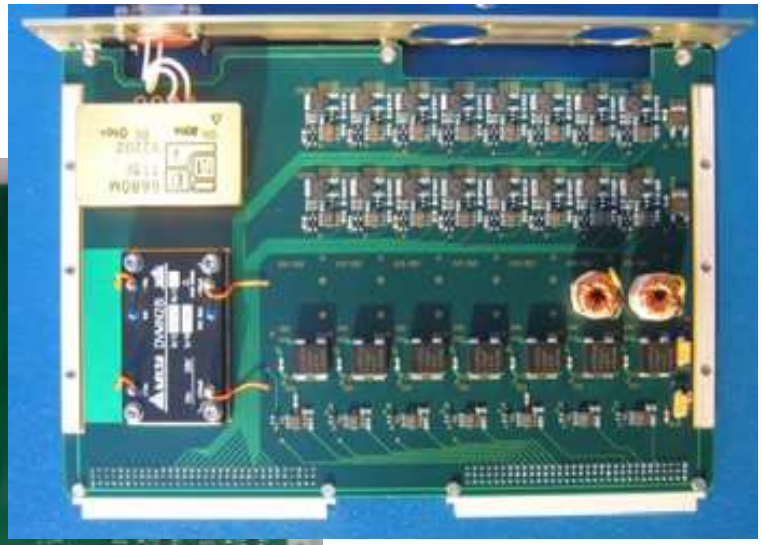
The Tracker Thermal Control Electronics crate.

The AMS-02 TTCE System (2)

The Tracker Thermal Control Electronics (TTEC) board contains the interface electronics for the slow control system of the experiment, the thermal sensor, the basic logical functions.



The Tracking Thermal Power Electronics (TTEP) board contains circuits for generating local supplies and the power conversion, and switch circuits for the heaters and peltier heat pump.



The TTPP board controls the pressure sensors and the pump interface.

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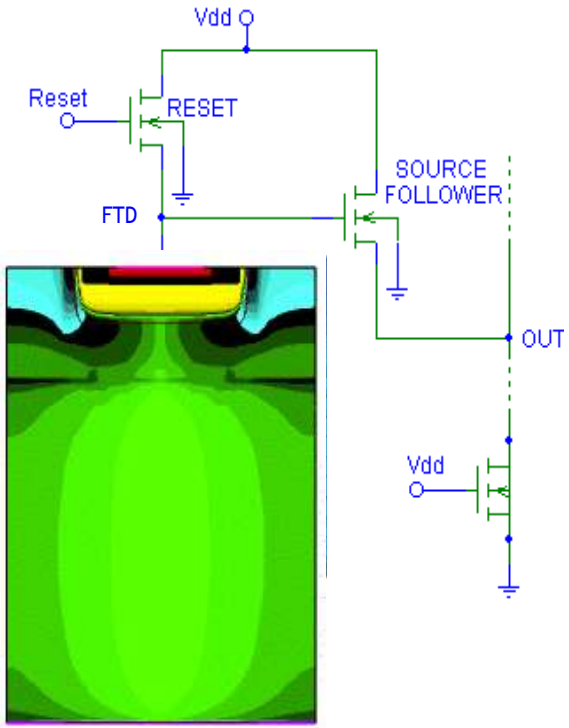
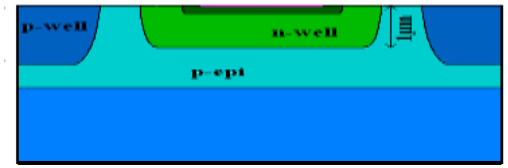
- ✓ Conclusions.

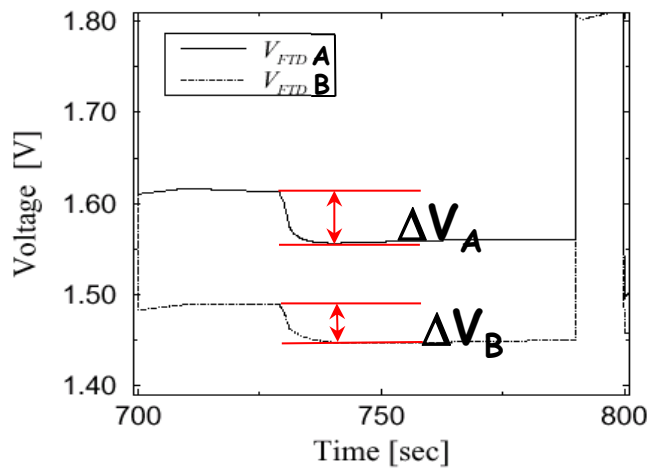
CMOS Radiation Active Pixel Sensors (RAPS)

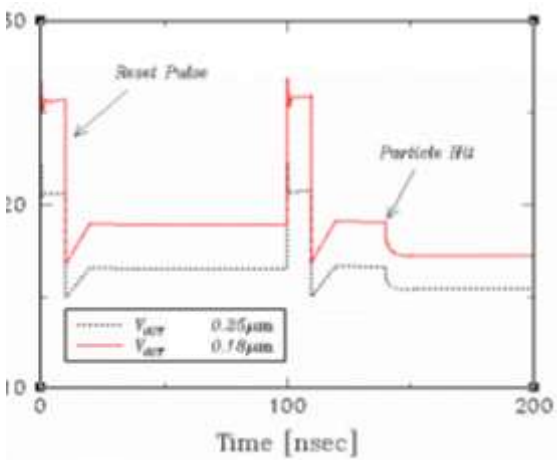
- ✓ CMOS Active Pixel Sensor detector for single ionizing particle detection.

Simple 3T pixel architecture







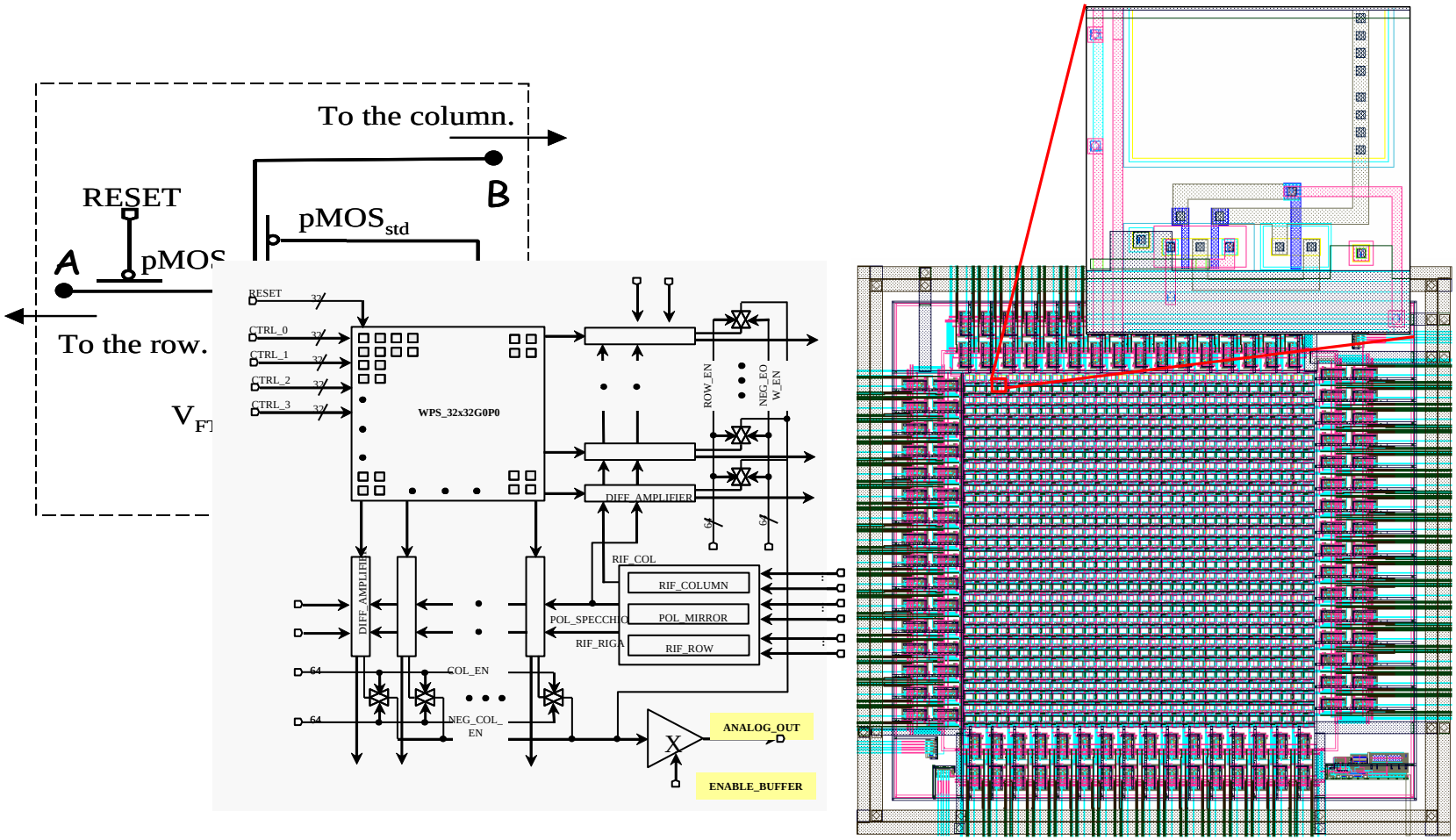


Year 2001/2002

- ✓ Technology nodes (0.25 / 0.18μm) & options evaluation (epi vs. no-epi).
- ✓ Pixel sensitive area and layout optimization.

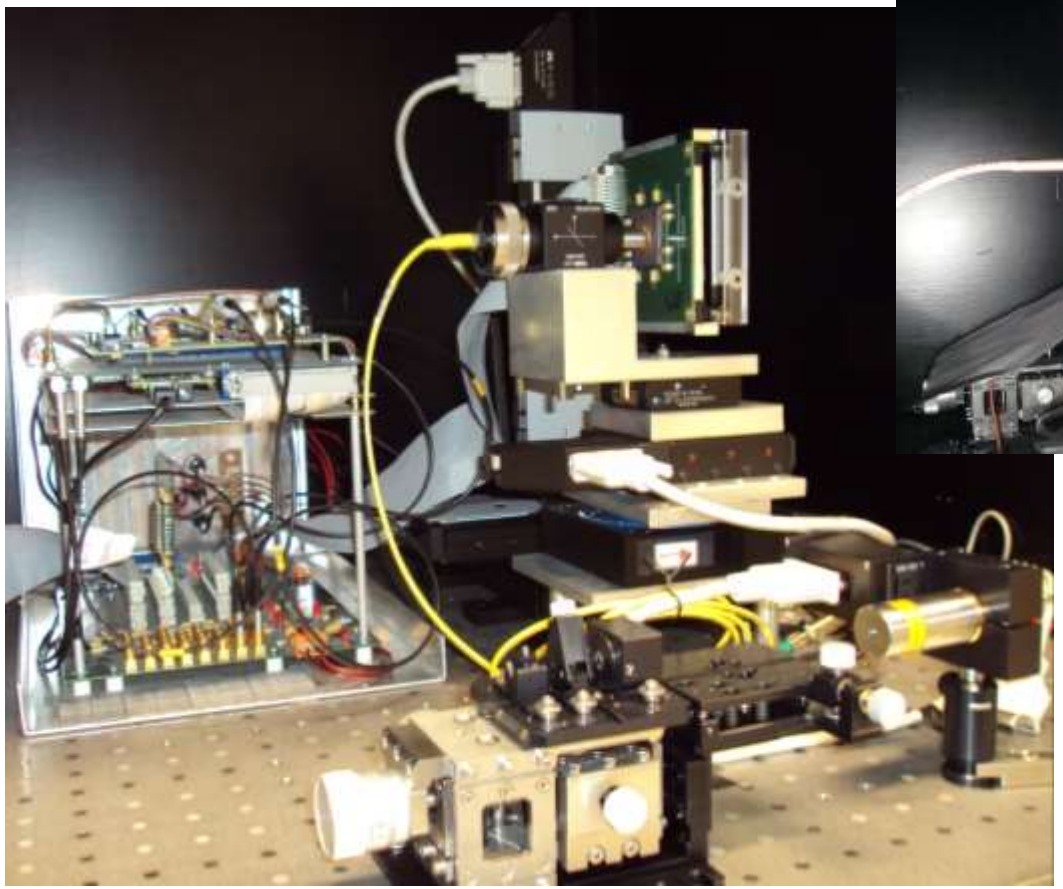
Weak Inversion Pixel Sensor (WIPS)

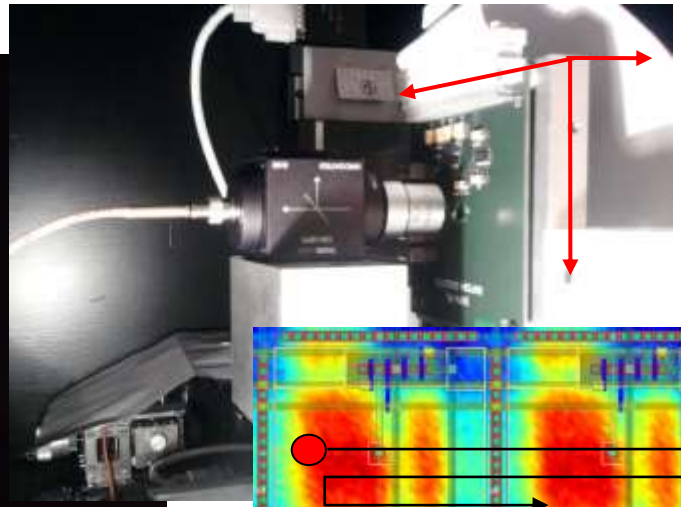
- ✓ Precharge-Evaluation scheme, speeding-up of the read out phase.

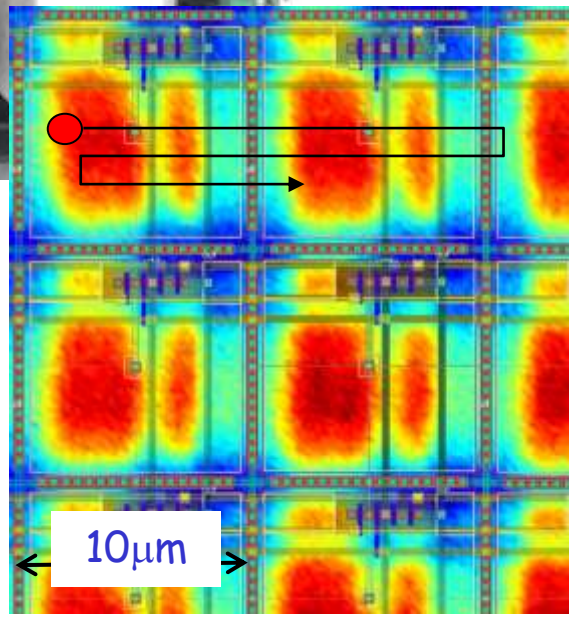


INFN PG Laser Test Bench

- ✓ Optical Workbench: IR, UV, VIS laser with μ-focusing and μ-positioning capabilities (spot size 1-2μm).

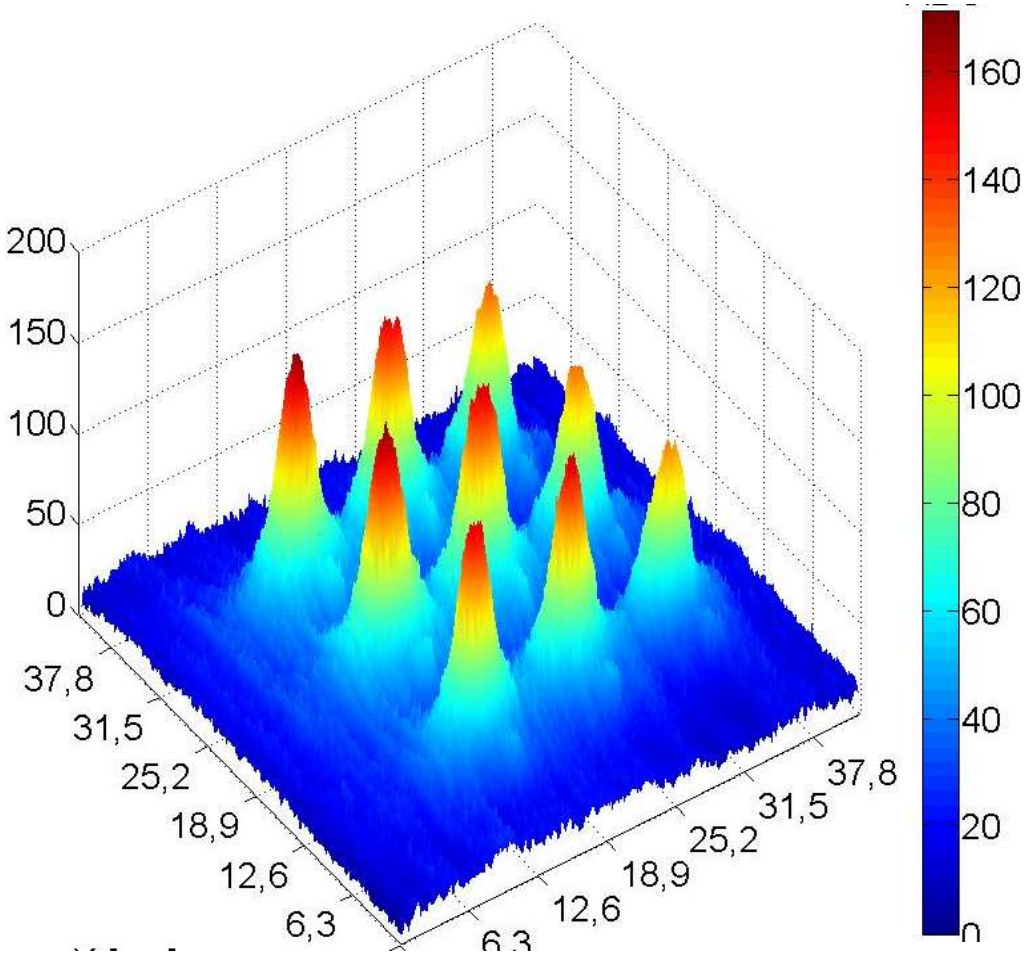


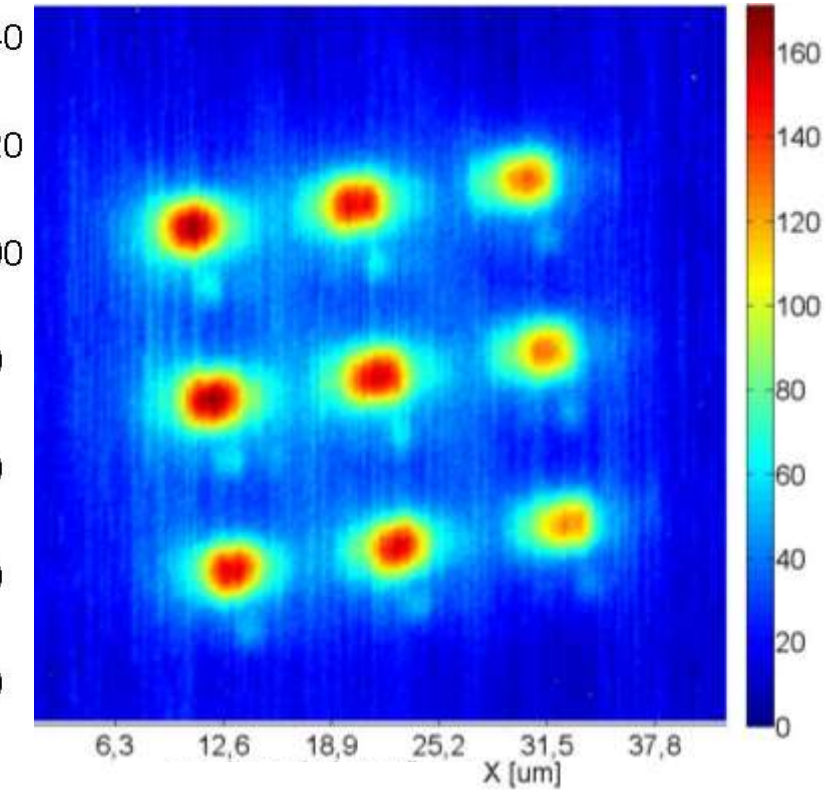




INFN PG Laser Test Bench (2)

- ✓ Surface mapping of small (<10μm) CMOS Active Pixel Sensors

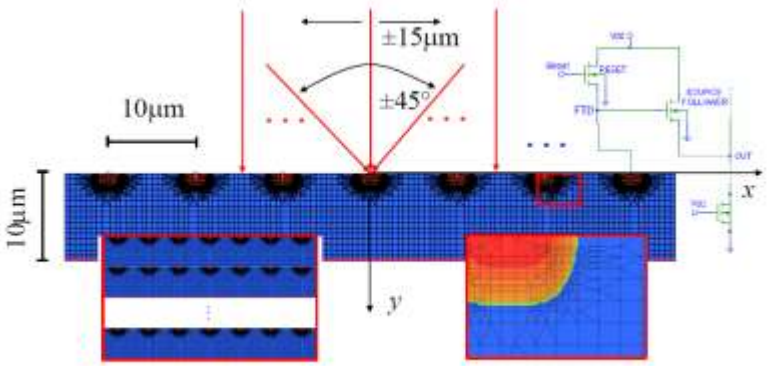


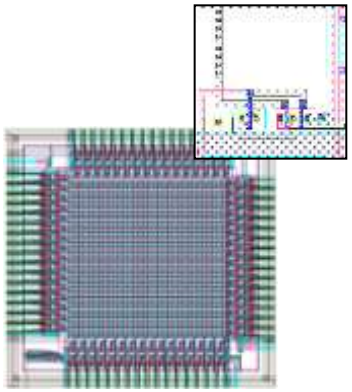


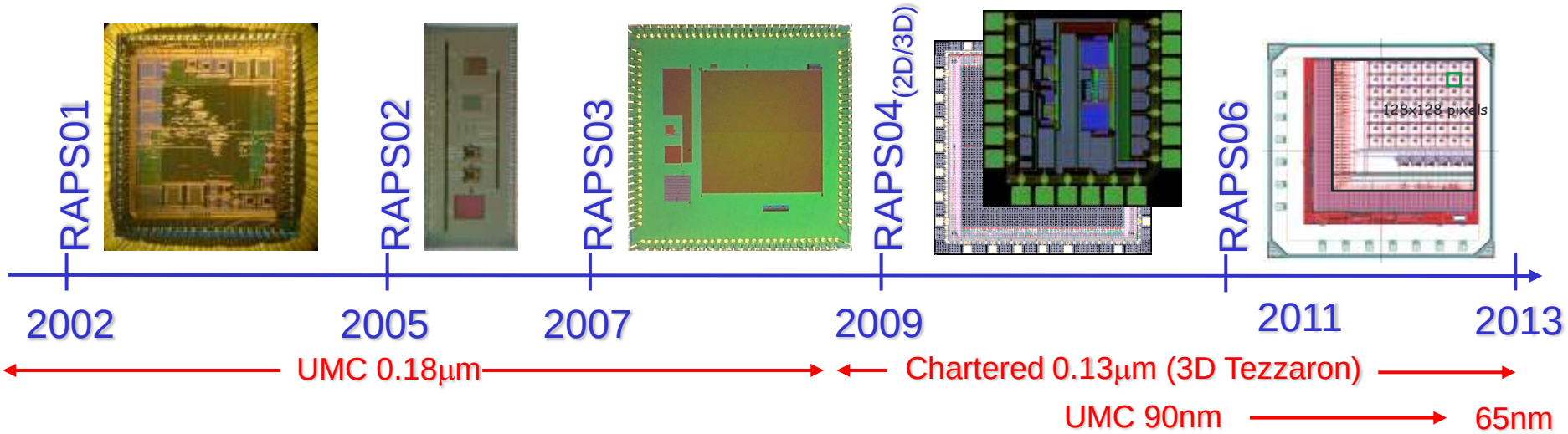
CMOS VLSI design PG activities

Numerical Analysis and Physical Modeling of solid-state devices.

VLSI Design and Characterization of integrated CMOS Active Pixel Sensors.







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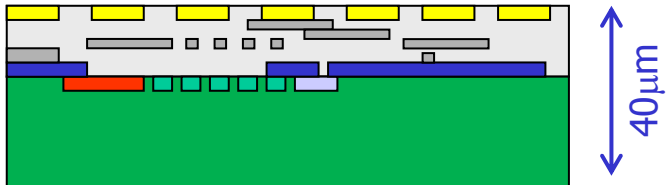
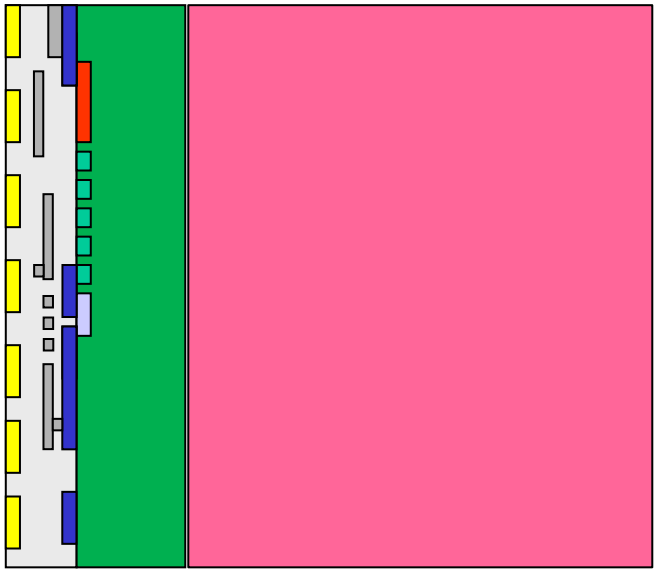
The RAPS on Diamond

- ✓ Proof of Principle: electrical and functional test of a real CMOS chip after thinning (down to 40 μm) and bonding to diamond.
- ✓ A CMOS Radiation Active Pixel Sensors (RAPS03) fabricated in CMOS 0.18μm technology has been thinned and bonded to a Diamond sample.

RAPS03



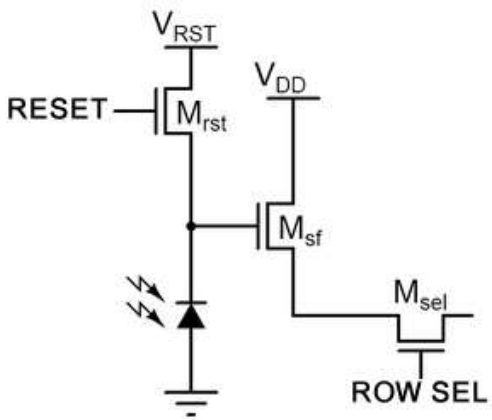


Collaboration with INFN Firenze

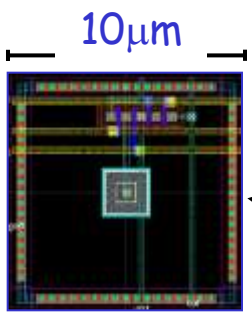
DIAMOND

The RAPS03 on Diamond

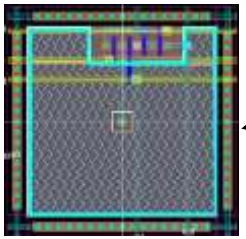
- ✓ CMOS Active Pixel Sensors commercially available technologies (MPW).
- ✓ No epitaxial substrate – charge collection from the bulk.
- ✓ Small pixels (simple 3T architectures) with different layout options.
- ✓ High-granularity, spacing…



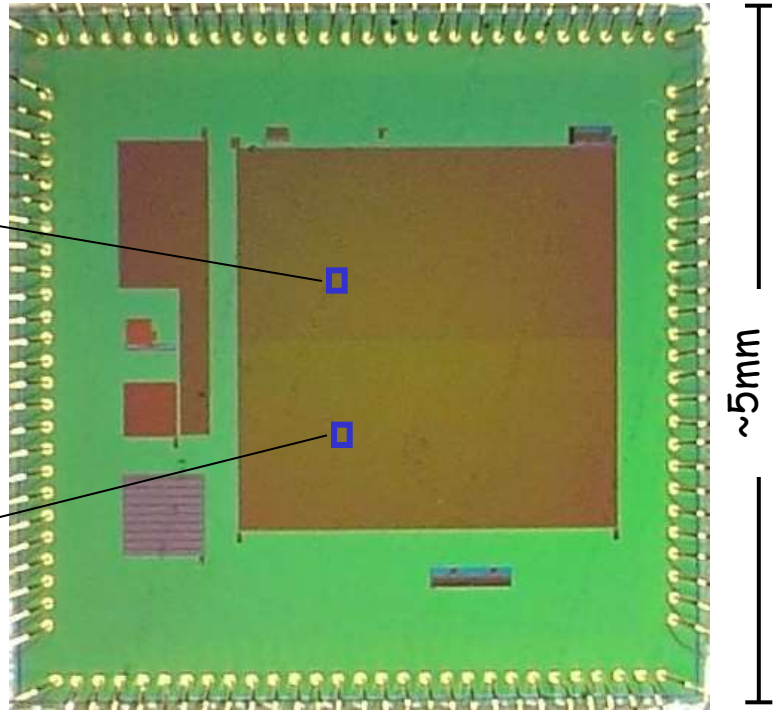
- ✓ Frame rate up to 300FPS (256×256pixels)
- ✓ Fast operation (digital core f_{max}= 120MHz)



Small n-well, Low C

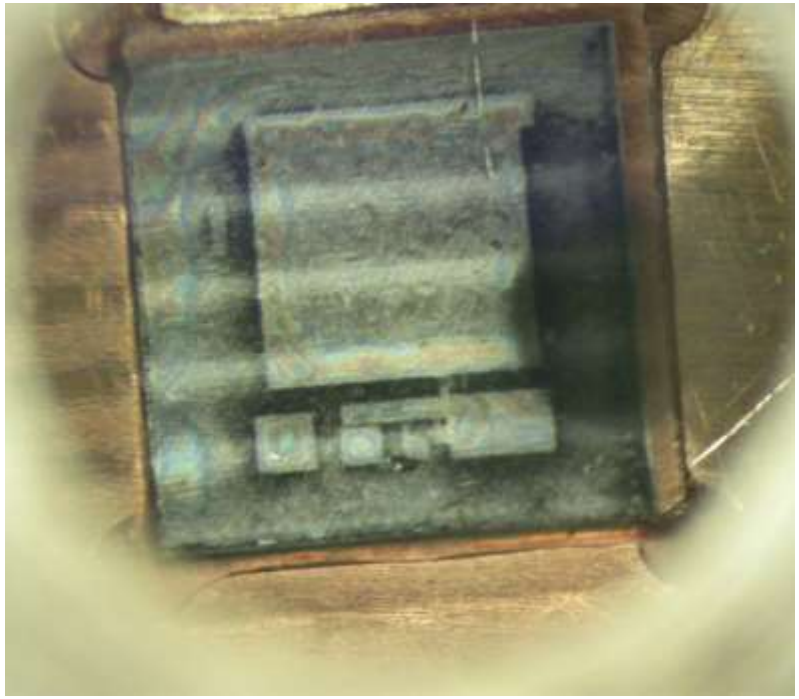


Large n-well, High FF

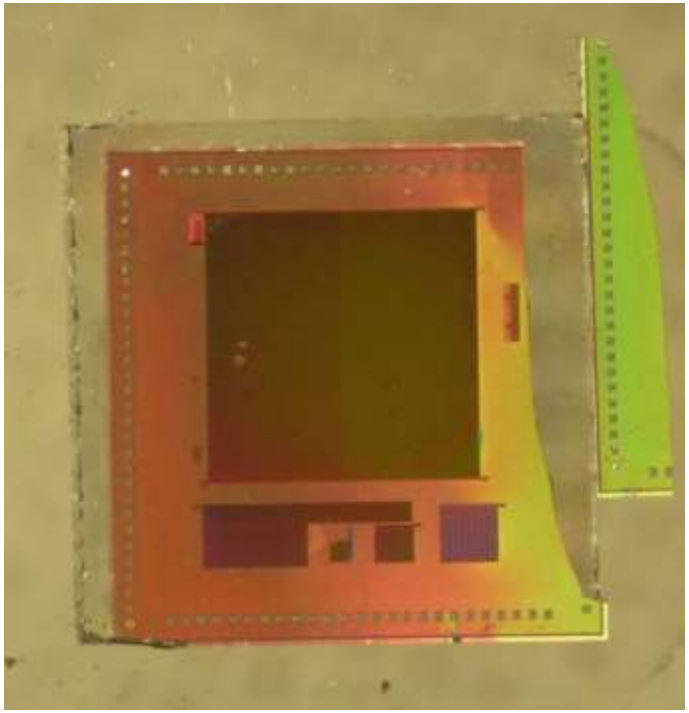


The RAPS03 on Diamond (2)

- ✓ The new concept of Silicon-on-Diamond (SoD) bonding has been adopted to couple the CMOS RAPS03 chip with a diamond substrate.



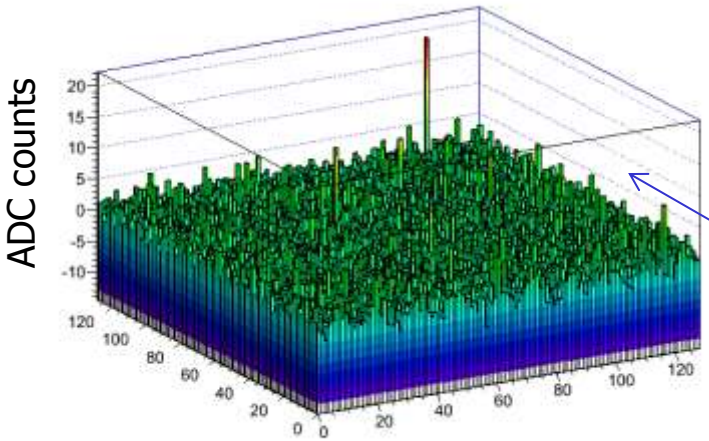
Bottom view (through the diamond and the quarz windows) after the bonding.



Top view (silicon side) after the bonding (broken sample).

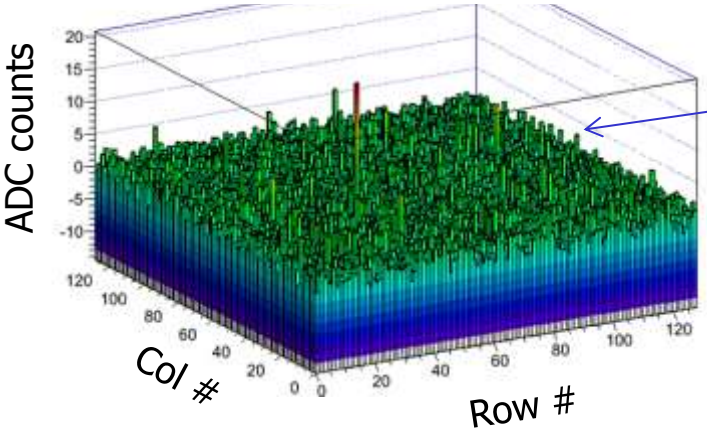
The RAPS03 vs. RAPS03 on Diamond

- ✓ Dark signal distribution and spatial distribution.



RAPS03

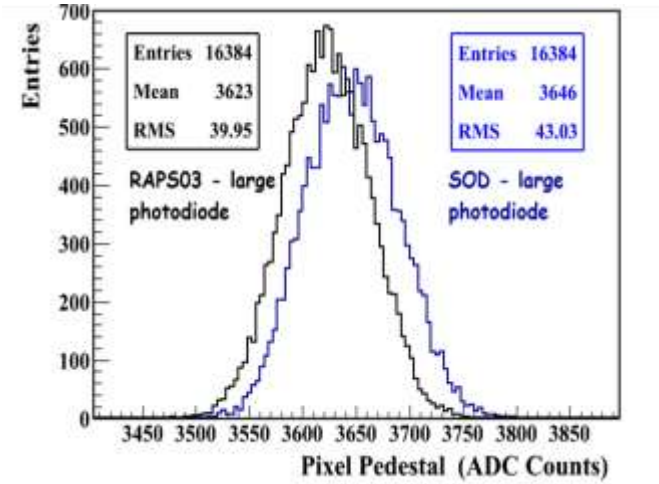
Typical signal fluctuations due to thermal noise

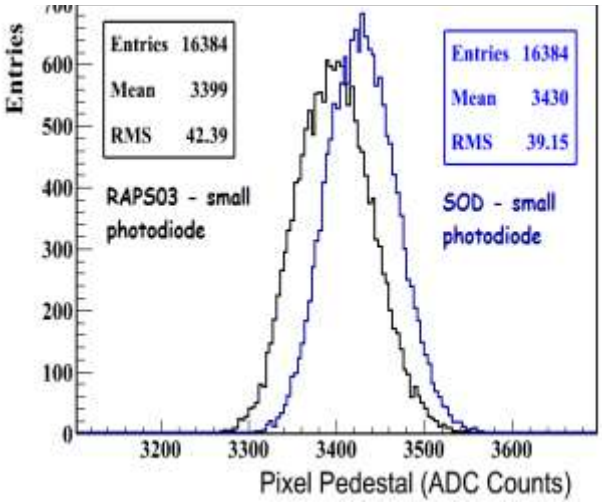


RAPS03

DIAMOND

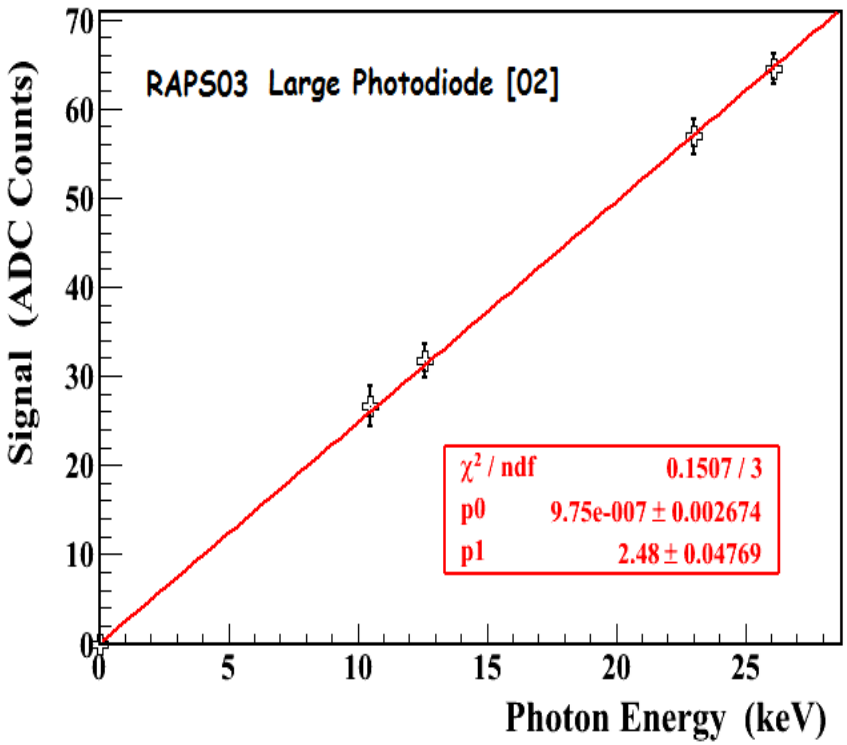
SoD

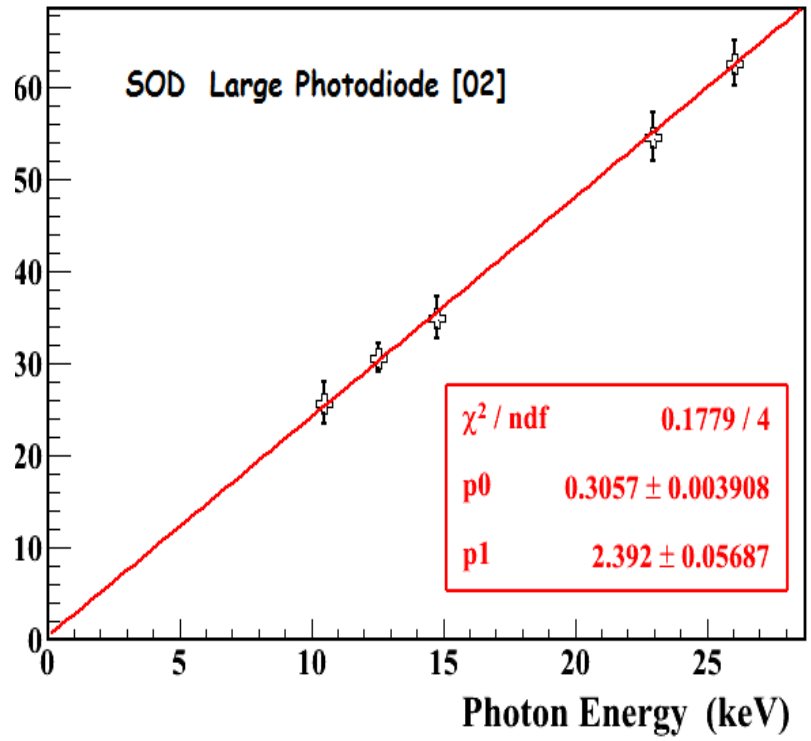




The RAPS03 on Diamond – X-ray calibration

- ✓ Signal calibration: exposure to a X-ray source (fluorescence mode)
- ✓ X-ray calibration: Cd (3.1 keV), Fe (6.4 keV), Pb (10.5 keV), Pb (12.6 keV), Cd (23.0 keV), Cd (26.0 keV)…





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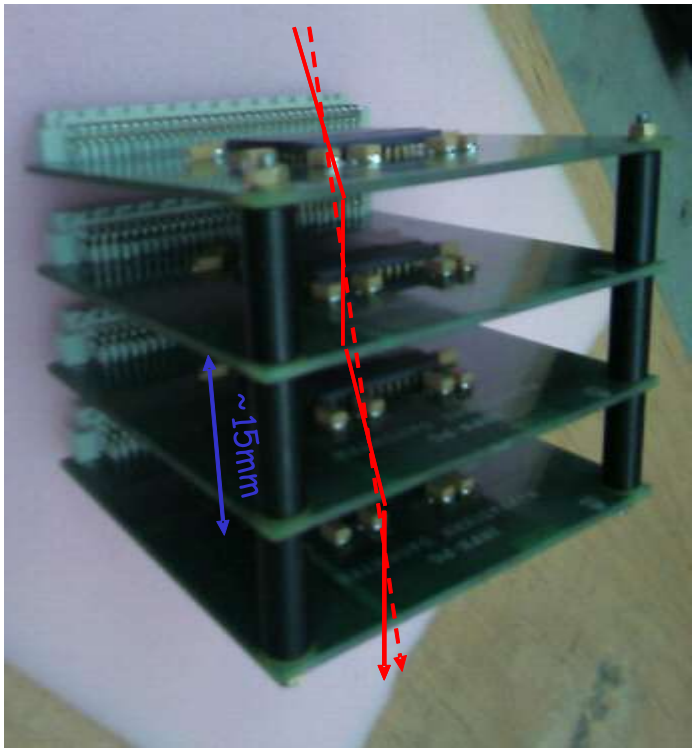
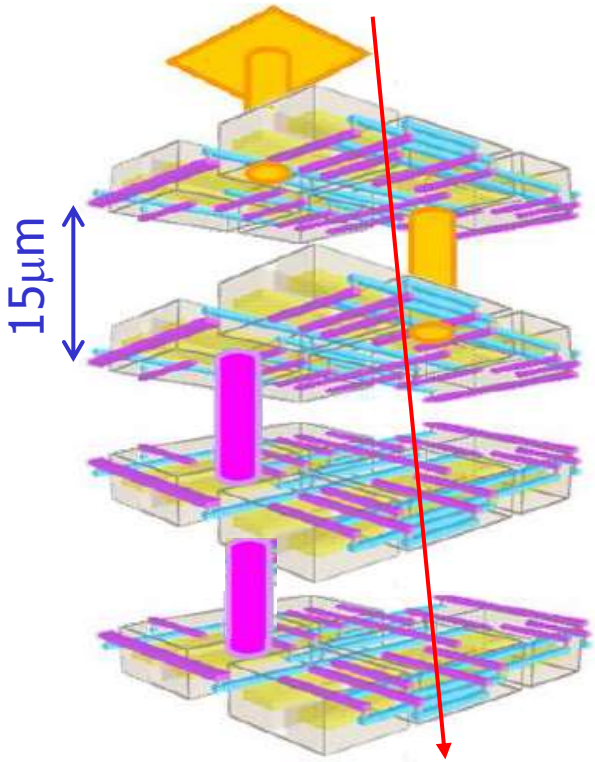
3D stacked CMOS Active Pixel Sensor

- ✓ 3D monolithically-stacked CMOS Active Pixel Sensor detector for single ionizing particle trajectory and momentum identification.



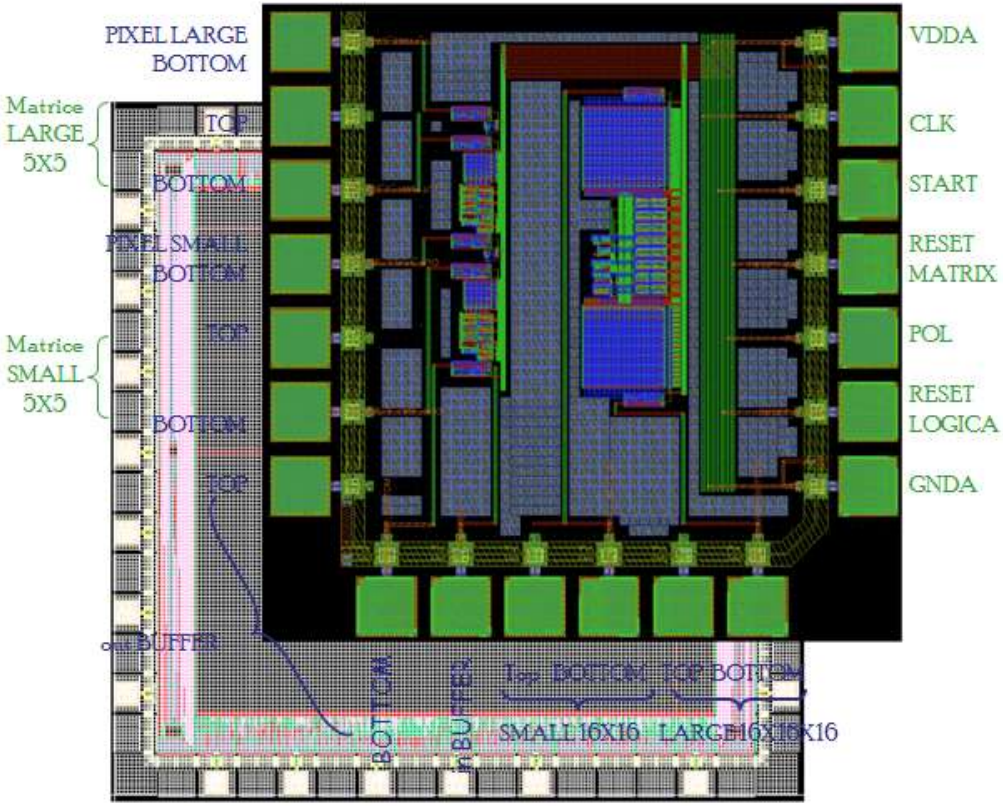
Stack of separate multi-layer CMOS Active Pixel detectors - Worries: multiple scattering and material budget…

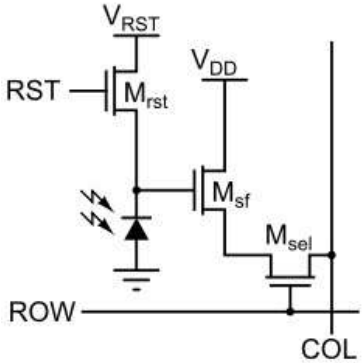


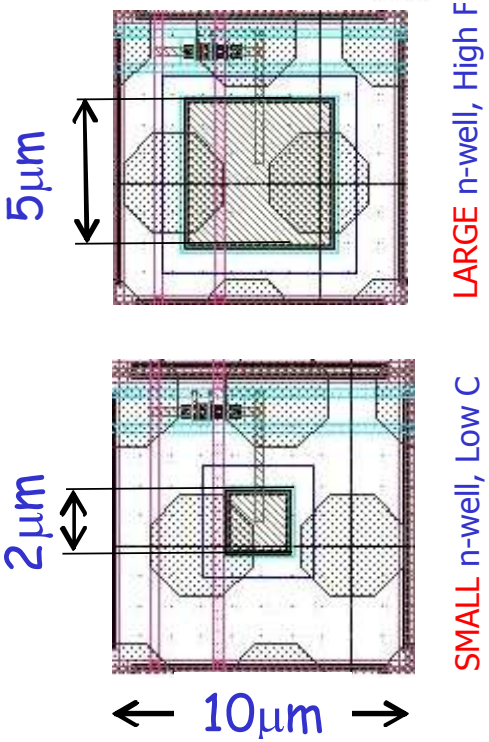
Stack of monolithically integrated (vertical scale or 3D) detectors.

The RAPS04-3D structures

- ✓ Active Pixel Sensor 3T architecture with different photodiode area.

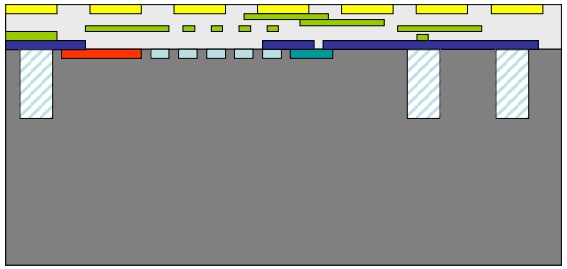


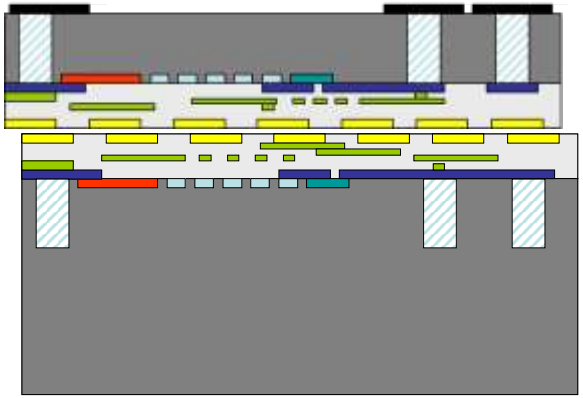


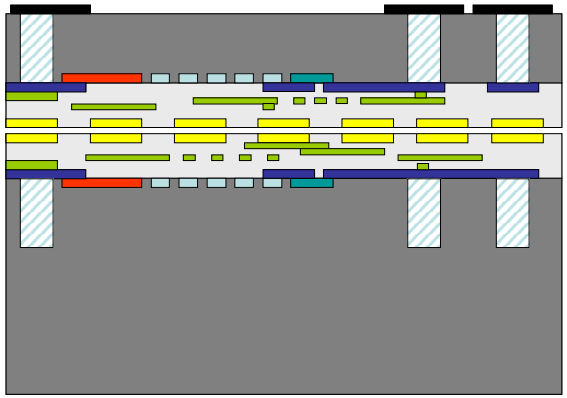


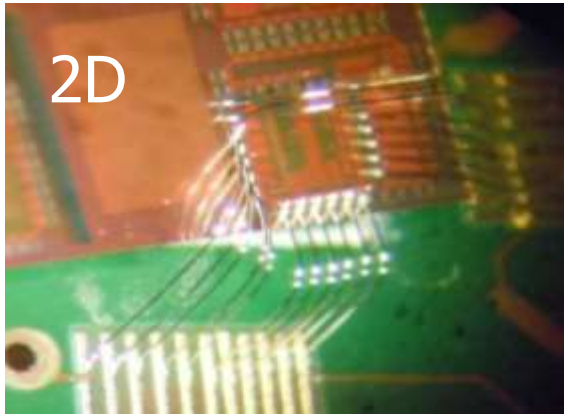
The RAPS04 chip structures

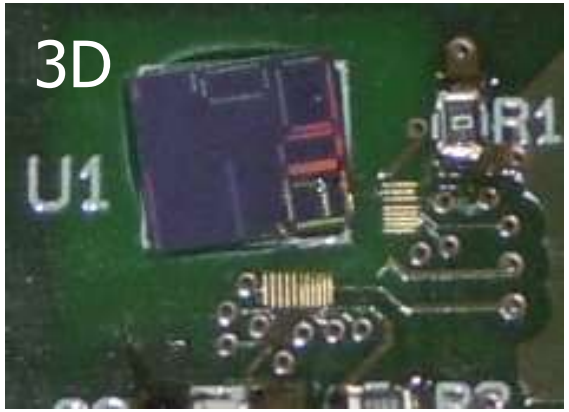
(Chartered) - GlobalFoundries/Tezzaron
3D-IC Integrated 2-tier stack
130nm CMOS

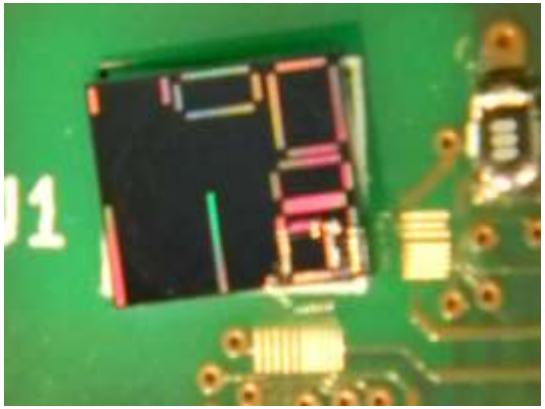












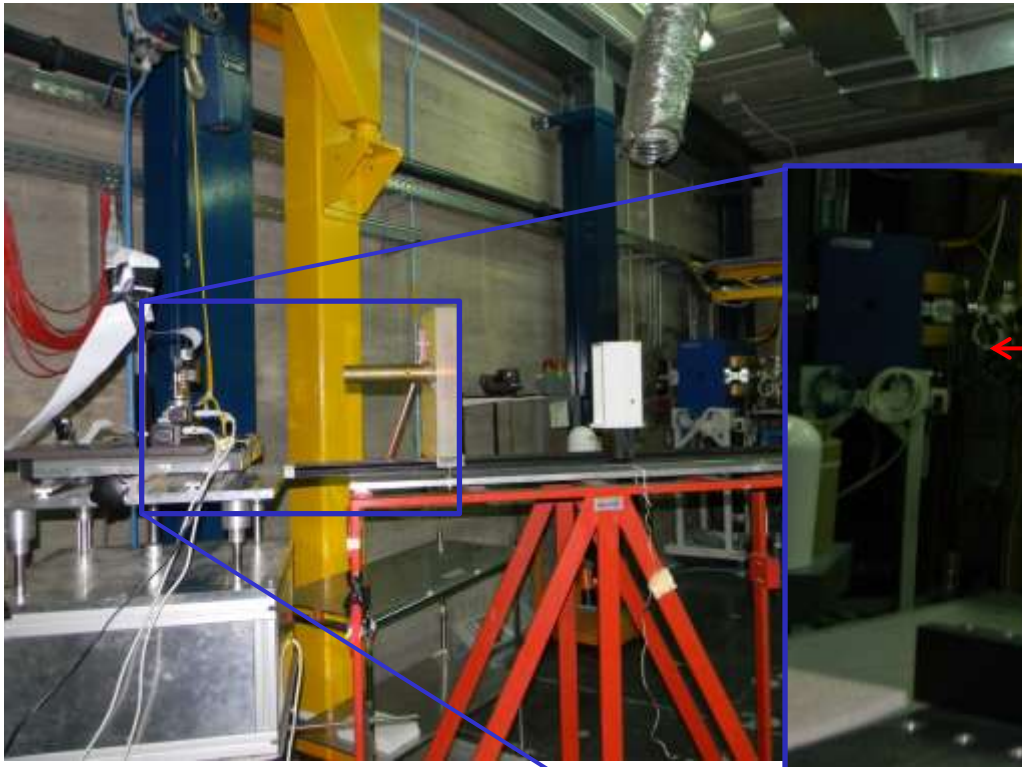
2D.

3D Not Aligned.

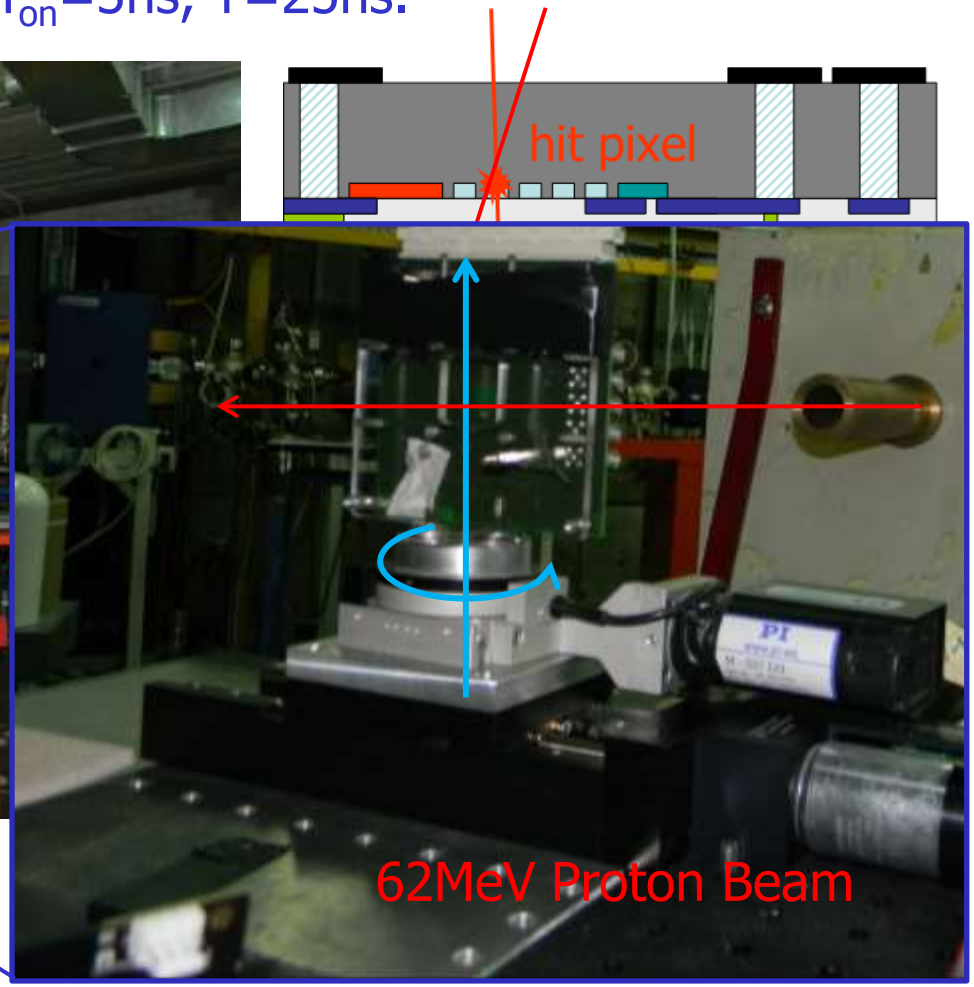
3D Aligned (Ziptronix/Tezzaron).

RAPS04-3D test at LNF (Catania, Italy)

- ✓ 62MeV protons, pulsed beam T_{on}=3ns, T=25ns.

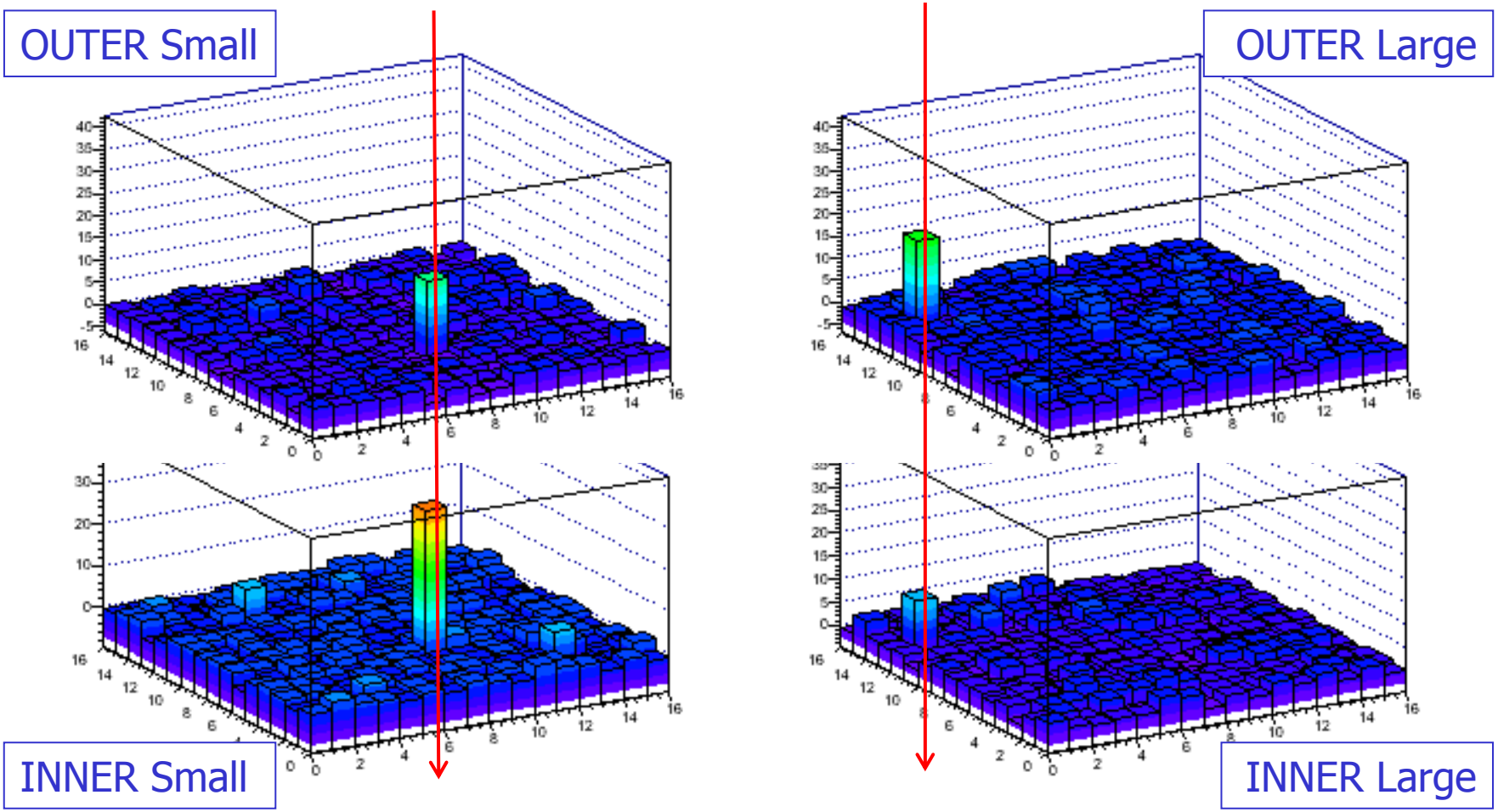


INFN Laboratori Nazionali del Sud beam test facilities, Catania (ITALY).



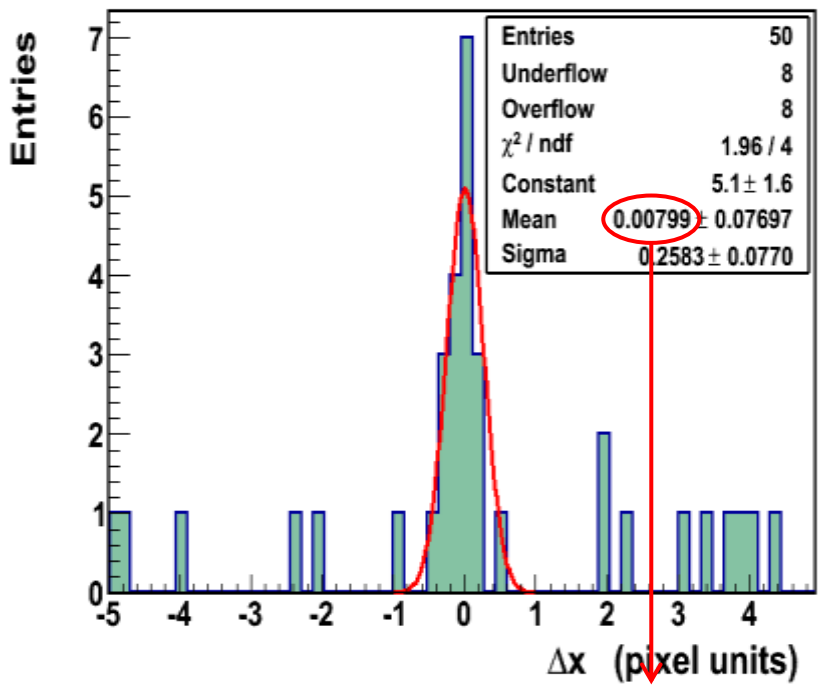
62 MeV protons response

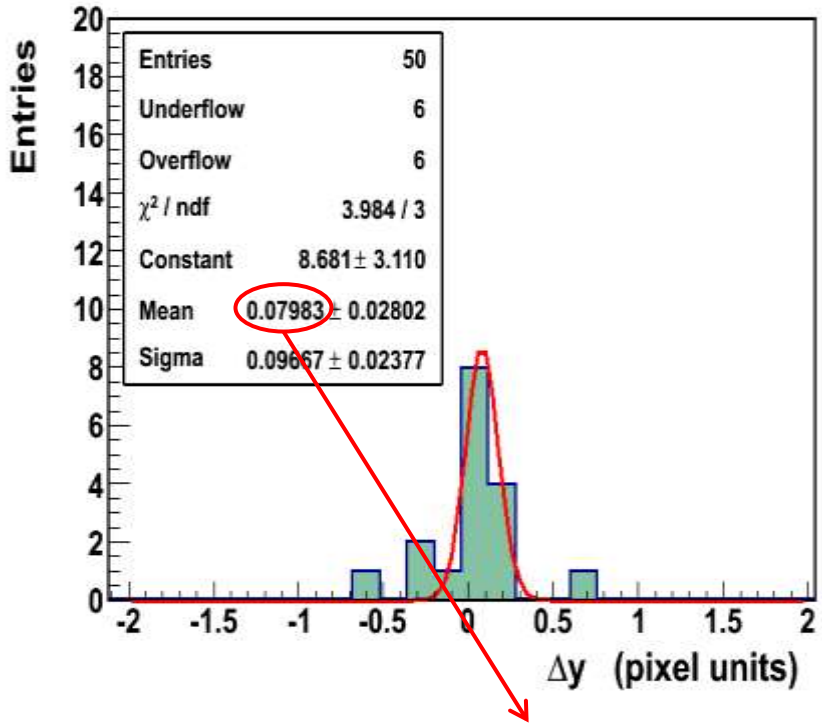
- ✓ RAPS04-3D 62MeV protons – Outer & Inner tier coincidence responses



62 MeV protons response

- ✓ RAPS03 3D Aligned (Tezzaron) 62MeV protons responses (tilt = 0°)
- ✓ Aligned Tier -> NO displacement!



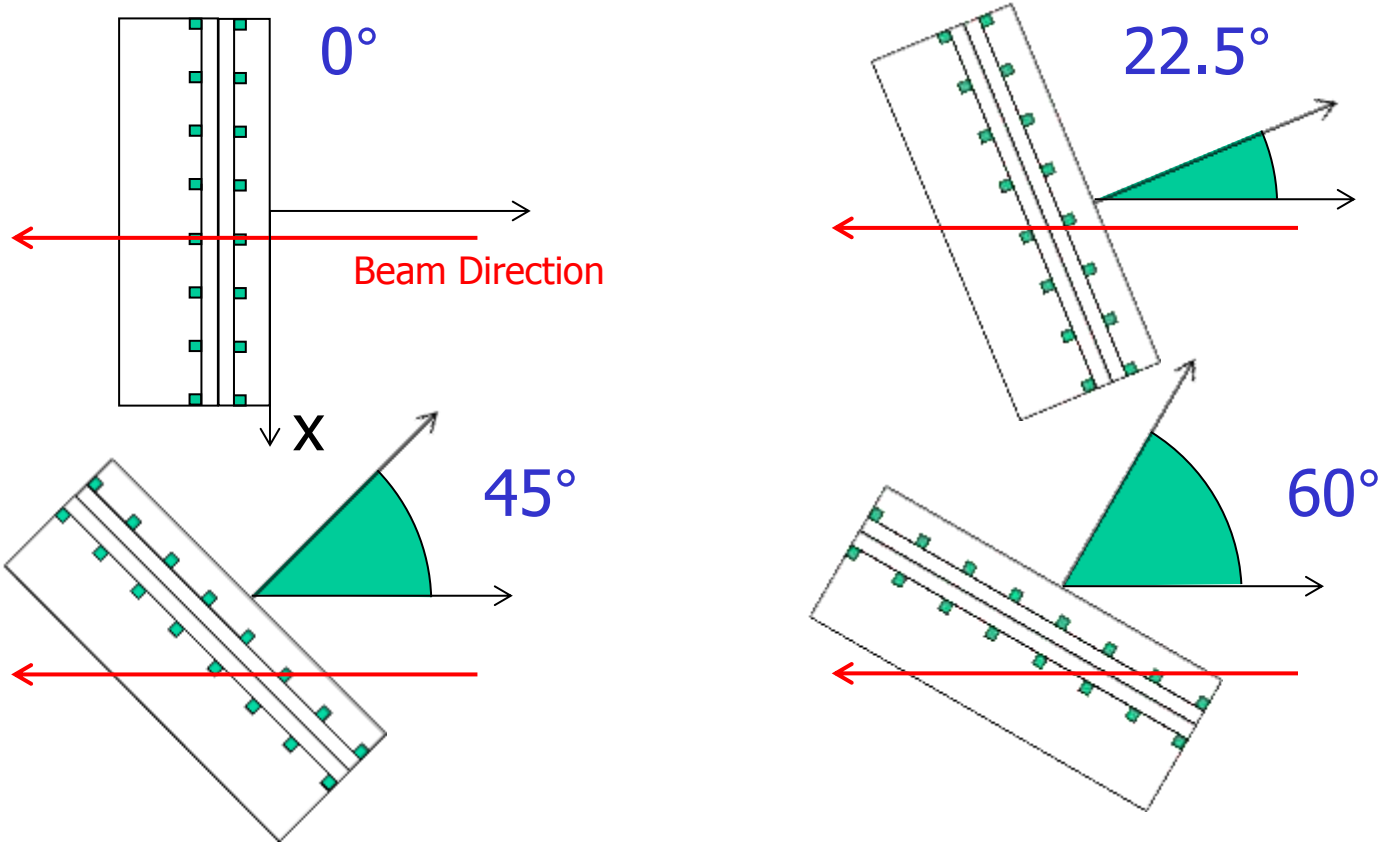


~0.08μm row displacement (~0.008 pixel units) with standard deviation ~2.5μm.

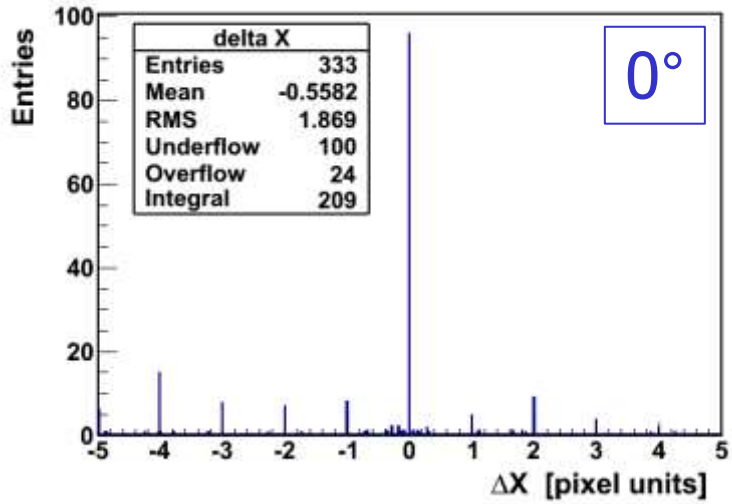
~0.8μm col displacement (~0.08 pixel units) with standard deviation ~0.9μm .

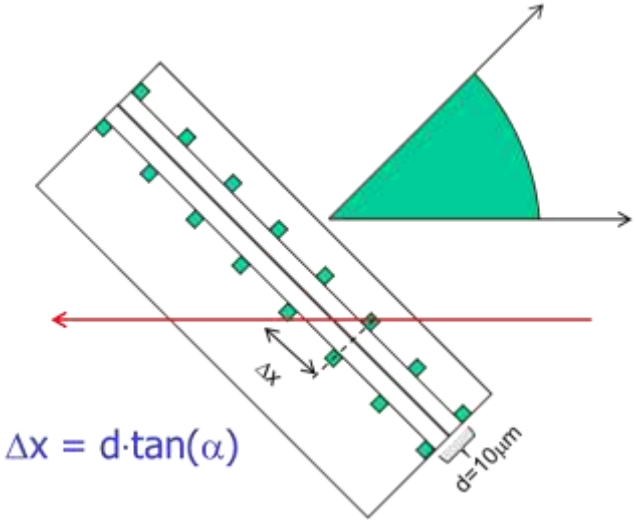
Angular measurements

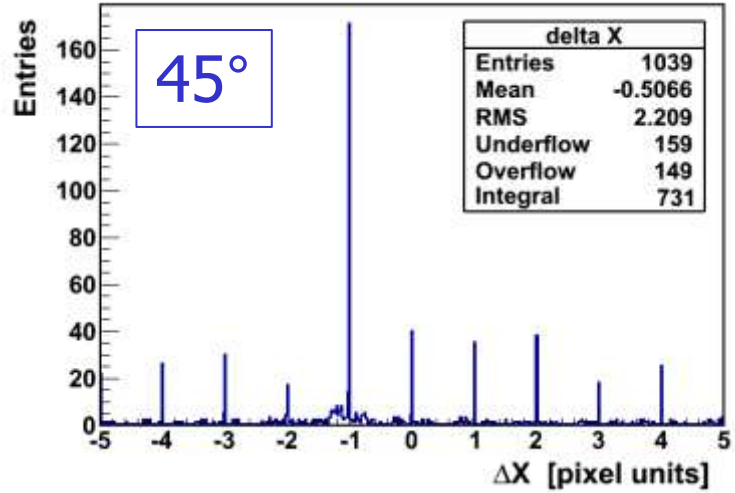
- ✓ RAPS03 3D Aligned (Tezzaron) 62MeV protons responses
  Small Photodiode pixels - Angular Measurements



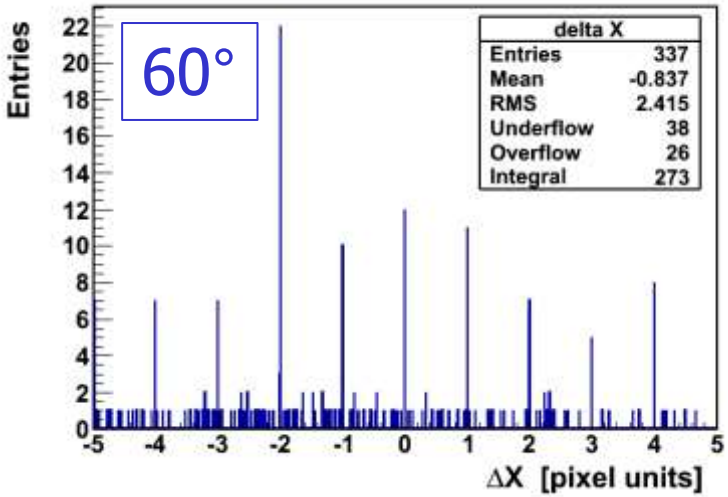
Angular measurements: x-axis displacement







$\alpha = 45° \rightarrow \Delta x = d \cdot 1.00 = 10.0\mu m \rightarrow 1$ pixel unit



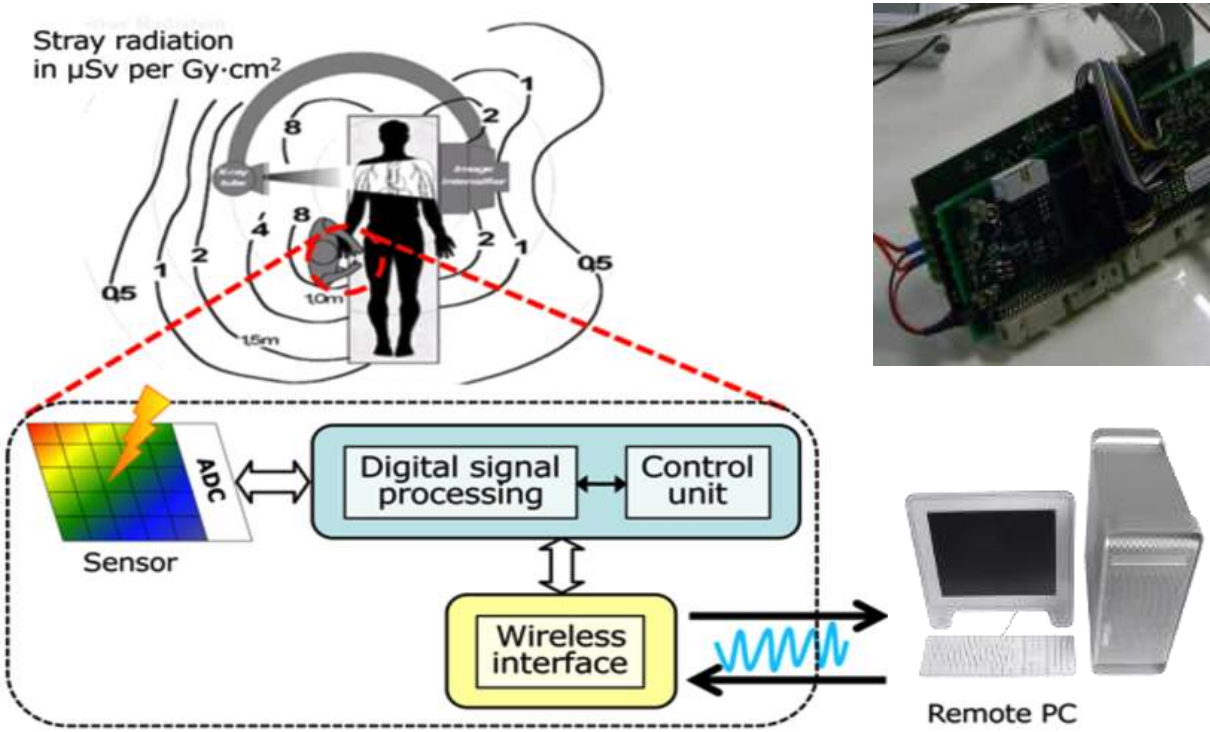
$\alpha = 60° \rightarrow \Delta x = d \cdot 1.73 = 17.3\mu m \rightarrow \sim 2$ pixel units

Outline

- ✓ Introduction: electronics background.
- ✓ The CMS (Compact Muon Solenoid) experiment:
  - the Silicon Strip Tracker: R&D, Opto-Hybrid and Construction;
  - the Phase-2 65nm Pixel Read-Out chip.
- ✓ The NA48 & NA62 experiments.
- ✓ The AMS-02 (Alpha Magnetic Spectrometer) experiment:
  - the tracker power supply & thermal control system.
- ✓ The R&D (INFN CSN5) experiments:
  - RAPS, RAPSODIA, VIPIX, RAPID,…
- ✓ Conclusions.

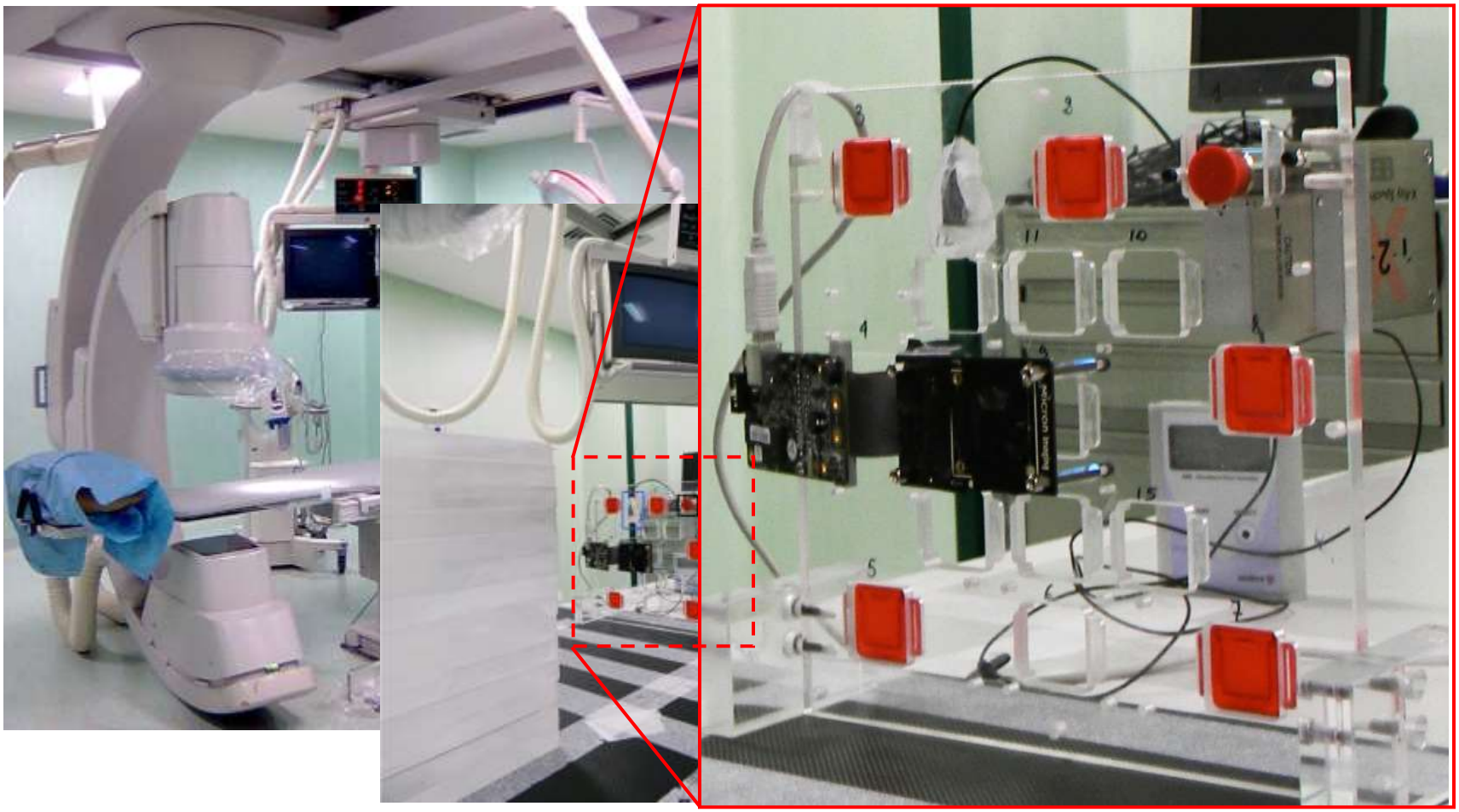
Real-time Active PIxel Dosimeter (RAPID)

- ✓ Exploiting commercial CMOS technologies for direct detection of X-rays for medical applications
- ✓ Real-Time Dosimeter System for Interventional Radiology



Real-time Active PIxel Dosimeter (2)

- ✓ Experimental setup in IR operating room



University / INFN PG industry relationships

- ✓ About ten years of collaborations.
- ✓ Very fruitful interactions.
- ✓ Educational program (academic course, Ph.D. funding)
- ✓ Extensive characterization of MICRON CMOS Imagers as ionizing and non-ionizing radiation sensors.
- ✓ Good performance in non-visible domain.
- ✓ Potential applications:
  - tracking systems (reference telescope);
  - triggering (particle identification);
  - direct X-ray spectrometer (and/or imagers for soft X-ray detection).

Conclusions

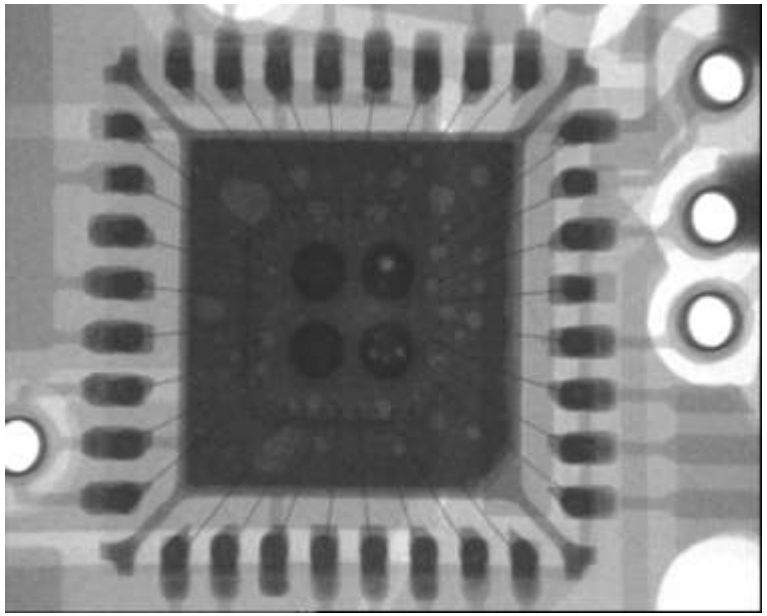
- ✓ Special thanks to G.M. Bilei, A. Santocchia, B. Checcucci, P. Placidi, E. Conti, M. Piccini, M. Menichelli, G. Ambrosi, L. Servoli.
- ✓ The "Electronics Service Team": B. Checcucci, M. Bizzarri, A. Papi, S. Bizzaglia.

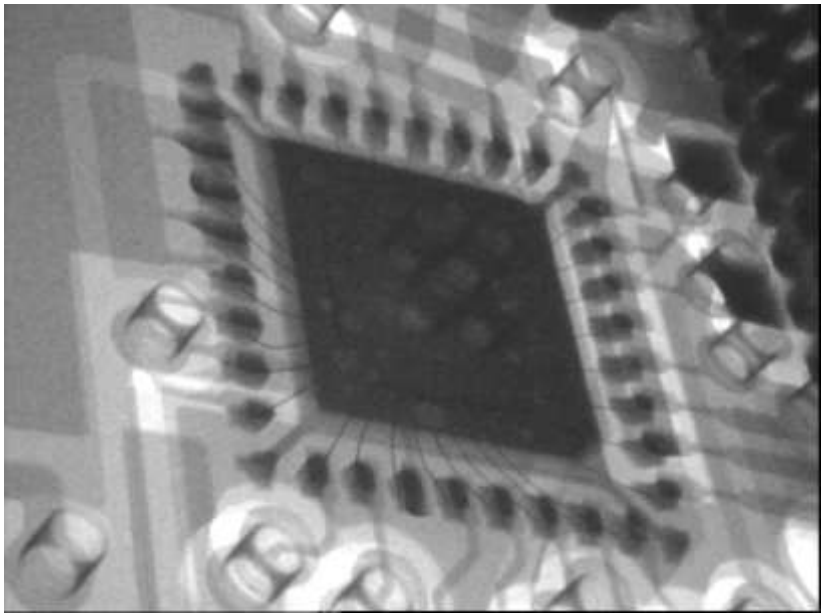
Thank You!

Backup Slides

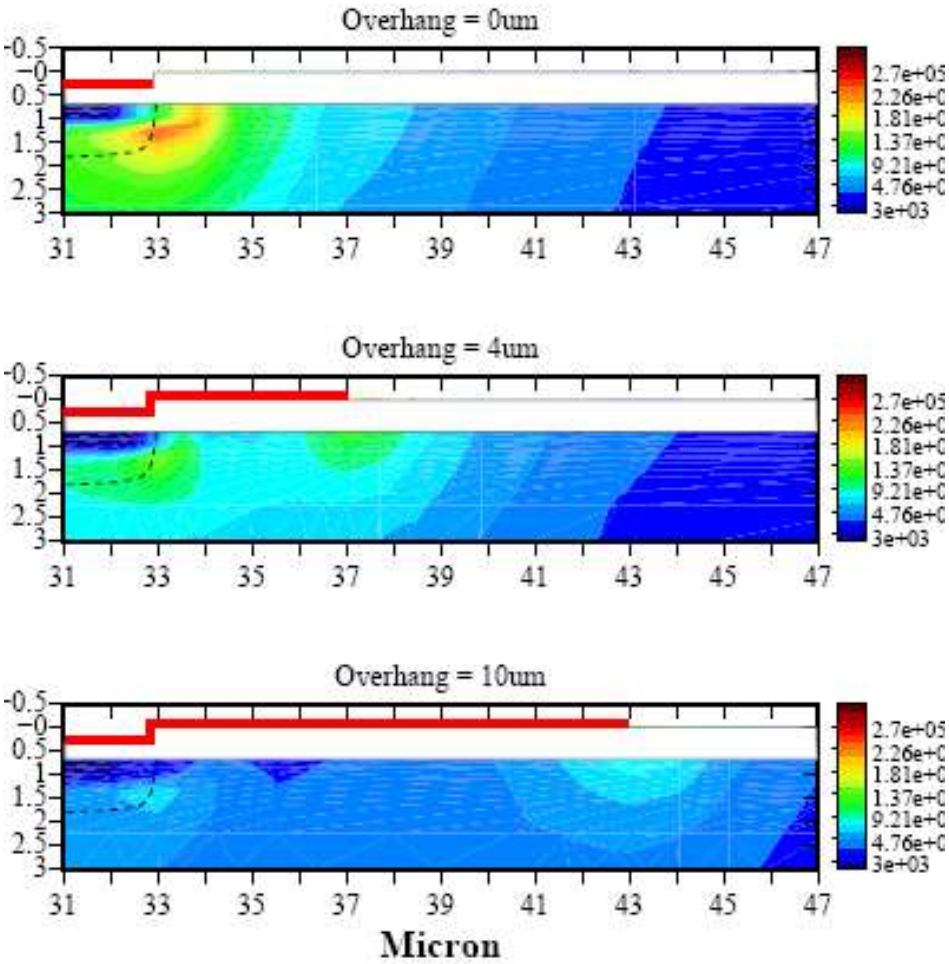
The CMS Opto-Hybrid description

- ✓ Due to a critical packaging, all the ASICS (laser drivers) have been x-ray tested (to exclude shorts as well as bad solder joints).

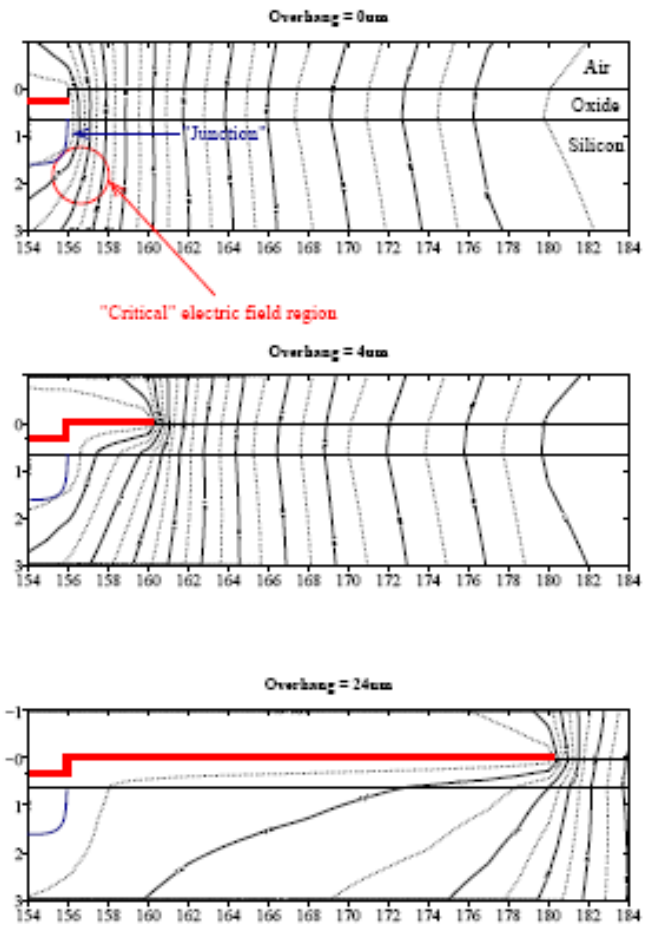




CMS Si Tracker technology options



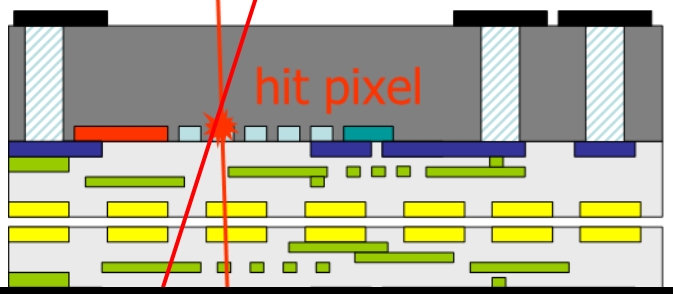
Metal overhang effetcs on the electric field distribution within Si substrate.

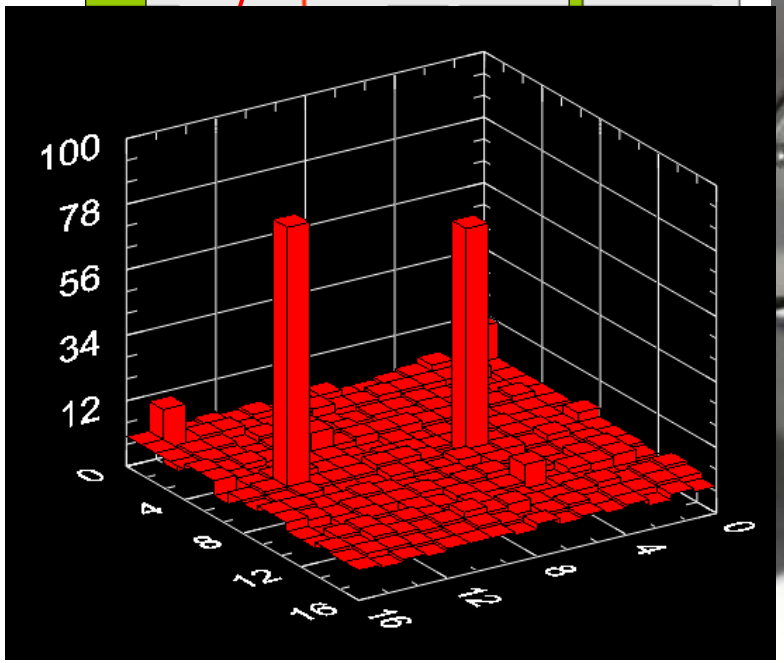


Metal overhang effetcs on the potential distribution within Si substrate.

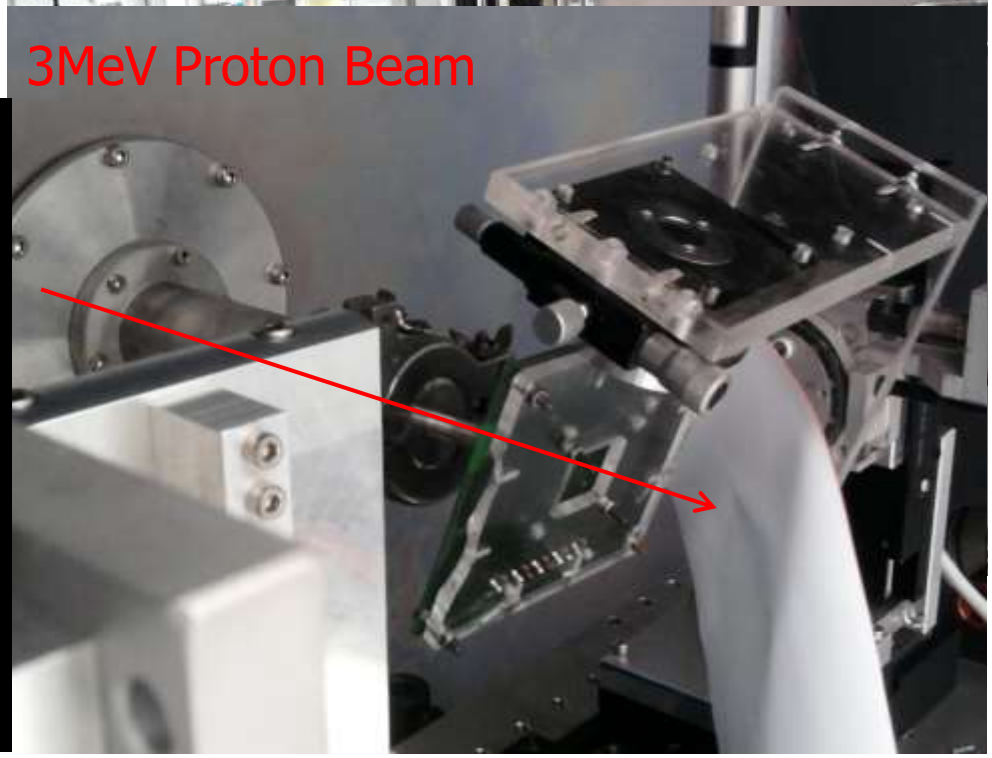
RAPS04-3D test at LABEC (Florence, Italy)

- ✓ 3MeV protons



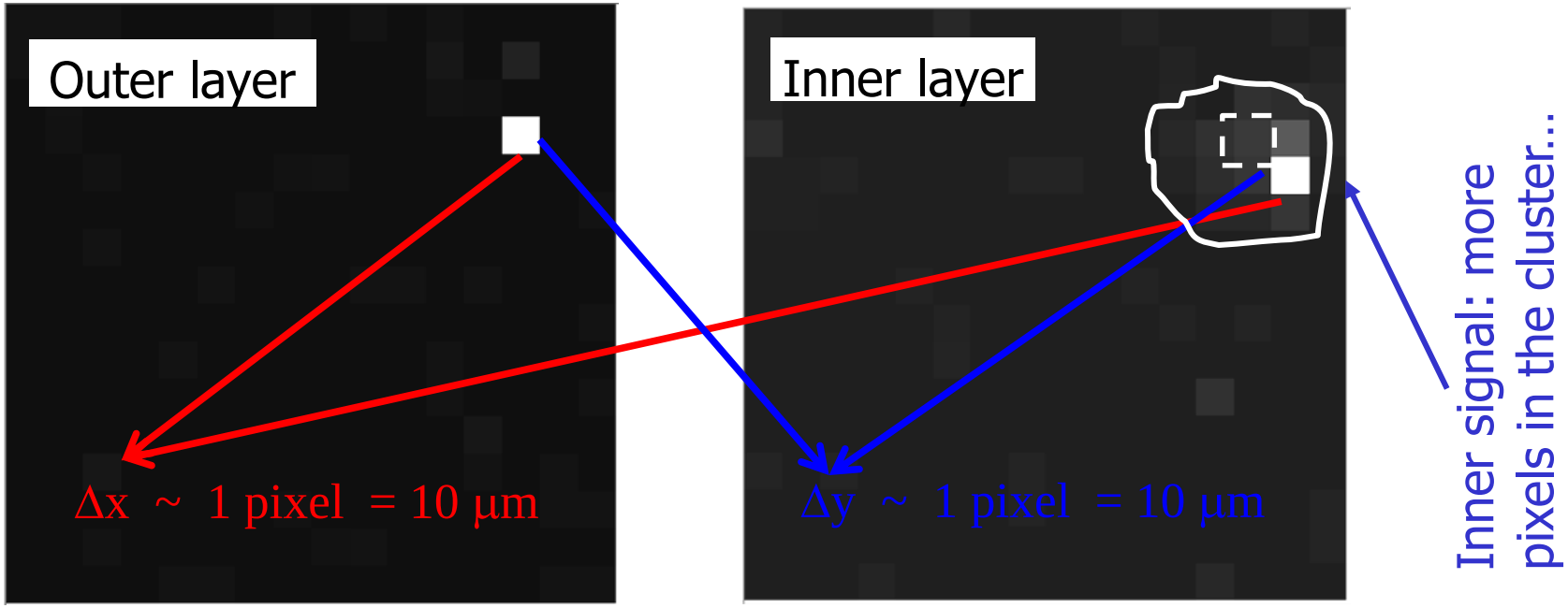


LABEC Florence, Italy



3 MeV protons response

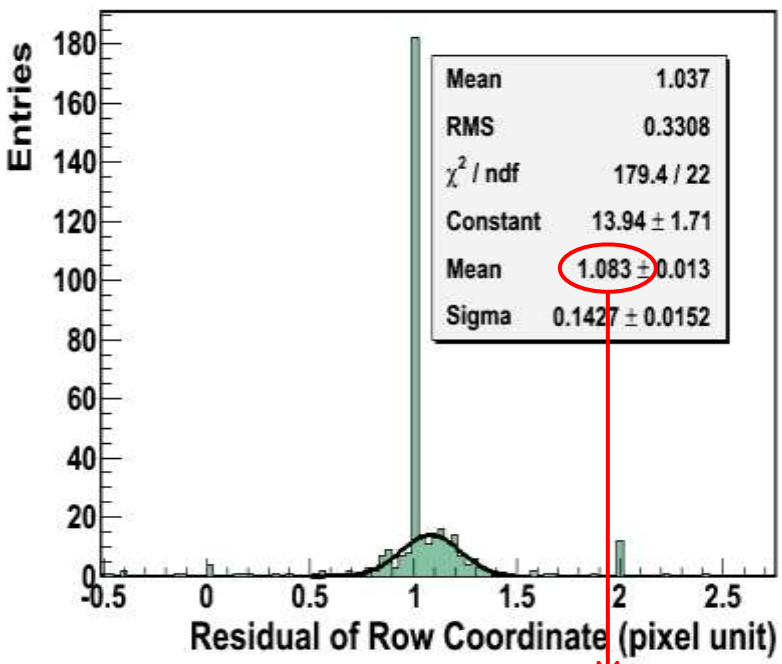
- ✓ RAPS03 3D 3MeV protons coincidence responses (tilt = 0°)
- ✓ Not aligned Tiers → displacement evaluation

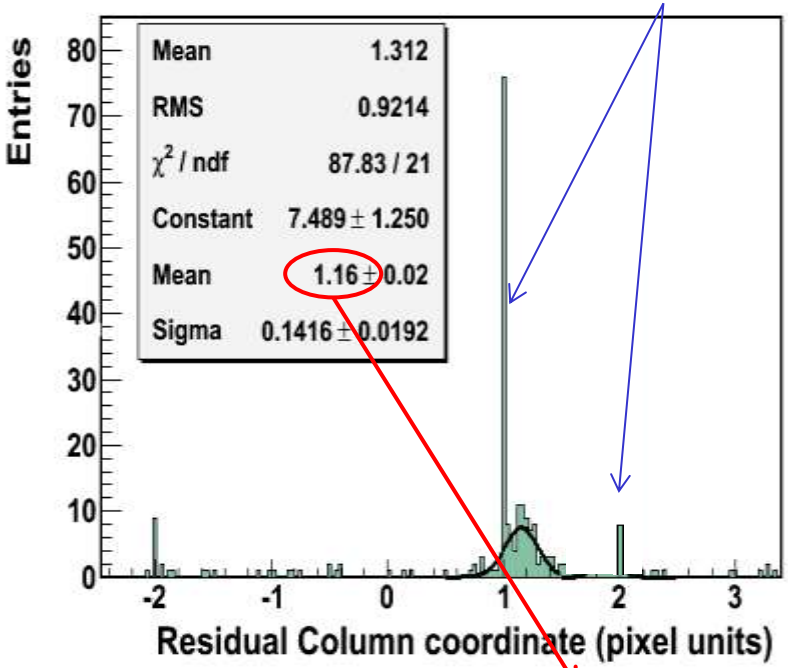


3 MeV protons response

✓ Tier displacement evaluation (tilt = 0°)

Mono-hit clusters - quantized spatial differences.



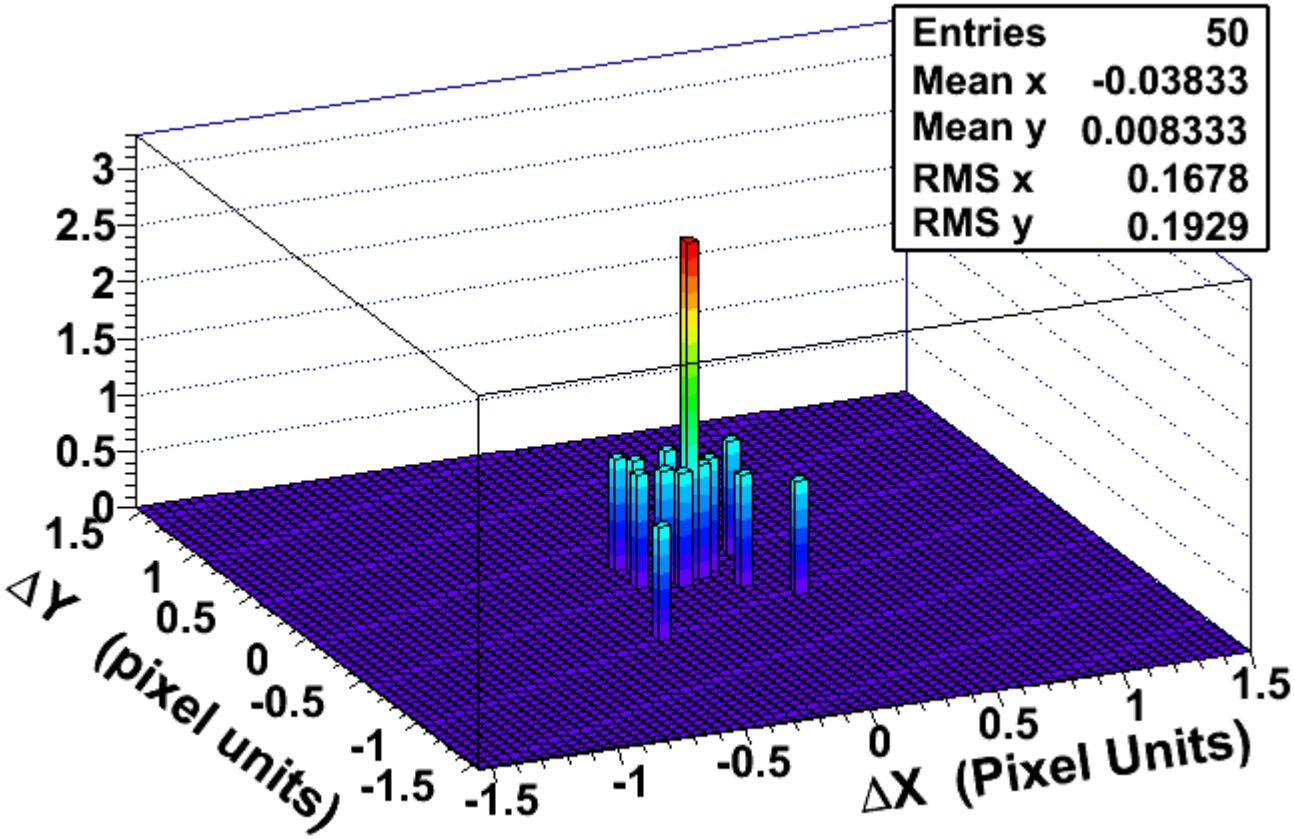


10.8μm row displacement (1.08 pixel units) with standard deviation of about 1.4μm.

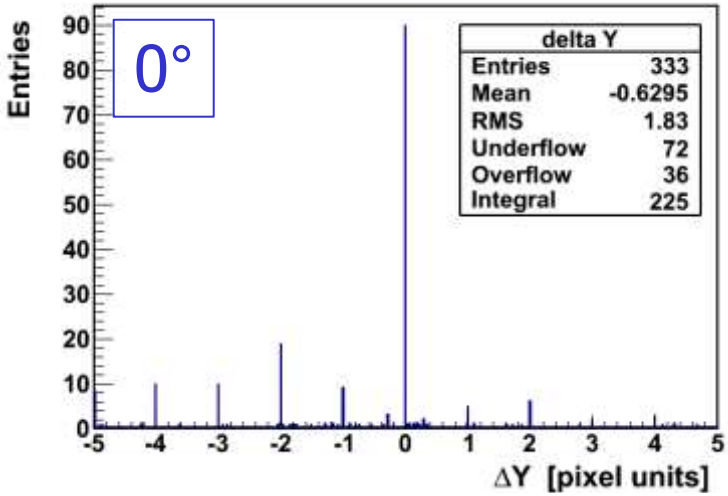
11.6μm col displacement (1.16 pixel units) with standard deviation of about 1.4μm.

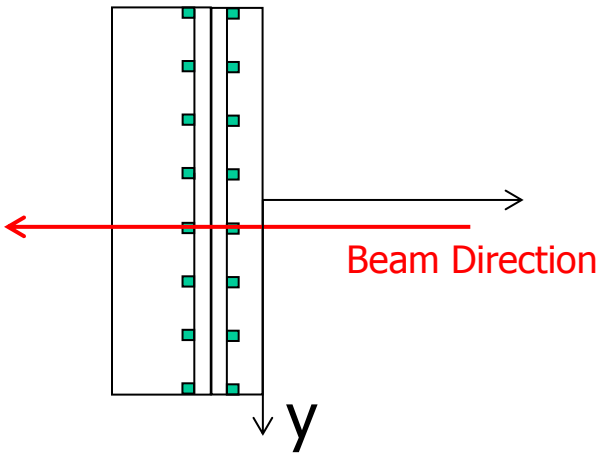
62 MeV protons response

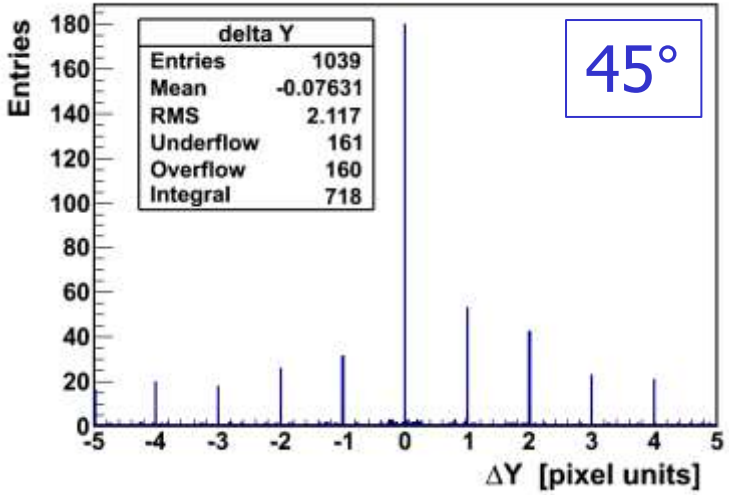
- ✓ RAPS03 3D Aligned (Tezzaron) 62MeV protons responses (tilt = 0°) Tier displacement evaluation

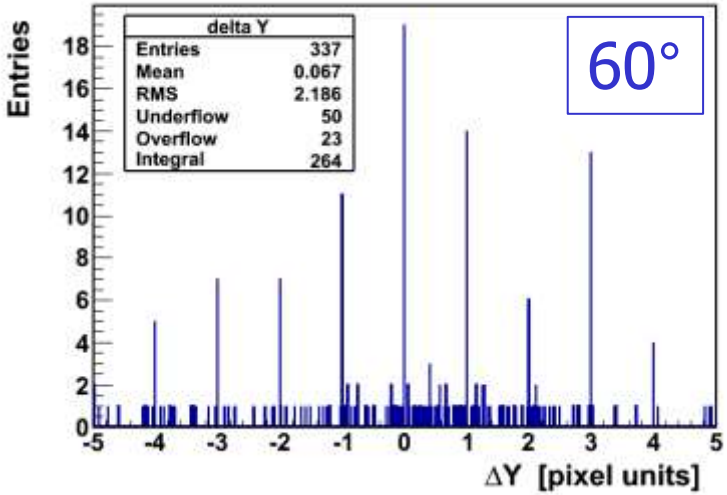


Angular measurements: y-axis displacement









The NA48 electronics PG contributions (2)

- ✓ Digital Delay to drive the control signals produced by the SPS (CERN accelerator) and by the NA48 control program to Read-Out systems of all detectors (first adoption of FPGA based system by the group - 1996).
- ✓ Contributions to the development of the trigger and Read-Out systems of the electromagnetic calorimeter.
- ✓ Contribution to the design and test of the 1GHz ADC used to read-out the beam tagger.