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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✓ Conclusions.
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 of the University of Perugia was founded in August 1986, featuring three main areas:

- Civil Engineering (1987/1988)
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 Italian Institute of Nuclear Physics (Section of Perugia).

www.infn.it -&gt; www.pg.infn.it

Particle physics

CSN1 studies fundamental interactions of matter in experiments using particle accelerators. At present, the best theory scientists have to describe our knowledge of subnuclear physics is the Standard Model. The aim of current research is to gain a deeper understanding of certain aspects, such as what generates the mass of these particles. In that context, discovering and determining the characteristics of the Higgs boson would represent a great leap forward. Scientists are hopeful that ongoing experiments will also enable them to discover new phenomena and fill some of the gaps in the Standard Model. One such example would be the discovery of...
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 $N_D=10^{12}\text{cm}^{-3}$ (high resistivity kΩ·cm);
  - high voltages - $V_{BIAS}$ 300V and more;
  - high electric fields (charge collection by drift).
Numerical analysis and physical modelling of semiconductor devices.

Modeling of ionizing particle / silicon substrates interaction at device level.

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

\[
\frac{\partial n}{\partial t} - \frac{1}{q} \nabla \cdot \vec{J}_n = G - R + G_{\text{rad}}
\]

\[
\frac{\partial p}{\partial t} + \frac{1}{q} \nabla \cdot \vec{J}_p = G - R + G_{\text{rad}}
\]

The \( G_{\text{rad}} \) 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)
Numerical modeling of radiation damage in semiconductor detectors:

- radiation induced $G^{\text{rad}}$ term;
- deep-level recombination centers (traps);
- explicit contribution of the trapped charges to the charge density.

\[
\nabla \cdot \left( -\varepsilon_s \nabla \phi \right) = q \left( N_D^+ - N_A^- + p - n + p_d - n_a \right)
\]

Continuity equations for both free and trapped charges.

\[
\begin{align*}
\frac{\partial n}{\partial t} - \frac{1}{q} \nabla \cdot \vec{J}_n &= -U_n \\
\frac{\partial p}{\partial t} + \frac{1}{q} \nabla \cdot \vec{J}_p &= -U_p \\
\frac{\partial n_a}{\partial t} - \frac{1}{q} \nabla \cdot \vec{J}_{na} &= -U_{na} \\
\frac{\partial p_d}{\partial t} + \frac{1}{q} \nabla \cdot \vec{J}_{pd} &= -U_{pd}
\end{align*}
\]
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"
- Specs: ISO 4 (FED 209D M 5,5)
- T range: ± 1°C
- Humidity: ± 5%
- Flux: M 3,5 n° 4-dim 120x60 cm

## Clean Room "B"
- Specs: ISO 2 (FED 209D M 3,5)
- T range: ± 1°C
- Humidity: ± 5%
- Flux: M 3,5 n° 1-dim 200x60 cm
INFN PG Clean Room (2)

SUSS PA 200 Semi-Automatic Prober.

Bonding Delvotec.
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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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- Conclusions.
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 ($5 \times 10^{34} \text{ cm}^{-1}\text{s}^{-1}$), 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)...

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**WG** | **Domain**
---|---
WG1 | Radiation test/qualification
- Coordinated test and qualification of 65nm for 16-rad TID and 10¹⁰ 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/optimization
- 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,...</n
Thanks to Jorgen CHRISTIANSEN CERN/PH-ESE
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)

See poster 52 I-16 by E. Conti
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The NA48 experiment

- To study neutral and charged kaons
  - Main phase from 1995 to 2001:
    - Measurement of $\text{Re}(\varepsilon'/\varepsilon) = (14.7 \pm 2.2) \times 10^{-4}$
    - 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.

$K^0_S$, $K^0_L$, $K^\pm$ beams
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.
The NA62 experiment

- First phase (2007-2008): measurement of the ratio $R_K=\frac{BR(K^+\rightarrow e\nu)}{BR(K^+\rightarrow \mu\nu)}$ exploiting the NA48 detector
  
  
  $R_K=(2.488\pm0.010)\times10^{-5}$
  

- Main phase (2014-201x): measurement of Branching Ratio of the decay $K^+\rightarrow \pi^+\nu\nu$ (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)
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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 $40 \times 70$ mm and 300$\mu$m thickness.
The AMS-02 Si strip readout

✓ The VA64HDR9A chip (3072 in-use chips)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VA64HDR9A</th>
<th>VA140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise, Cd=50pF (eRMS)</td>
<td>520</td>
<td>430</td>
</tr>
<tr>
<td>DNR</td>
<td>+100fC,-200fC</td>
<td>± 200fC</td>
</tr>
<tr>
<td>Power cons. (mW/channel)</td>
<td>0.8</td>
<td>0.29</td>
</tr>
<tr>
<td>Peaking time (µs)</td>
<td>5</td>
<td>6.5</td>
</tr>
<tr>
<td>SEL thrshd (MeV·cm²/mg)</td>
<td>22</td>
<td>21-22</td>
</tr>
</tbody>
</table>
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.
Target and collimator customization.
The AMS-02 power supply system test (2)

- The Thermo-Mechanical Test

T- Film Slip Table System
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 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 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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CMOS Radiation Active Pixel Sensors (RAPS)

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

Simple 3T pixel architecture

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

Year 2001/2002
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


VLSI Design and Characterization of integrated CMOS Active Pixel Sensors.

CERN PS Irradiation Facilities

RAPS01 2002
RAPS02 2005
RAPS03 2007
RAPS04 (2D/3D) 2009
RAPS06 2011

UMC 0.18μm → Chartered 0.13μm (3D Tezzaron) → UMC 90nm → 65nm
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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.

Collaboration with INFN Firenze
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 (256×256 pixels)
- Fast operation (digital core $f_{max} = 120$ MHz)
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 quartz 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.

Typical signal fluctuations due to thermal noise.
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)...

![Graphs showing signal vs photon energy for RAPS03 and SOD photodiodes with statistical information for each dataset.]
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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 $T_{on}=3\text{ns}$, $T=25\text{ns}$.

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!

- Δx (pixel units): ~0.08μm row displacement (~0.008 pixel units) with standard deviation ~2.5μm.
- Δy (pixel units): ~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

Beam Direction

0°

X

45°

22.5°

60°
Angular measurements: x-axis displacement

\[ \Delta x = d \cdot \tan(\alpha) \]

\( \alpha = 45^\circ \rightarrow \Delta x = d \cdot 1.00 = 10.0\mu \text{m} \rightarrow 1 \text{ pixel unit} \)

\( \alpha = 60^\circ \rightarrow \Delta x = d \cdot 1.73 = 17.3\mu \text{m} \rightarrow \sim 2 \text{ pixel units} \)
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 PInel Dosimeter (2)

✓ Experimental setup in IR operating room
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 effects on the electric field distribution within Si substrate.

Metal overhang effects on the potential distribution within Si substrate.
RAPS04-3D test at LABEC (Florence, Italy)

✓ 3MeV protons

LABEC Florence, Italy

3MeV Proton Beam
RAPS03 3D 3MeV protons coincidence responses (tilt = 0°)

Not aligned Tiers → displacement evaluation

Δx ~ 1 pixel = 10 µm

Δy ~ 1 pixel = 10 µm

Inner layer

Inner signal: more pixels in the cluster...
3 MeV protons response

✓ Tier displacement evaluation (tilt = 0°)

Mono-hit clusters - quantized spatial differences.

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

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

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

0°

Beam Direction

45°

60°
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.