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MC PAD

Project P2: Hybrid Pixel Detectors
Jennifer Sibille (ESR)

Paul Scherrer Institut, Villigen, CH
Supervisor: Dr. Tilman Rohe
Thesis Advisor: Prof. Alice Bean

MC-PAD Closing Event

19-22 September, 2012

Laboratori Nationali di Frascati, INFN

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Outline

- Biography
- Introduction
  - Project P2: Hybrid Pixel Detectors
  - CMS pixel detector
  - Radiation effects on detector operation
- Research Work
  - Charge collection efficiency measurement
  - Interpixel capacitance
  - Charge as a function of position within a pixel
  - Single-sided sensors
  - Conclusions
- Present Status
- Evaluation of MC-PAD ITN

About Me

Start date: 01 April, 2009
End date: 31 March, 2012
Home Country: USA

Education Background:

- BS in Physics and Mathematics, May 2006
  - Louisiana Tech University, Ruston, LA, USA
- MS in Physics, December 2008
  - University of Kansas, Lawrence, KS, USA
  - “Charge Collection Efficiency Measurement of CMS Pixel Detector”

Details of ESR Position:

- Institute: Paul Scherrer Institut (PSI), Villigen, CH
- Project: P2 Hybrid Pixel Detectors
- Supervisor: Dr. Tilman Rohe
- PhD Thesis: “Radiation Hard Hybrid Pixel Detectors, and a $b\bar{b}$ Cross-Section Measurement at the CMS Experiment”
  - Thesis advisor: Prof. Alice Bean
  - University of Kansas, Lawrence, KS, USA

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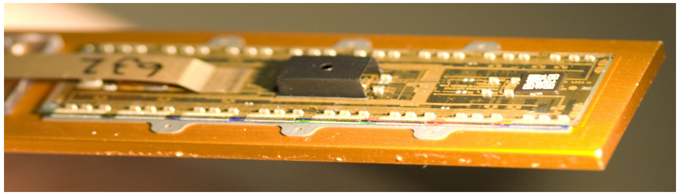
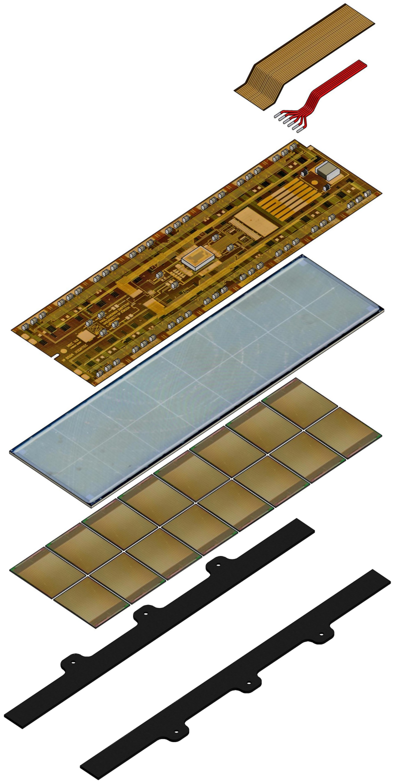
Project Overview

- Motivation: Tracking detectors at LHC and X-FEL are exposed to large radiation doses which degrade performance after a few years
- Project Focus: Cost-effective and radiation-hard hybrid pixel detectors using standard components
- First step is to understand operational limit of current detectors
- Measurements and simulations of the degradation of sensors as a function of integrated fluence



CMS barrel pixel module



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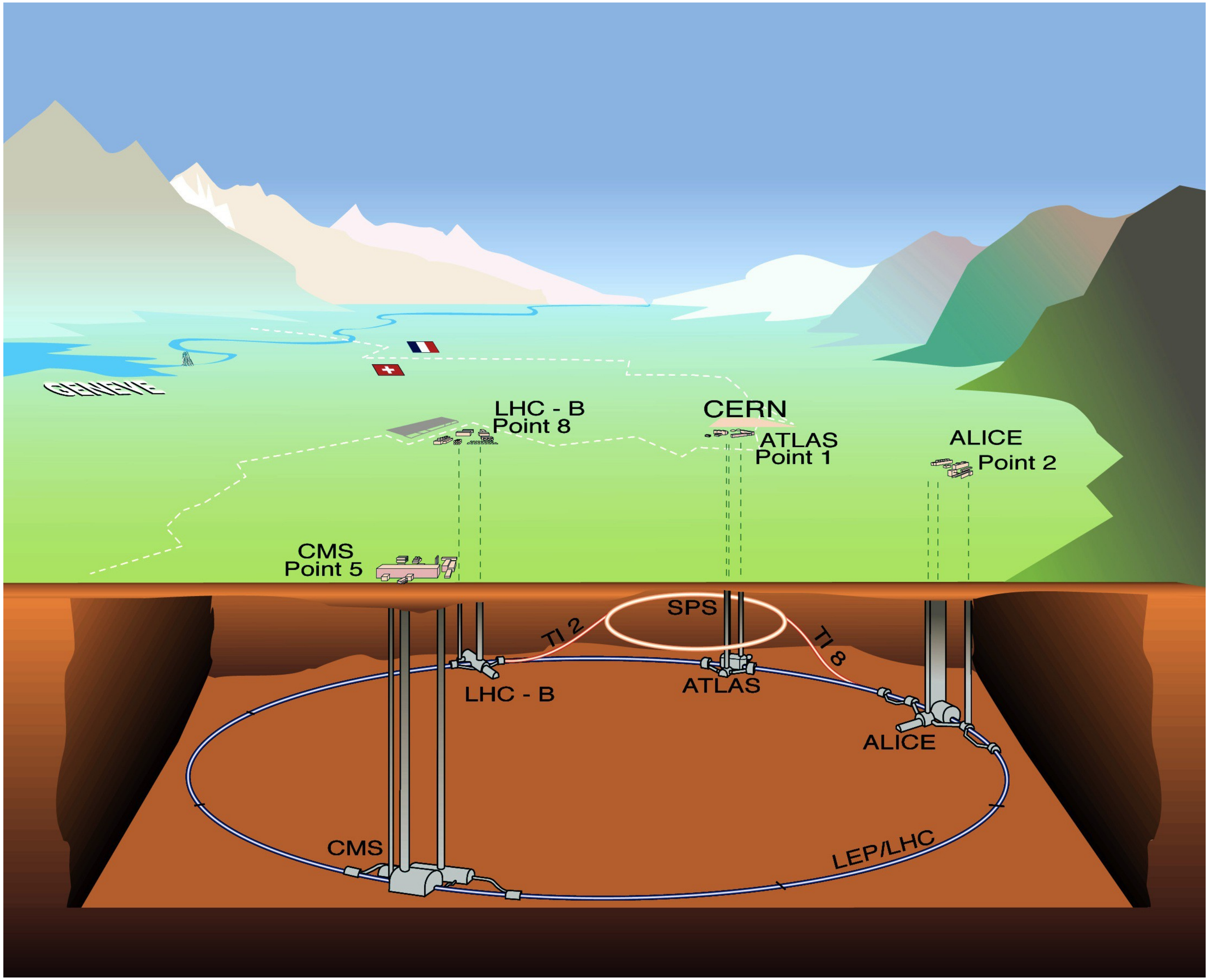
Large Hadron Collider



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The CMS Detector

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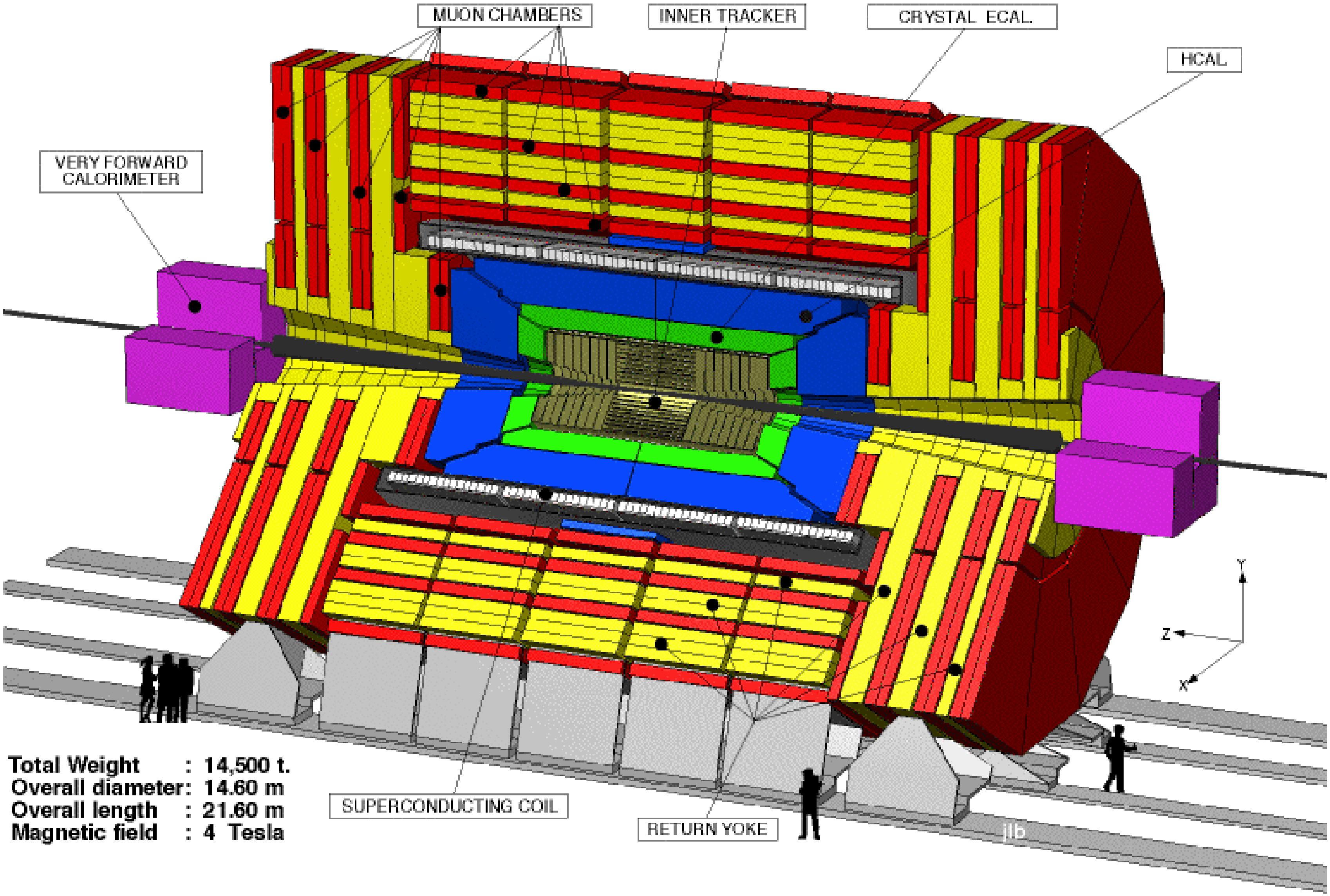

Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla

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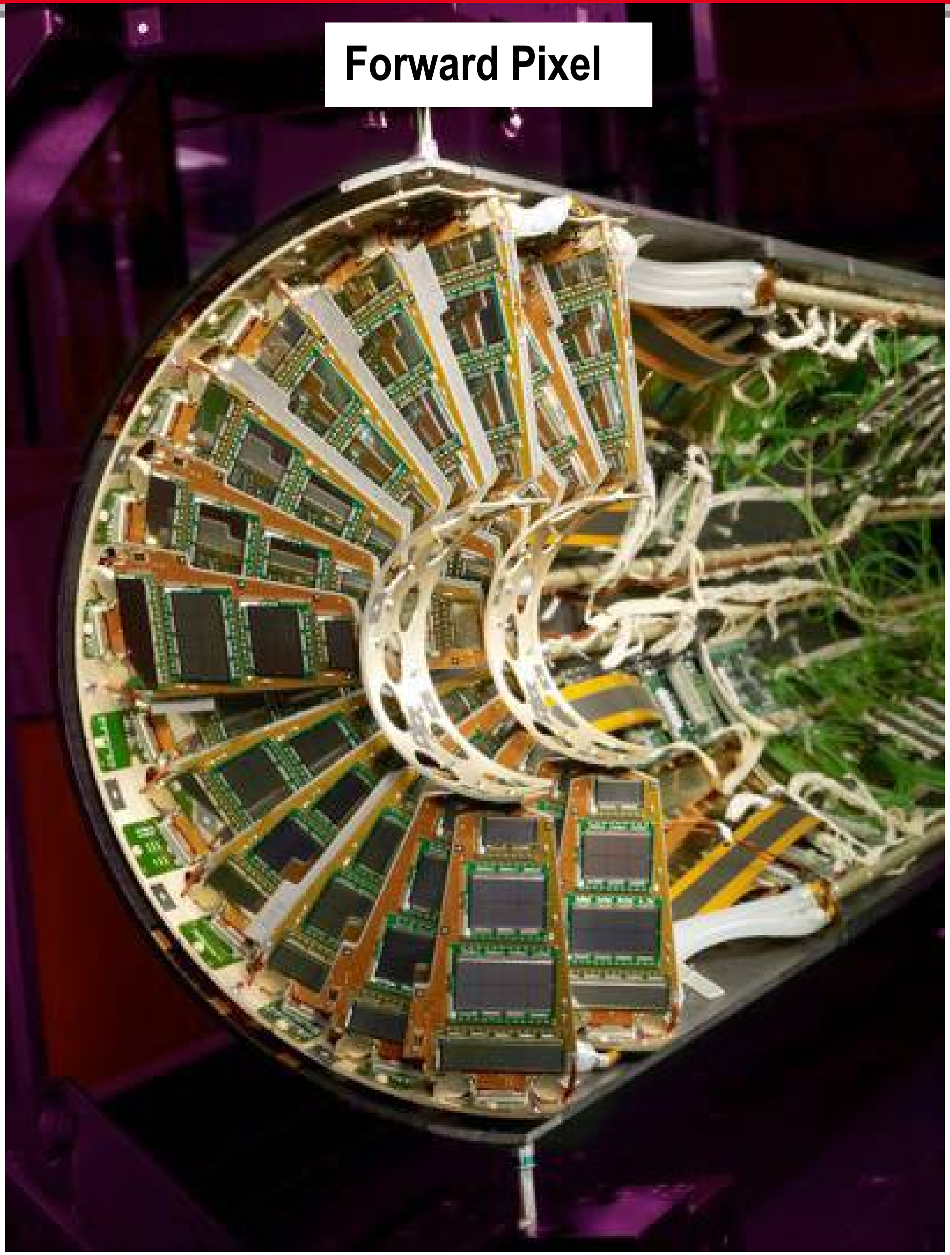
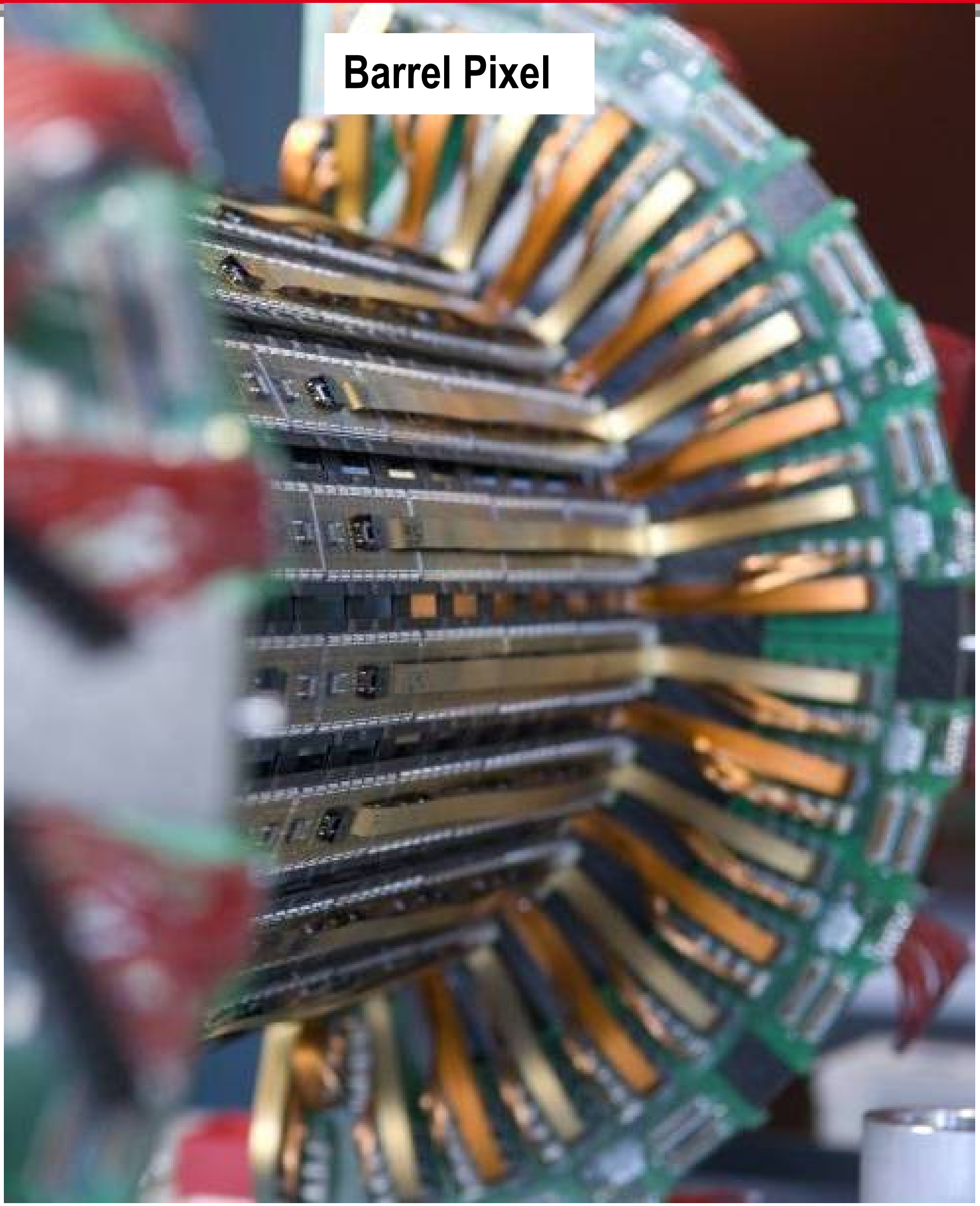
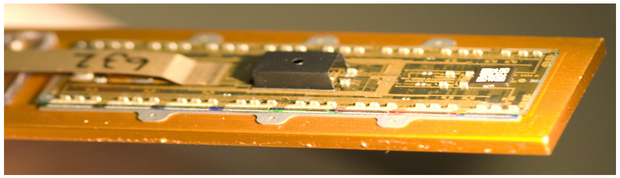
The CMS Pixel Detector

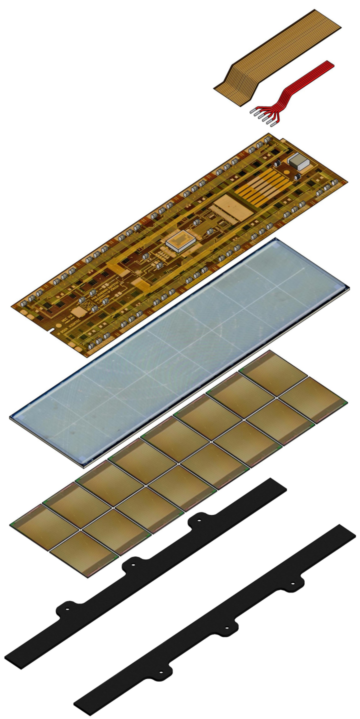




CMS Barrel Pixels



CMS barrel pixel module



Cables

HDI (printed circuit)

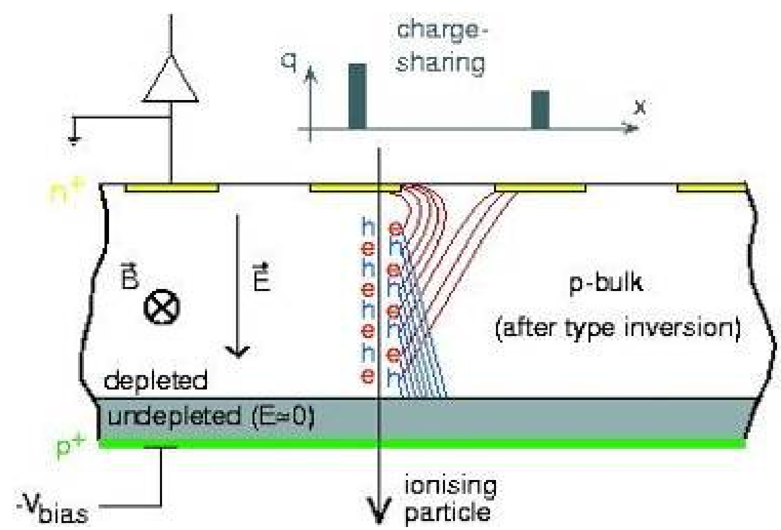
Silicon sensor

2x8 Readout chips (ROC)

Si-Nitride base strips

Pixel detector:
- High granularity, good spatial resolution
  - vertexing
- Close to interaction point, subjected to large radiation dose

Magnetic field:
- Charges in sensor experience Lorentz force
- Better spatial resolution due to charge sharing between pixels



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Radiation Damage

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Particles passing through the sensor cause radiation damage!

For layer at 3 cm from interaction point, $\sqrt{s}$ = 14 TeV:

$\Phi < \sim 1.5 \times 10^{15}\ n_{eq}/cm^2$ ($\int L\, dt < \sim 250\ fb^{-1}$):

- Bias voltage has to be increased
- Spatial resolution degrades
- Cooling necessary to limit leakage current, reverse annealing

$\Phi > \sim 1.5 \times 10^{15}\ n_{eq}/cm^2$ ($\int L\, dt > \sim 250\ fb^{-1}$):

- Charge trapping leads to reduced signal and loss in efficiency
- Recent measurements (e.g. University of Hamburg, University of Liverpool, University of Freiburg) show that measured signal is higher than expected if bias voltage can be increased to values >> 600 V
- Connectors, cables and power supplies in CMS only qualified to 600 V
- Leakage current rising proportional with Φ becomes significant fraction of the power load (cooling)

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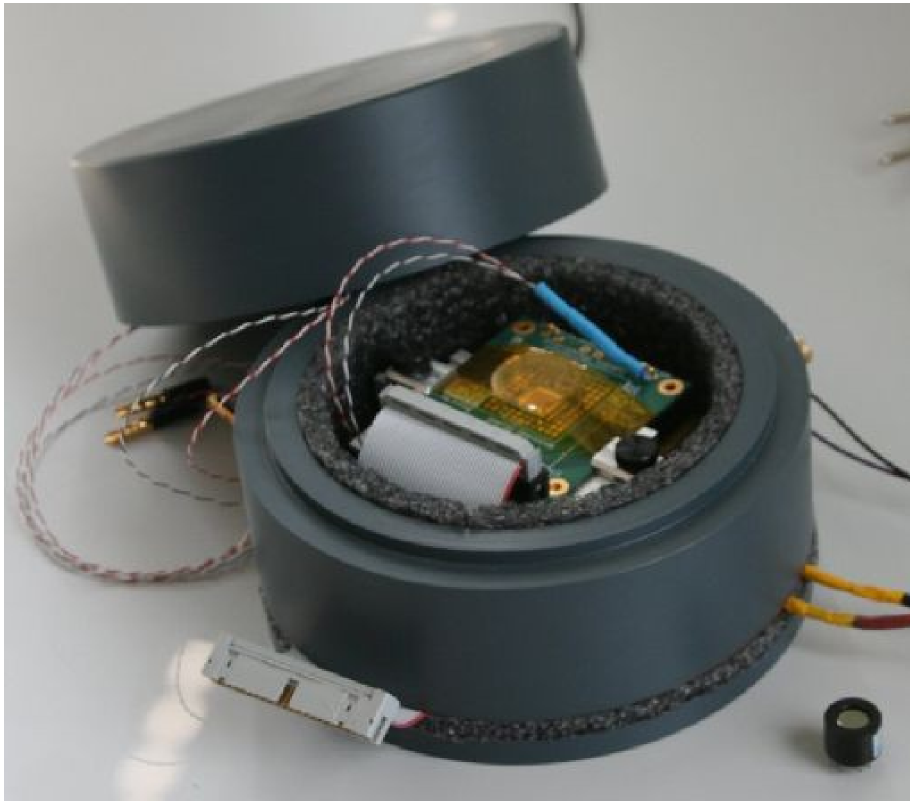
Charge Collection Efficiency

- Samples irradiated up to fluence of $5e10^{15}\ n_{eq}/cm^2$
  - Pions (300 MeV) at PSI Pi-E1 up to $\sim 6\times10^{14}\ n_{eq}/cm^2$ ($>10^{15} n_{eq}/cm^2$ Aug 2010)
  - Protons (21 GeV) at CERN-PS up to $\sim 5\times10^{15} n_{eq}/cm^2$
  - Protons (24 MeV) at Karlsruhe up to $\sim 5\times10^{15} n_{eq}/cm^2$
- ^{90}Sr source for measurement
- Samples tested at -20°C
- No independent trigger, so no efficiency measurement with this setup

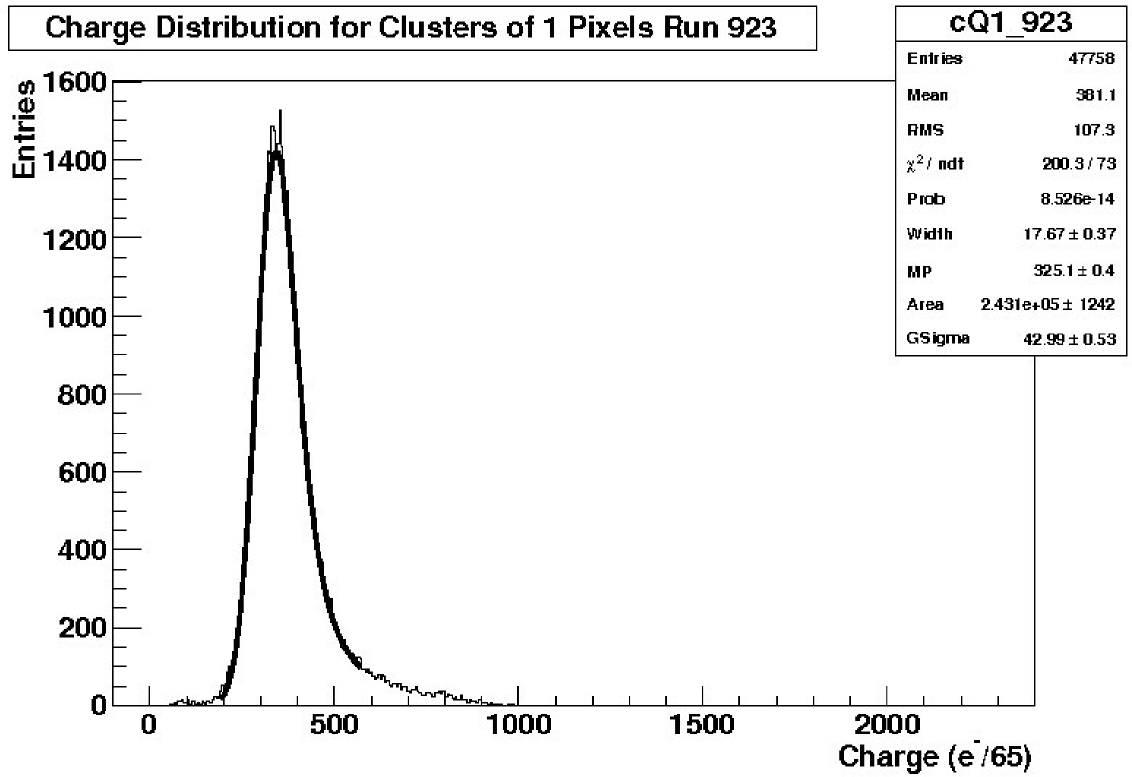


Cold box for testing irradiated samples

Data Analysis

- Charge deposited by a charged particle passing through silicon is Landau distribution

- “Signal” is defined as the most probable value of charge distribution



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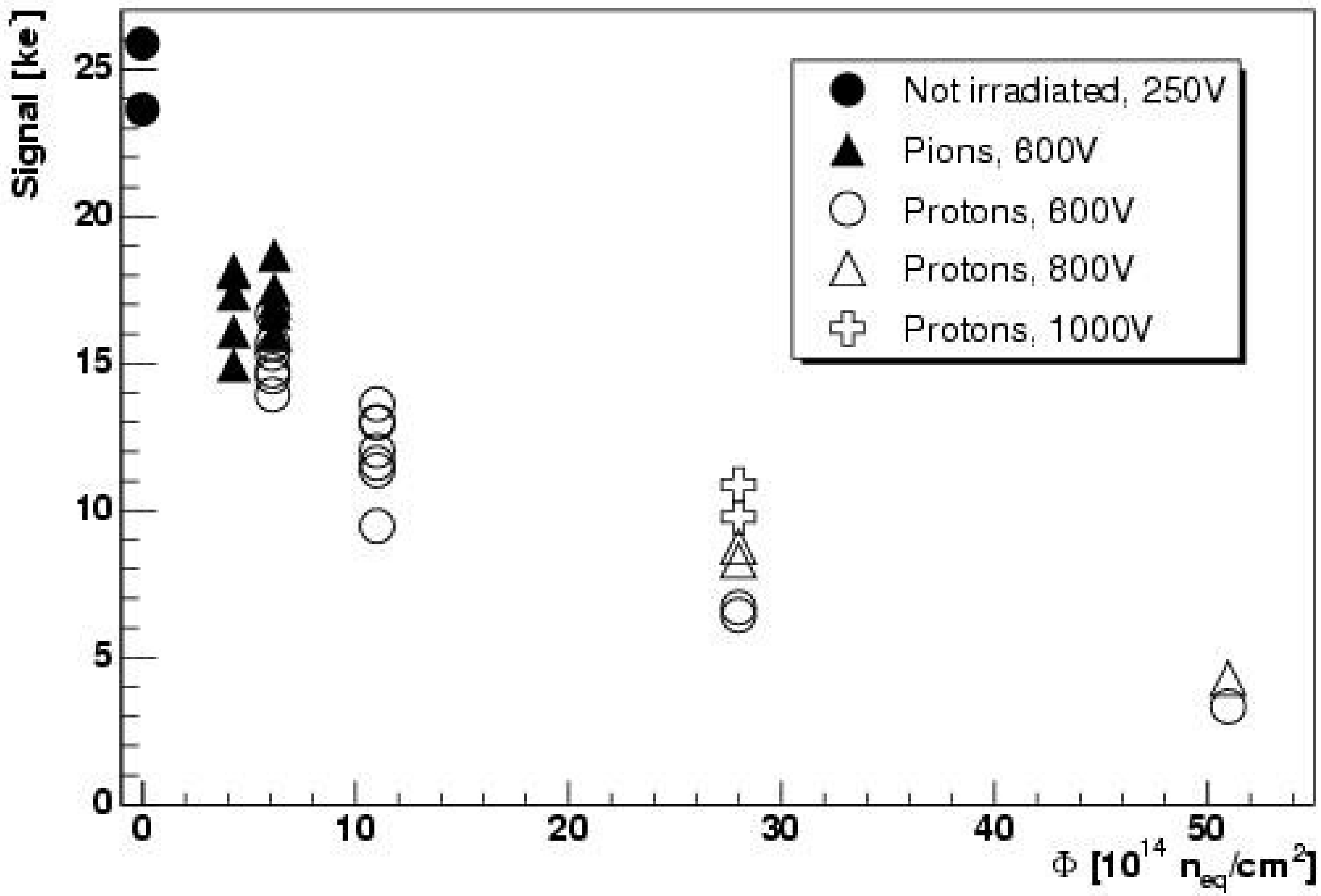
CCE Results



Collected charge vs. fluence

CCE Summary

- Can still get significant charge (with high bias) up to ~3e15 n_{eq}/cm^2
  - Results for 5e15 n_{eq}/cm^2 inconclusive
  - No sign of saturation of signal at 3e15 n_{eq}/cm^2
- However:
  - Cables in CMS only qualified for 600 V
  - Couldn't go to higher bias
    - Problems with sparking on PCB, humidity, connectors
    - Redesigned PCBs so this is possible in future

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Interpixel Capacitance

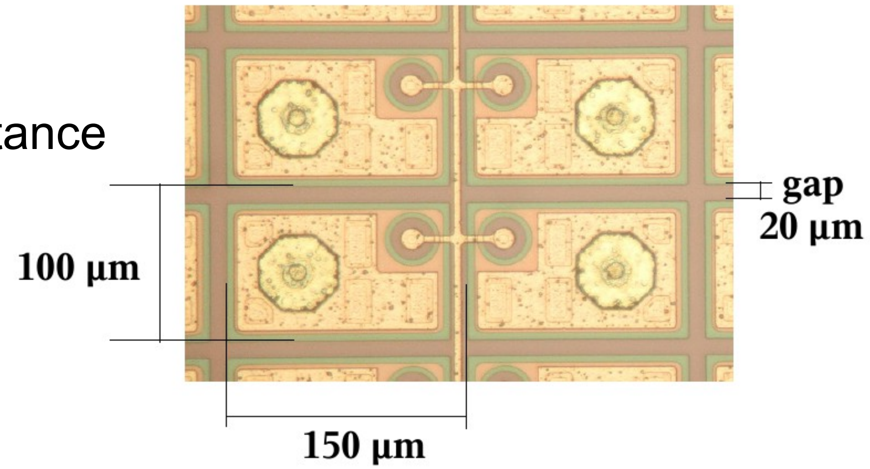
•Capacitance leads to cross-talk, degrades resolution

•Small gap: more uniform drift field, but higher capacitance

•Trade-off between low capacitance and small gap

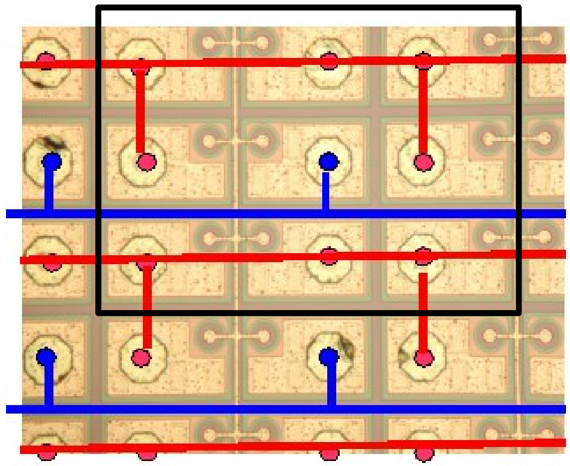
•Current pixels have 20 μm gap

•Want to see if increasing gap size is beneficial



- Designed a "readout chip replacement" – simple chip to connect groups of pixels together
  - Groups connected together and routed to pads on periphery
  - Only 2 pads which can be contacted by needles

1 pixel (blue) surrounded by 8 neighbors (red)



Measured sensors with different gap sizes and geometries

Irradiated some sensors with ^{60}Co

Interpixel Capacitance - Results

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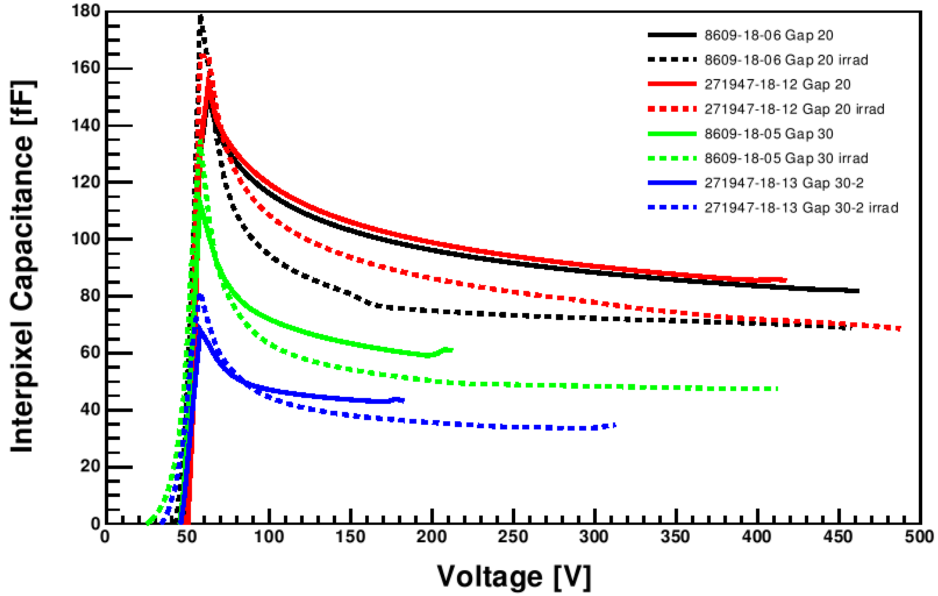
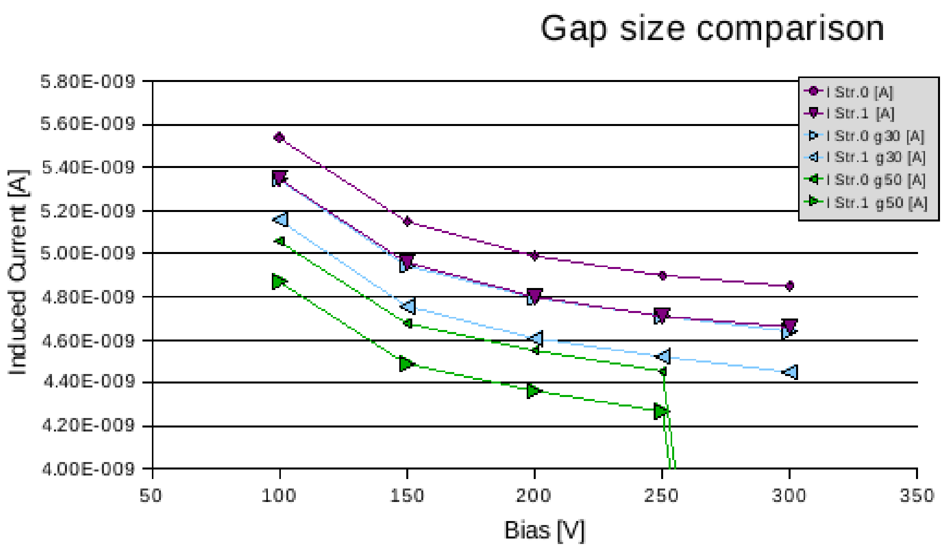
Measurements



Black/Red: 20 µm
Blue/Green: 30 µm

Solid: Unirradiated
Dashed: Irradiated

Simulations



Purple: 20 µm   Blue: 30 µm   Green: 50 µm

NB: Pixels are not isolated before full depletion (ignore everything before 50 V)
Qualitative agreement between simulations and measurements – no quantitative comparison
Capacitance decreases with increasing bias voltage – possible depletion of p-spray
Capacitance decreases with irradiation

Planned to measure other devices (open p-stop, 3D), unable to obtain samples until Summer 2012
- Plan to publish results

Charge vs. Position in Pixel

- As exchange with project partner, I went to the University of Hamburg in December 2010 for a small project
- Irradiated some sensors (with ROC) in the DORIS F4 beamline (~1 MGy)
- Induce charge in a very localized area using red laser
- Questions:
  - Are there areas of the pixel which have lower charge collection?
  - How does this change with irradiation?
- Made 2D scan over pixel, starting outside edges of pixel
- Laser spot width ~5 µm
- Steps of 10 µm
  - Unfortunately we ran out of time so were unable to do a finer scan
- Unable to operate irradiated readout chips
- Charge collection fairly homogenous, reproducible – nothing unexpected

Many thanks to Jiaguo Zhang and Thomas Pöhlsen for their help!

Single-Sided Sensors

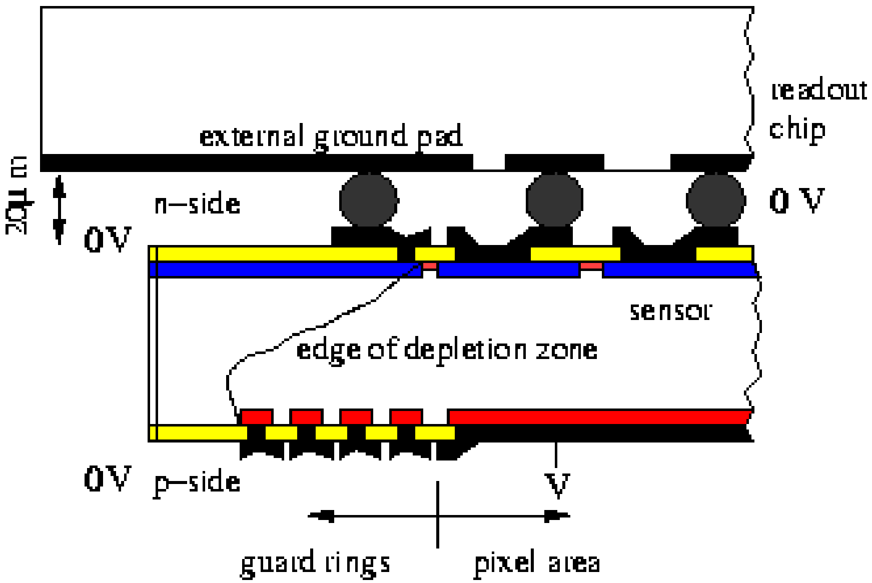
Apart from bump-bonding, sensors are most expensive part of detector -> try to reduce costs

Single-sided processing cheaper (factor 2-3!)

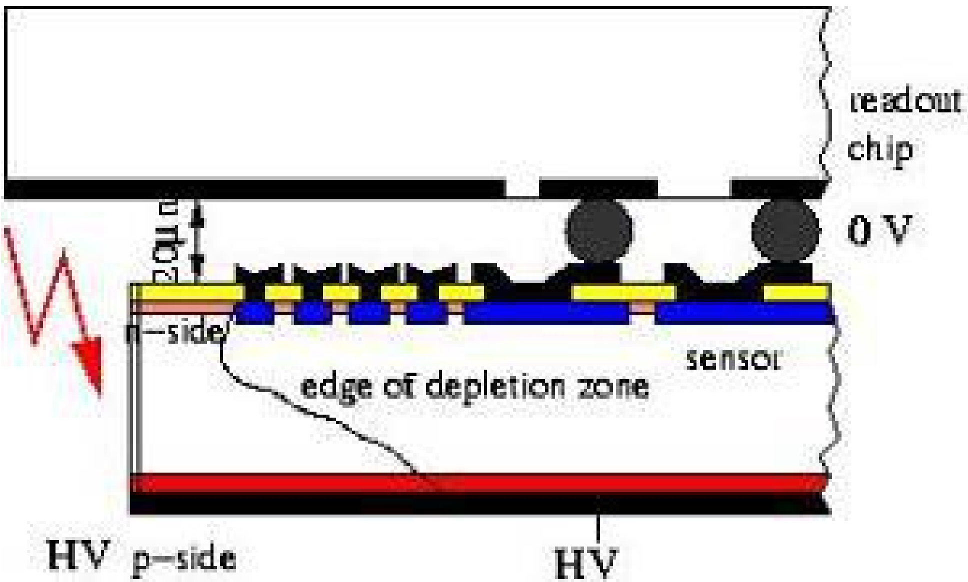
BUT edges of chip remain at high voltage in single-sided sensors

- Risk of sparking to readout chip (ground)

Need a cheap and reliable method to prevent this problem in order to be feasible



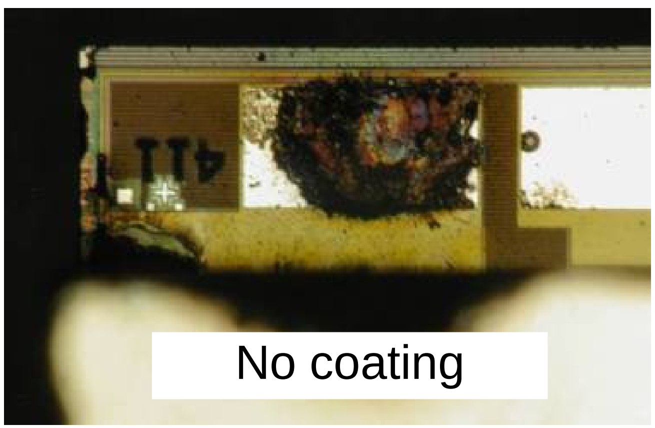
Double-sided

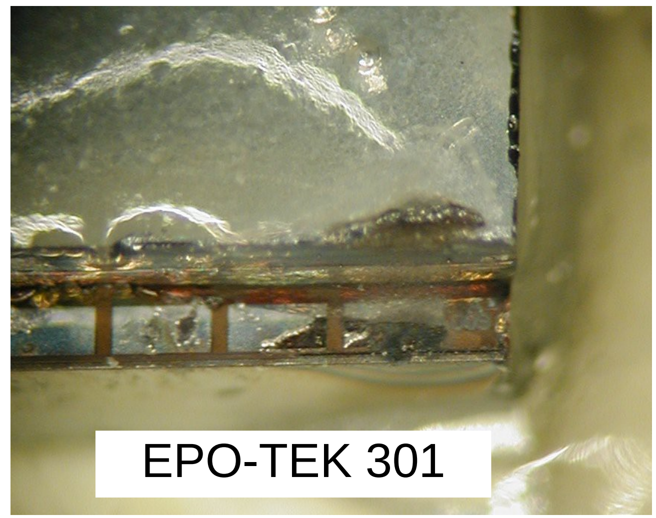


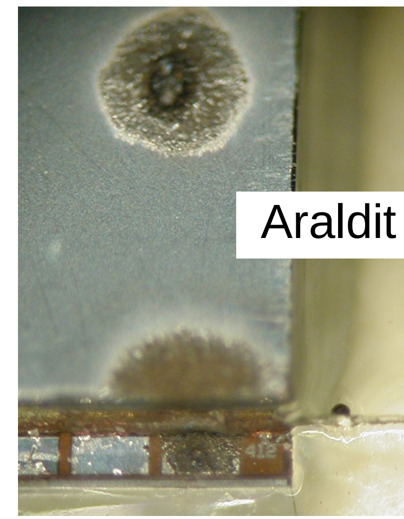
Single-sided

Single-Sided Sensors

Maybe can cover edges with another material to prevent sparking?
- Tried two different glues (Araldit and EPO-TEK 301) without success
- Sparks at 500-700 V







Coated with polymer (Paralyene C) with chemical vapor deposition process
- Standard industrial procedure
- Held at 1000 V for several hours with no sparks
- Possible solution to be investigated further, has problems to be solved
  - Wire bond pads should not be covered

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Conclusions

- Charge Collection Efficiency
  - Can get significant charge (with high bias) up to ~3e15 n_{eq}/cm^2
- Interpixel Capacitance
  - Capacitance decreases with larger gap size
  - Finally decided to keep same gap size for upgrade
- Single-Sided Sensors
  - Coating sensors with glue has no effect on sparking
  - Problem may be solved by coating with polymer
- In the end, measurements helped to show that the current sensors are still suitable for Phase 1 upgrade

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Present Status

- Finishing thesis, PhD expected by end of the year
- Postdoc position at University of Hamburg (16.05.2012)
  - Working on the CMS pixel phase 1 upgrade
  - Production and testing of 350 barrel pixel modules
    - Build up module assembly stations
    - Build setup for testing/calibrating modules with x-rays

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Evaluation of MC-PAD ITN

Positive aspects:

- Training events were a great opportunity to learn about other research areas and meet people from other institutes
  - I found the event on CV writing and interviewing especially helpful
  - Build a relationship with other people, which you don't get from summer schools, etc
- Exchange with project partner also interesting
  - Chance to work with another group

Negative aspects:

- Would have liked more participation from the industry partners
- So many travel opportunities sometimes made it difficult to balance work in the lab and travel

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In Conclusion...

MC-PAD ITN was a great experience, and I would definitely recommend it!

Thank you for the wonderful opportunity!

PUBLICATIONS AND PRESENTATIONS

“Radiation hardness of CMS pixel barrel modules.” Rohe, T. et al. Nucl.Instrum.Meth. A624 (2010) 414-418.

“Signal height in silicon pixel detectors irradiated with pions and protons”. Rohe, T. et al. Nucl.Instrum.Meth. A612 (2010) 493-496.

XI ICFA School on Instrumentation in Elementary Particle Physics, San Carlos de Bariloche, Argentina, January 2010

- Presented poster: “Design of CMS Pixels for an LHC Upgrade”

14th RD50 Workshop, Freiburg, Germany, June 2009

- Presentation: "Sensor R&D for an upgrade of the CMS pixel barrel"

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Back-up Slides

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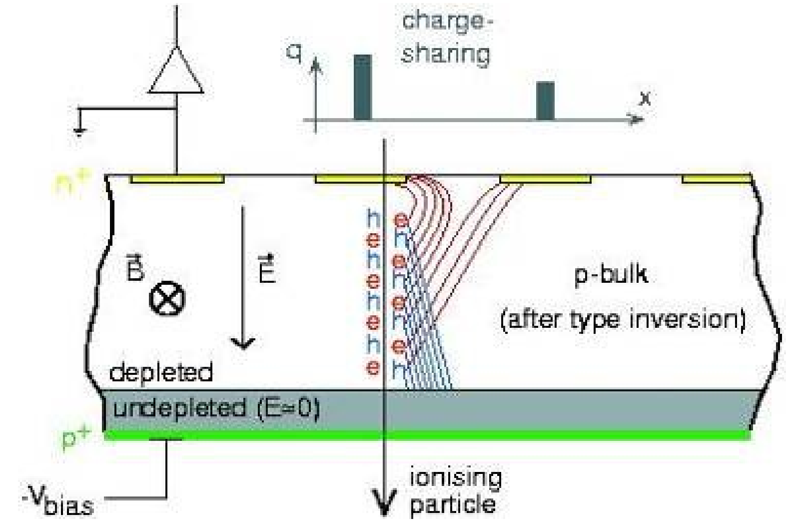
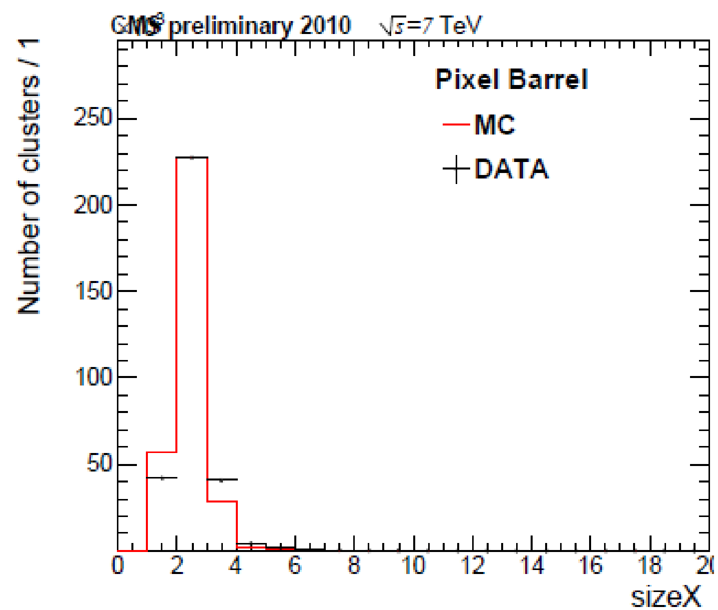
Spatial Resolution (rφ)

- Present CMS-pixel detector displays good spatial resolution (~13 µm)
- High fraction of 2-pixel clusters
  - High magnetic field (3.8 T)
  - High mobility of electrons
  - Low bias voltage (150 V in the barrel)
- Interpolation techniques in 2-pixel clusters



- Cumulative radiation damage requires increase of bias voltage
- High electric field reduces mobility of charge carriers
- Lorentz angle is also reduced
- Fraction of double hits is reduced
- Resolution slowly degrades up to the binary value (pitch/sqrt(12)~ 30 µm with current pitch)
- Process is slow and steady
- Detector might become "useless" for impact parameter measurement although detection efficiency is still high (>95%)



Distribution of cluster size (in rφ)

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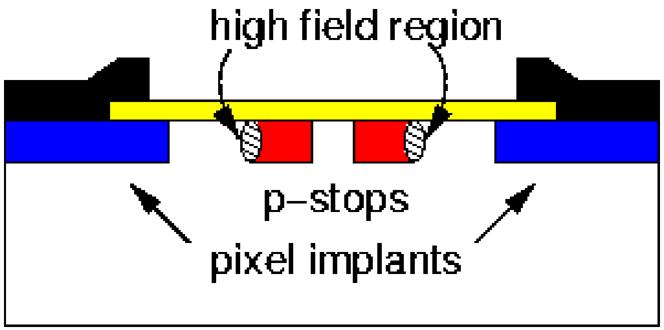
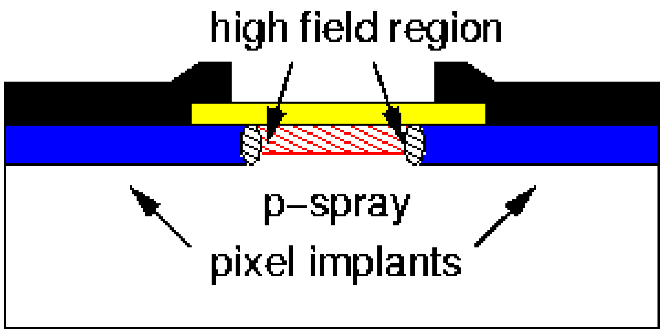
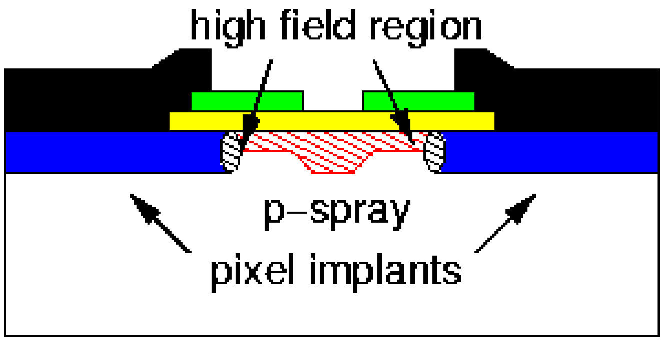
Interpixel Isolation

- In n+-in-n sensors, electron accumulation layer would short out implants without some sort of isolation (p-type implant)
- p-stop: high dose p-implant between n+ implants
  - Requires extra photolithographic step
- p-spray: medium dose boron implant uniformly over surface
  - No extra photolithographic step
- moderated p-spray: p-spray process performed later in the process, any structures are reproduced in the doping profile
  - Can use higher dose to ensure sufficient isolation, no breakdown







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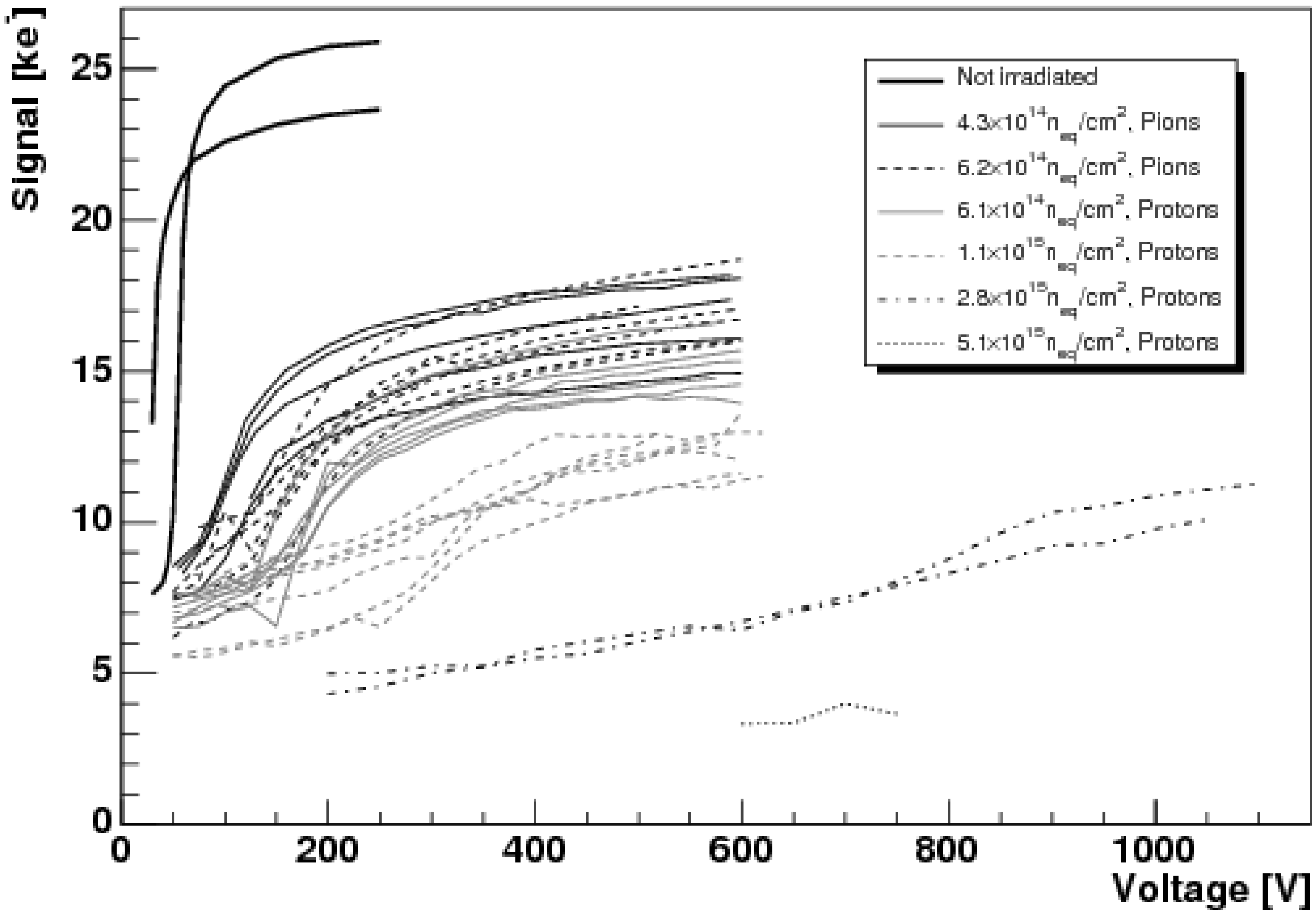
CCE Results



Collected charge vs. bias voltage for samples irradiated to different fluences

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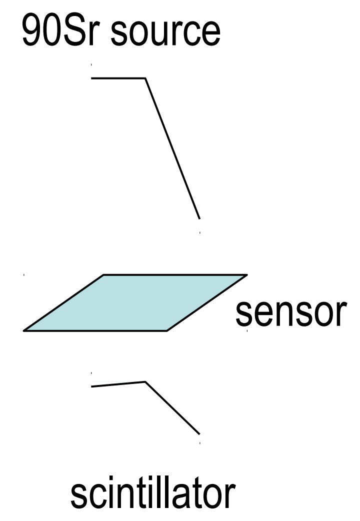
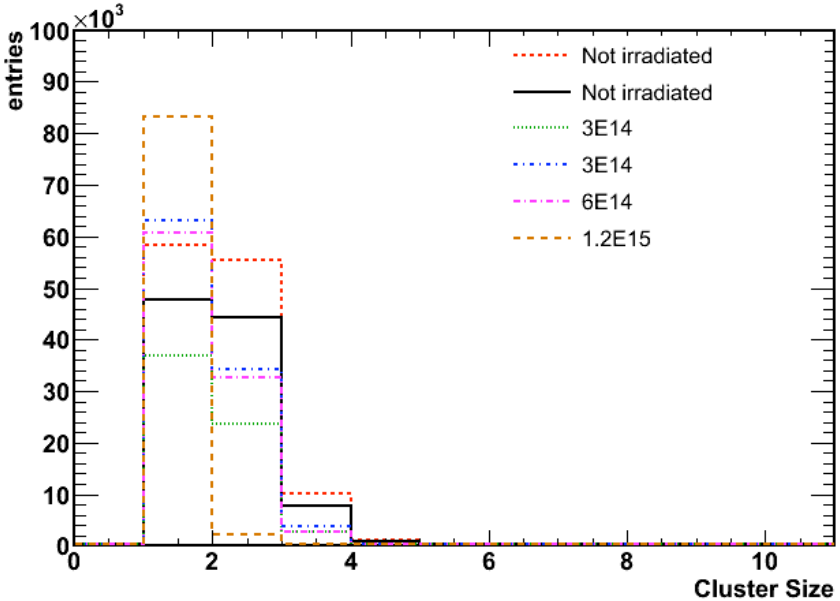
Measurements with Upgraded Setup

- CCE setup was upgraded to include a scintillator and photomultiplier tube – independent trigger
  - Wanted to make detection efficiency measurements
  - Reflections and geometry artificially lower the efficiency, so unable to make absolute efficiency measurements

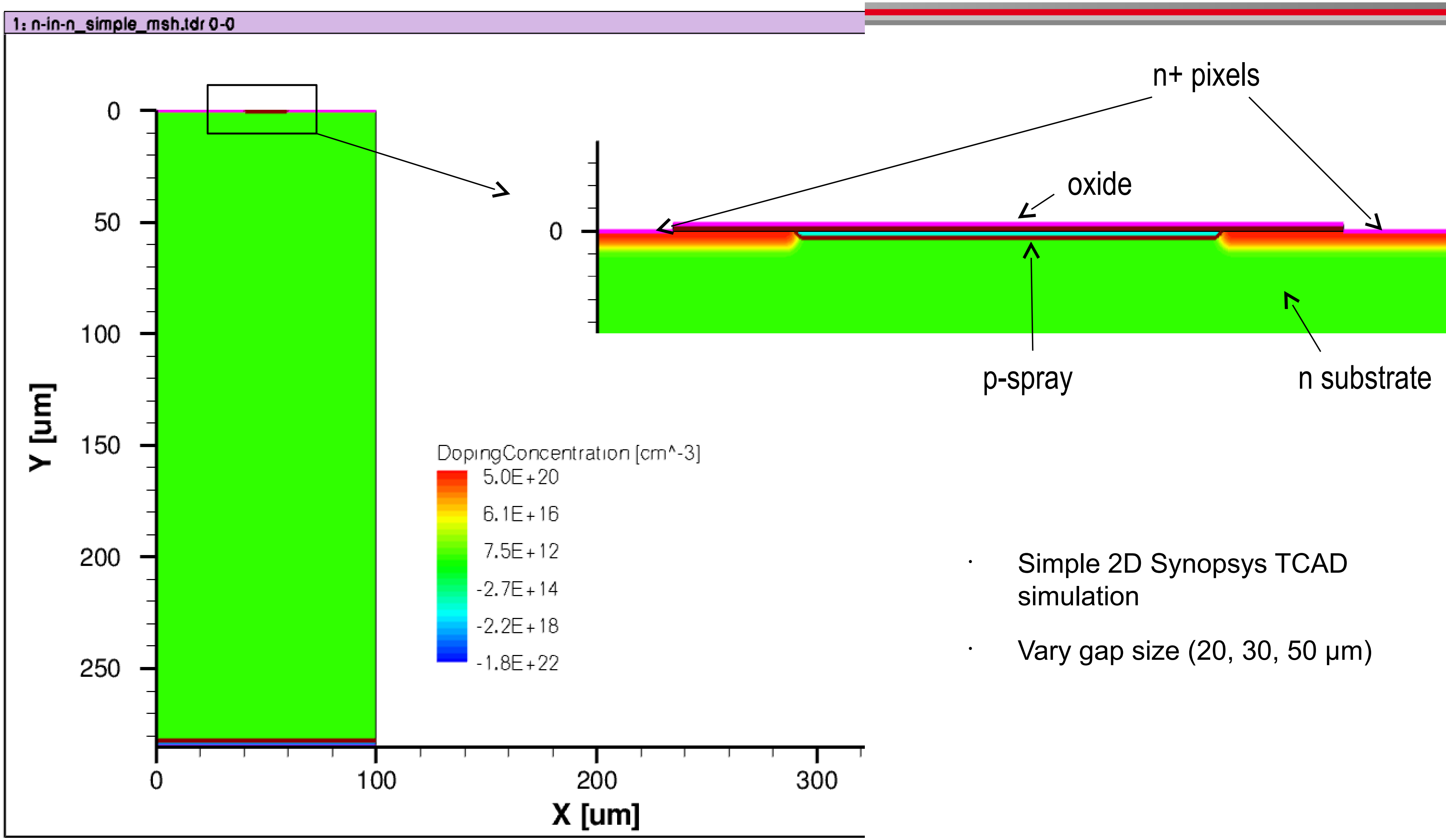


- Measurements were performed by Joaquin Siado (Master's student from University of Puerto Rico Mayaguez) as part of the PIRE program*
  - New CCE results agree with previous measurement
  - Setup changes also introduce an energy cut, reduces tail of large clusters – better data quality



* PIRE program funded by US National Science Foundation

Interpixel Capacitance - Simulation



- Simple 2D Synopsys TCAD simulation
- Vary gap size (20, 30, 50 µm)

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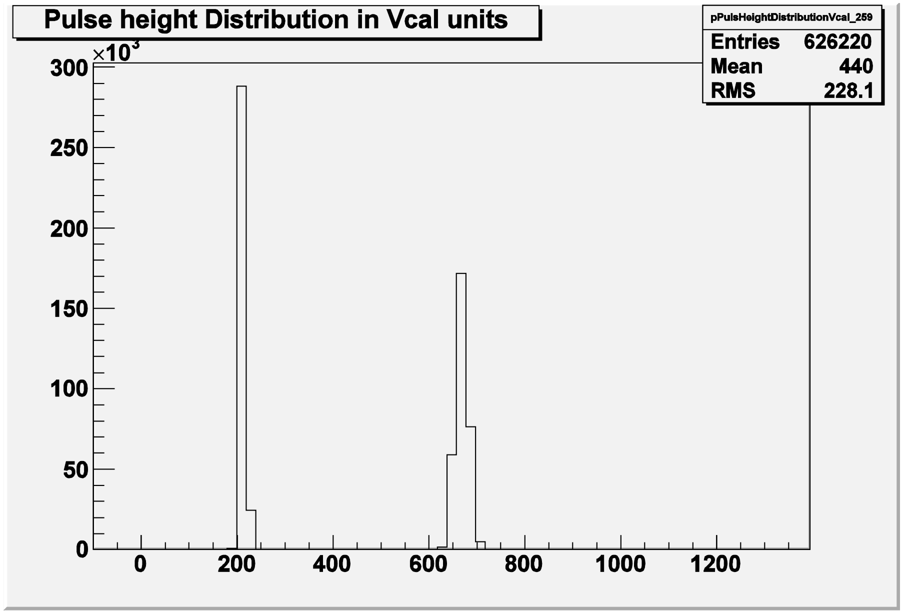
Charge vs. Position in Pixel

- When close to pixel border, some charge collected by neighboring pixel(s)

- Pulse height distribution for charge near pixel edges shows clearly multiple peaks
  - 2, 3, or 4 based on position

- Charges are added together to get “cluster charge”



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