CMS Tracker sensors Upgrade

- **R&D proposals Summary**

CMS-Tracker Italia
A.Messineo

SLHC experimental issues

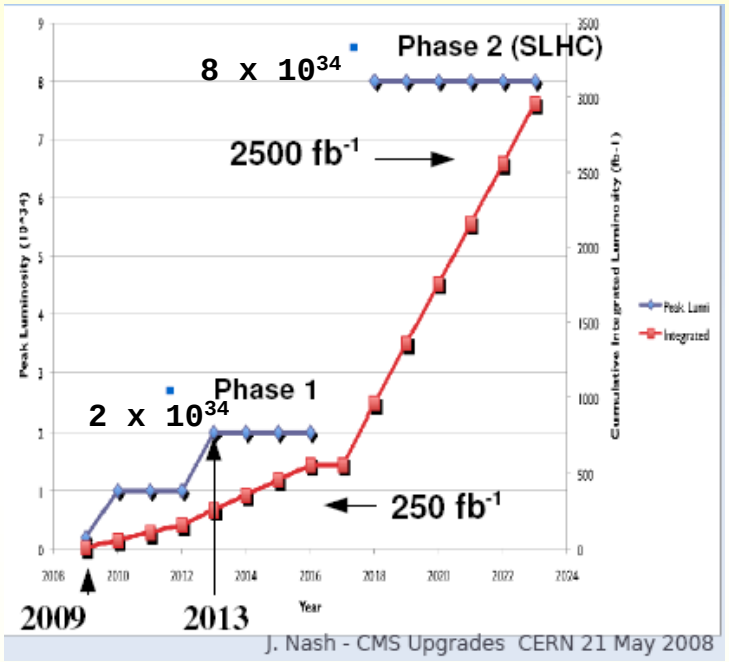
- **Tracker systems at SLHC will experience:**
  - **Heavy Radiation damage**
  - **High Local occupancy**
  - **Harsh experimental condition**

- **More powerful and new performance required, as triggering at L1**

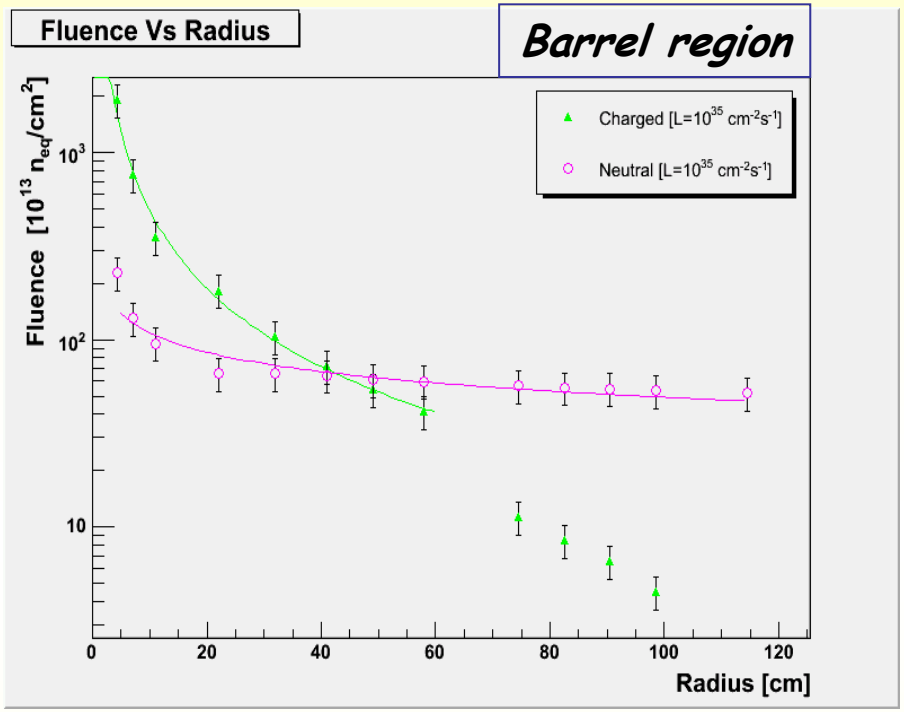
➢ **Dedicated R&D to design new tracking systems**

Radiation level in CMS

SLHC Machine Performance



Barrel region



Integrated detector fluences LHC (simulation) scaled to SLHC

Phase II :

Φ at 4 cm ~1.9 ÷ 1.5 10^{16} n_{eq}/cm^2 mainly charged

Φ at r> 50cm ~6 ÷ 4 10^{14} n_{eq}/cm^2 mainly neutral

Present CMS sensors radiation hardness technology

Pixels (n+/n)	*Φ~6 10^{14} n_{eq}/cm^2*	*4 inch tech.*
Micro-strips (p+/n)	*Φ~2 10^{14} n_{eq}/cm^2*	*6 inch tech.*

Sensor issues & challenges

- **Challenges/issues**
  - Radiation hardness
  - High Devices Occupancy
  - Power consumption
  - Sensors Operational conditions (Bias, T,…)
  - Detector module integration
  - New tracker layout
  - Cost
  - ……
- **Today promising "list of options" for sensors optimization at SLHC:**
  - Collect electrons
  - Use [O] enriched silicon
  - Active thickness
  - Device engineering:
    - small pixel, Macro Pixel, stri-xel, micro strips
  - Design and Integration
- **….....new ideas/solutions needed to equip innermost layer (3D,SOI,MAPS,3D vertical integration……)**

➢ **Multi-project approach for SLHC tracker sensors/detector/system optimization**

R&D proposal n.1

R&D for Thin Single-Sided Sensors with HPK

(submitted: January 28, 2008)

Institutions :
CERN, UCSB, Purdue, FNAL, Perugia, Bari, Pisa, Karlsruhe, Vienna, PSI

Led by M. Mannelli

Present status : Approved by CMS

R&D proposal n.2

Development of pixel and micro-strip sensors on radiation tolerant substrates for the tracker upgrade at SLHC

(submitted: April 9, 2008)

Institutions:
Bari, Catania, Firenze, Padova, Perugia, Pisa, Torino, PSI, FNAL, Purdue

Led by M. de Palma

Present status : Approved by CMS

Proposals are now official CMS upgrade projects

http://cmsdoc.cern.ch/cms/electronics/html/elec_web/docs/slhcusg/proposals/proposal_list.htm

R&D collaborations:

- **Large collaboration for each R&D proposal**
  - **Planned and supported by:**
    - **INFN groups and non Italian Institution**
    - **Size of the team: ~23 FTE**

- **Teams involved have experience in**
  - **CMS pixels and micro-strips design**
  - **Specific experiment for radiation hardness**
    - ***SMART (INFN-G5)***
    - ***RD50 (CERN)***

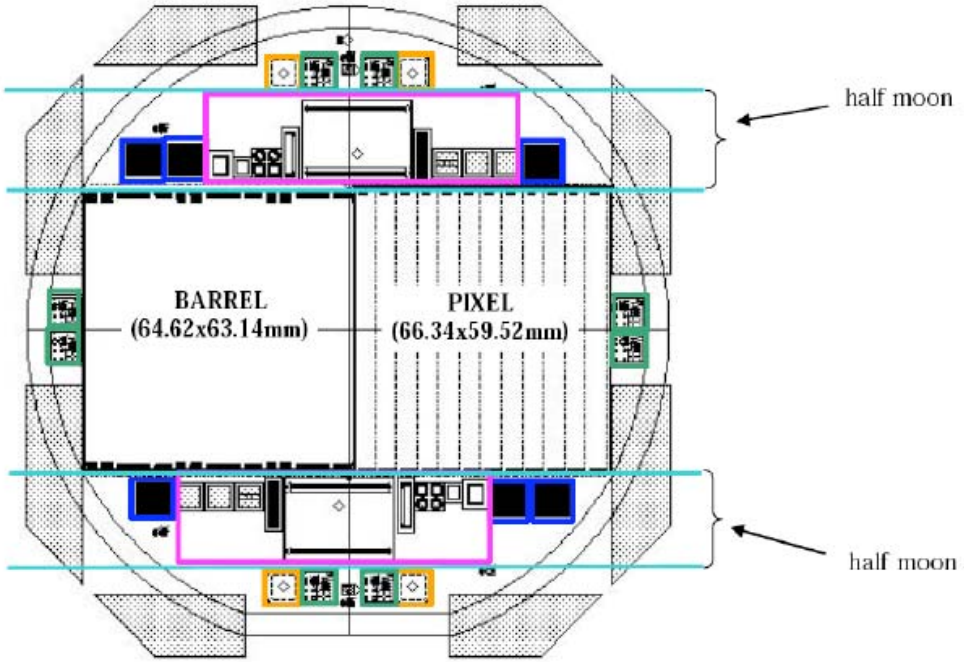
R&D n. 1 : Abstract

- The goals of this R&D are to determine the characteristics of thin (<300um) Single-Sided Silicon Sensors, and establish production techniques and capabilities suitable for high quality, large scale and low cost production of such sensors, for the CMS SLHC Tracker Upgrade.
- Both p-on-n and n-on-p sensors will be investigated, as will be different substrate types (FZ, MCZ and Epitaxial).
- The CMS SLHC Tracker will likely see large scale deployment of short strips (~2cm), and/or long pixels (~2mm).
- This R&D program will be carried with Hamamatsu Photonics, and continues to build on this successful Industrial Partnership in preparation for the SLHC.

Wafer Layout

- **The masks include a set of**
  - **Multi-Geometry Strip sensors,**
    - **benchmark for substrate thickness less than or equal to the strip pitch.**
  - **Multi-Geometry Long Pixels with the pixel length as an additional parameter**
- **The studies will include**
  - **Strip Capacitance: to back-plane, inter-strip, and total**
  - **Critical fields, depletion and break-down voltage**
  - **Charge collection**
- **Range of: strip pitch, w/p, and metal overhang and substrate thickness**

6 inch wafer



Proposed Multi-Geometry Pixels

12 Sets of Pixel Geometries

- Each Set with independent Bias and Guard Rings
- Pixels are DC coupled to Al Layer & Daisy-Chained
  - (see below)
- Fixed Pixel Pitch = 120um
- Fixed Pixel w/p = 0.25; implant width = 30um
- Fixed Over-Metal = Implant width + 8um
  - Both across & along Pixel

4 Pixel Lengths

- Pixel Lengths = 1, 2, 3, 4 mm

For Each Pixel Length

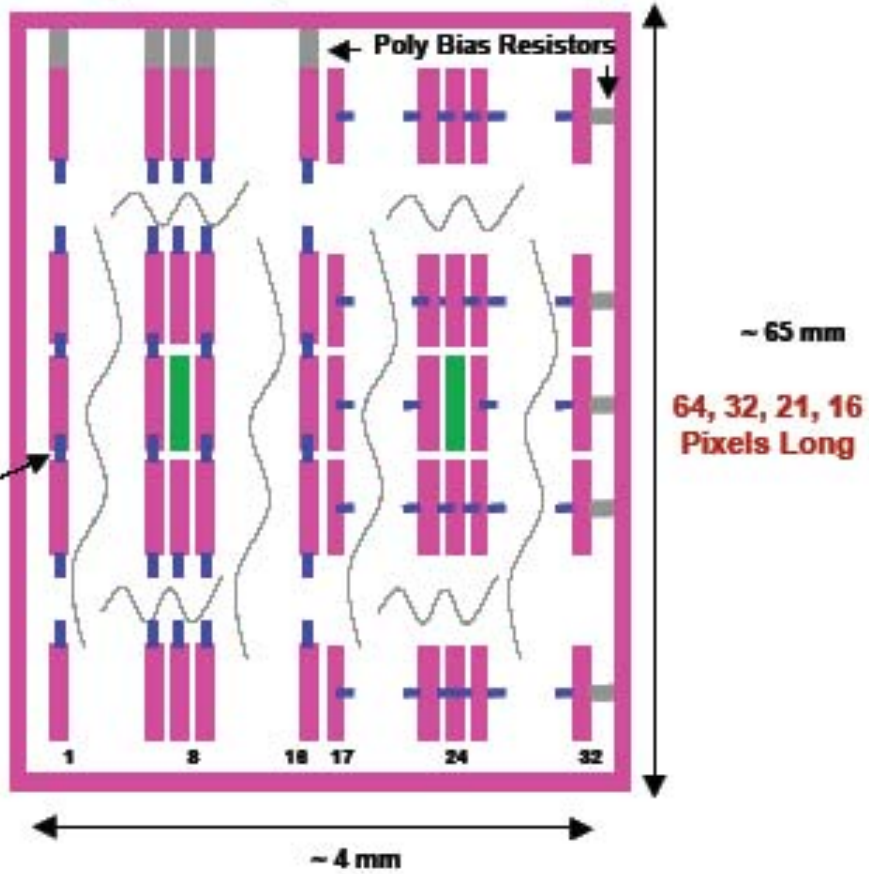
3 Gaps (along Pixel Length)

- Inter-Pixel Gaps = 60, 90, 120 um

32 Pixels (strips) across, in Two Groups of 16

- 16 biased from top & Daisy-Chained Length-wise
- 16 biased from the side & Daisy-Chained Across
- Central Pixel (green) is NOT Daisy-Chained (isolated)

Inter-Pixel Daisy-Chaining
Along Pixel Length / Across Pixel Length



Production plan

		N-FZ	P-FZ pspray	P-FZ pstop	n-MCZ	P-MCZ pspray	P-MCZ pstop	N-epi	P-epi pspray	P-epi pstop
200 um thick by thinning	QTY	9	6	6	9	6	6	0	0	0
100 um thick on carrier substrate	QTY	9	6	6						
100 um thick epitaxial	QTY							9	6	6
50 um thick epitaxial	QTY							9	6	6
200 um thick on carrier substrate & double metal	QTY	6		6						

Processing of:
- ***1 Layout***
- ***117 wafers in total***

- ***Total cost ~560K CHF***

- **This R&D should come to a full set of results in about one year.**
  - **Sensor fabrication will take about 6 months.**
  - **Sensor characterization and functionality tests, including irradiation will take another approximately 6 to 9 months.**
  - **Test-beam measurements of charge collection efficiency, making use of the common infrastructure currently being set up, will complete the program.**
- **Negotiation and technical discussion with HPK already in an advanced stage, project is about to take off**

R&D n.2 : Abstract

- **The present project addresses the R&D activity to improve and optimize the production technology of radiation tolerant silicon sensors to stand the fluences foreseen for the new CMS tracker at SLHC.**

- **The goal is to reduce substantially the lot of options now available (process type, doping type, substrate thickness) in order to build radiation-hard sensors capable of measuring the impact position of the particle with high precision.**

- **Sensors will be designed and produced with planar technology:**
  - **micro-strip, pixel and macro pixel sensors,**

- **Synergies with industrial partners:**
  - **a first approach to the industrial preproduction of Silicon Detectors optimized for the tracker at SLHC.**

- **Activity tuned to plan and study the most promising solutions for Phase I/II.**

Goals

We expect to clarify technological aspects:

- the use of the 6 inch technology with single side process for both electron and hole collecting devices, (p-type & n-type bulk);
- the production of devices with material not commonly used such as Magnetic Czochralski or Epitaxial silicon;
- standardization of sensor process in order to make the large scale production affordable;
- the features of the process and design rules for producing radiation resistant devices capable of stable operation at high bias voltages;
- the influence of the thickness of the wafer to decrease power dissipation after radiation damage;
- the limits on sensor design (size and geometry of the active area) given by current technology;
- the methods of interconnection between sensors and sensors to electronics (wire/bump);
- the technique for prototyping of tracker detectors.

- **The proposed R&D plans to optimize device geometry to fulfill the following requirements:**
  - low occupancy levels,
  - high coordinate measurement resolution,
  - trigger track primitive generation, to be applied for the "cluster width trigger" (see F.Palla talk) technique

R&D plan

- The project foresees a set of scheduled submissions of improved wafer layouts
- A tentative and preliminary priority list for the layout submissions

Submission 1 :

Design of single chip prototypes on different materials

Material / Thickness	Fz-p	Fz-n	MCz-p	MCz-n	Epi-p	Epi-n
300 um	H	H	H	H	-	-
200 um	L	-	H	H	-	-
100 um	L	-	L	-	L	L

Goals:
Optimal devices designs ;
Best radiation tolerant material ;
Production of mini batches

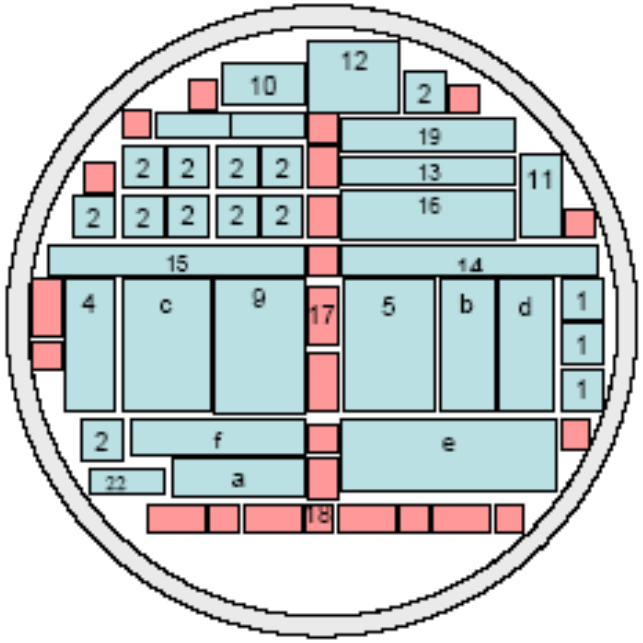
Example p-type processing	P-FZ	P-MCZ	P-epi
320um thick with DML (wf qty)	5	5	-
200 um thick without DML (wf qty)	5	5	-
100 um thick epi with DML (wf qty)	-	-	5

Quotation from HPK:
Mask, development and production
1 Layout
25 wafers
3 material 'flavours'

TOTAL COST ~142K €

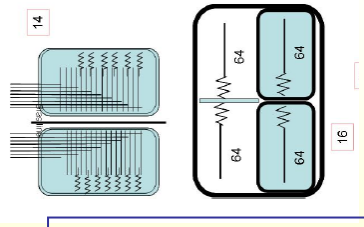
1st Submission: preliminary layout

6 inch wafer

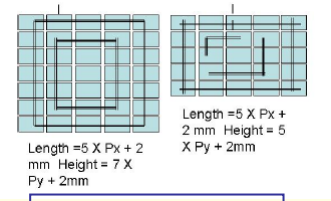


	CMS design	benchmark
Pixels	CMS design	Pixel C measurement
	CMS modified W and inter P	performance of new geometries
Macro Pixels	pitches: 50, 100 um	long pixel regime (a few mm long)
	pitches : 30 , 60 , 100, 120 um	cluster width trigger study
Microstrips	AC / DC strips coupling	
	short strips : pitch 120 um	short strips regime (a few mm long)
Microstrips	pitch 80 um	interconnection schemes test
	CMS design	Process study & Producer comparison
Test structures	Devices Capacitance study	Pixels C , strips C
	Diodes	Radiation tests

Devices with geometry suitable to equip SLHC-tracker layers at different radii
Pixels : inner region
Strips : outer region



DM / Det. Chain for integration



Capacitance

Device design compatible with present F.E. electronics available in CMS (PSI42, pixels, and APV25, strips)

R&D plan: 2nd and 3rd Submissions

Submission 2 :

- **Scale to devices with real size**

- **The new masks will include:**
  - few “real size” detector both pixel (inner tracker region) and micro-strip (outer tracker region)
  - optimized and better proved interconnection of devices
- **These devices will be produce on the**
  - First promising substrate
  - Second promising substrate

Submission 3 :

- **Full batch and pre-production**

- **Two new sets of masks: one Pixel, one micro-strip will be designed. Production of detector will be done on the “best” material**
  - real size “final” pixel detector
  - real size “final” micro-strip detector

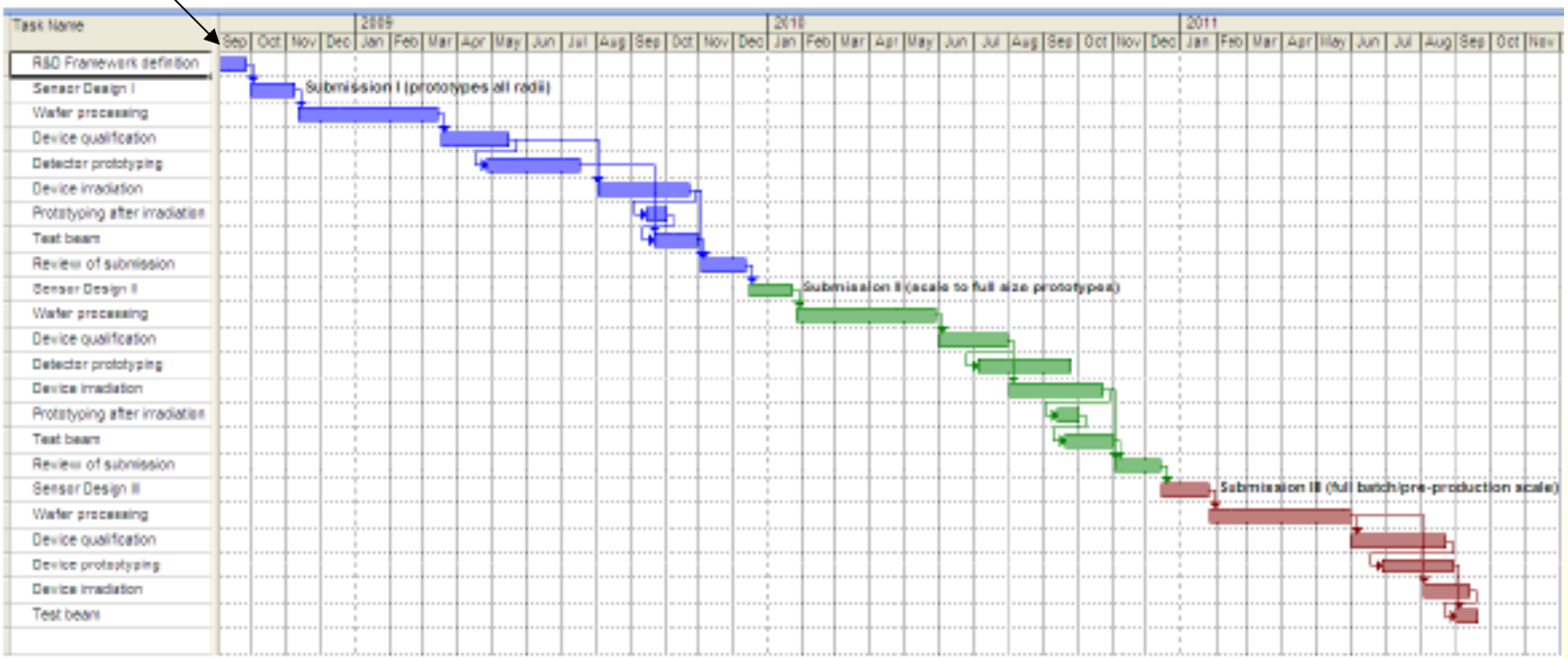
Activity matrix

- **Activity 1: Framework definition for sensors upgrade.**
- **Activity 2: Sensor design and wafer layout.**
- **Activity 3: Wafer processing.**
- **Activity 4: Device and production qualification.**
- **Activity 5: Device irradiation**
- **Activity 6: Sensor-ROC interconnection**
- **Activity 7: Beam tests**
- **Activity 8: Module assembly**

Table 1 : Activity Matrix

Institution	Act. 1	Act. 2	Act. 3	Act. 4	Act. 5	Act. 6	Act. 7	Act. 8
INFN-Bari	X	X	X	X	X		X	
INFN-Catania	X			X	X		X	
INFN-Firenze	X	X		X	X		X	X
INFN-Padova				X	X		X	
INFN-Perugia	X	X	X	X	X		X	X
INFN-Pisa	X	X	X	X	X	X	X	X
INFN-Torino				X	X		X	X
PSI	X	X		X	X	X		
FNAL	X	X		X	X	X	X	X
Purdue University	X	X		X		X	X	

- **The present R&D project foresees duration of 36 months, to cover the full R&D activities up to preproduction.**
  - **A year-based time schedule of milestones is foreseen to verify the achievements in coordination with the CMS-WG on SLHC activities, and eventually to readdress specific activities/goals.**
  - **Activities of the project are also tuned and scheduled to address specific R&D for Phase I and Phase II tracker upgrade.**
- **Preliminary discussion with producers already started.**



Milestone list:

1) milestone 1 : approval of mask set for submissions
2) milestone 2 : sensors productions (Submission I , II and III)
3) milestone 3 : test beam (2009 , 2010, 2011)

Financial plan for INFN

- **2 R&Ds with different time schedule**
- **Some room to further optimize Layout, production plan and costs.**

- **R&D n.1 : total cost 380K€ (almost already all collected)**
  - **Maybe in a time scale of 3 years a new processing iteration will be needed, no cost estimation today**
- **R&D n.2**
  - **First year estimation:200K€**

ITEM	Attività	Costo (K€)
Sensori MCz/Fz/Epi (25-bulk p-type & 10-n-type)	Contr. per Maschere e produzione batch	160
	Consumi caratterizzazione	30
	Consumi irraggiamento	10
totale		200

  - **Second year: ~400K€**
    - **1 mask set (hopefully), 2 processed materials, internal splitting**
  - **Third year : ~400K€**
    - **2 mask sets, 1 processed material (hopefully), internal splitting**

Summary

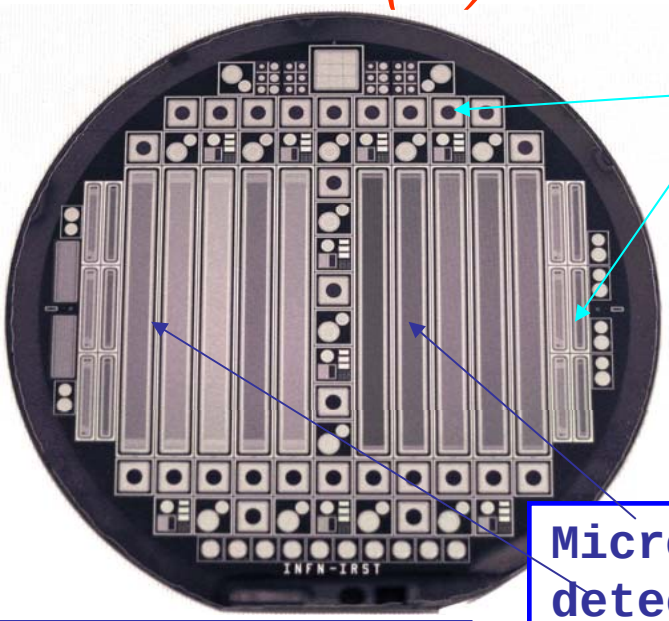
- **CMS-INFN tracker Italian community involved in two R&Ds:**
  - Approved by CMS (committee/referees): considered as promising for the CMS tracker upgrade, and recognized as CMS upgrade projects
  - International collaboration for each R&D
  - Cover wide range of options for silicon devices upgrade, for both inner (pixels) and outer (strips) tracker region
  - Supported teams with experience in the field of radiation hardness research
  - Overlap with other R&D (cluster width trigger)

- **Ready to start the planned activity inside CMS:**
  - We should support, in CMS, our contribution to “the Ideas” of the R&Ds with clear answers about:
    - Projects fit within INFN plans ?
    - T_0, starting time : when? Will fit the CMS needs & timescale for Phase I & II?
    - Resources: can we afford the plan?

extra

Wafers layout:

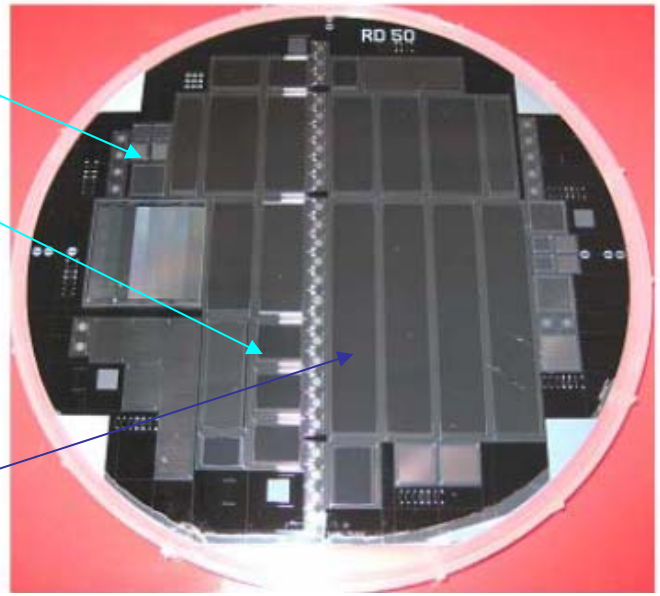
SMART (4")



✓*Wafer Layout designed by SMART collaboration*
✓*Masks and process by ITC-IRST (Trento)*
✓*n-on-p & p-on-n*

15 irr. sensors

MICRON (6")



✓*6" wafer*
✓*Wafer Layout designed by R&D50*
✓ *Masks and process by Micron*
✓*n-on-p & p-on-n*

2 irr. sensors

Pad, diodes, test struct., pixels ...

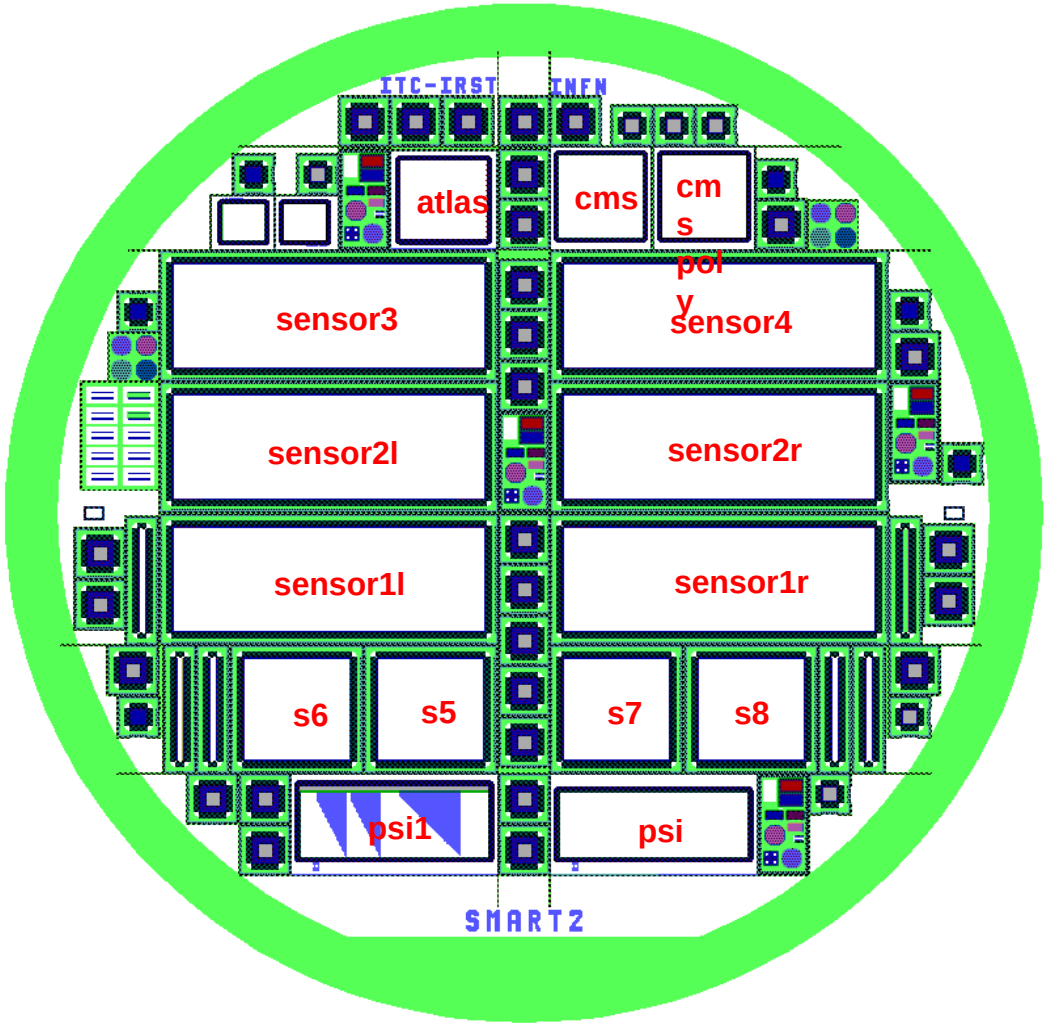
Micro-strip detectors

P-type strip isolation:

✓*Low/High dose p-spray (SMART)*

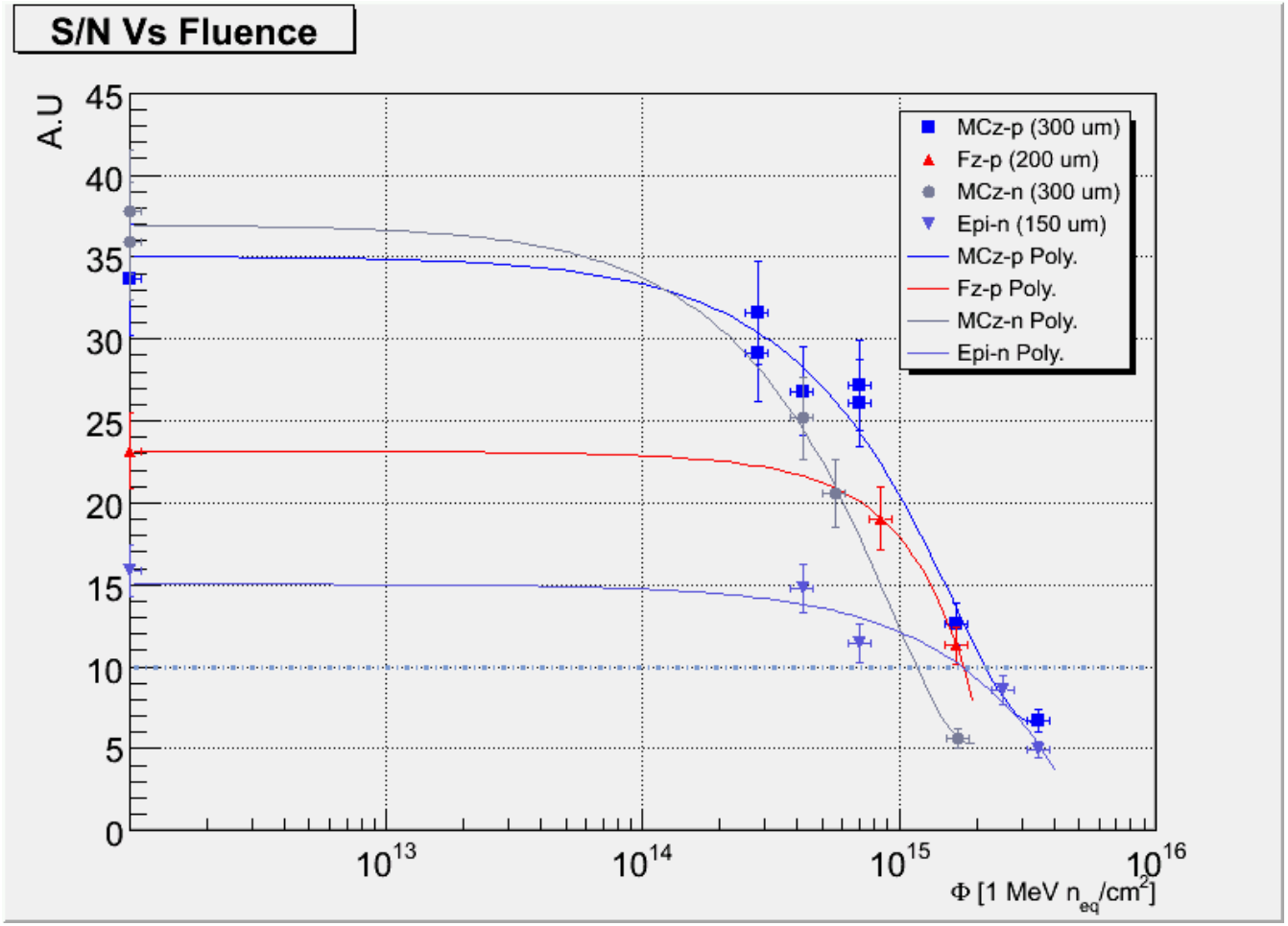
✓*Moderate p-spray (Micron)*

WAFER layout “SMART2”



Summary: S/N for irradiated detectors

Detector operation limit S/N >= 10 (safe value)



MCz(p) ϕ=2.5 10^{15}

Epi(n) ϕ= 2 10^{15}

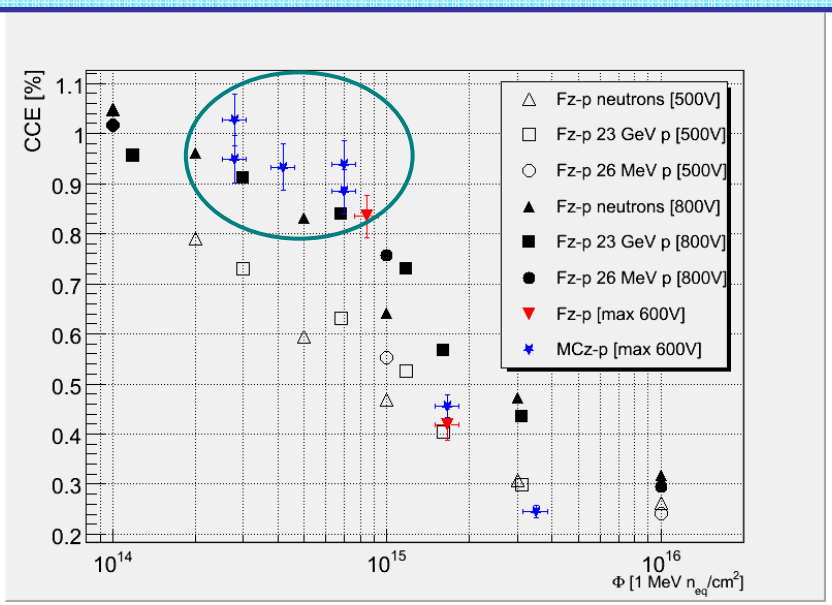
Fz(p) ϕ= 2.1 10^{15}

MCz(n) ϕ = 1.1 10^{15}

P-type and Epi good candidates to use in the CMS Tracker Inner Barrel detector (22 < R < 60cm at SLHC)

ϕ (22 cm) ~ 2.4 10^{15}

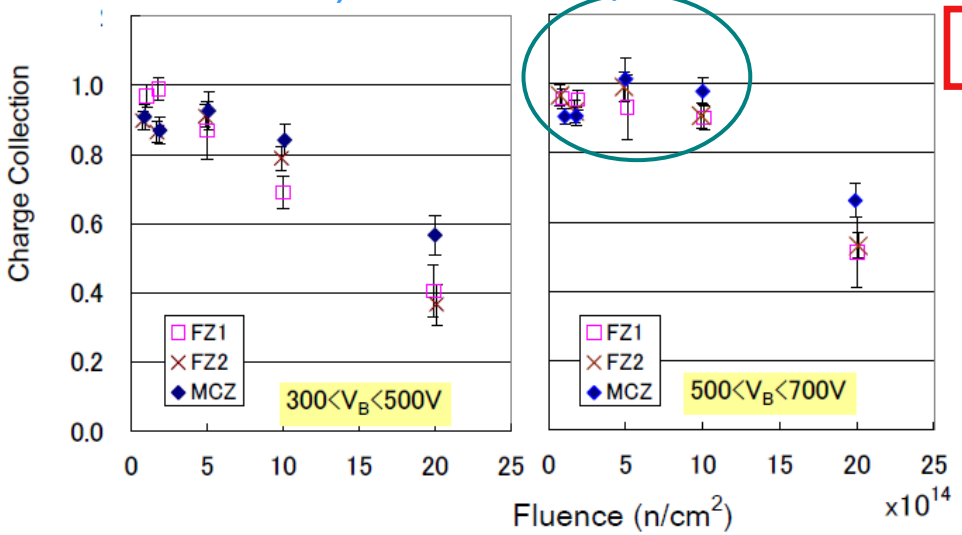
Comparison to Casse measurements:



G.Casse, 12 R&D50 workshop June 2008

Difficult to compare absolute charge, better with CCE (or possibly S/N)

- *Different read-out: Digital Vs Analog;*
- *Difference in running conditions (Temperature, source, sensor geometry, bias voltage)*
- *Source of irradiation.*



better agreement with ATLAS data

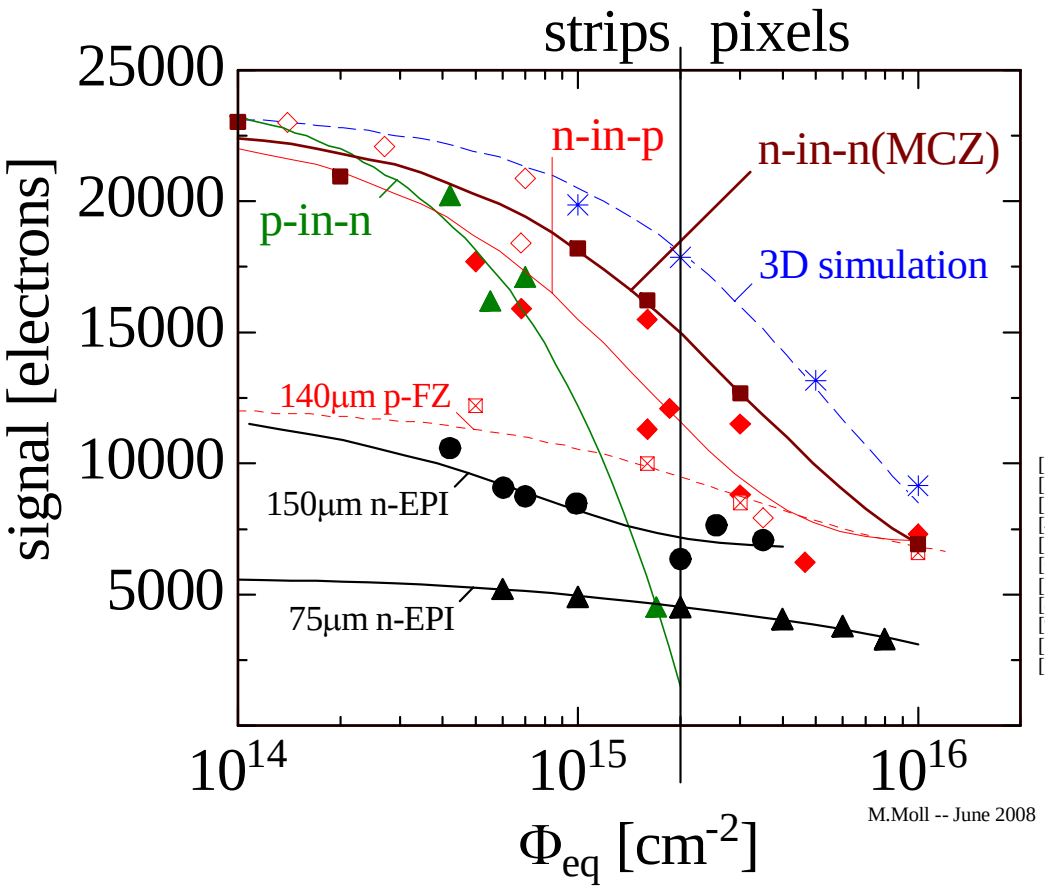
Y.Unno (ATLAS), 3rd Workshop on Advanced Silicon Radiation Detectors, Barcelona, Spain, 14-16 April. 2008

, RESMDD'08

Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

Note: Measured partly under different conditions! Lines to guide the eye (no model/no fit)!



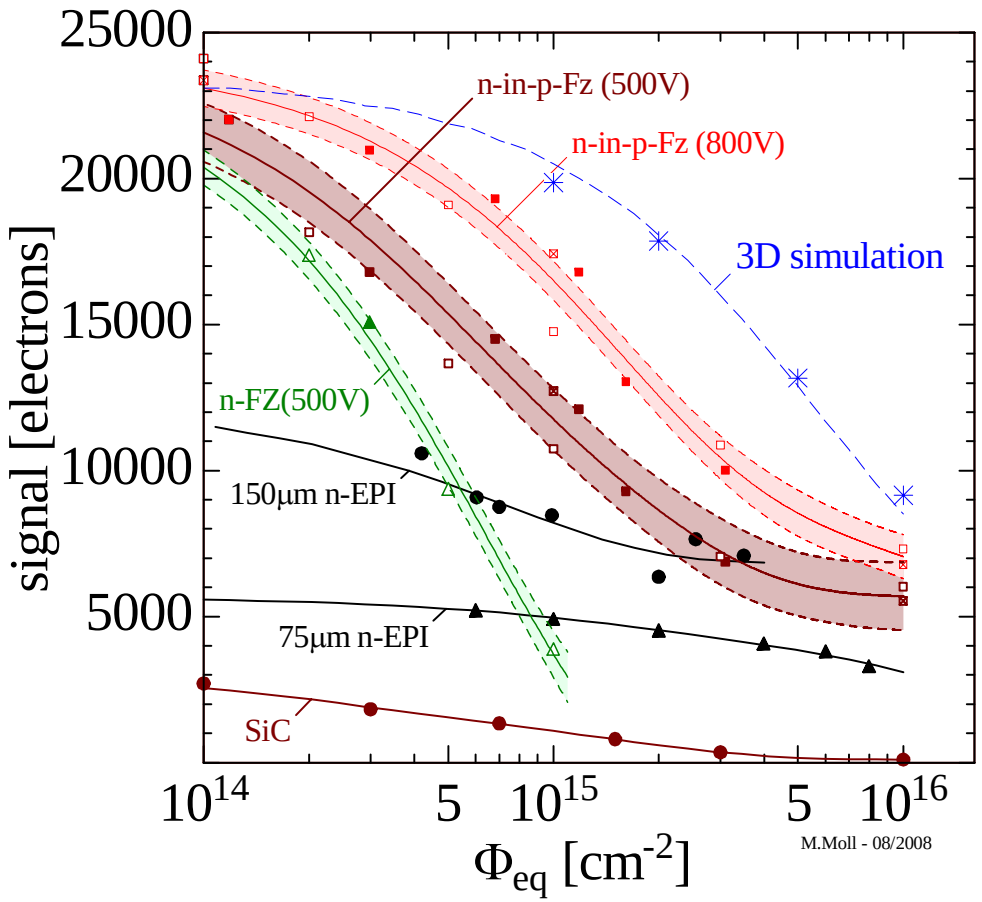
- ✳ Double-sided 3D, 250 µm, simulation! [1]
- ◆ n-in-p (FZ), 280 µm [2,3]
- ◇ n-in-p (MCZ), 300µm [4,5]
- ▲ p-in-n (MCZ), 300µm [6]
- ⊠ n-in-p (FZ), 140 µm, 500V [7]
- ● p-in-n (EPI), 150 µm [8,9]
- ▲ p-in-n (EPI), 75µm [10]
- ■ n-in-n (MCZ), 300µm, 800V [11]

[1] 3D, double sided, 250µm columns, 300µm substrate [Pennicard 2007]
[2] p-FZ, 280µm, (-30°C, 25ns), strip [Casse 2007]
[3] p-FZ, 280µm, (-30°C, 25ns), strip [Casse 2004]
[4] p-MCZ, 300µm, (-30°C, µs), pad [Bruzzi 2006]
[5] p-MCZ, 300µm, (<0°C, µs), strip [Bernadini 2007]
[6] n-MCZ, 300µm, (-30°C, 25ns), strip [Messineo 2007]
[7] p-FZ, 140µm, (-30°C, 25ns), strip [Casse 2007]
[8] n-EPI, 150µm, (-30°C, 25ns), strip [Messineo 2007]
[9] n-epi Si, 150µm, (-30°C, 25ns), pad [Kramberger 2006]
[10] n-epi Si, 75µm, (-30°C, 25ns), pad [Kramberger 2006]
[11] n-MCZ Si, 300µm, (-25°C, 25ns), n-strip [Casse 2008]

Silicon materials for Tracking Sensors

- **Signal comparison for various Silicon sensors**

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!



Silicon Sensors

- p-in-n (EPI), 150 µm [7,8]
- p-in-n (EPI), 75µm [6]
- n-in-p (FZ), 300µm, 500V, 23GeV p [1]
- n-in-p (FZ), 300µm, 500V, neutrons [1]
- n-in-p (FZ), 300µm, 500V, 26MeV p [1]
- n-in-p (FZ), 300µm, 800V, 23GeV p [1]
- n-in-p (FZ), 300µm, 800V, neutrons [1]
- n-in-p (FZ), 300µm, 800V, 26MeV p [1]
- p-in-n (FZ), 300µm, 500V, 23GeV p [1]
- p-in-n (FZ), 300µm, 500V, neutrons [1]
- Double-sided 3D, 250 µm, simulation! [5]

Other materials

- SiC, n-type, 55 µm, 900V, neutrons [3]

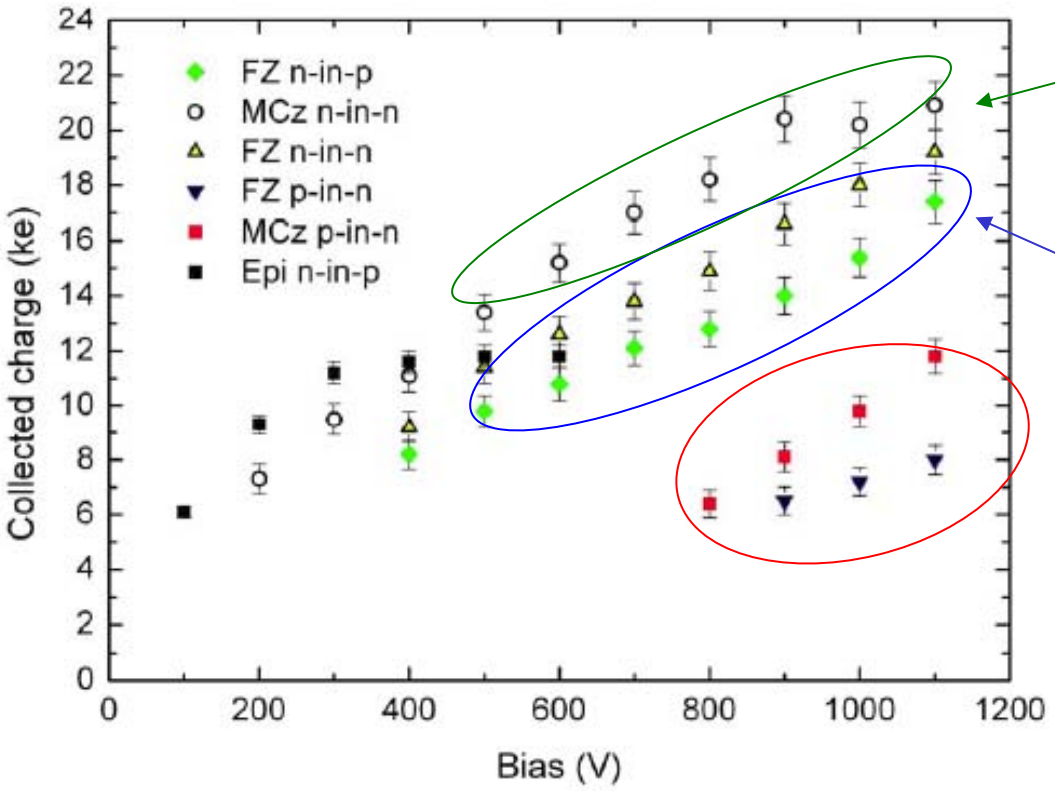
References:

[1] p/n-FZ, 300µm, (-30°C, 25ns), strip [Casse 2008]
[2] p-FZ,300µm, (-40°C, 25ns), strip [Mandic 2008]
[3] n-SiC, 55µm, (2µs), pad [Moscatelli 2006]
[4] pCVD Diamond, scaled to 500µm, 23 GeV p, strip [Adam et al. 2006, RD42]
Note: Fluenze normalized with damage factor for Silicon (0.62)
[5] 3D, double sided, 250µm columns, 300µm substrate [Pennicard 2007]
[6] n-EPI,75µm, (-30°C, 25ns), pad [Kramberger 2006]
[7] n-EPI,150µm, (-30°C, 25ns), pad [Kramberger 2006]
[8] n-EPI,150µm, (-30°C, 25ns), strip [Messineo 2007]

Strip detectors – MCZ silicon

- **Gianluigi Casse (Liverpool) [RD50 Workshop – June 2008]:**
  "Charge Collection Measurements on MICRON RD50 sensors"

Neutron irradiations: medium doses ($1x10^{15}$ n cm^{-2})



MCZ
n-in-n

FZ sensors
n-in-n
and
n-in-p

p-in-n sensors
(MCZ, FZ)