CMS Beam Tests for the Sensor Upgrade Program

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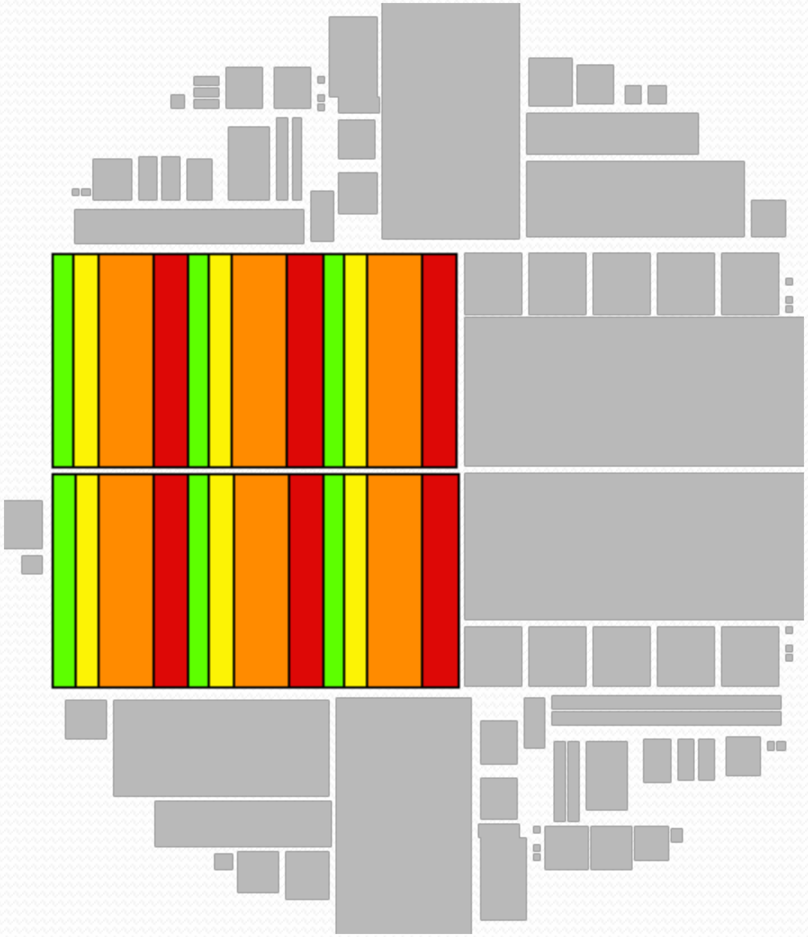
On behalf of the CMS Tracker Collaboration
With special thanks to J. Härkönen, P. Luukka, and T. Mäenpää for input

CMS sensor upgrade program

- The overall aim of the program is to identify a silicon material for the strip tracker region (R>20cm) of CMS for the HL_LHC era.
  - 3000 fb^{-1}
  - **Improvement in material budget if possible**
- Detailed comparisons of
  - silicon types (FZ, MCz, Epi)
  - n and p bulk doping
  - thickness, strip parameters
- Wafers acquired from a single vendor
- Several types of test structures and many different measurements before and after irradiation, and at different temperatures
  - IV, CV
  - TCT, CCE, Lorentz angle, noise
  - Microscopic (DLTS and TCS)
  - Oxygen concentration
  - Source, laser, and test beam



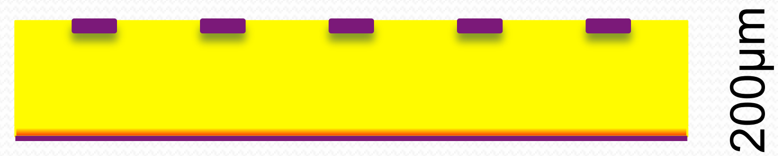
The focus of this talk is the test beam results for the Multi-geometry strip detectors (MSSD)

HPK wafer types

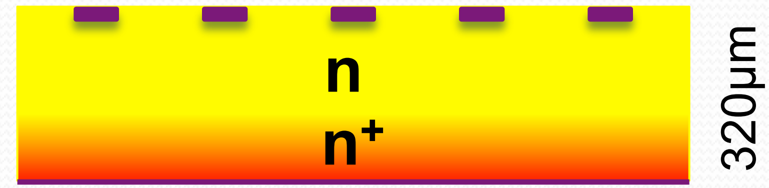
	Label	n-type	p-type (p-stop)	p-type (p-spray)
FZ320	FZ320N/P/Y	6	6	6
FZ200 deep diff.	FZ200N/P/Y	6	6	6
FZ120 deep diff.	FZ120N/P/Y	6	6	6
MCz200 thinned	MCZ200N/P/Y	6	6	6
Epi100	Epi100N/P/Y	6	6	6
EPI50	Epi50N/P/Y	6	6	6
FZ200 thinned	FTH200N/P/Y	6	6	4
FZ120 on carrier	FDB120N/P/Y	6	6	4
FZ200 with 2. metal	F200DN/DP/DY	6	6	6

Received second batch of six FTH200N with better IV (_2x)

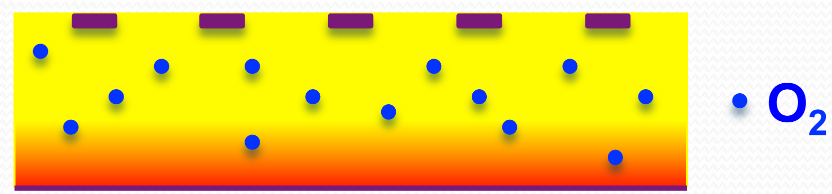
Received only 2 Epi100N but 4 Epi70N



Thinned



Deep Diffusion

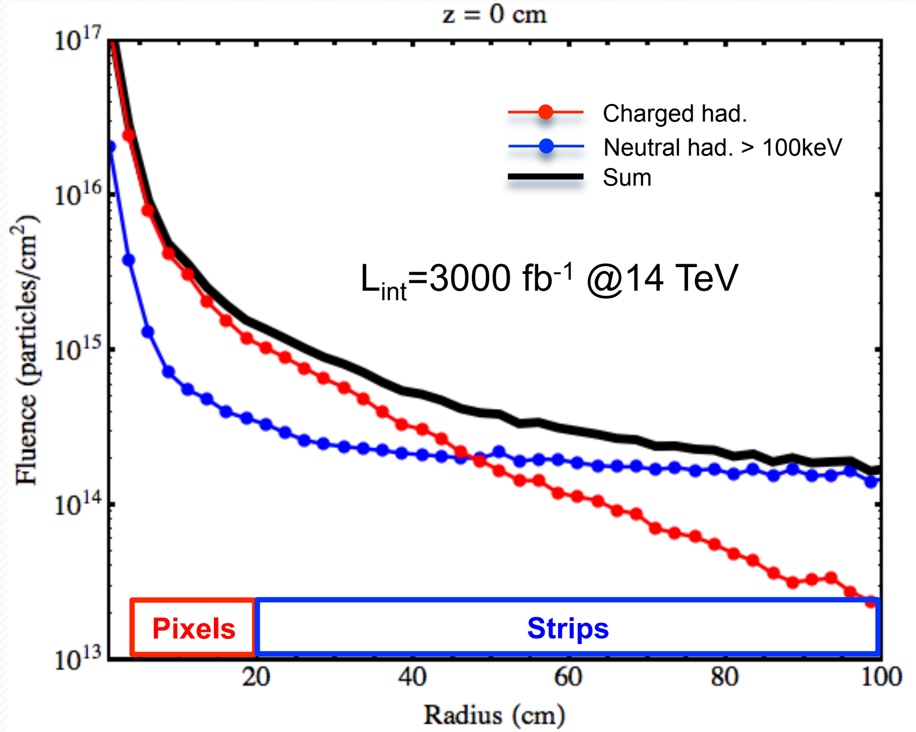


Oxygen byproduct of DD process

The oxygen content in the deep diffusion FZ silicon has been measured to be comparable to that of the 200µm MCz silicon (3-6x10^{17}). Irradiation/test beam studies for FTH200 silicon are still in process.

Irradiation

- Charged and neutral hadron
  - Protons
    - **23 MeV (Karlsruhe cyclotron)**
    - 23 GeV (CERN PS)
    - 800 MeV (Los Alamos)
  - Neutrons
    - ~1 MeV (TRIGA Reactor Ljubljana)
- Mixed fluences corresponding to R=20cm after 3000 fb^{-1} for MSSDs are the subject of this talk
  - Protons $1x10^{15}$ 1 MeV n_{eq}/cm^2 (all from Karlsruhe)
  - Neutrons $0.5x10^{15}$ 1 MeV n_{eq}/cm^2
- There are test beam results for the separate irradiations.

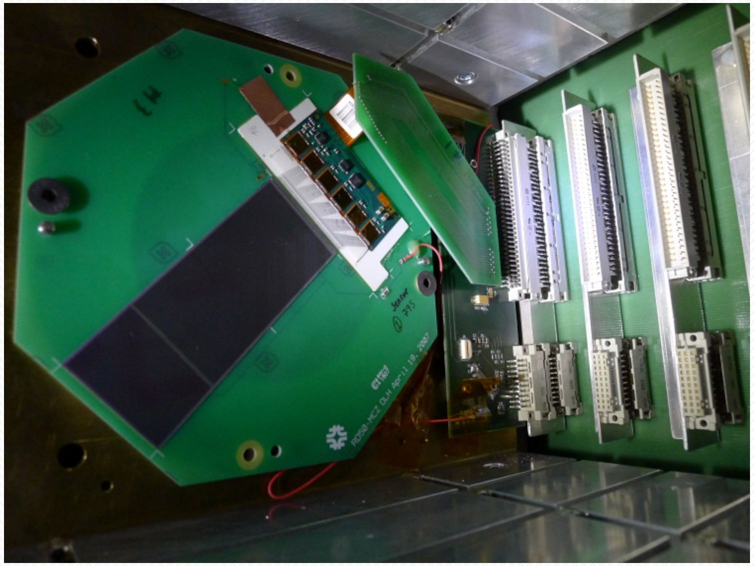


From a MARS simulation of the present CMS Tracker. The fluence is in particles/cm², but the sum is very close to the NIEL fluence.

www.uscms.org/uscms_at_work/dmo/siTracker/lhcCalcform.html

CMS Silicon Beam Telescope (SiBT)

- Beam telescope houses 4 reference planes + (up to) 4 DUTs + 4 reference planes.
- Based on CMS module burn-in ("Vienna") system.
  - Older version of CMS Tracker DAQ
- Upper and lower plates are cooled down to ~-20°C by Peltier elements.
- Reference and DUT sensors connected to CMS APV25 based hybrids.
- D0 Run IIb HPK sensors used for reference planes.
  - 4cm x 9cm with 60μm pitch, intermediate strips
  - **Mounted at ±45° so 4cm x 4cm overlap**
- SiBT analysis carried out within CMS software framework and independently within the EuDet framework. Results shown in this talk are based on CMSSW.



HPK Test Beam History

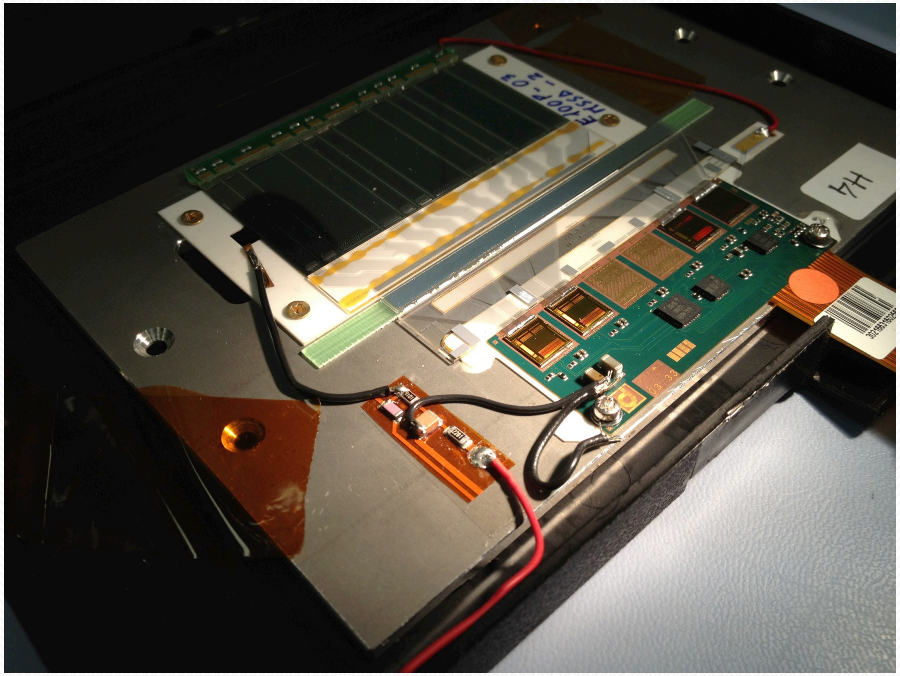
- March 2011 (FNAL)
  - Non-irradiated sensors
- September 2011 (CERN)
  - Some sensors with either proton or neutron irradiation
  - A few non-irradiated sensor from the previous test and for subsequent tests
- May 2012 (CERN)
  - Sensors with both proton and neutron irradiation
- October 2012 (CERN)
  - Irradiated sensors after annealing
- Scheduled for June 2013 (DESY)
  - Emphasis on irradiated physically thinned FZ sensors
  - DATURA telescope. SiBT used for all other tests.

HPK beam tests at CERN

	Non-irradiated	Irradiated	p	n	notes
September 2011	F200P_04_1	F200P_06_1		4.0E+14	
	F320N_04_1	F200P_06_2	3.0E+14		
		F200Y_02_2		4.0E+14	
		F200Y_10_2	3.0E+14		
		F320N_08_2		4.0E+14	
		M200P_07_2	3.0E+14		
May 2012	F200P_04_1	F200N_04_2	1.0E+15	5.0E+14	
	F320N_04_1	F200P_01_2	9.5E+14	5.0E+14	
	M200N_02_2	F200Y_06_1	9.5E+14	5.0E+14	
		F320N_05_1	8.6E+14	5.0E+14	
		F320P_02_2	8.4E+14	5.0E+14	broken in shipment
		F320Y_05_1	8.4E+14	5.0E+14	
		M200N_04_1	8.2E+14	5.0E+14	
		M200P_01_2	8.6E+14	5.0E+14	
		M200Y_05_1	8.2E+14	5.0E+14	
October 2012	F200P_04_1	F200N_04_2	1.0E+15	5.0E+14	FNAL annealed
	F320N_04_1	F200P_01_2	9.5E+14	5.0E+14	CERN annealed, broken
	FTH200N_24_2	F200Y_06_1	9.5E+14	5.0E+14	CERN annealed
	FTH200P_08_1	F320N_05_1	8.6E+14	5.0E+14	FNAL annealed
	FTH200Y_03_1	F320Y_05_1	8.4E+14	5.0E+14	FNAL annealed
	M200N_02_2	M200N_04_1	8.2E+14	5.0E+14	FNAL annealed
		M200P_01_2	8.6E+14	5.0E+14	CERN annealed
		M200Y_05_1	8.2E+14	5.0E+14	CERN annealed

Module grounding improvement

- Prior to the October 2012 beam test an improvement to the module grounding scheme was found.
- Also verified in CMS single module (ARC) test station.

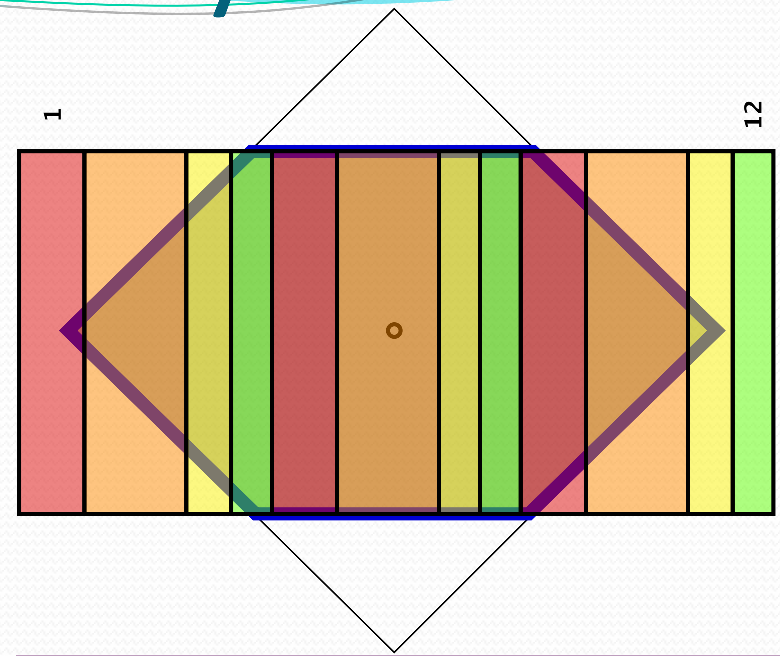


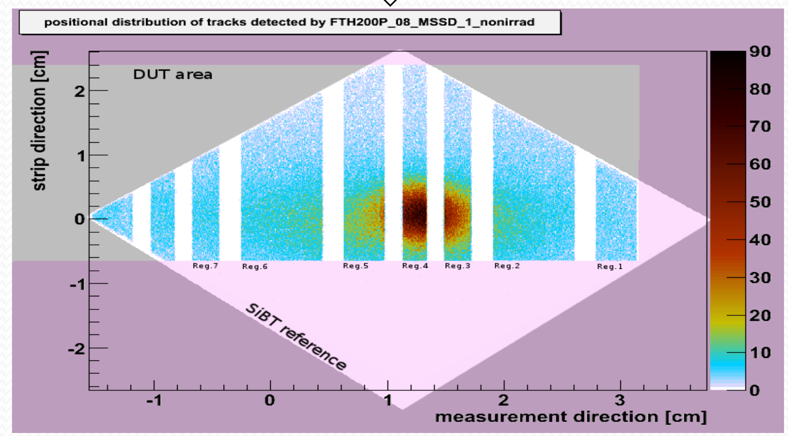
	Median Raw Noise												
FZ200P_04_1	1.8	8.8	1.9	1.9	3.0	11.3	2.0	3.1	1.9	12.3	2.0	2.5	May 2012
	1.1	1.1	1.1	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.1	1.2	Oct 2012
MCZ200N_02_2	4.8	5.0	3.4	3.3	4.5	4.9	6.6	7.2	5.9	5.3	6.0	6.7	May 2012
	1.7	1.8	1.8	1.8	1.9	2.0	1.9	1.8	1.9	2.0	1.9	1.8	Oct 2012
MSSD Region	1	2	3	4	5	6	7	8	9	10	11	12	

MSSD geometry

MSSD Region	Pitch (mm)	Low channel	High channel
1	120	353	384
2	240	321	352
3	80	289	320
4	70	257	288
5	120	225	256
6	240	193	224
7	80	161	192
8	70	129	160
9	120	97	128
10	240	65	96
11	80	33	64
12	70	1	32

There are deliberate variations in the implant width and Al strip width for each pitch.

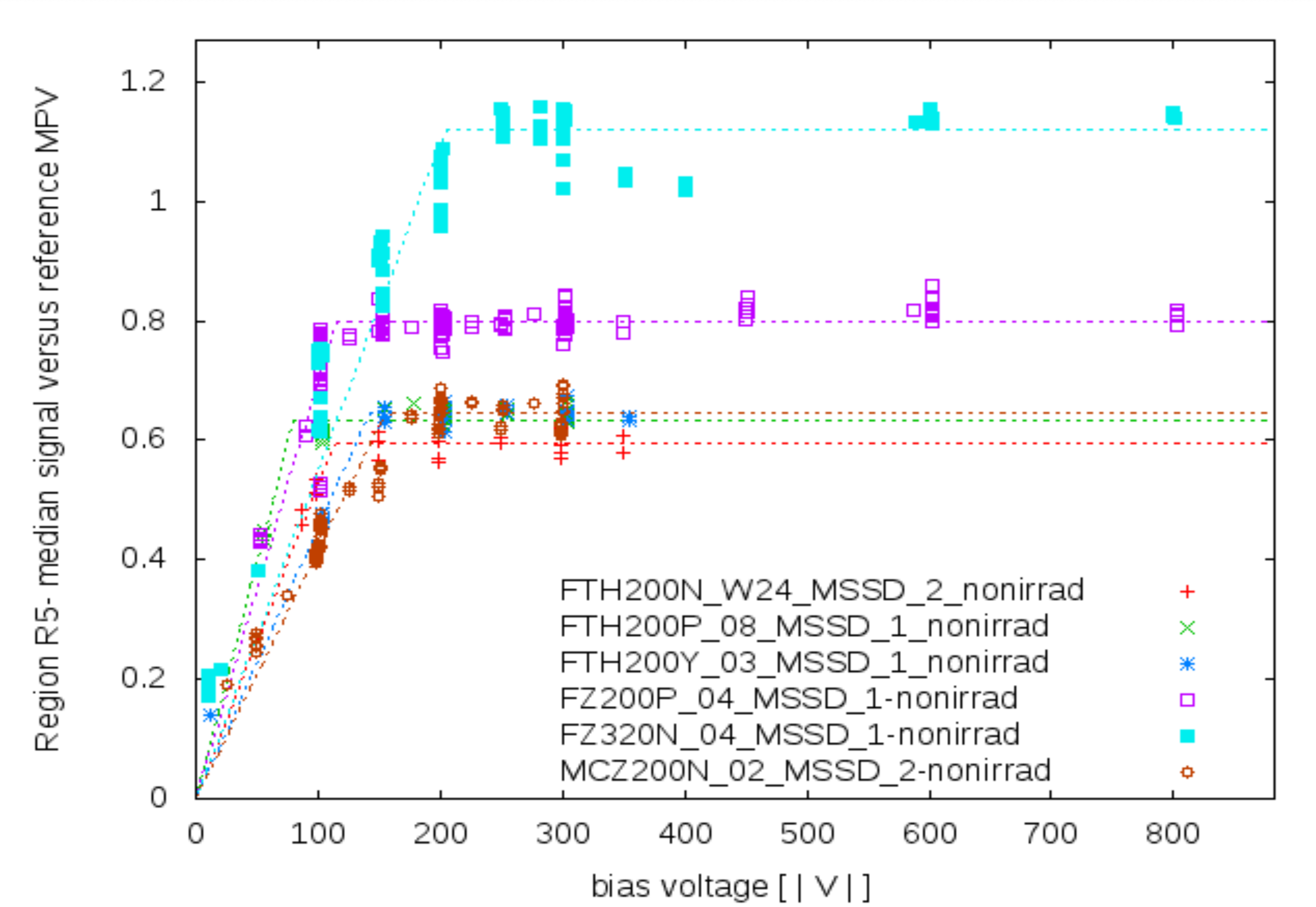




Observations from beam tests

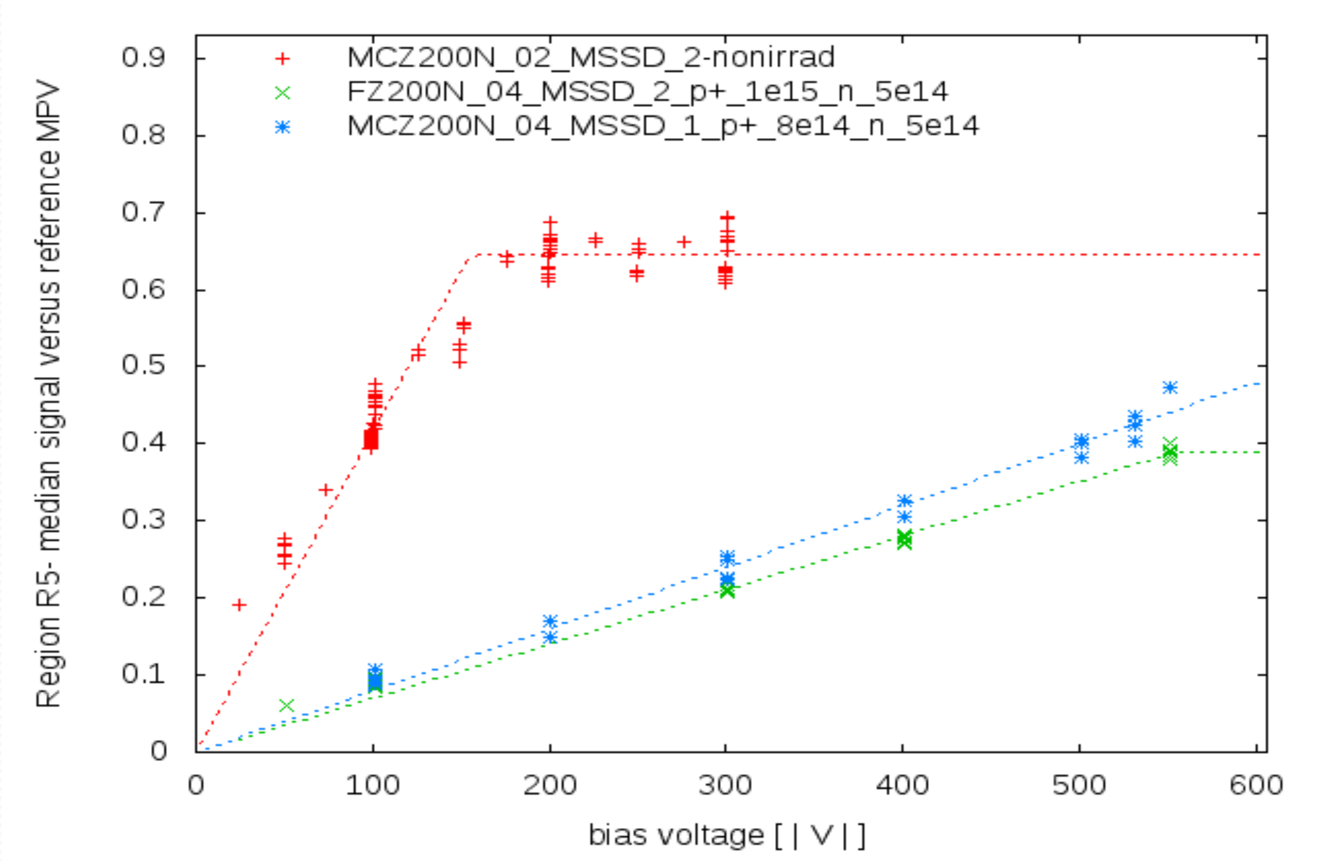
- Before irradiation the sensors have relative signals consistent with thickness although the deep diffusion active thickness may be somewhat larger than 200μm.
- After irradiation there is not much difference in signals from MCz and deep diffusion FZ, for either the n-type or p-type.
- Also, the advantage of a longer active thickness is basically gone after 1.5×10^{15} 1 MeV n_{eq}/cm^2
- After irradiation the n-type detectors appear to be more prone to high-side non-Gaussian tails
  - Micro-discharges?
  - At the present time there is no explanation for this (assuming the effect is real).

Before irradiation



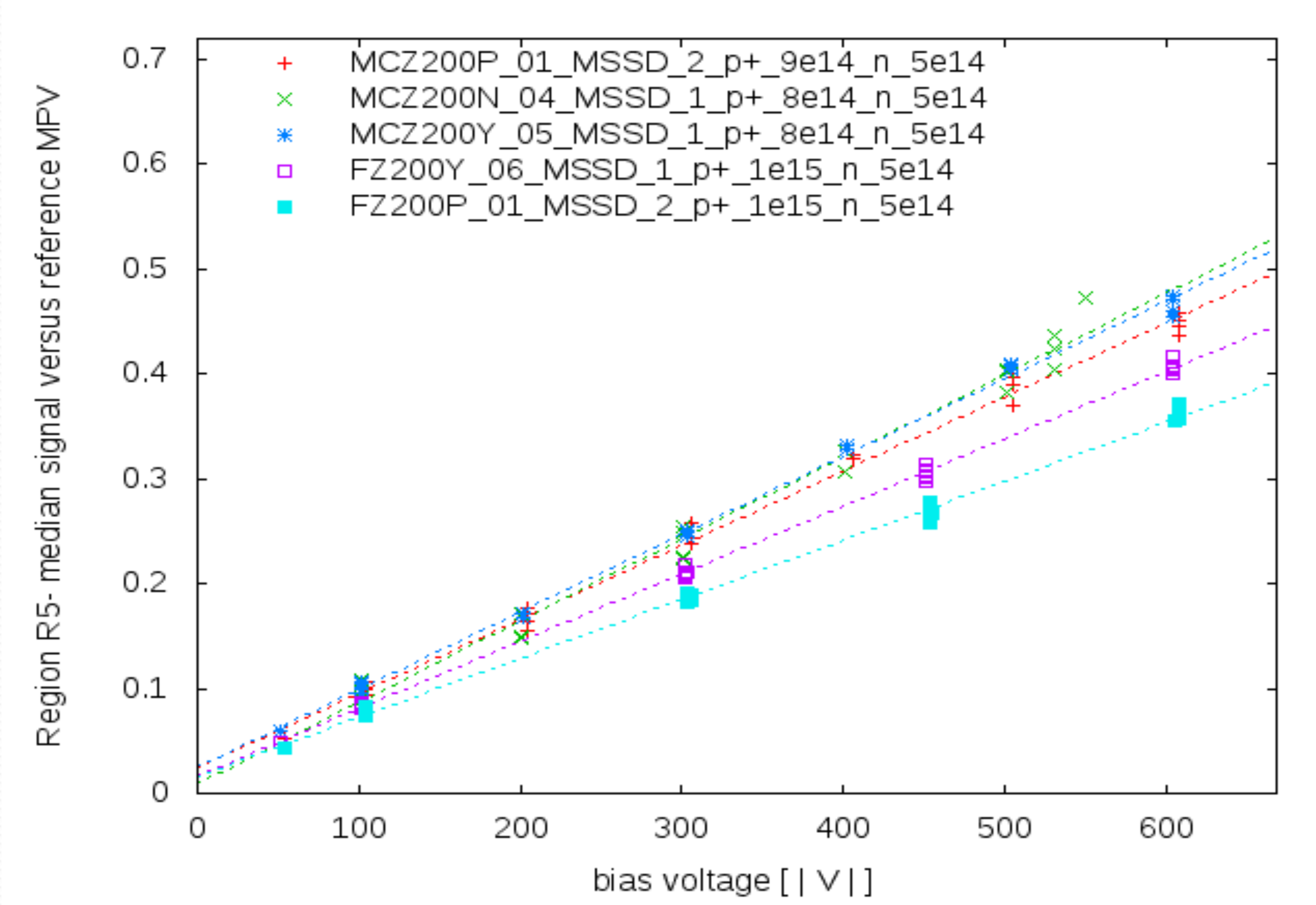
Deep diffusion 200 µm FZ shows a higher plateau compared with thinned 200µm FZ and MCz. The latter are closer to a simple 200/320 prediction.

MCz vs. FZ n-type



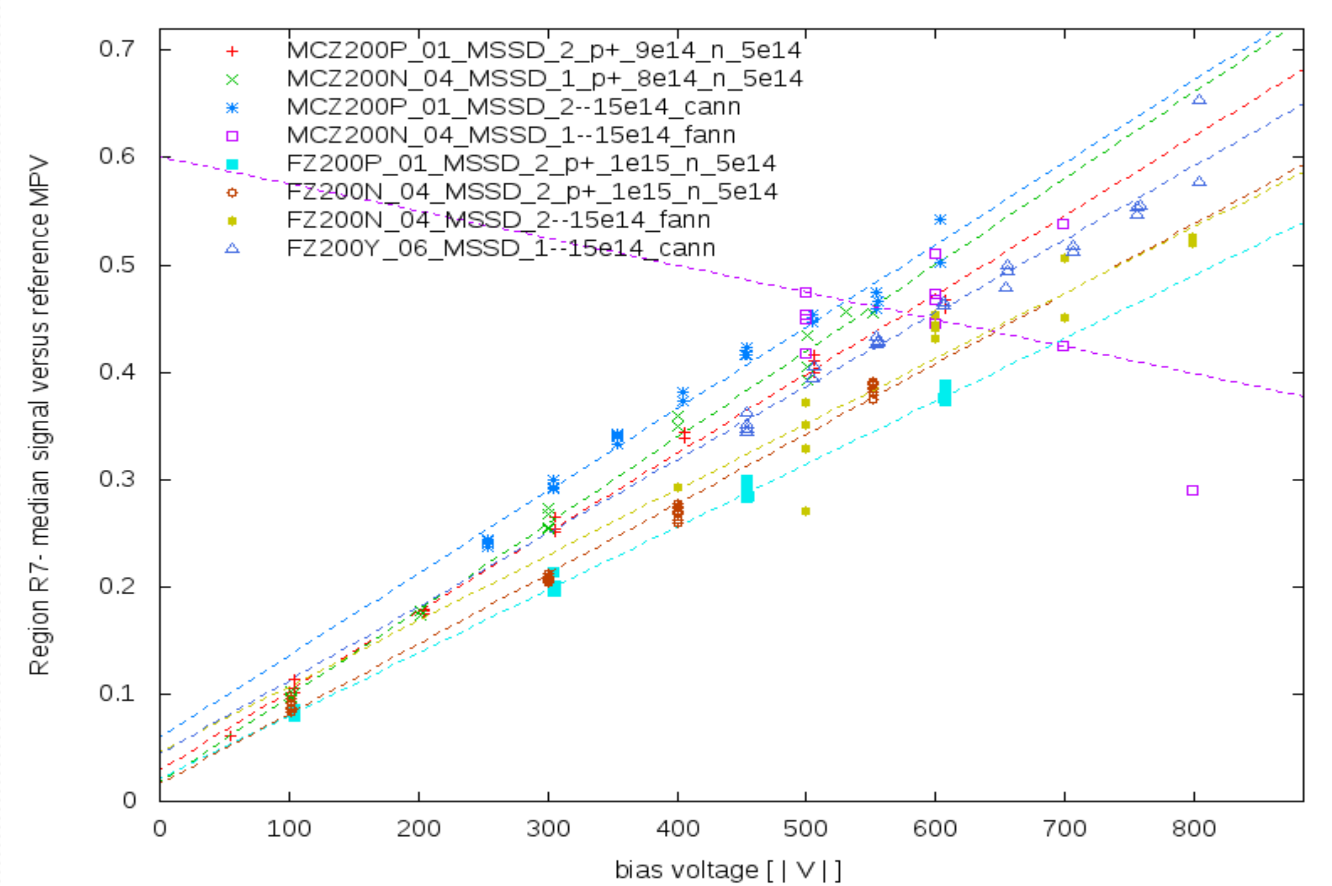
Slight advantage for MCz n-type over deep diffusion FZ n-type after irradiation.
May reflect relative oxygen concentrations?

MCz vs. FZ p-type



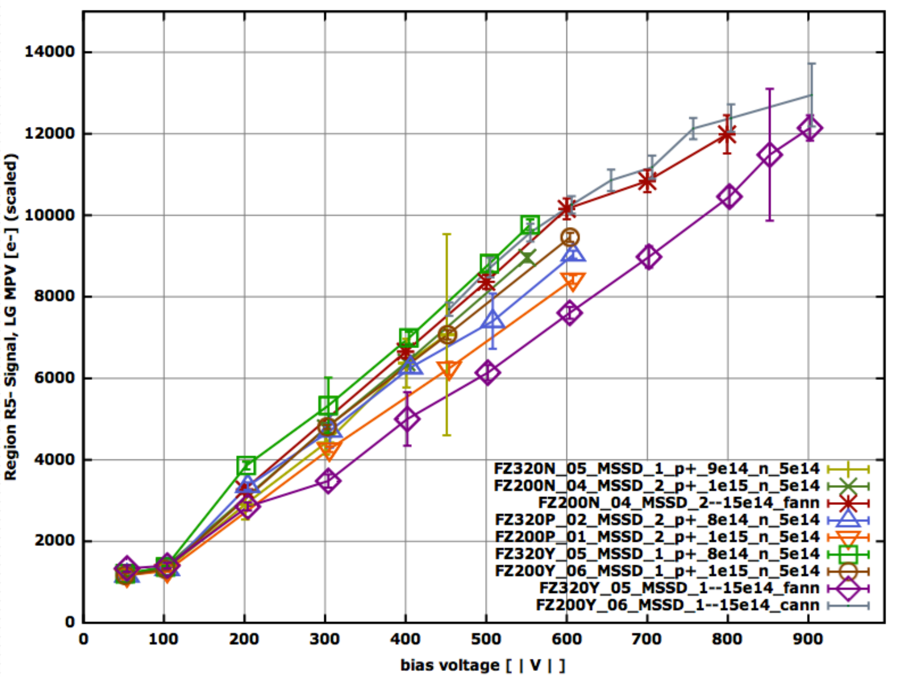
Signals are normalized to reference plane MPV to minimize beam type/energy variations in expected signals.
MCz shows slightly higher signals than deep diffusion FZ after irradiation.
P-spray (Y) might have a small advantage over p-stop (P) – after irradiation.

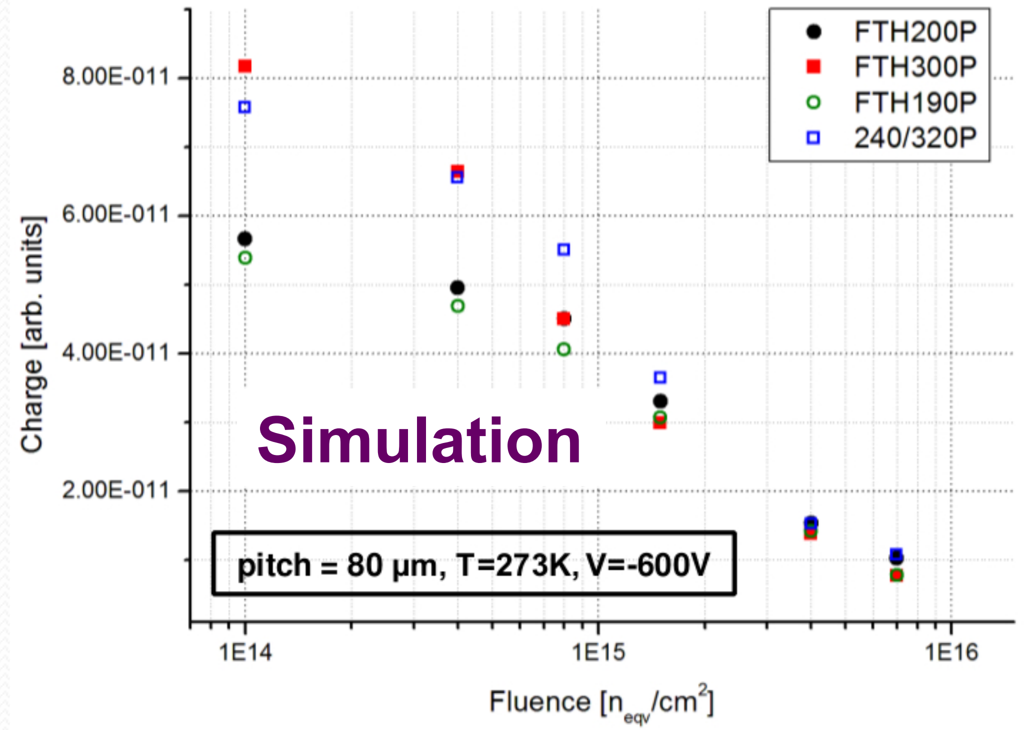
Grand comparison at 200µm



cann = annealed at CERN, fann = annealed at FNAL

Depletion depth independence

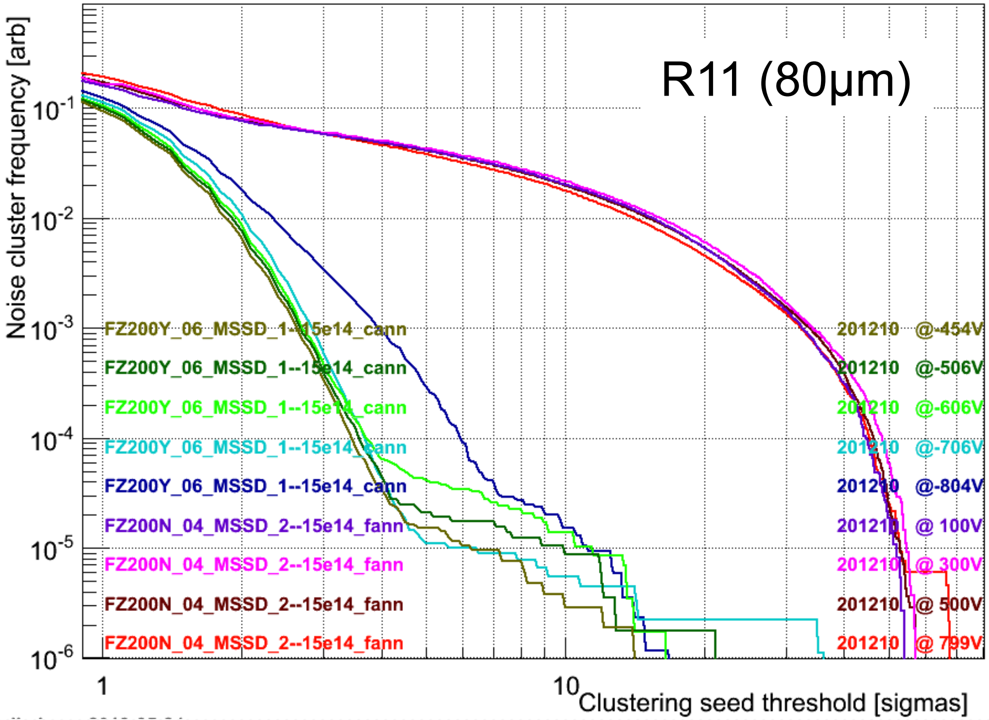


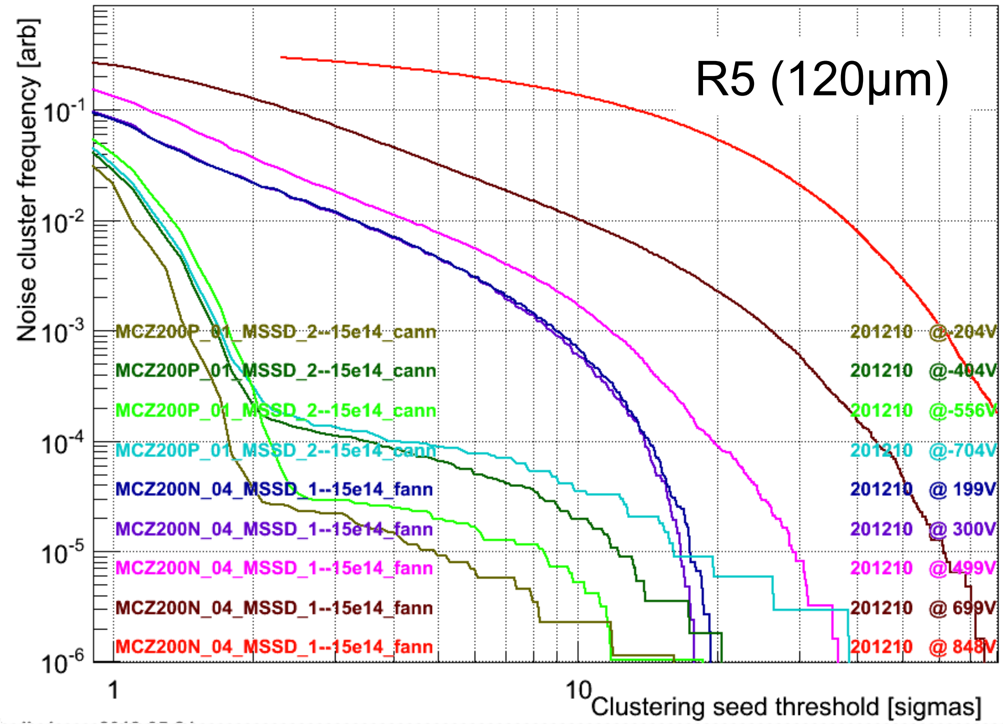


Simulation is from a study by T. Peltola (HIP) using the Petasecca defect model. In heavily irradiated sensors charge tends to be collected near the ends of the depletion volumes due to stronger electric fields and shorter transits.
CMS HV lines may be limited to 600V even in the upgrade.

Non-Gaussian noise

Single strip probability for non-track, non-edge signal to exceed $N \times \sigma_{median}$



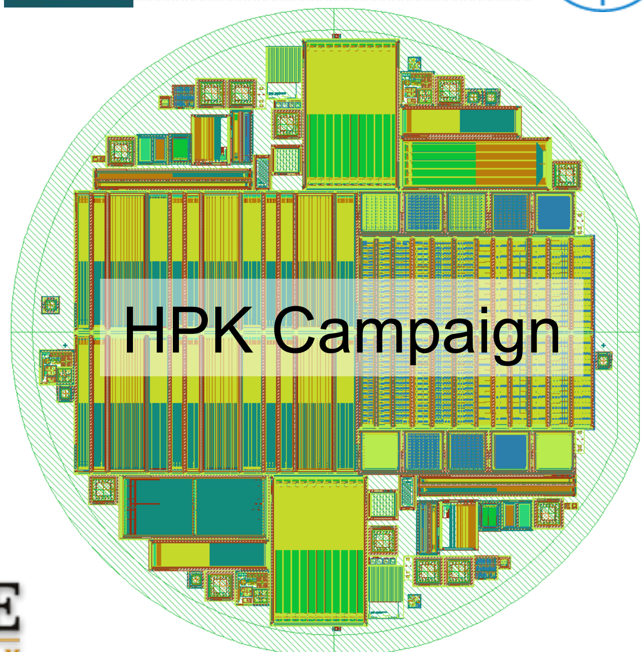


- After irradiation there is some evidence that n-type sensors are noisier than p-type sensors, with the effect increasing with pitch.
  - Not all sensors and all regions show this trend
  - Even in the p-type there is evidence for non-Gaussian tails; it is just not as pronounced.

Summary

- There has been an extensive effort on the part of the CMS Sensor Upgrade group to identify a sensor material for the HL-LHC era.
  - The test beam results are just one component of the program.
  - Eventually all of the data will need to be synthesized to reach a final decision.
- There will be at least one more beam test, with the focus on irradiated thinned FZ sensors.
- From the perspective of the beam studies, either MCz silicon or deep diffusion FZ, in either n-type or p-type, would probably be acceptable.
  - The test beam results support the idea that 200μm silicon is more “efficient” than 320μm silicon. For thinned silicon this would be in line with the goal of reducing the amount of material in the Tracker.
  - There is some evidence that n-type silicon may be noisier than p-type after irradiation.

Backup


HPK Campaign

HPK Campaign wafer layout