Development of radiation hard Sensors & Cables for the CBM Silicon Tracking System

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On behalf of CBM-STS Collaboration

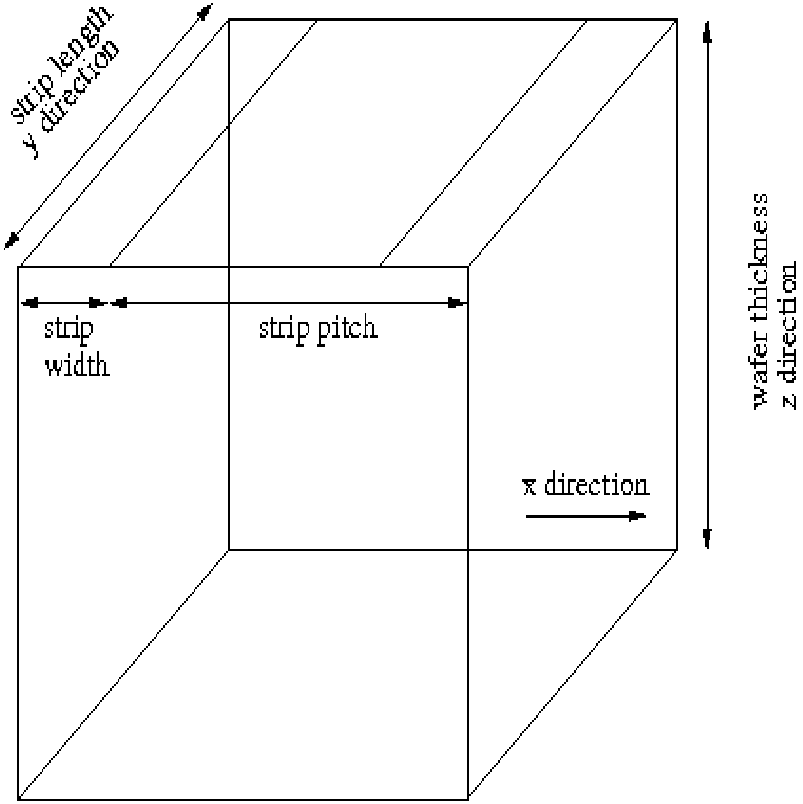
GSI Helmholtz Centre for Heavy Ion Research

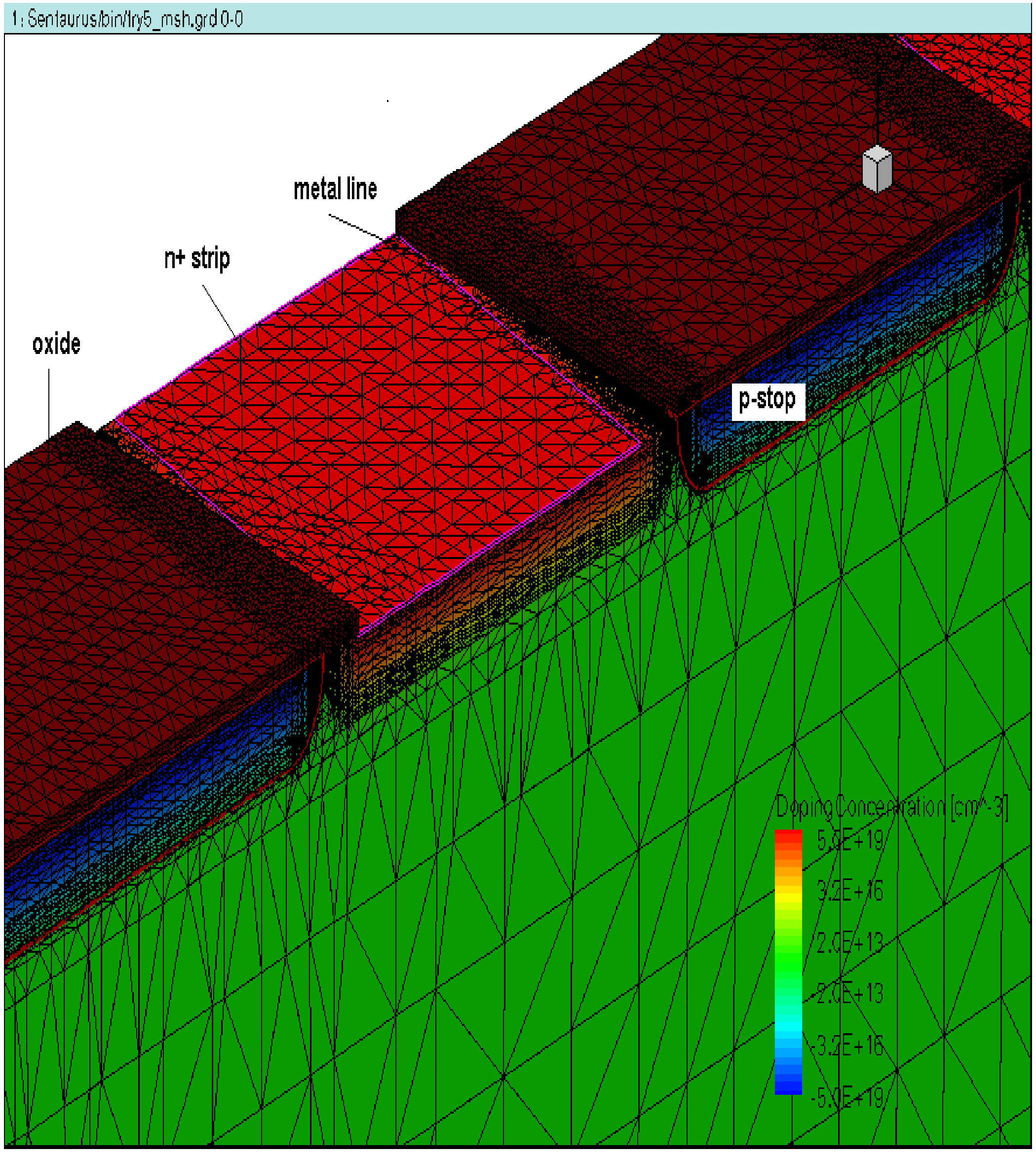
6th Trento Workshop on Advanced Silicon Radiation Detectors

04 March, 2011

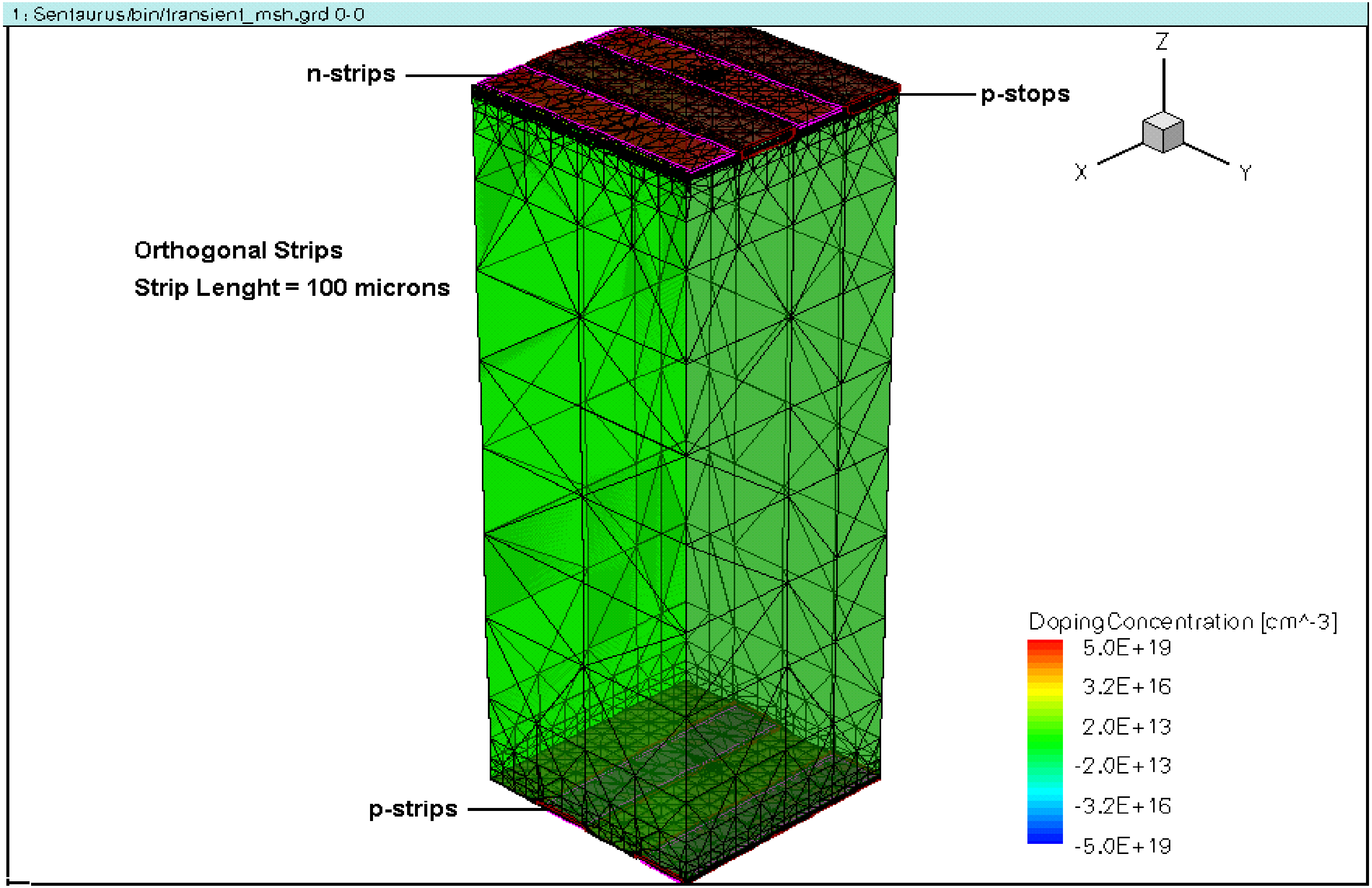
3-Dimensional Grid

- ❖ 3-D TCAD simulation tools “SYNOPSYS”
- ❖ Sub packages
    - ➢Sentaurus
    - ➢Inspect
    - ➢Tecplot
    - ➢SPICE (Mixed Mode)
    - ➢Raphael (Used for Kapton simulation)





3-D Grid for orthogonal strips

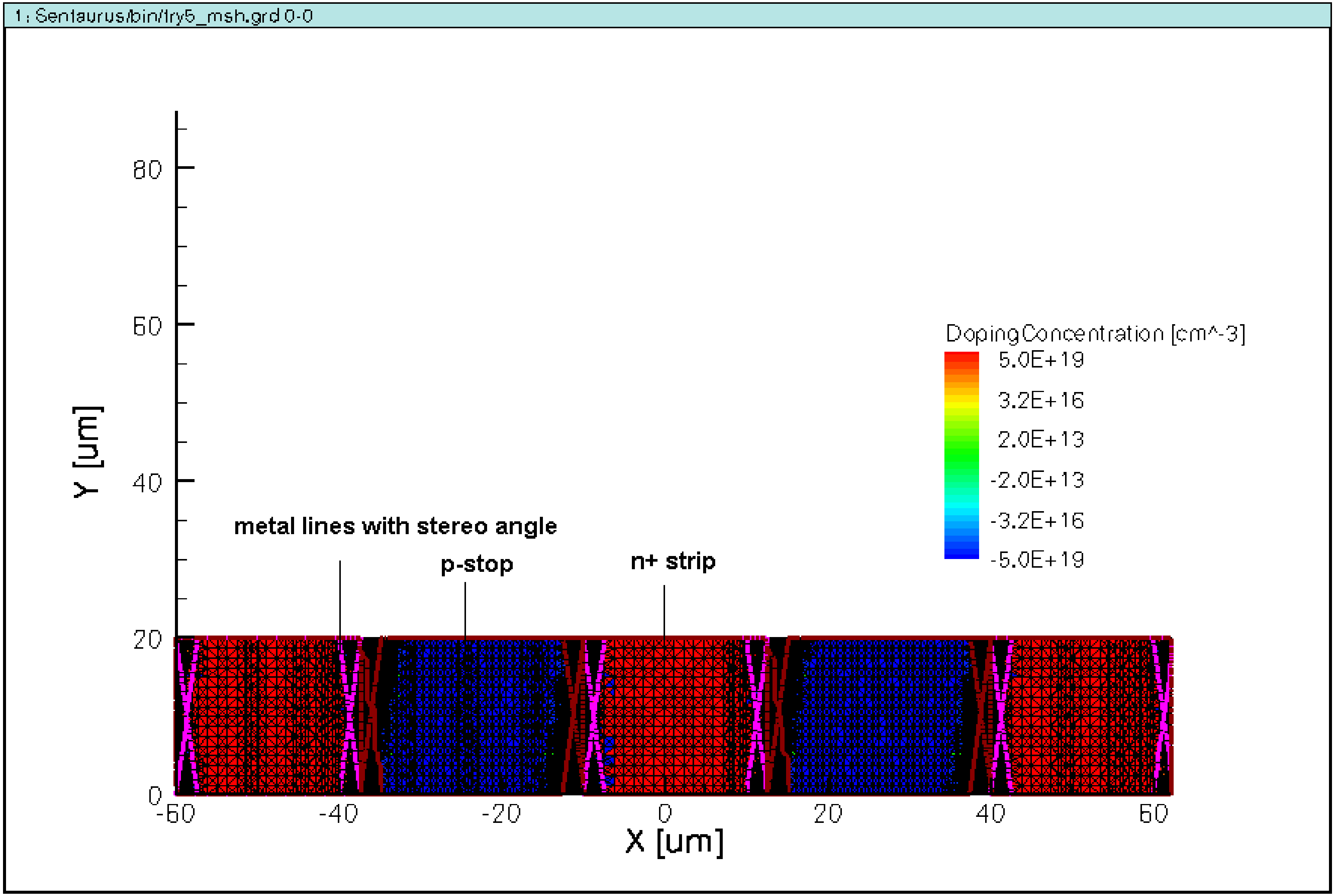


1: Sentaurus/bin/transient_msh.grd 0-0

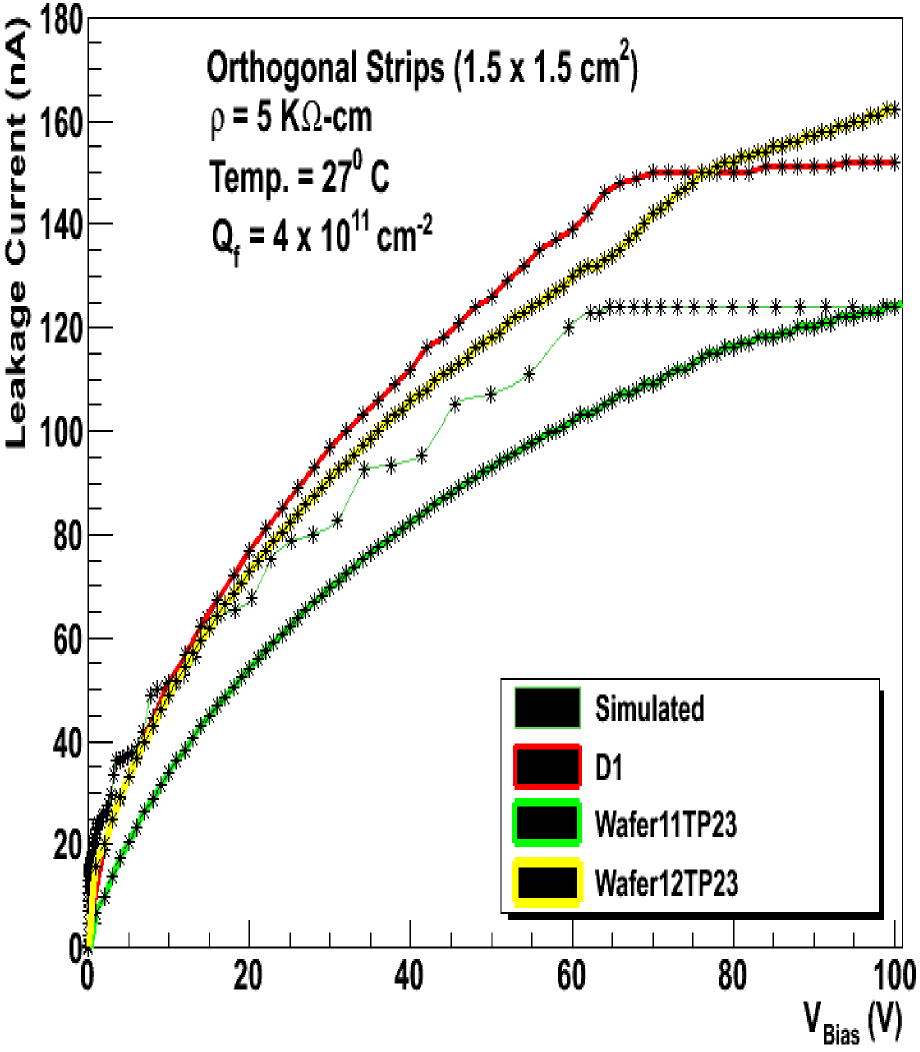
Orthogonal Strips

Strip Lenght = 100 microns

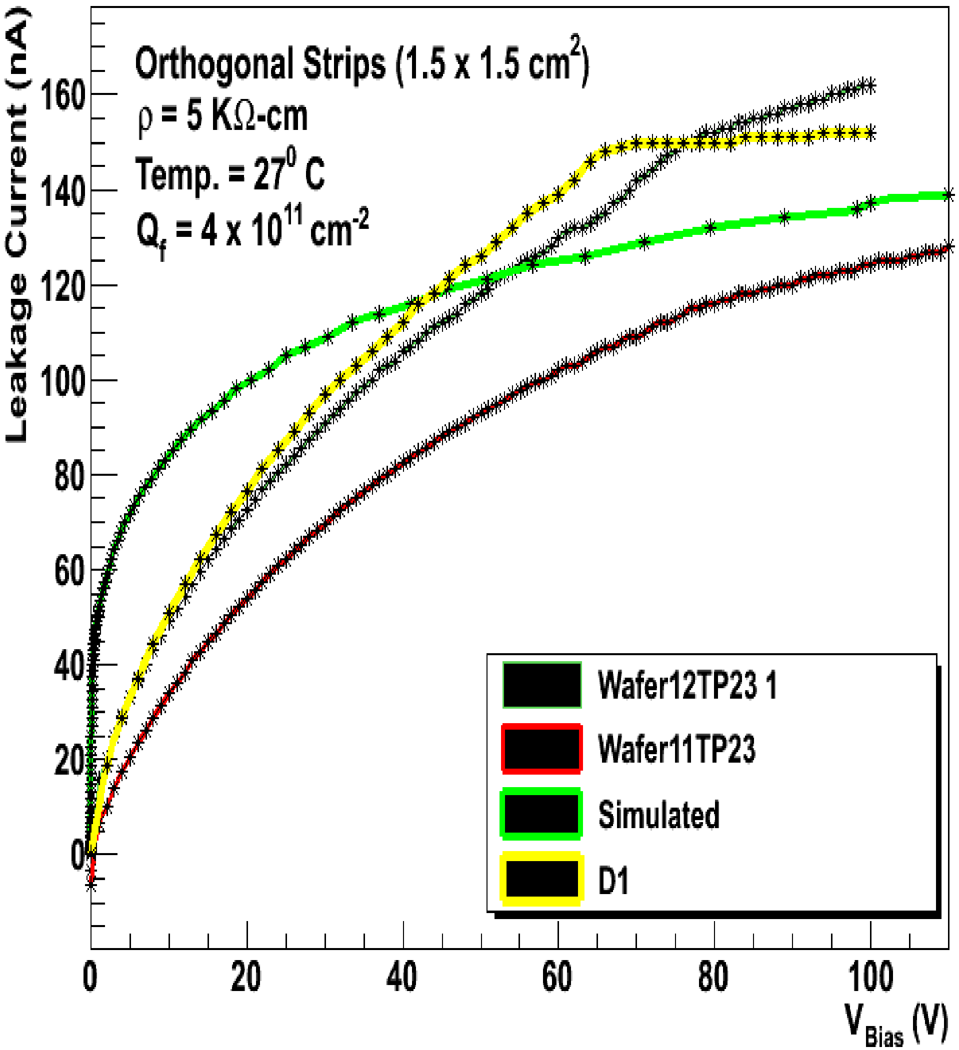
X-Y plane of the 3-D Stereo Angled Grid



Simulated Vs. Measured Leakage Current

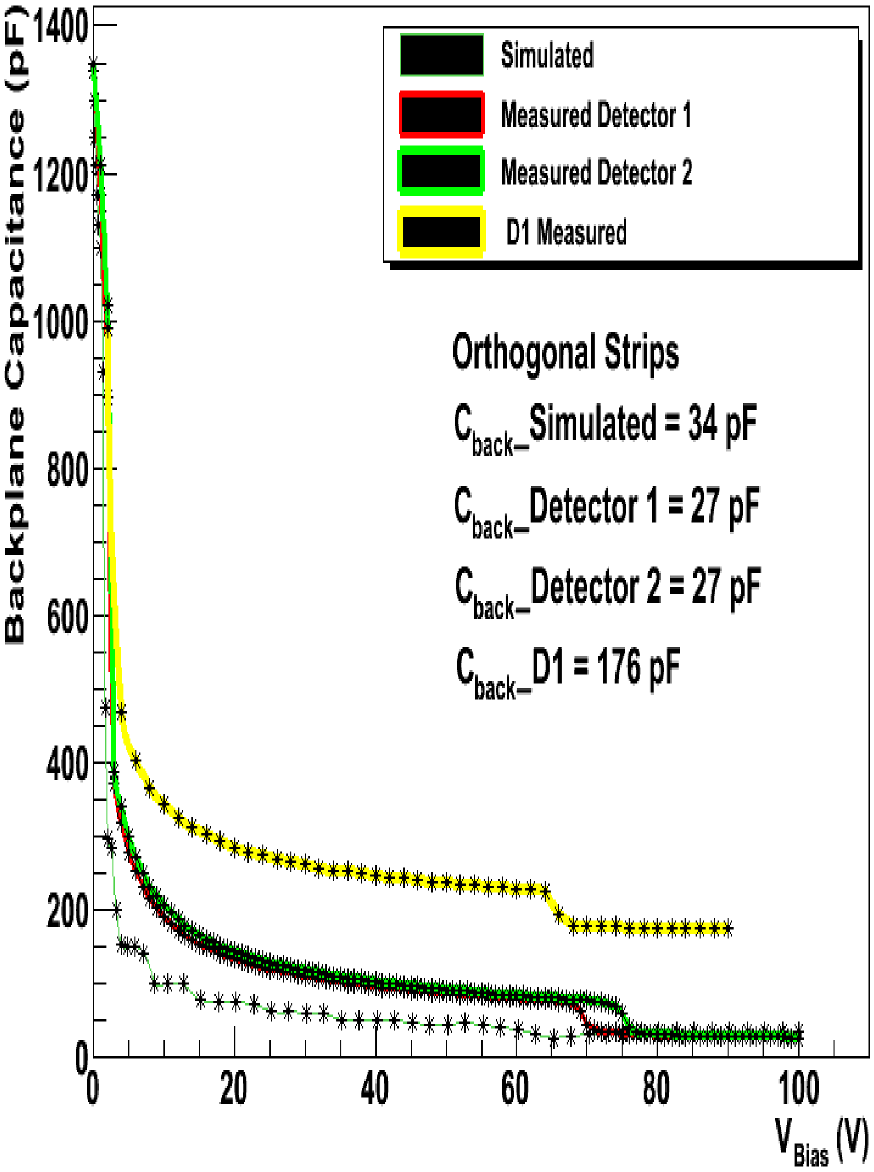


Default Minority Carrier lifetime
Electrons = 1e-5 s; Holes = 3e-6 s



Modified Minority Carrier life time
Electrons = 1e-3 s; Holes = 3e-4s

Simulated Vs. Measured Backplane Capacitance



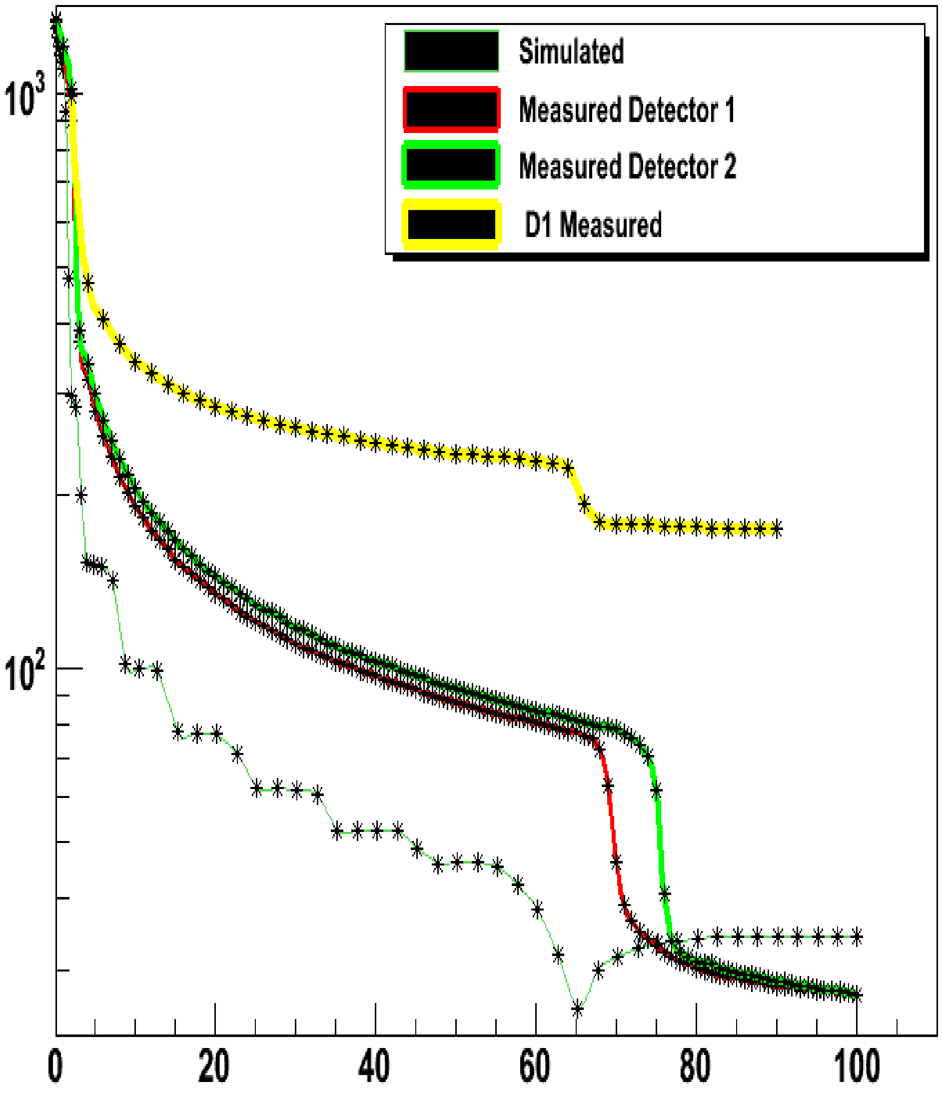
Orthogonal Strips

$C_{back_}$Simulated = 34 pF

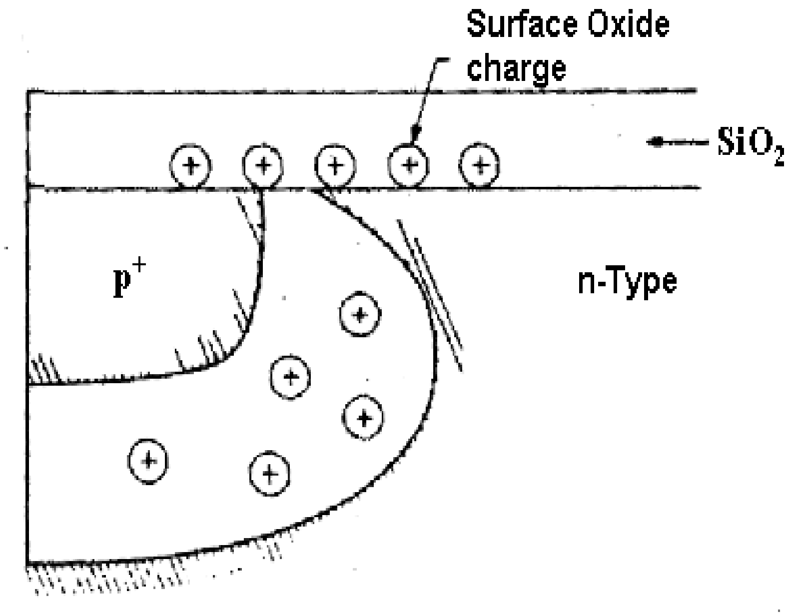
$C_{back_}$Detector 1 = 27 pF

$C_{back_}$Detector 2 = 27 pF

$C_{back_}$D1 = 176 pF



Radiation Damage in Silicon



Fluence profile of neutrons expected for CBM

Year	Int.Fluence $*10^{14}(n/cm^{-2})$	$N_{eff}*10^{11}$ (cm^{-3})	τ_e (μsec.)	τ_h (μsec.)
0	0	9	1000	300
0.049	0.05	7.41	4.98	4.92
0.29	0.3	-1.72	0.833	0.831
1	1.0	-34.3	0.250	0.250
2	2.0	-89.9	0.125	0.125
3	3.0	-150	0.083	0.083
4	4.0	-214	0.062	0.062
5	5.0	-278	0.05	0.05
6	6.0	-343	0.041	0.041

N-type float zone silicon trap model

Type	Energy (eV)	Defect	σ_e cm^{-2}	σ_h cm^{-2}	η cm^{-1}
Acceptor	E_c-0.42	$VV^{(-/0)}$	$2x10^{-15}$	$1.2x10^{-14}$	13
Acceptor	E_c-0.50	VVO (?)	$5x10^{-15}$	$3.5x10^{-14}$	0.08
Donor	E_v+0.36	C_iO_i	$2x10^{-18}$	$2.5x10^{-15}$	1.1

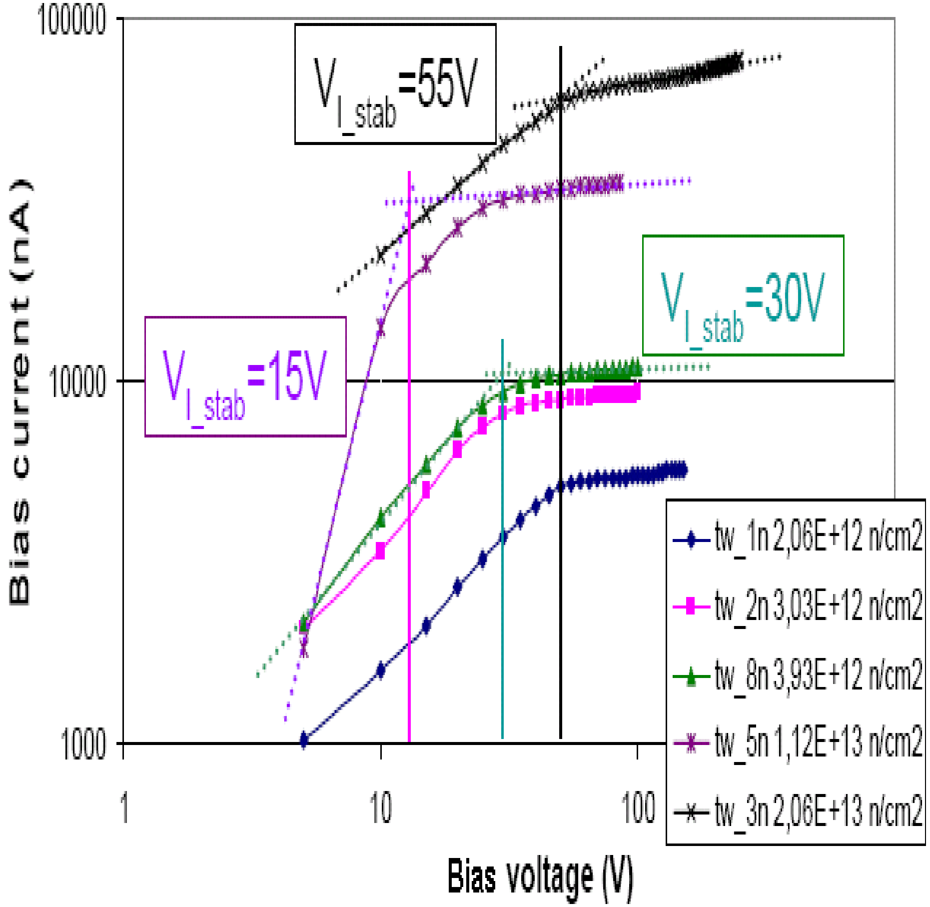
P-type float zone silicon trap model

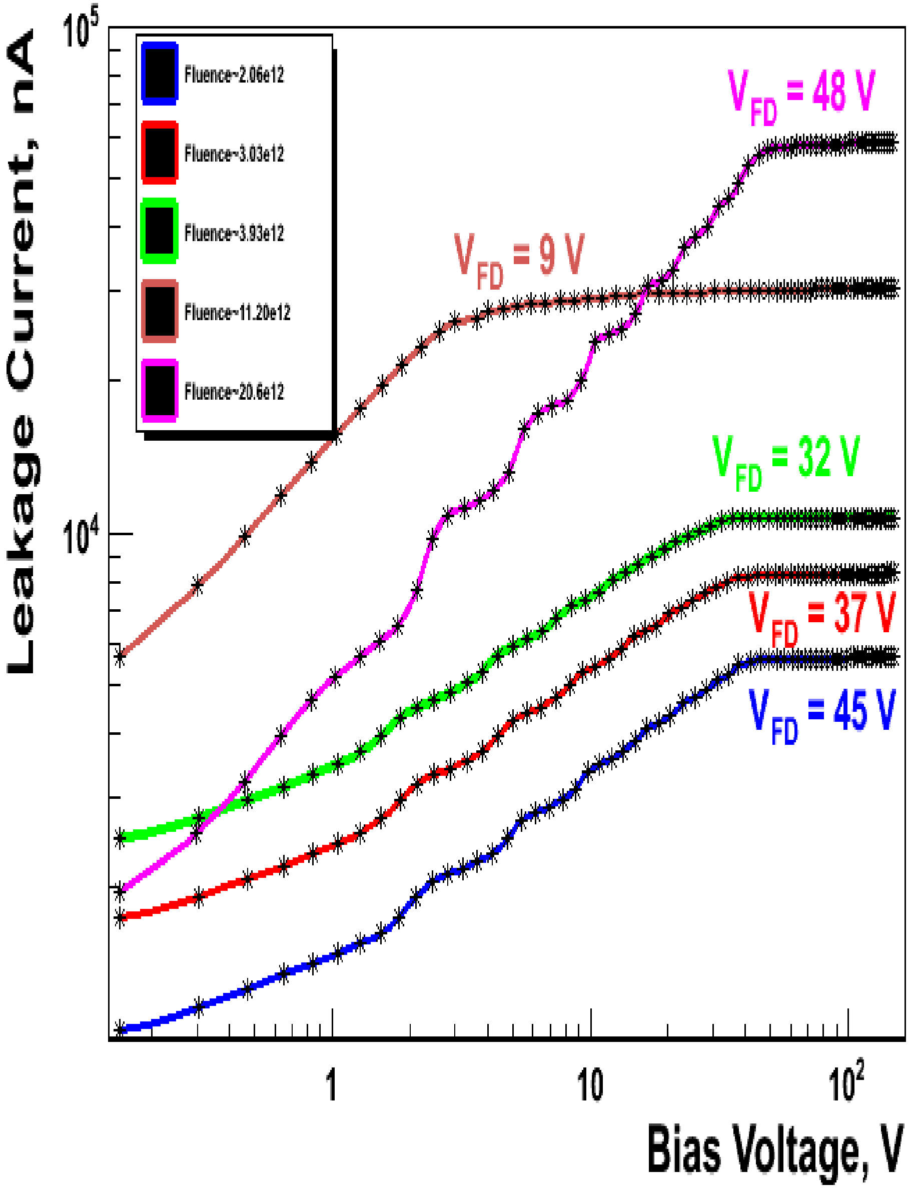
Type	Energy (eV)	Defect	σ_e cm^{-2}	σ_h cm^{-2}	η cm^{-1}
Acceptor	E_c-0.42	$VV^{(-/0)}$	$2x10^{-15}$	$1.2x10^{-14}$	13
Acceptor	E_c-0.50	VVO (?)	$5x10^{-15}$	$3.5x10^{-14}$	0.08
Donor	E_v+0.36	C_iO_i	$2x10^{-18}$	$2.5x10^{-15}$	1.1

$Cond(cm^{-3}) = \Phi_{eq}\eta$ University of Perugia Trap Model

Comparison with Irradiated Sensors

Bias current VS Bias voltage
for different integral flux of neutrons (1MeV)
[for n-side; normalize at temperature +20C].



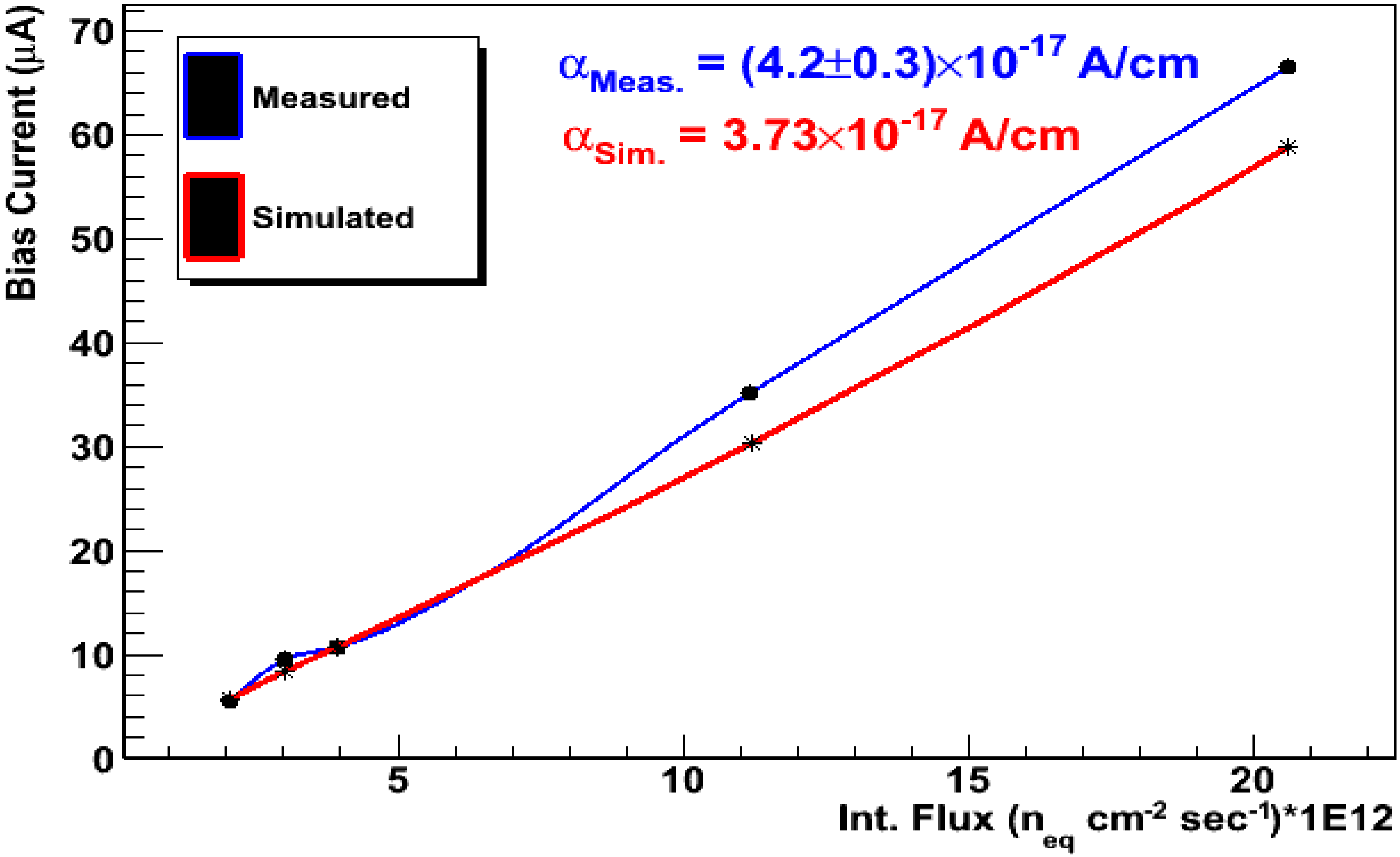


Comparison with Irradiated Sensors

Sample	Int . flux (n/cm^2)	Bias current (at +20) (nA) Measured	Bias current (at +20) (nA) Simulated	V_ fd (V) Measured	V_ fd (V) Simulated
tw_1	2.06e12	5.4e3	5.68e3	47±5	45
tw_2	3.03e12	9.5e3	8.31e3	29±5	37
tw_8	3.93e12	1.07e4	1.07e4	29±5	32
tw_5	11.20e12	3.51e4	3.03e4	9±6	9
tw_3	20.60e12	6.65e4	5.88e4	31±5	48

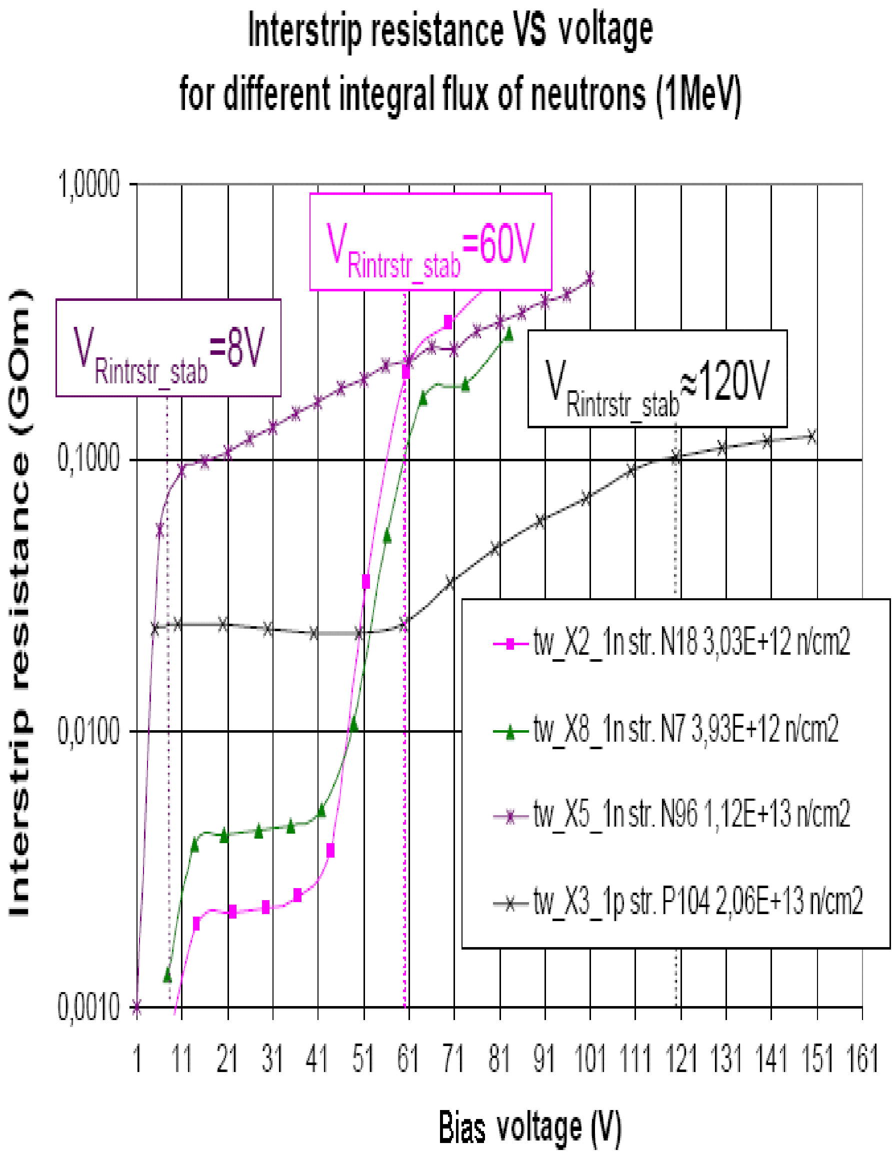
- Simulated leakage current bit smaller than measured.
- Due to high value of Minority Carrier life time?

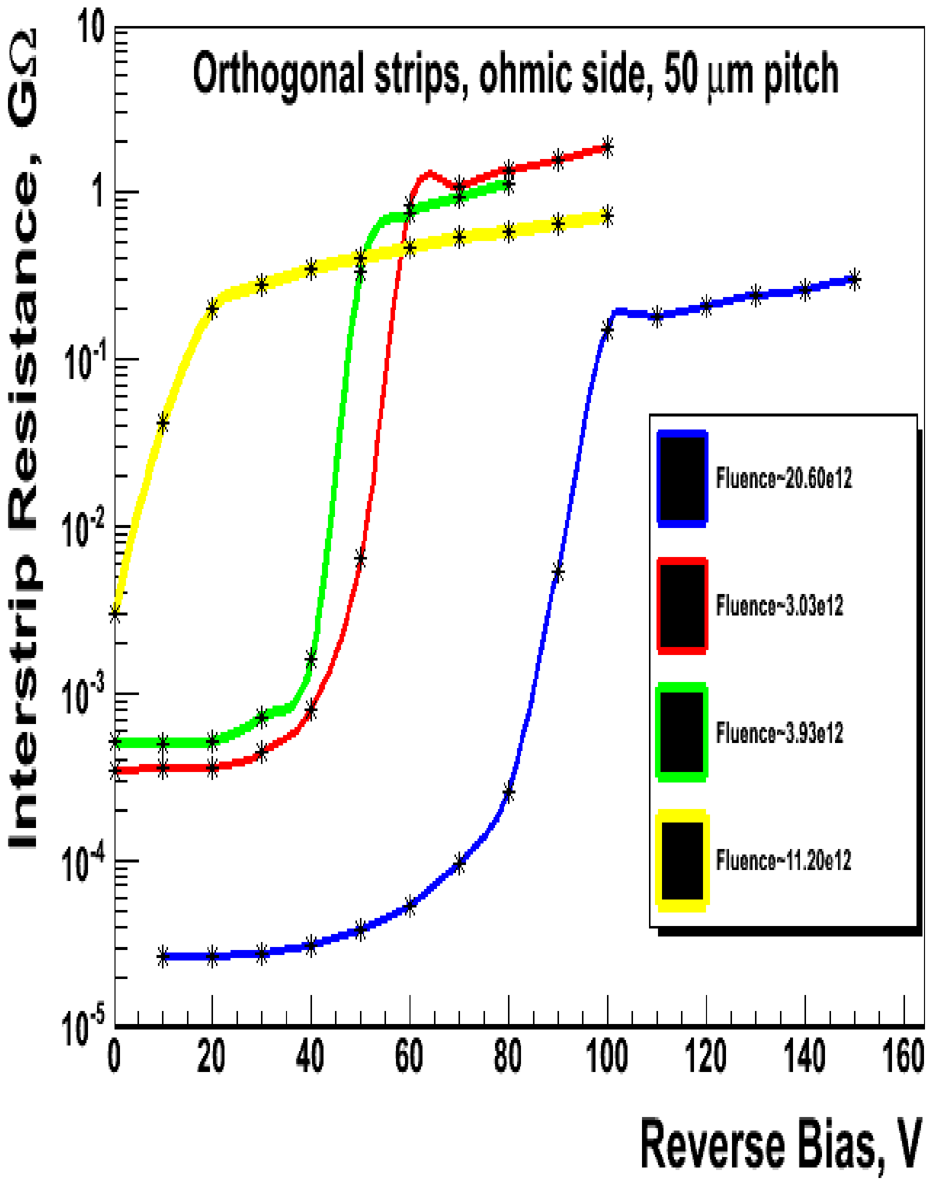
Comparison with Irradiated Sensors



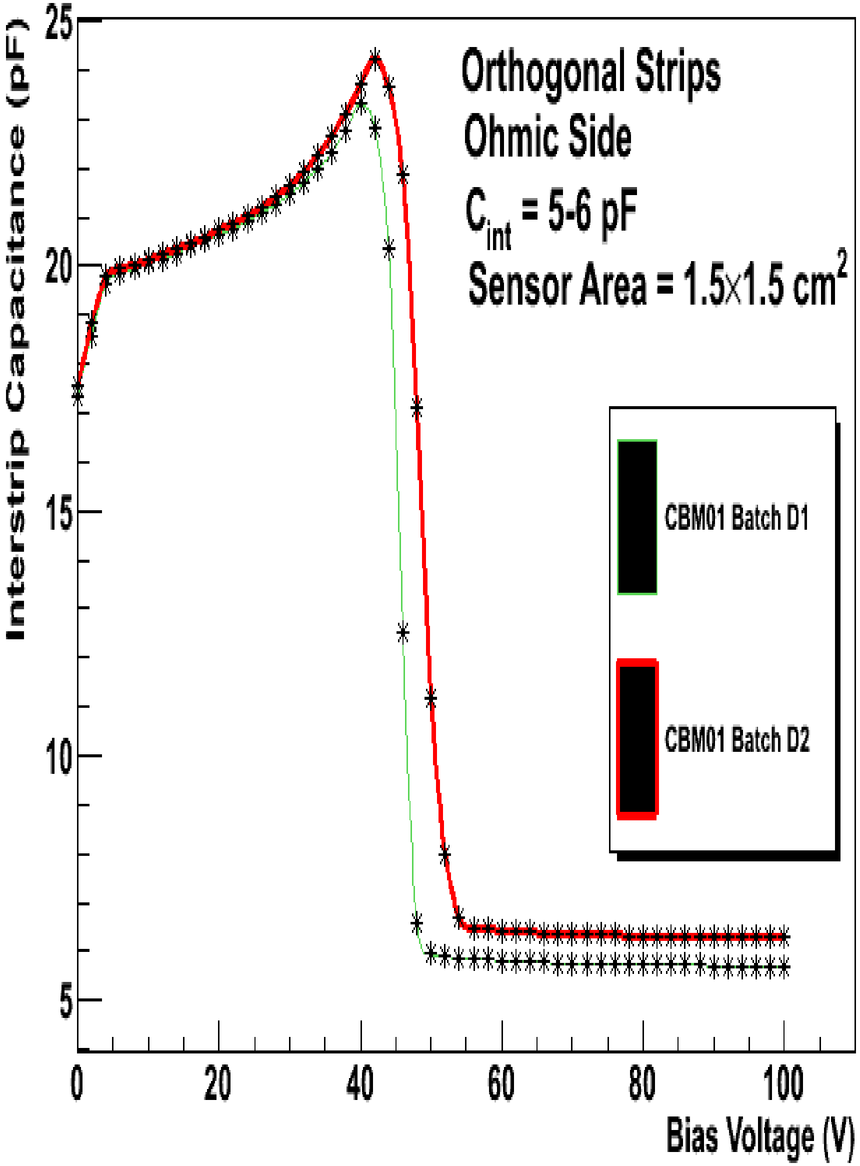
$\alpha = (3.99 \pm 0.03) \times 10^{-17}$ A/cm @ 293K after an annealing of 80 min@600 C
Ref: M.Moll, Radiation damage in silicon particle detectors – microscopic defects and Macroscopic properties, Thesis/Dissertation, Hamburg, 1999.

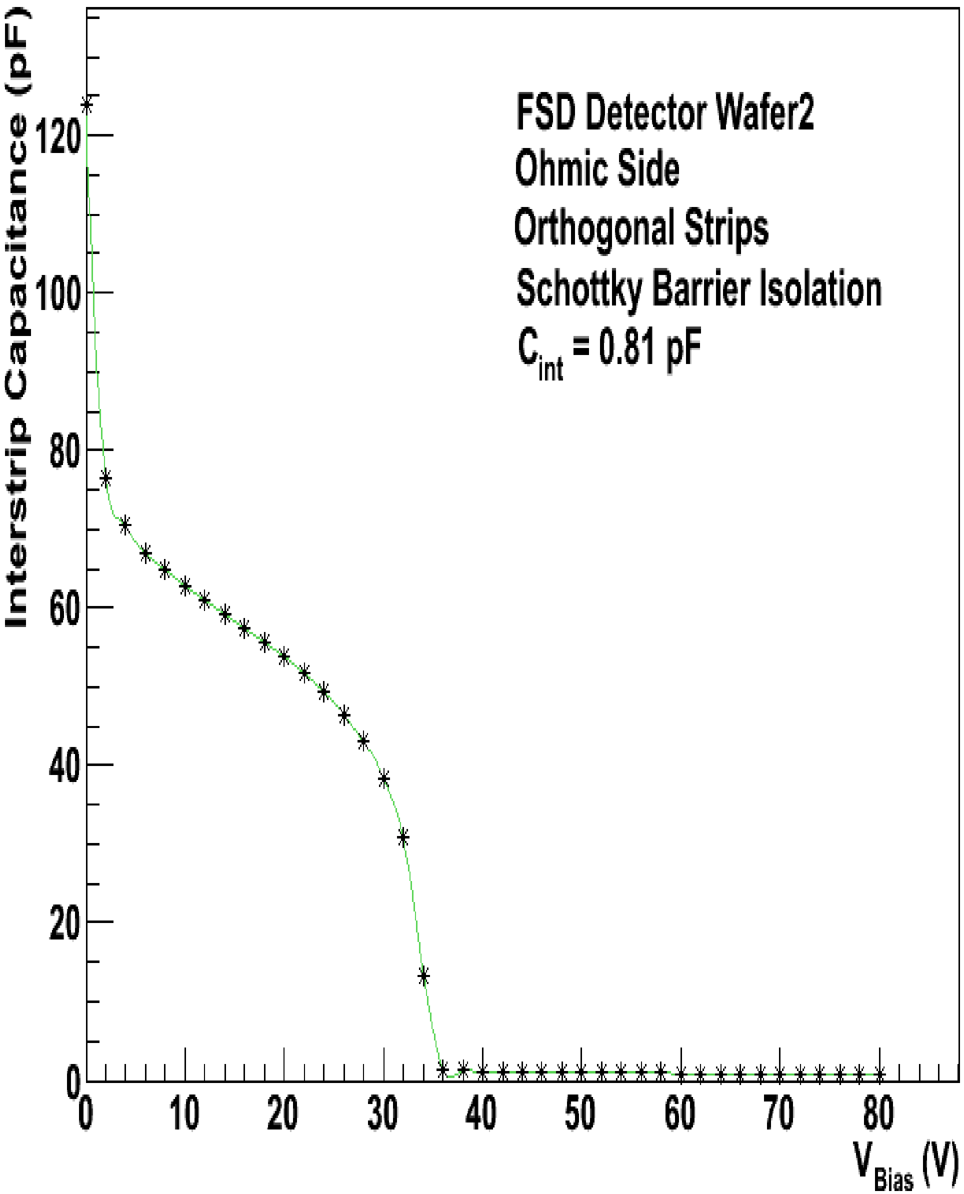
Comparison with Irradiated Sensors



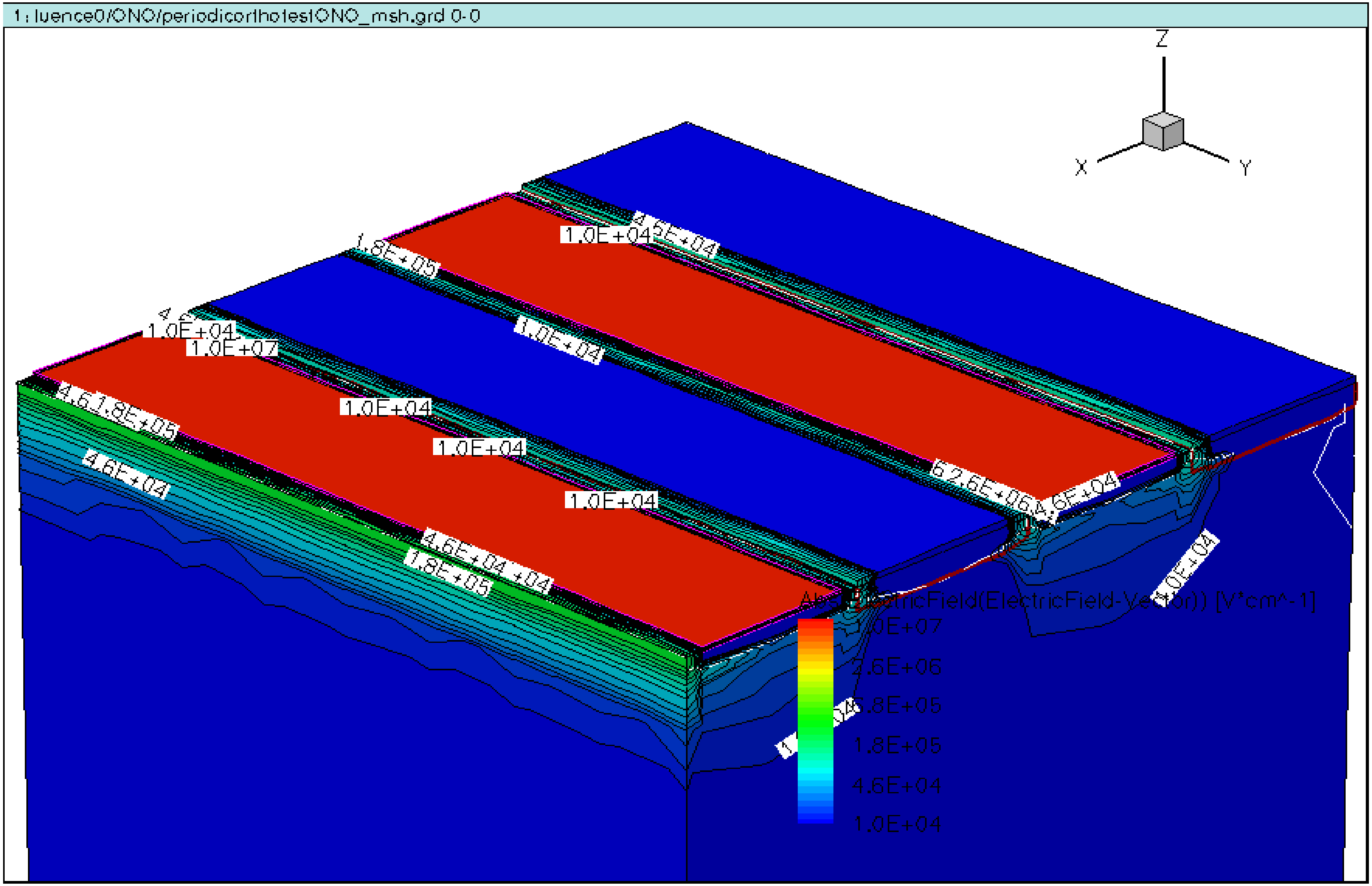


Exploring Isolation Techniques



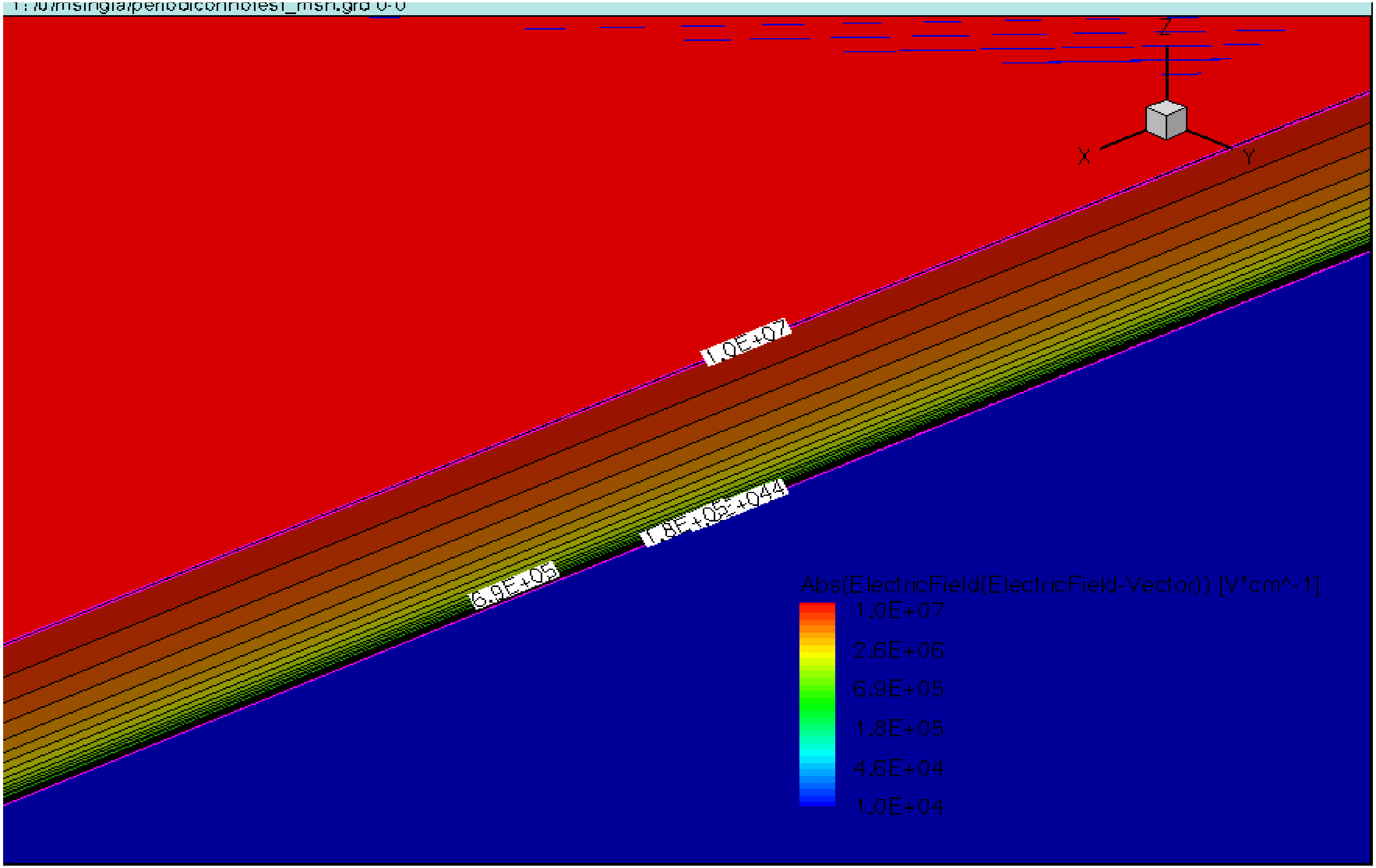


Breakdown Mechanism in DSSDs

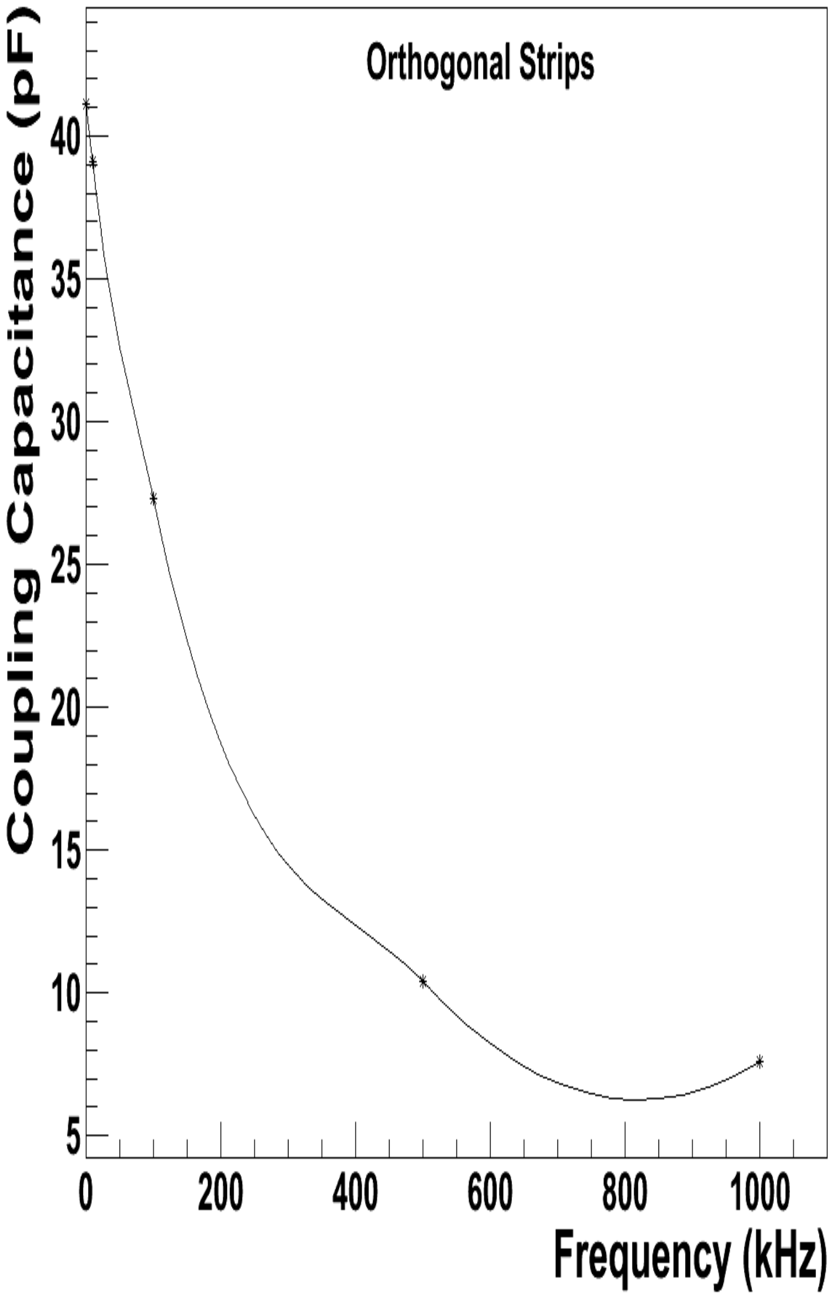


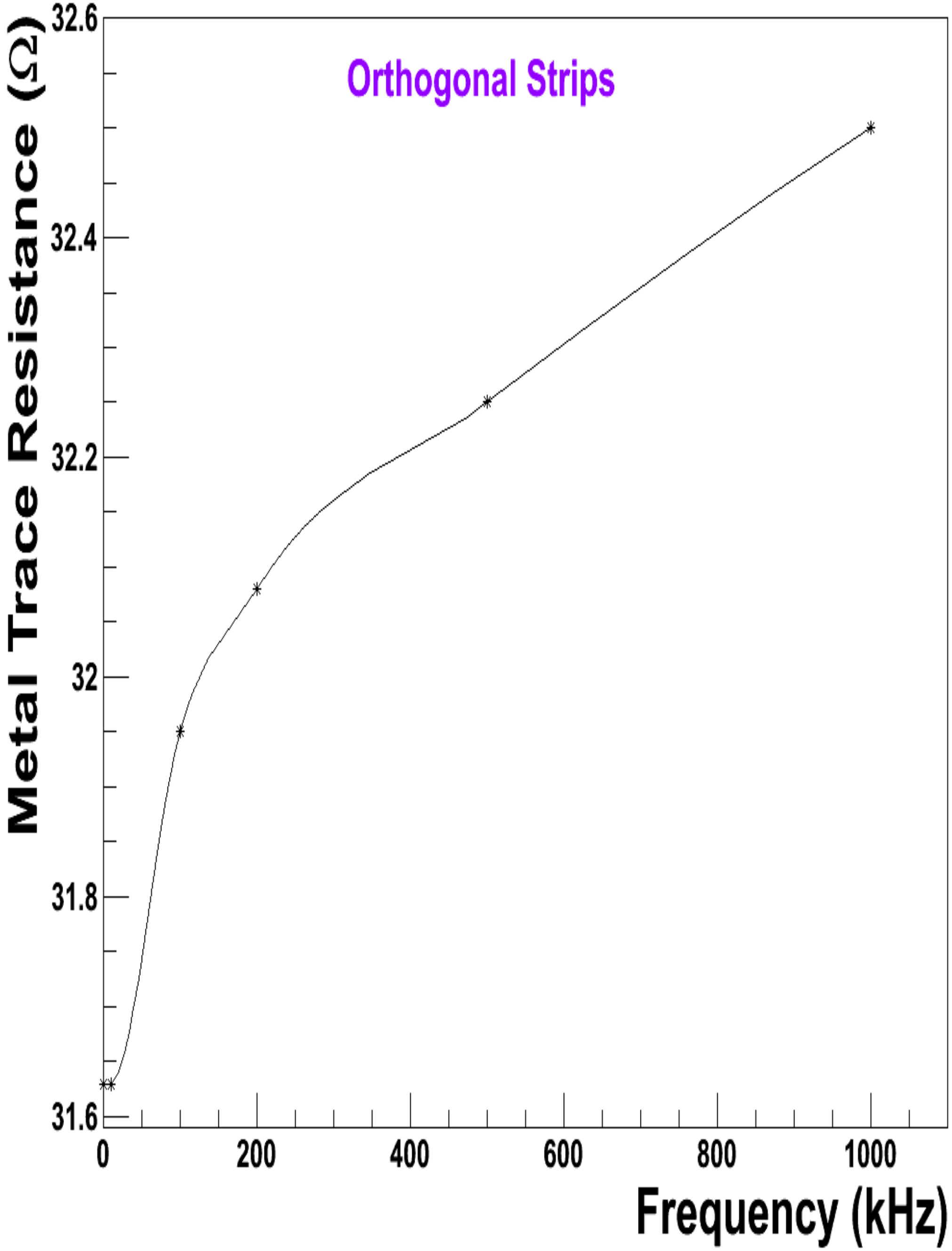
Electric Field Distribution on the Ohmic Side

Breakdown Mechanism in DSSDs

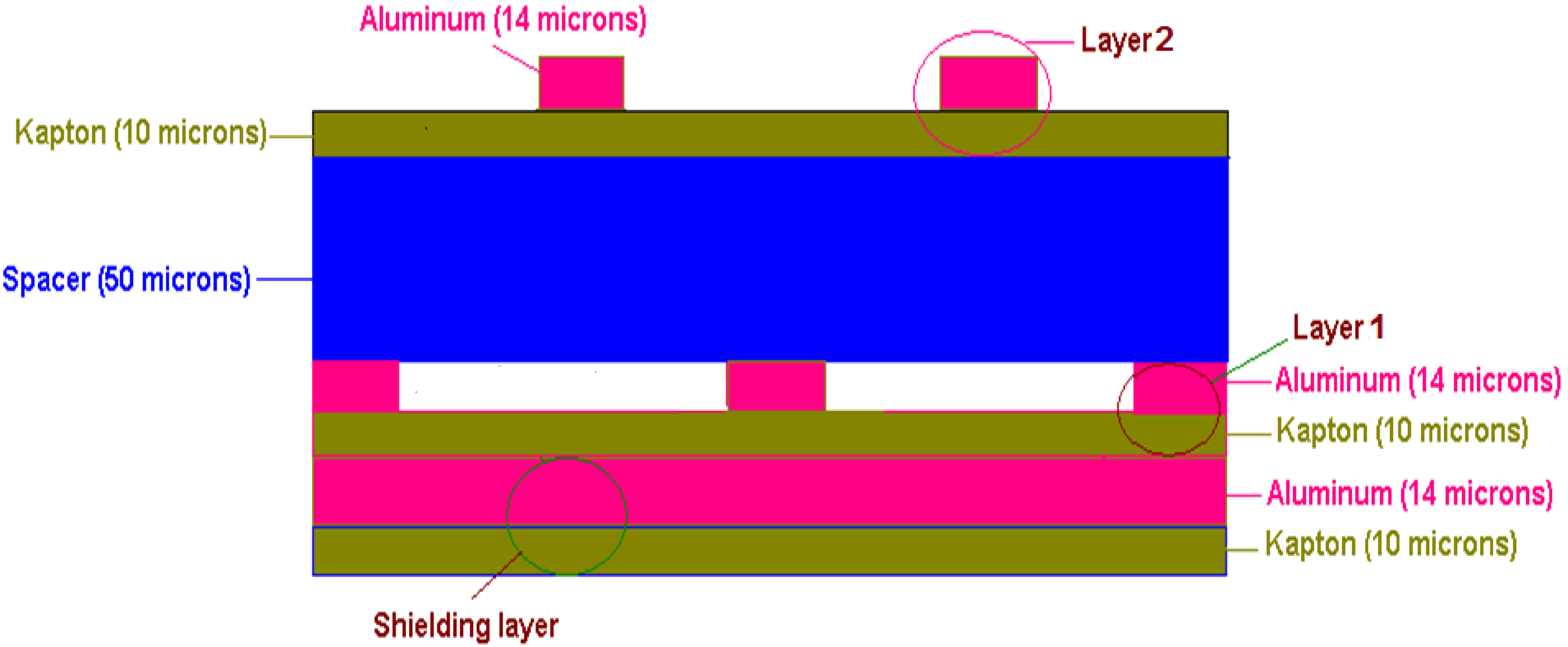


Breakdown occurs in the Coupling Oxide


Orthogonal Strips
Coupling Capacitance (pF)
40
35
30
25
20
15
10
5
0
200
400
600
800
1000
Frequency (kHz)

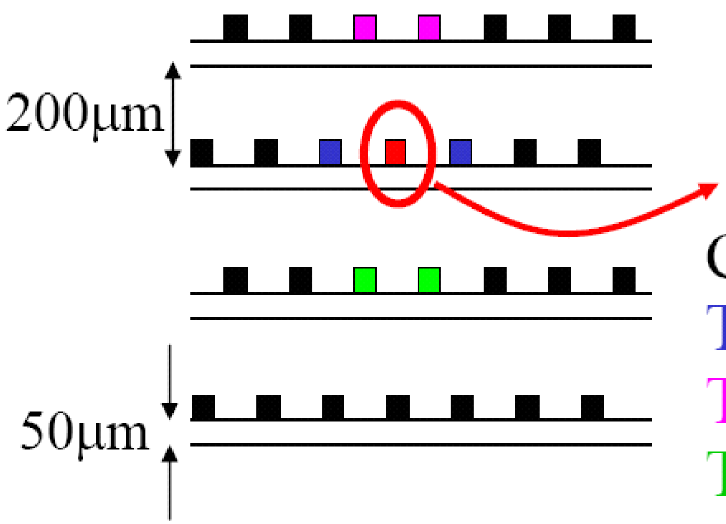

Orthogonal Strips
Metal Trace Resistance (Ω)
32.6
32.4
32.2
32
31.8
31.6
0
200
400
600
800
1000
Frequency (kHz)

Structure of kapton cable



- Two connecting layers with constant pitch of 100 µm are laminated together with a lateral shift of 50 µm.
- A spacer layer is inserted between the two layers to reduce the capacitance.
- An external shielding layer is applied to reduce the noise.

Analog Cable Design (cont'd)



100µm pitch
8 x 16µm traces

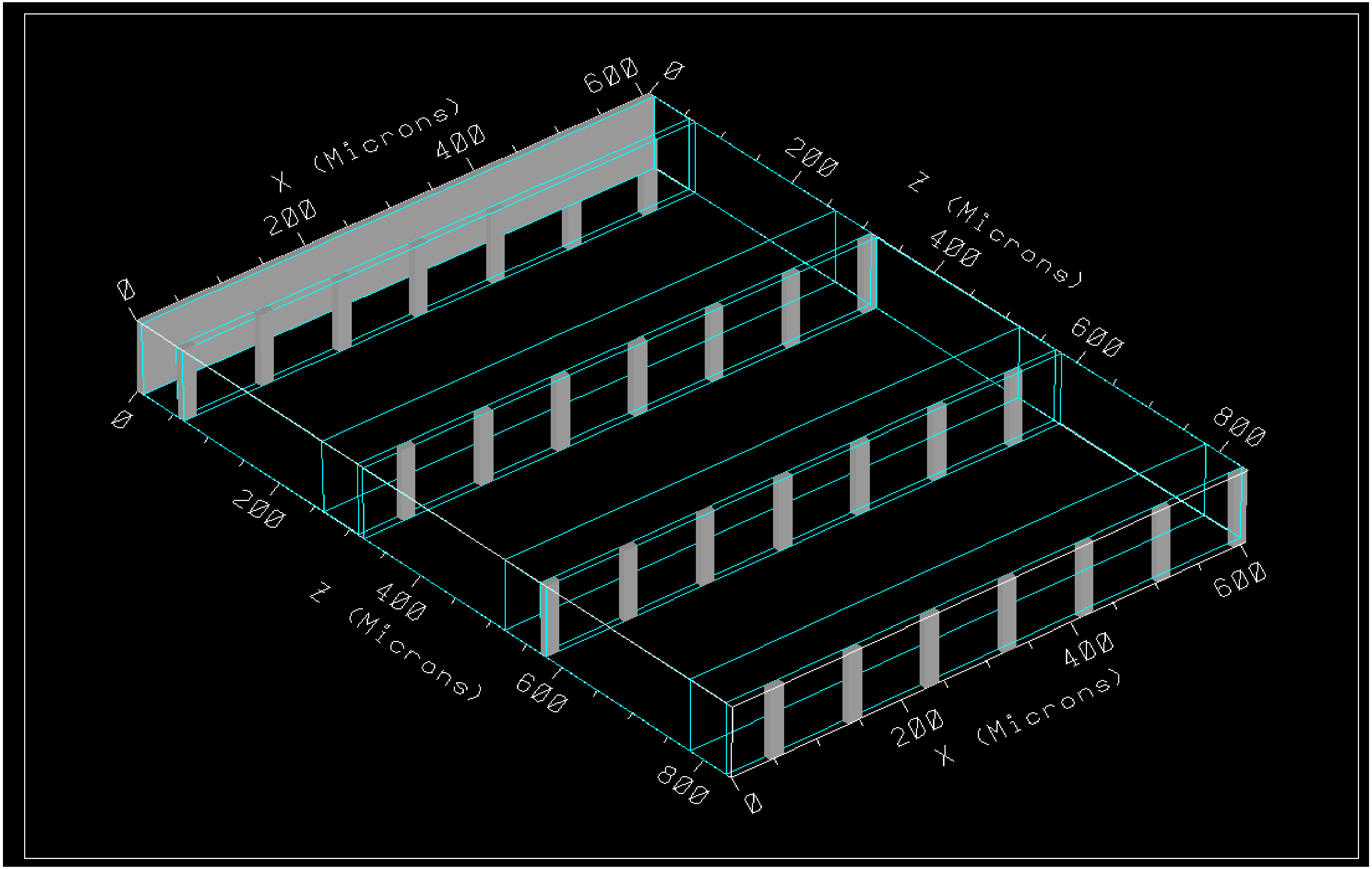
C = 0.328 pF/cm

Contribution from:
Two neighbors = 0.208 pF/cm
Two top neighbors = 0.014 pF/cm
Two bottom neighbors = 0.017 pF/cn

- 200 µm is enough to avoid significant contribution from other cables.
- Low ε_r material for spacer. ← polypropylene mesh.

ε_r (spacer)	C (pF/cm)
1	0.328
2	0.449
3	0.566

Simulation of D0 cable using RAPHAEL



Cables for D0 collaboration

By ANSYS

ε_r	C_total (pF/cm)	C int (top)	C int (bottom)	C int (imm.)
1	0.328	0.014	0.017	0.208
2	0.449	-	-	-
3	0.566	-	-	-

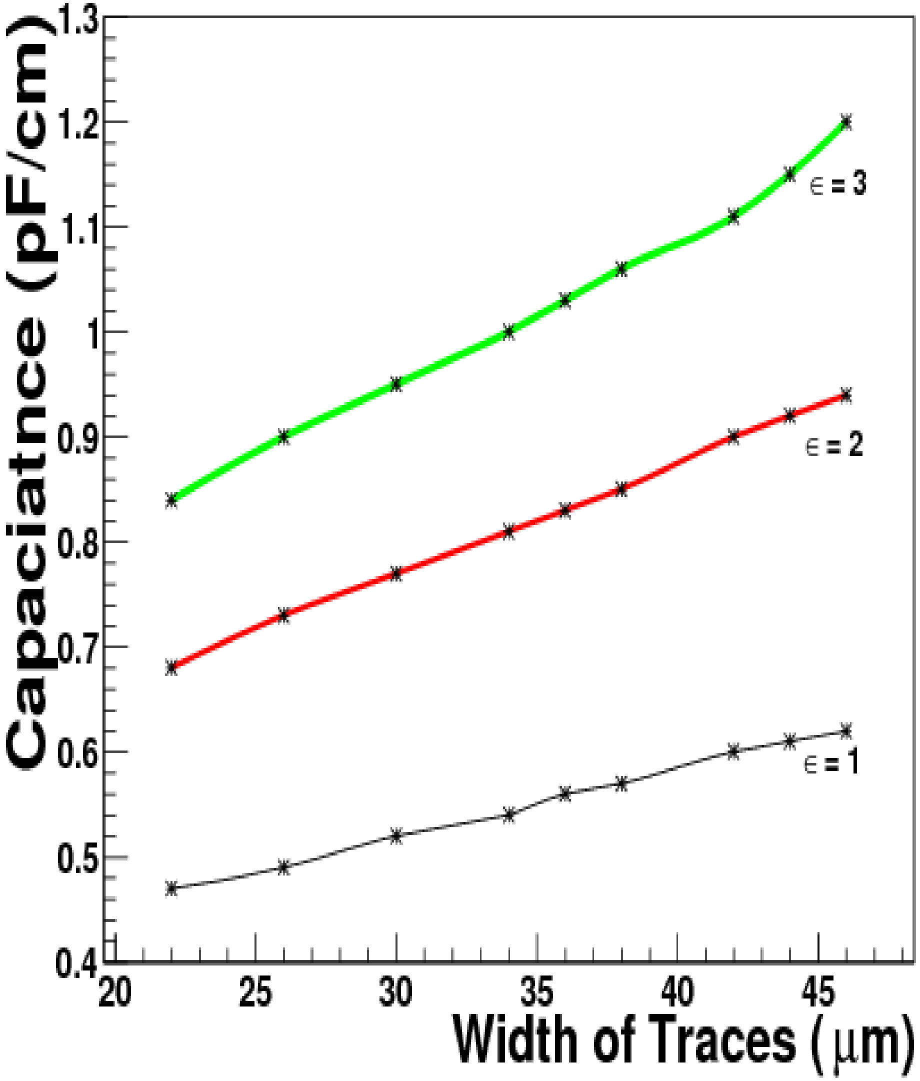
By RAPHAEL

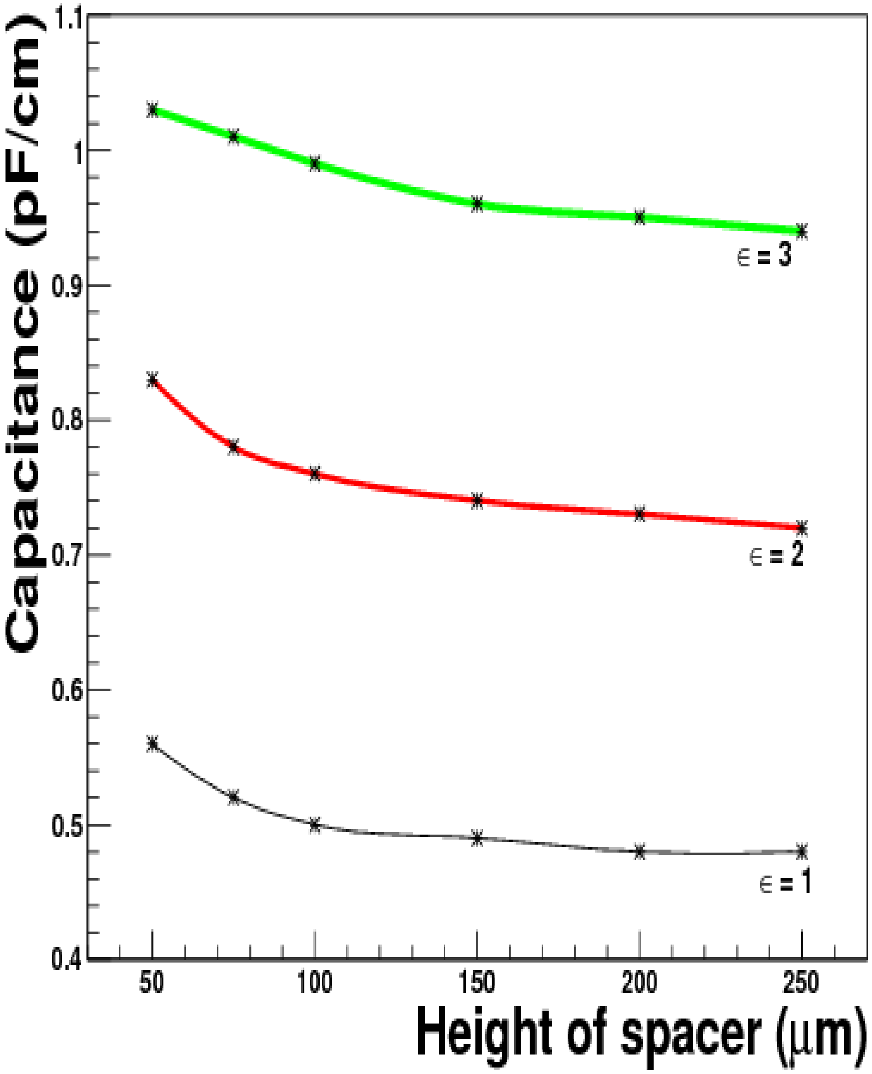
ε_r	C_total (pF/cm)	C int (top)	C int (bottom)	C int (imm.)
1	0.46	0.019	0.017	0.174
2	0.58	0.026	0.024	0.184
3	0.69	0.032	0.028	0.20

Comparison of CBM, D0 and LHCb kapton cables

Parameters	CBM cables (new)	D0 cables	LHCb Cables
Trace width	36µm (46µm)	16µm	16µm
Trace height	14µm	8µm	8µm
Aspect Ratio	2.6 (3.3)	2	2
Metal traces	Aluminum	Copper	Copper
Height of kapton layer	10µm	50µm	100µm
Height of spacer	50µm	200µm	-
Pitch	100µm	100µm	112µm
Total Capacitance (pF/cm)	0.8 (1.0)	0.5	0.4

Ways to reduce the capacitance of cables

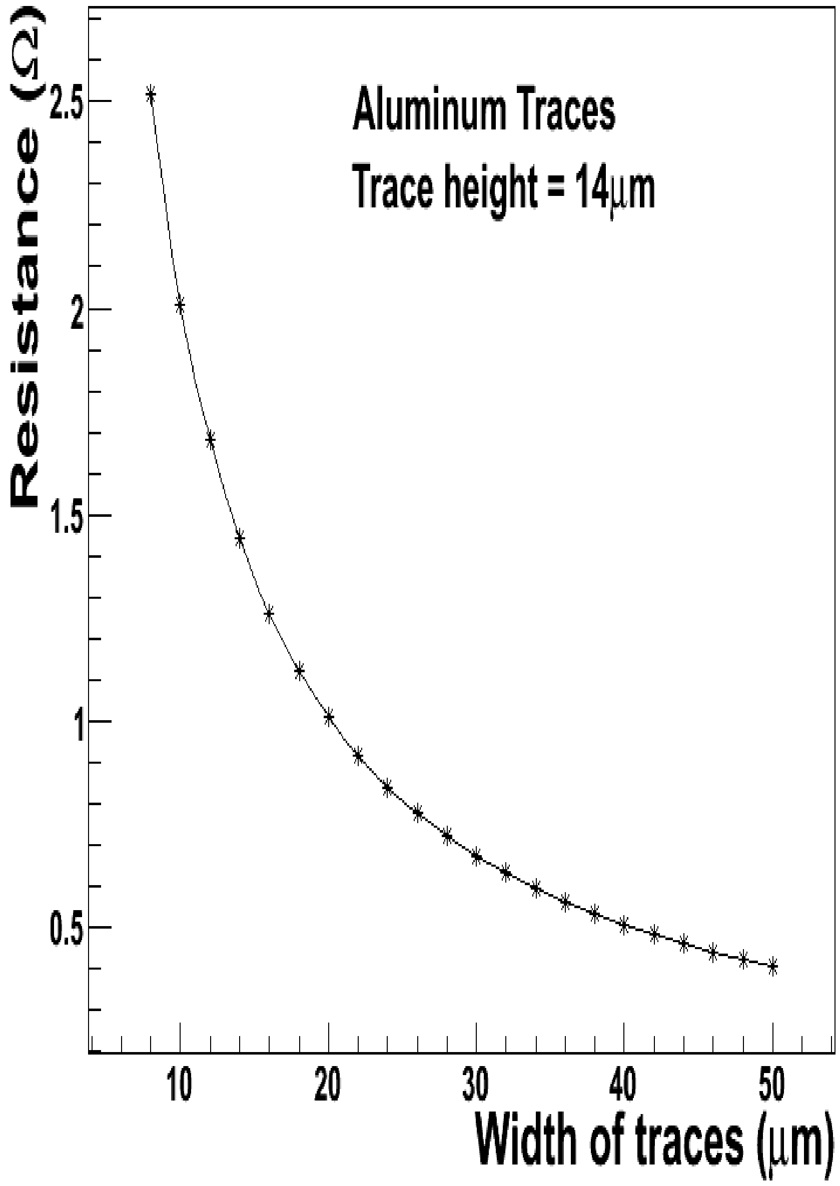


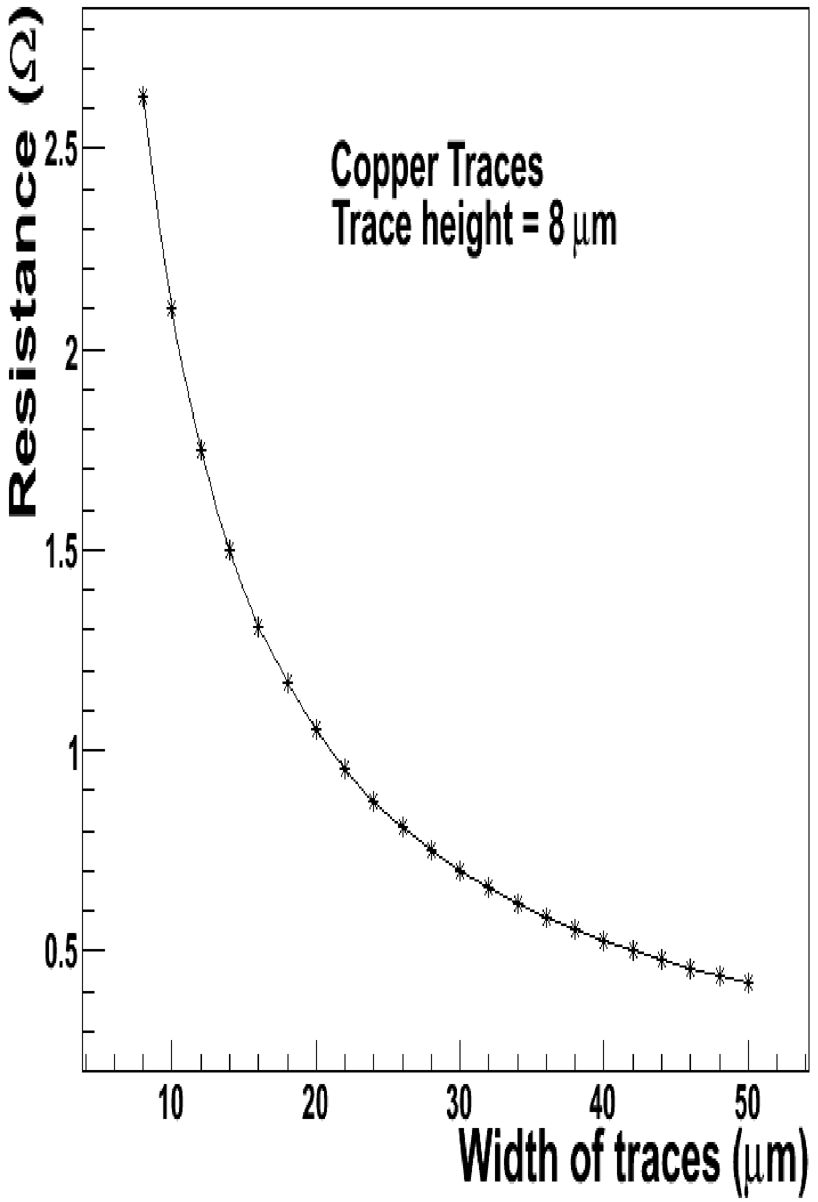


⇒ Capacitance decreases with decreasing the width of traces

⇒ Capacitances decreases with increase in height of spacer

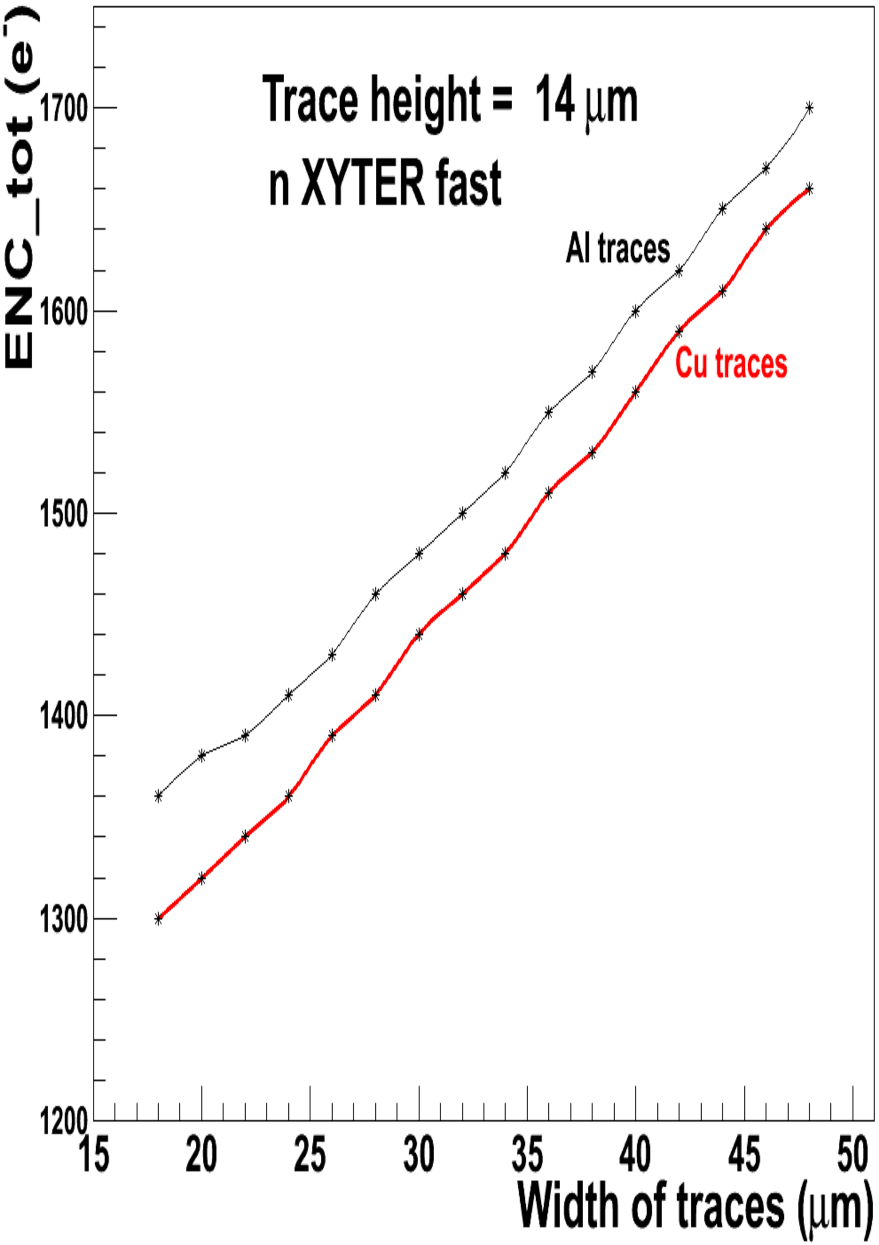
Effect of trace width on Resistance

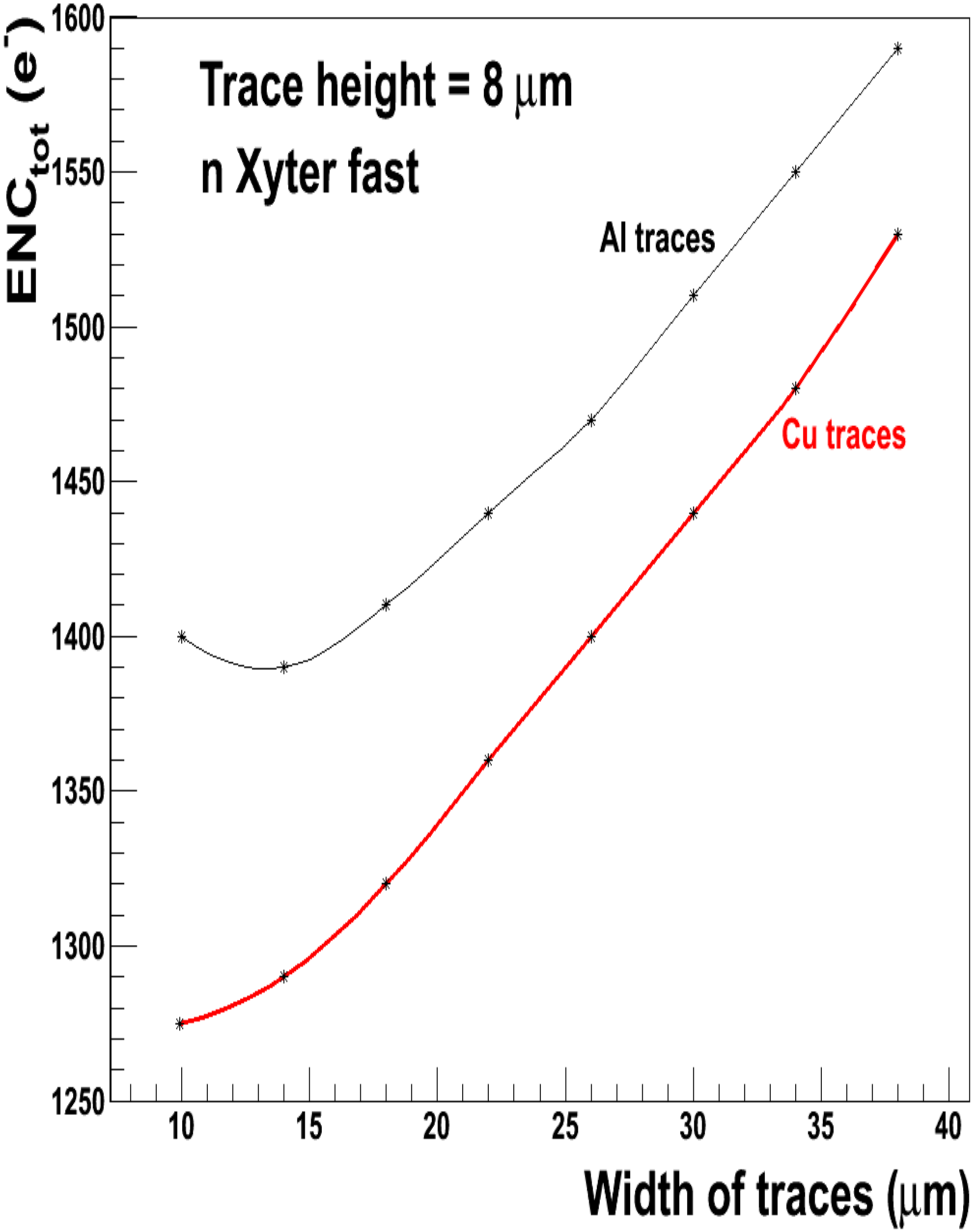




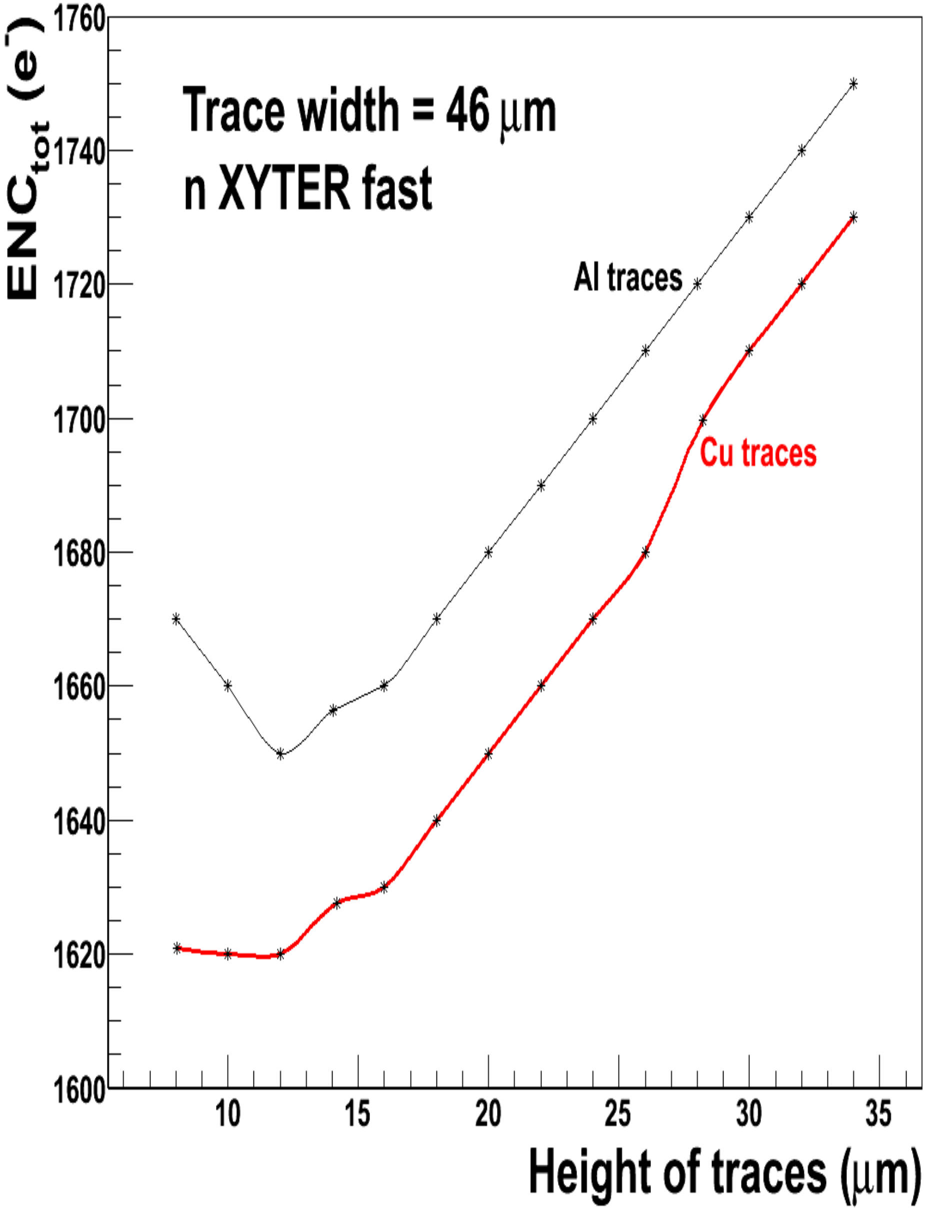
ENC = 13 * C_tot*$\sqrt{R/\tau}$

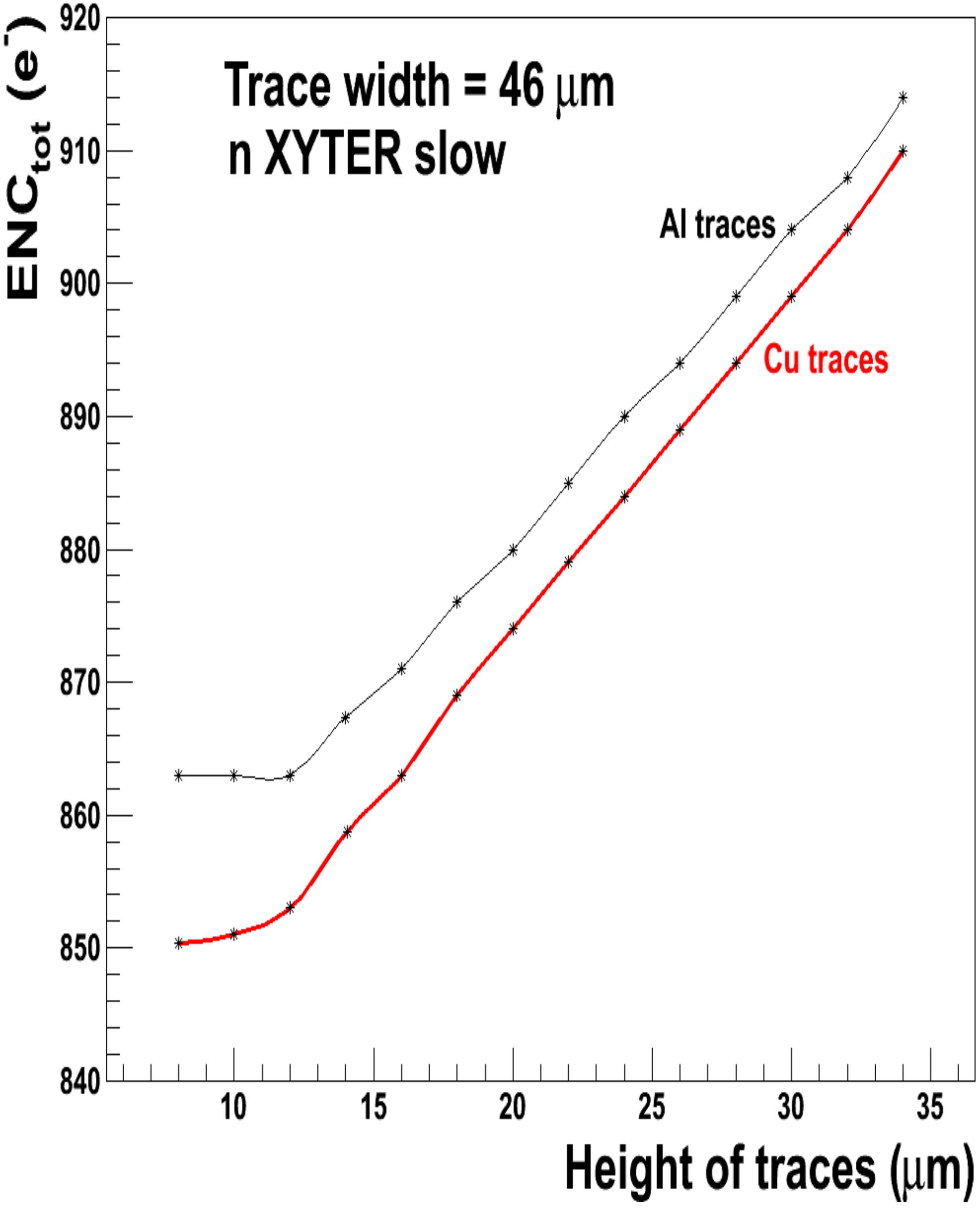
ENC versus trace width in kapton cables





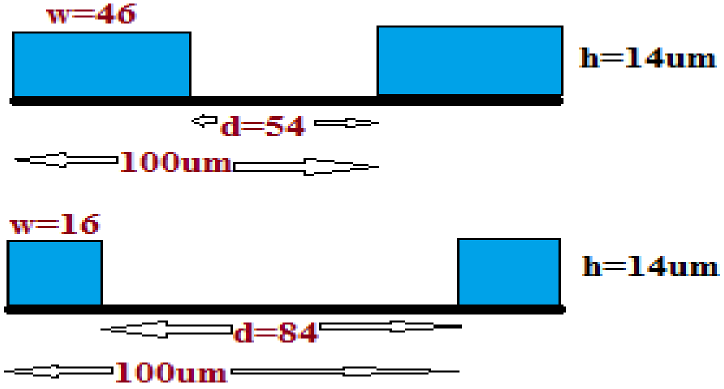
ENC versus trace height in kapton cables





Summary and Future Plans

- Major contributors to noise are the capacitance and series resistance
- Detector trace resistance can be ↓ed by ↑ing the thickness of AC pad
- Detector capacitance will ↑ after irradiation, hence noise will ↑ with irradiation
- Lesser the width of traces less is the capacitance contributions from cable as trace width contributes more to the capacitance value than the trace height



$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

- Using Copper can help in reducing cable noise
- Combination of small sensor + large cables is better than big sensor + small cables

- Study aspect ratio factor

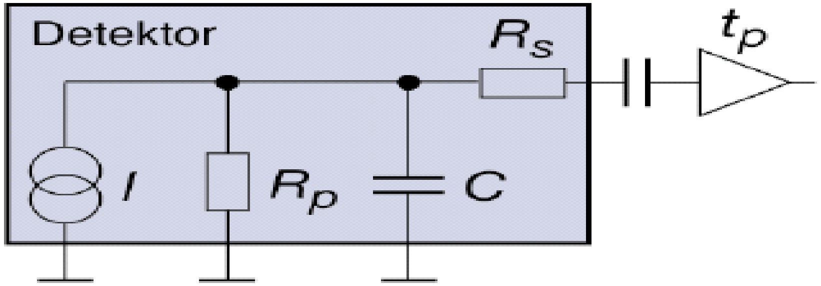
- Understand the impact on strip isolation after irradiation and hence on charge collection.

Backup Slides

Signal to Noise Ratio

The most important noise contributions are:

1) Detector Leakage Current (ENC_I)
2) Detector + Cable Capacitance (ENC_C)
3) Detector Parallel Resistor (ENC_{RP})
4) Detector + Cable Series Resistor (ENC_{RS})



Alternate circuit diagram of a silicon detector.

The overall noise is the quadratic sum of all contributions:

$$\boxed{ENC = \sqrt{ENC_C^2 + ENC_I^2 + ENC_{Rp}^2 + ENC_{Rs}^2}}$$

Noise due to Leakage Current

Assuming an amplifier with an integration time ("peaking time") t_p followed by a CR-RC filter the noise contribution by the leakage current can be written as:

$$\boxed{\mathrm{ENC}_I = \frac{e}{2}\sqrt{\frac{I t_p}{e}}}$$

e .... Euler number (2.718...)

e ... Electron charge

Using the physical constants, the leakage current in nA and the integration time in μs, the formula can be simplified to:

$$\mathrm{ENC}_I \approx 107\sqrt{I t_p} \qquad \left[I \text{ in nA},\ t_p \text{ in } \mu\text{s}\right]$$

To minimize this noise contribution the detector should be of high quality with small leakage current and the integration time should be short.

Noise due to Capacitance

The detector + Cable capacity at the input of a charge sensitive amplifier is usually the dominant noise source in the detector system.

This noise term can be written as:

$$\boxed{\mathrm{ENC}_C = a + b \cdot C}$$

The parameter a and b are given by the design of the amplifier.
C is the total capacitance at the input of the amplifier.

Typical values are (amplifier with 1µs integration time):

a = 160 e and b = 12 e/pF

“a” increases as the electronics become faster.

Noise due to Parallel Resistor

The parallel resistor R_P in the alternate circuit diagram is the bias resistor. The noise term can be written as:

$$\boxed{\mathrm{ENC}_{Rp} = \frac{e}{e}\sqrt{\frac{kTt_p}{2R_p}}}$$

e .... Euler number (2.718...)
e ... Electron charge

Assuming a temperature of 300 K, t_P in µs and R_P in MΩ the formula can be simplified to:

$$\mathrm{ENC}_{Rp} \approx 772\sqrt{\frac{t_p}{R_p}} \qquad \left[R_p \text{ in M}\Omega,\ t_p \text{ in } \mu\text{s}\right]$$

To achieve low noise, the parallel (bias) resistor should be large!

However the value is limited by the production process and the voltage drop across the resistor (high in irradiated detectors).

Noise due to Series Resistor

The series resistor R_S in the alternate circuit diagram is given by resistance of connection between strips and amplifier input (e.g. aluminum readout lines, hybrid connections etc.). It can be written as:

$$\boxed{\mathrm{ENC}_{\mathrm{Rs}} \approx 0.395\, C \sqrt{\frac{R_s}{t_p}}}$$

C .... Detector capacity on pF
t_p ... Integration time in μs
R_s ... Series resistor in Ω

Note that, in this noise contribution t_P is inverse, hence a long t_P reduces the noise. The capacitance (from Sensor + Cable) is again responsible for larger noise.

To avoid excess noise the aluminum lines should have low resistance (e.g. thick aluminum layer) and all other connections as short as possible.

Noise dependence on shaping time

DELPHI Microvertex:

★ readout chip (MX6):
$a = 325$ e, $b = 23$ e/pF, $t_p = 1.8\ \mu s$

★ 2 detectors in series each 6 cm long strips, $C = 9$ pF
➔ $\text{ENC}_\text{C} = 532$ e

★ typ. leakage current/strip: $I \approx 0.3$ nA
➔ $\text{ENC}_\text{I} = 78$ e

★ bias resistor $R_p = 36\ \text{M}\Omega$
➔ $\text{ENC}_\text{Rp} = 169$ e

★ series resistor = 25 Ω
➔ $\text{ENC}_\text{Rs} = 13$ e

➔ **Total noise: ENC = 564 e** (SNR 40:1)

CMS Tracker:

★ readout chip (APV25, deconvolution):
$a = 400$ e, $b = 60$ e/pF, $t_p = 50$ ns

★ 2 detectors in series each 10 cm long strips, $C = 18$ pF
➔ $\text{ENC}_\text{C} = 1480$ e

★ max. leakage current/strip: $I \approx 100$ nA
➔ $\text{ENC}_\text{I} = 103$ e

★ bias resistor $R_p = 1.5\ \text{M}\Omega$
➔ $\text{ENC}_\text{Rp} = 60$ e

★ series resistor = 50 Ω
➔ $\text{ENC}_\text{Rs} = 345$ e

➔ **Total noise: ENC = 1524 e** (SNR 15:1)

Calculated for the signal of a minimum ionizing particle (mip) of 22500 e.

ENC calculation for CBM tracker

CBM Tracker: Small sensor +Large Cables (n XYTER slow)

★ readout chip:

a = 200 e, b = 13 e/pF, tp = 140 ns

★ 1 detector of 1.5 cm long Strips, *C = 6.11 pF* and a cable of length 40cm, *C = 37.2 pF*

➔ ENC_c = 763 e

★ max. leakage current/strip: *I ≈ 0.5 nA*

➔ ENC_I = 27 e

★ bias resistor *Rp = 2 MΩ*

➔ ENC_Rp = 204 e

★ series resistor from sensors of 1.5cm long strips = 32 Ω, from cable of length 40cm = 17.5 Ω

➔ ENC_Rs = 322 e

➔ **Total noise: ENC = 853 e**

ENC calculation for CBM tracker

CBM Tracker: Small sensor +Large Cables (n XYTER fast)

★ readout chip:

a = 200 e, b = 27 e/pF, tp = 19 ns

★ 1 detector of 1.5 cm long Strips, *C = 6.11 pF* and a cable of length 40cm, *C = 37.2 pF*

➔ **ENC_c = 1369 e**

★ max. leakage current/strip: *I ≈ 0.5 nA*

➔ **ENC_I = 10 e**

★ bias resistor *Rp = 2 MΩ*

➔ **ENC_Rp = 75 e**

★ series resistor from sensors of 1.5cm long strips = 32 Ω, from cable of length 40cm = 17.5 Ω

➔ **ENC_Rs = 873 e**

➔ **Total noise: ENC = 1625 e**

ENC calculation for CBM tracker

CBM Tracker: Big sensor + Small Cables (n XYTER fast)

★ readout chip:

a = 200 e, b = 27 e/pF, tp = 19 ns

★ 1 detector of 10 cm long Strips, *C = 40.7 pF* and a cable of length 10cm, *C = 9.3 pF*

➔ **ENC_c = 1550 e**

★ max. leakage current/strip: $I \approx 3.1nA$

➔ **ENC_I = 26 e**

★ bias resistor $Rp = 2\ M\Omega$

➔ **ENC_Rp = 75 e**

★ series resistor from sensors of 10 cm long strips = 213 Ω, from cable of length 10cm = 4.4 Ω

➔ **ENC_Rs = 2114 e**

➔ **Total noise: ENC = 2623 e**

ENC calculation for CBM tracker

CBM Tracker: Big sensor + Small Cables (n XYTER slow)

★ readout chip:

a = 200 e, b = 13 e/pF, tp = 140 ns

★ 1 detector of 10 cm long Strips, *C = 40.7 pF* and a cable of length 10cm, *C = 9.3 pF*

➔ **ENC_c = 850 e**

★ max. leakage current/strip: $I \approx 3.1 nA$

➔ **ENC_I = 71 e**

★ bias resistor $Rp = 2\ M\Omega$

➔ **ENC_Rp = 204 e**

★ series resistor from sensors of 10 cm long strips = 213 Ω, from cable of length 10cm = 4.4 Ω

➔ **ENC_Rs = 779 e**

➔ **Total noise: ENC = 1173 e**