Simulation of guard ring influence on the performance of ATLAS pixel detectors for inner layer replacement

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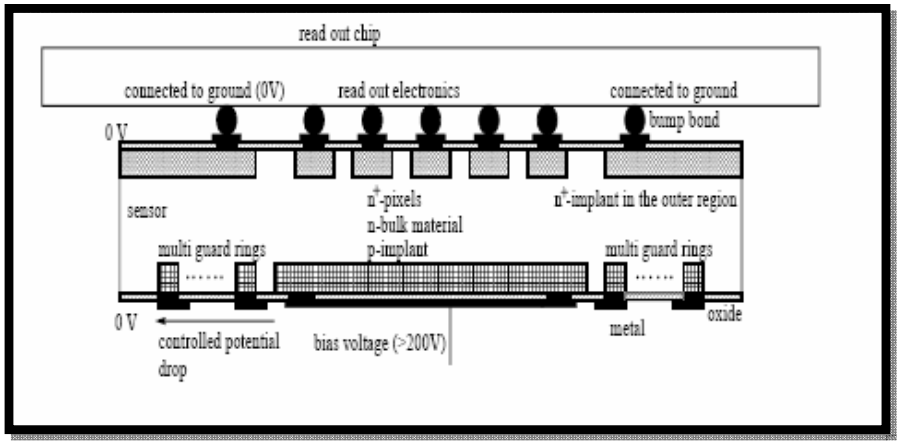
On behalf of ATLAS-planar-pixel upgrade group

The ATLAS pixel sensor

- n+/n sensor (n bulk, high resistivity)
- P-Spray or p-stop insulation of pixel's n doping regions
- p-n junction on back-side
- Multi-Guard Ring Structure on back side with controlled voltage drop
    - 22 ring with increasing pitch from 20 to 50 microns
    - p-doping structure

- Sustain high over-depletion Voltage
- Good radiation hardness
- MGRS allow long term stability

- Double-sided processing needed
- more trapping than p type material



The ATLAS planar pixel sensor & b-layer replacement, S-LHC

- S-LHC consists of a 10-fold increase in luminosity
- Inner layer will see 10^{16}neq/cm^2
- Increased occupancy (x10)
- Electronics and sensors need a redesign to operate in these conditions
- Planar pixel has proven to be radiation hard , improvement are possible

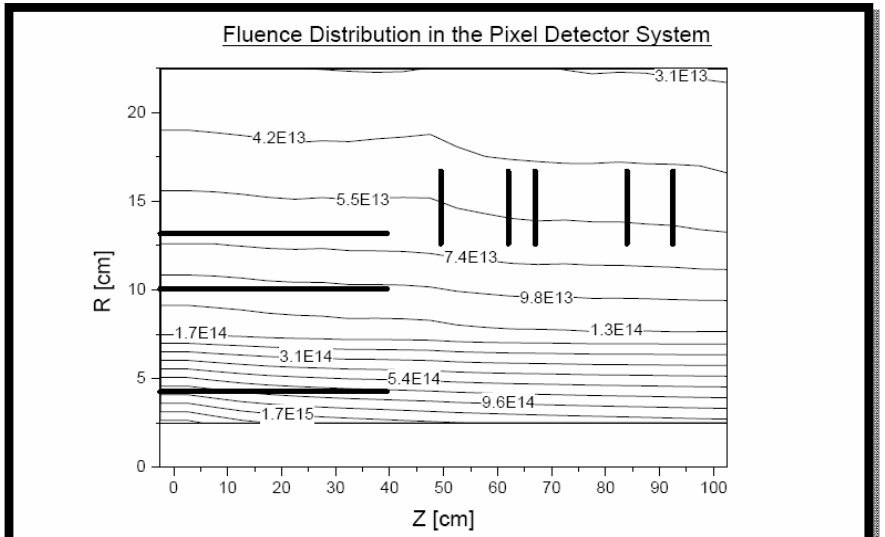
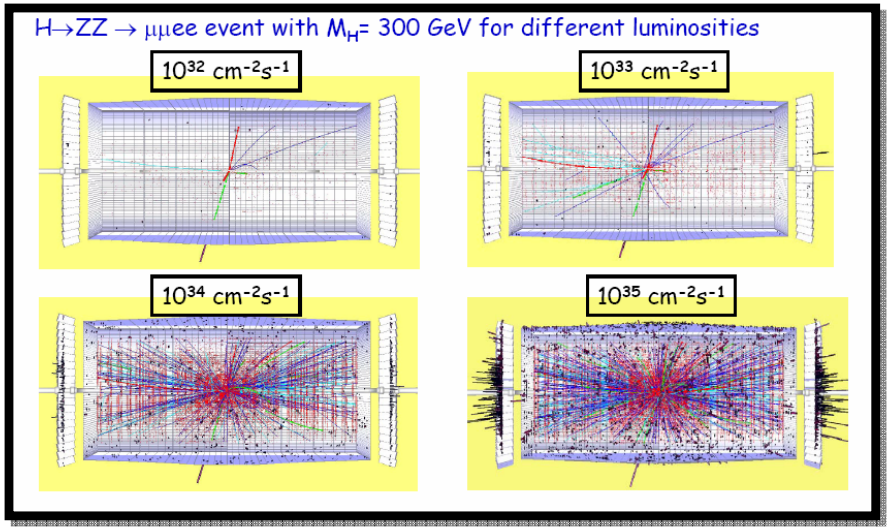
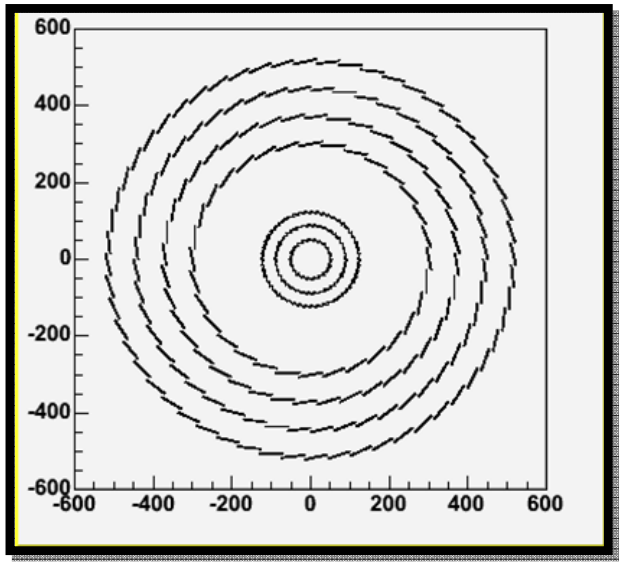


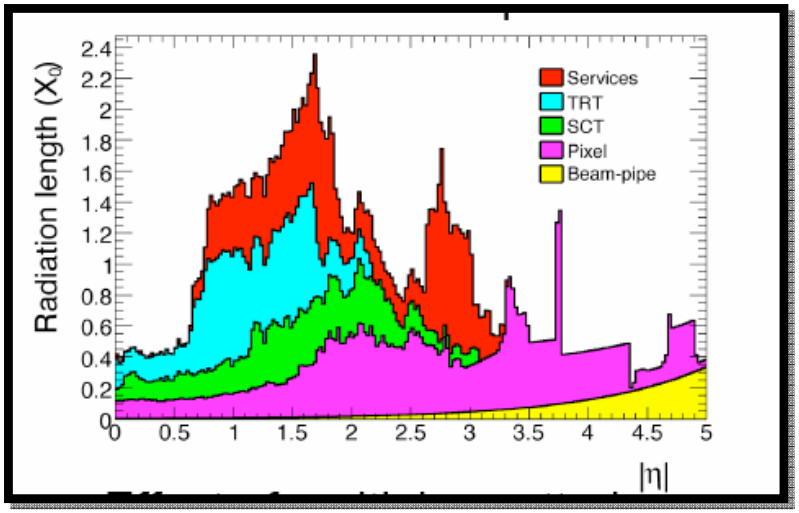
Figure 4-1 The annual 1 MeV neutron equivalent fluence ($cm^{-2}yr^{-1}$) in the pixel detector region



Improving tracking by ATLAS pixel

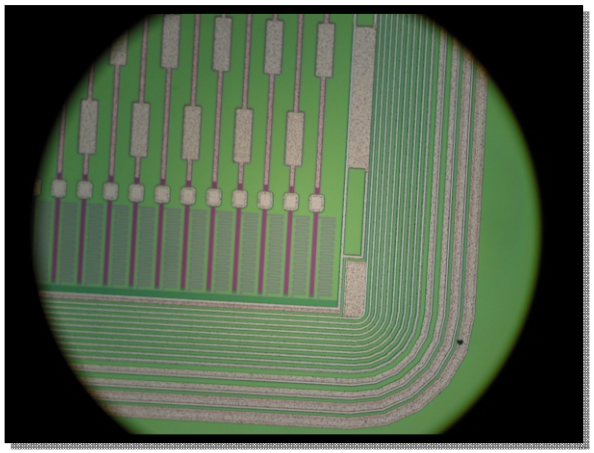
- Material budget (X_0) is the critical parameter of the pixel detector design
  - Lower X_0 means less multiple scattering, hence higher outer layer spatial , P⊥ resolution
  - Minimize bremstralhung photon production
- Reducing sensor overlapping and sensor thickness will reduce the Xo and simplify the layout.

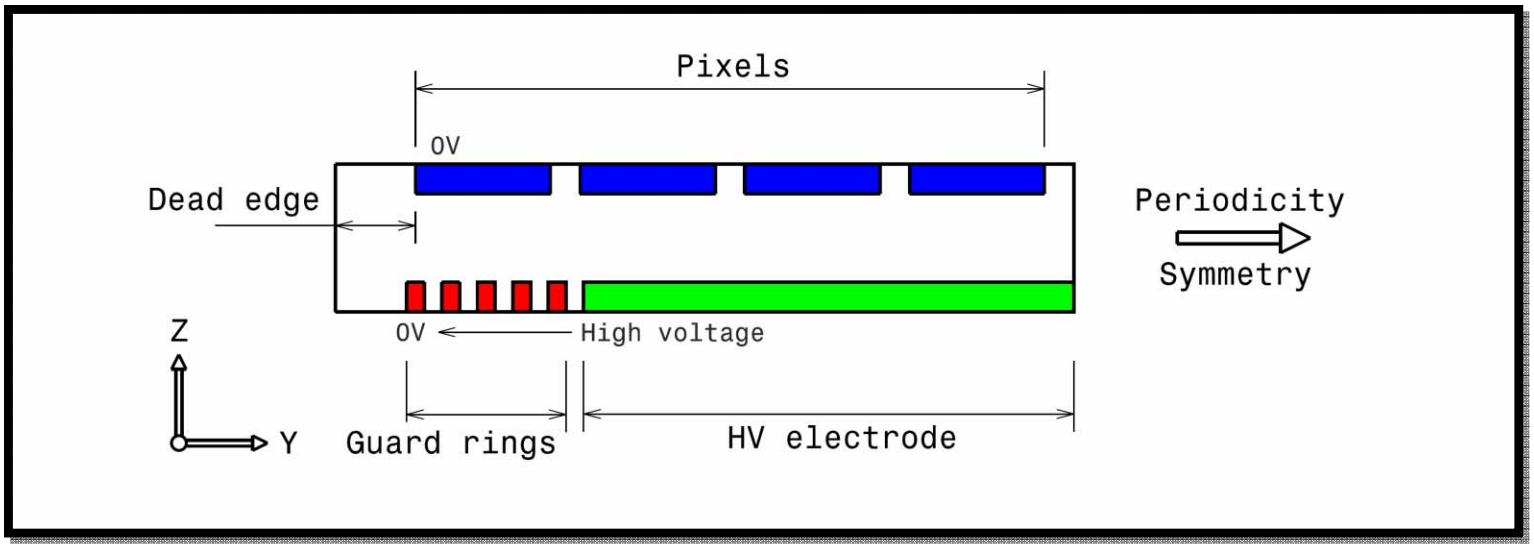




Multi-Guard Ring structure (MGRS)

- Guard ring structure serve multiple purpose:
  - Collect edge & surface current
  - Ensure a gradual potential drop towards the edge of the sensor and prevent breakdown due to high electrical field
- Guard rings is an unsensible part of the sensor

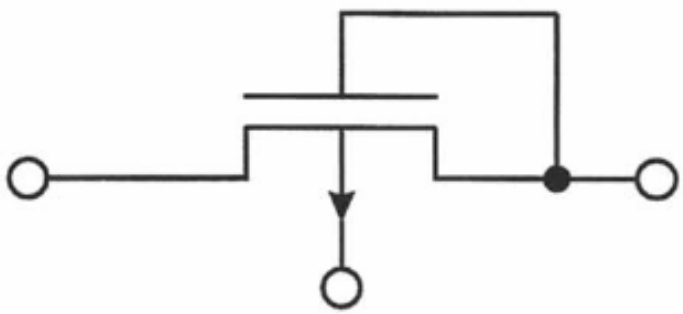




Our goal is to simulate different MGRS , minimize E field and unsensible zone of the sensor while keeping the protection from edge

Guard rings

- Can be represented as serial connection of p-enhanced MOSFET with gate connected to source
- The ring are left floating , potential drop is created by punchthrough
- Breakdown occurs when potential drop between two ring is larger that the p-MOSFET punchthrough threshold
- Geometry must be optimized to ensure a smooth potential drop, provide good depleted volume under edge pixel



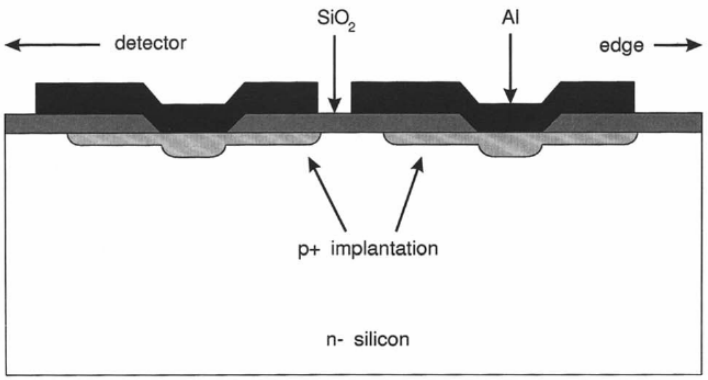


Fig. 3. Layout of the guardring structure with non-overlapping gate.

SILVACO TCAD simulation

- We use a commercial product that solve drift-diffusion equation coupled to Poisson equation in our geometry

$$q\frac{dn}{dt} = q(G_n - R_n) + \nabla \cdot \vec{J}_n(n, V, \mu_n, n_i)$$

$$q\frac{dp}{dt} = q(G_p - R_p) + \nabla \cdot \vec{J}_p(p, V, \mu_p, n_i)$$

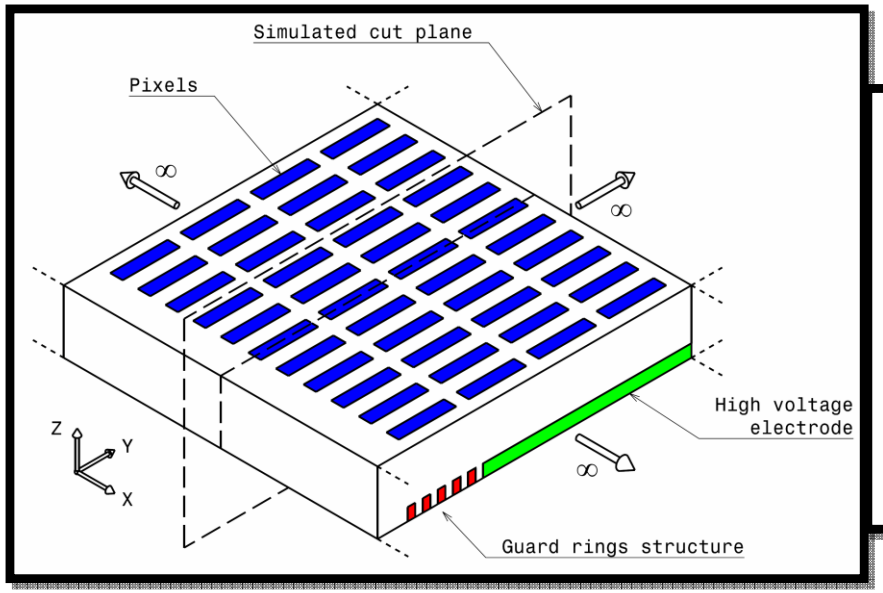
$$J_{n,p} = q \cdot (n, p) \cdot \mu_{n,p}\vec{E} + qD_{n,p}\nabla(n, p)$$

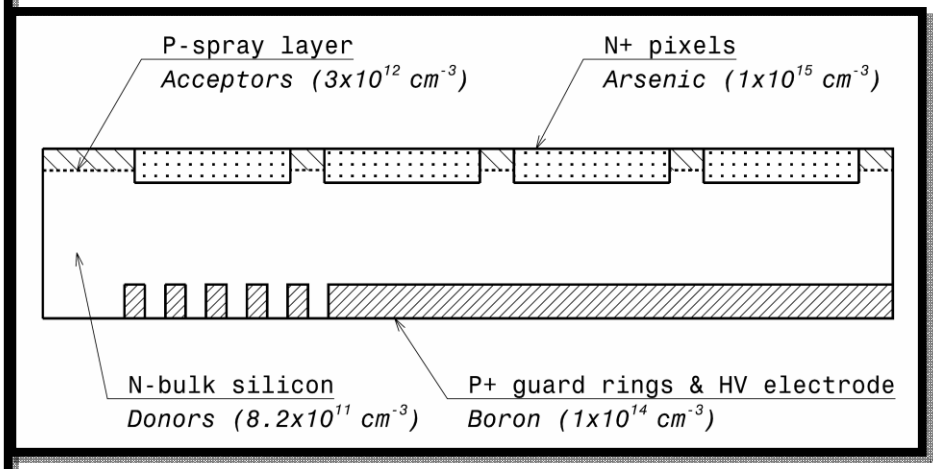
$$R_{n,p} = \sum R_i$$

$$R_i = \frac{pn - n_i^2}{\tau_{ni}(p + \Gamma n_{\text{int}} e^{(Ef-Ei)/kT}) + \tau_{pi}(n + \frac{n_{\text{int}} e^{(Ei-Ef)/kT}}{\Gamma})}$$

$$G_{n,p} = G_{photon} + G_{phonon} + G_{mip}$$

- We built a parametric model to sweep different parameters and optimise MGRS

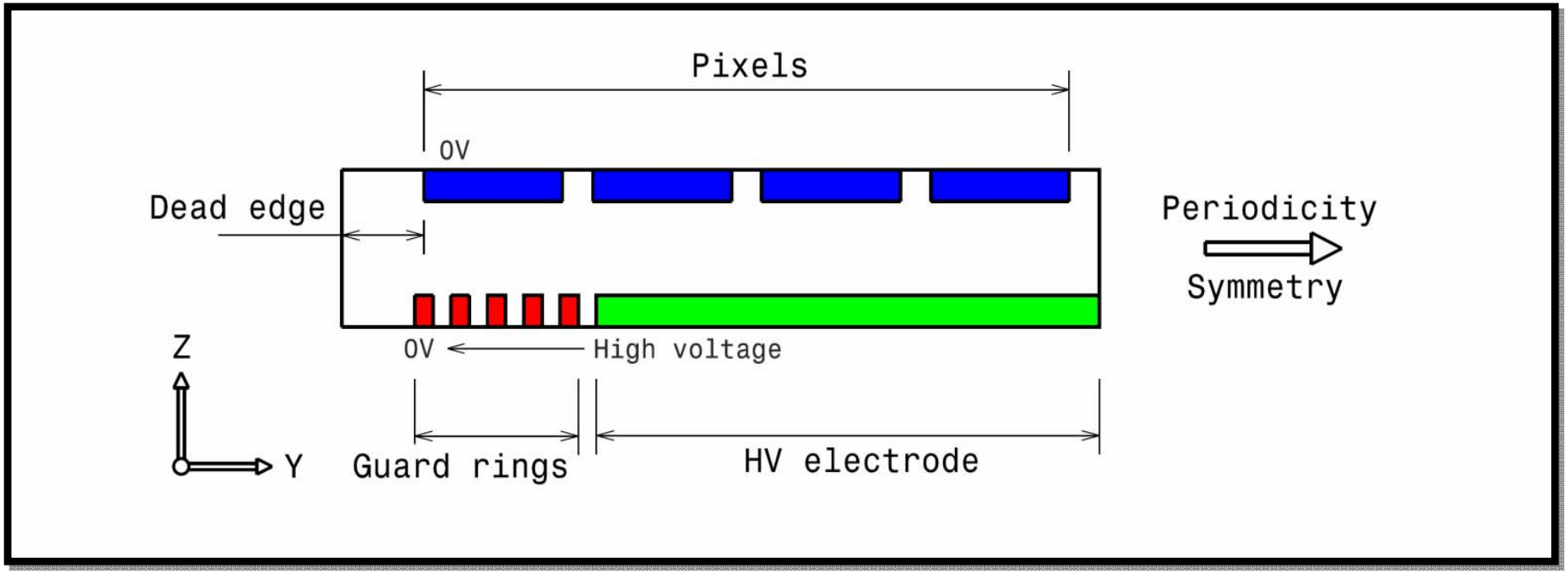




Simulation model

- Concentration dependent Shockley-Read-Hall Generation-Recombination
  - Leakage current, depletion
- Concentration & Electric field dependent mobility
  - Taken from experimental data on Silicon
- Band-gap narrowing
- Impact ionization
  - Simulate breakdown due to high electric field

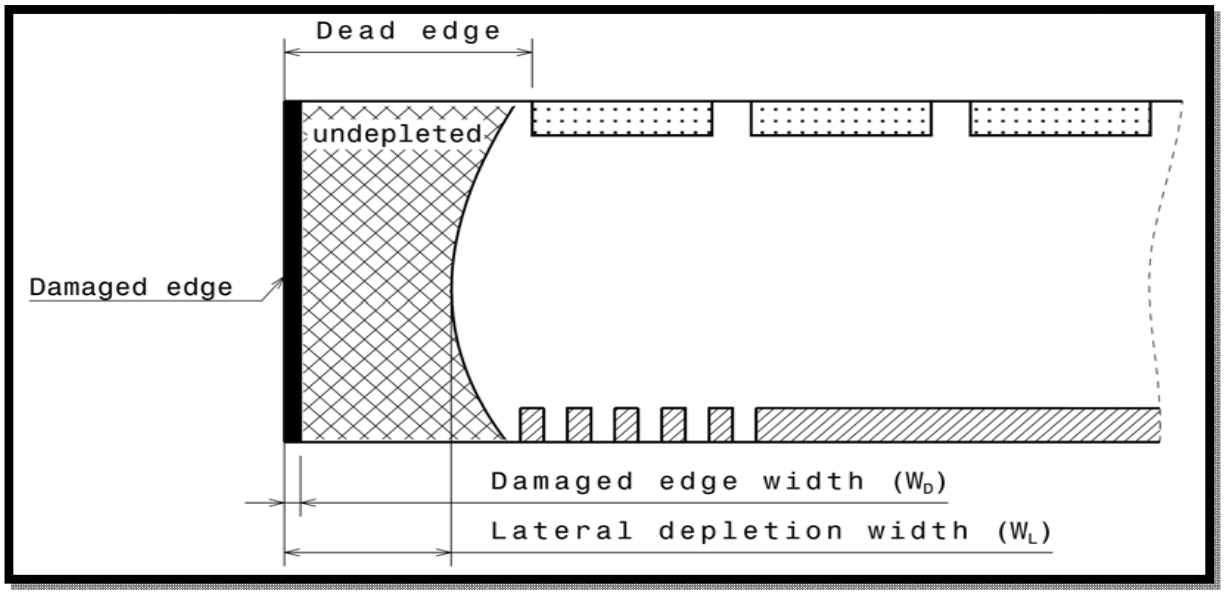
Boudary conditions



- Oxide-Semiconductor interface : No current, fixed charge layer Q=1e12
- Pixels and High-Voltage contact : Ohmic contact, fixed potential
- Guard rings : No current
- Symmetry periodicity: No Electric field perpendicular to surface

SILVACO TCAD simulation

Doping and dimensions taken from ATLAS Pixel TDR

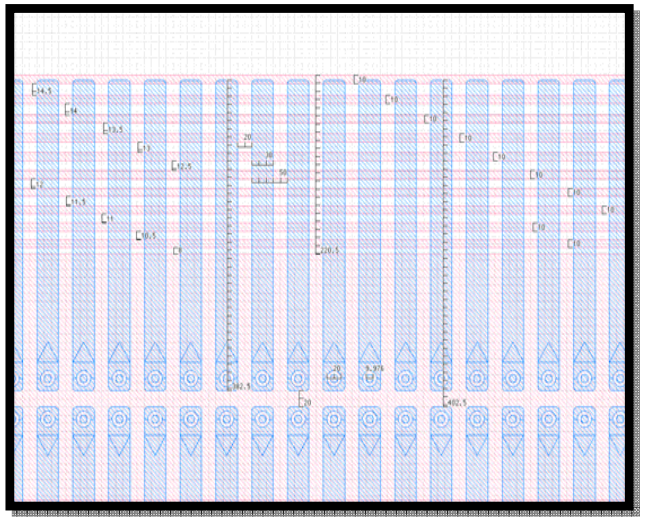


To optimize the sensor geometry, we swept through :

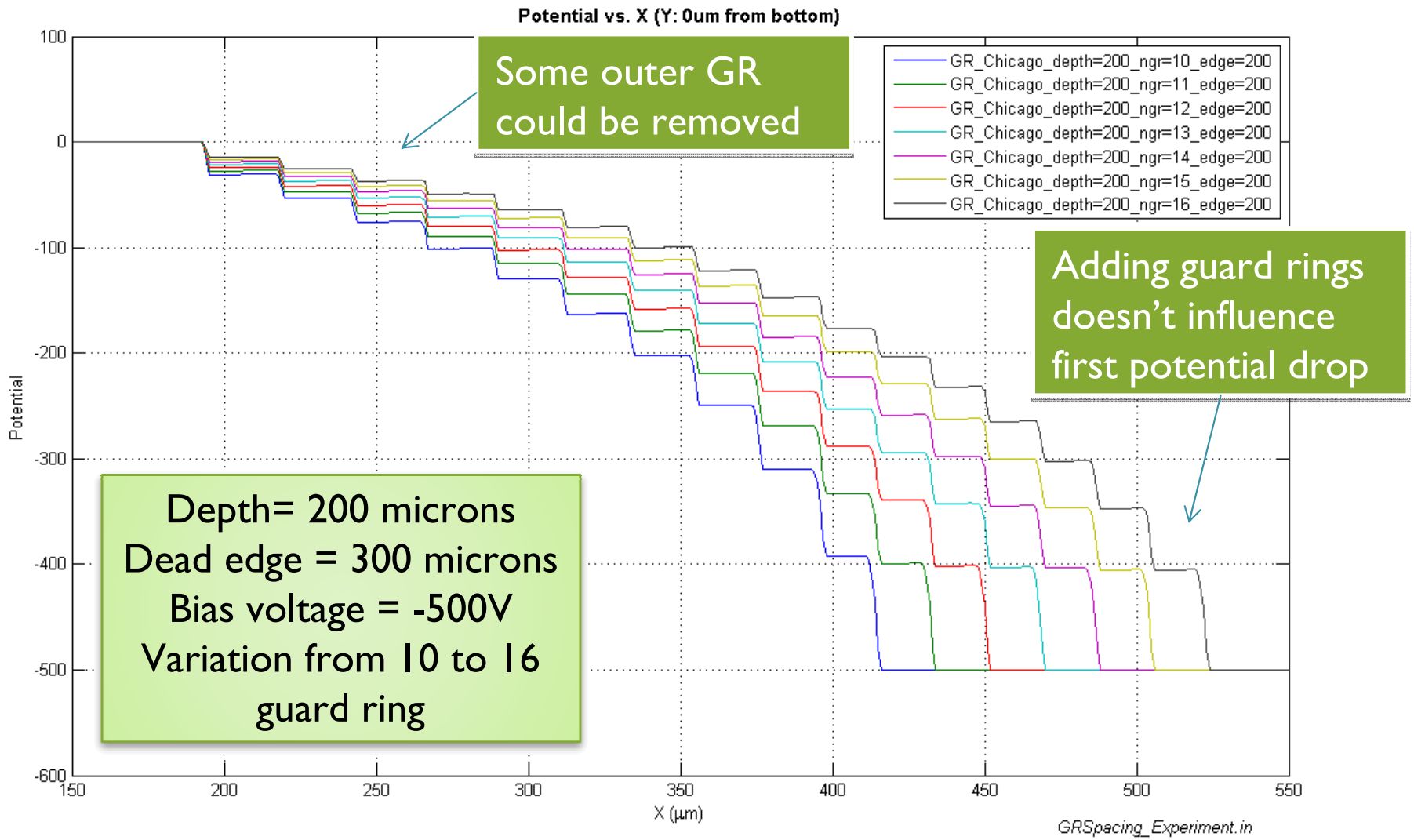
- Number of guard rings (10 to 16)
- Spacing for GR kept as actual (from 15 to 8 microns, 10 microns wide)
- Sensor thickness (100 to 300 microns)
- Dead edge width (50 to 400 microns)

We look at :

- Electric field distribution
- Depleted volume
- Current
- breakdown voltage



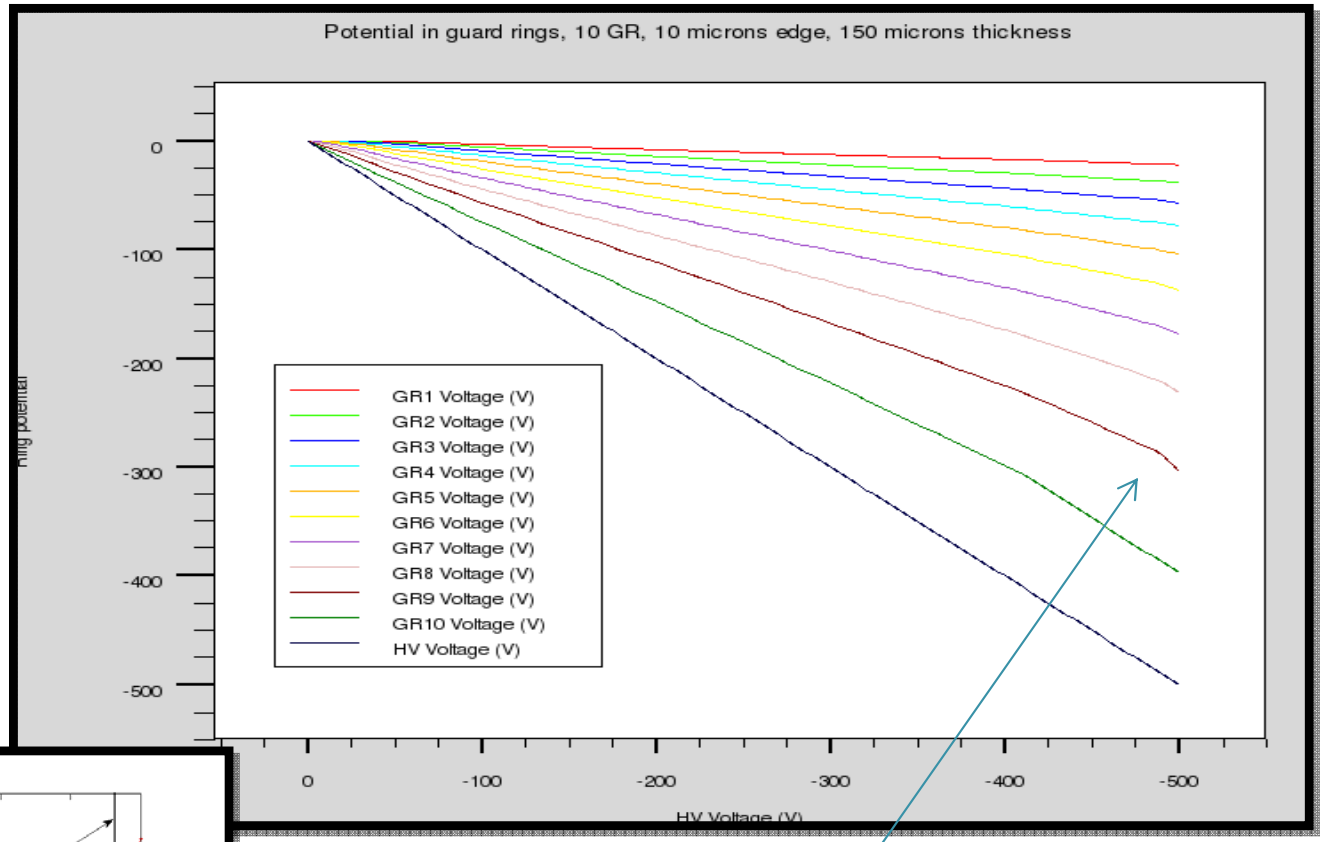
Potential distribution

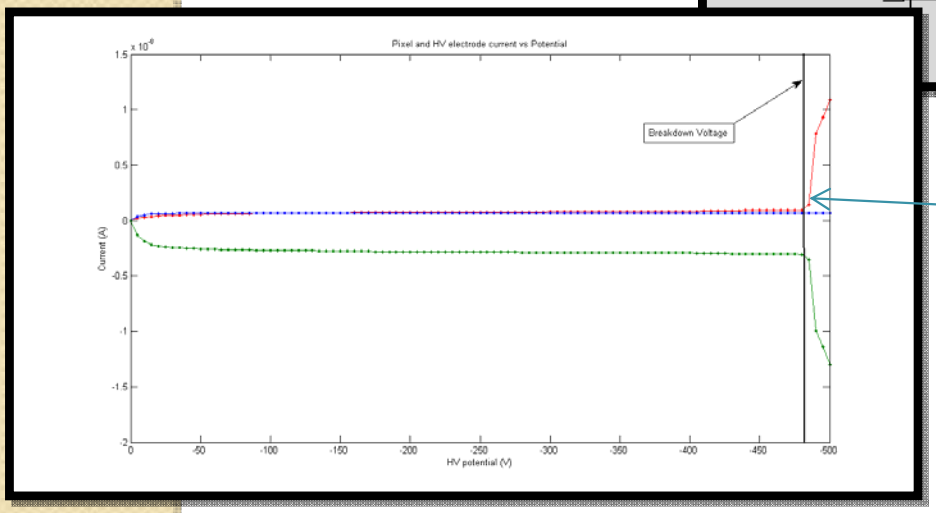


Depth= 200 microns
Dead edge = 300 microns
Bias voltage = -500V
Variation from 10 to 16 guard ring

Potential distribution

We can simulate the formation of breakdown due to avalanche formation by impact ionization

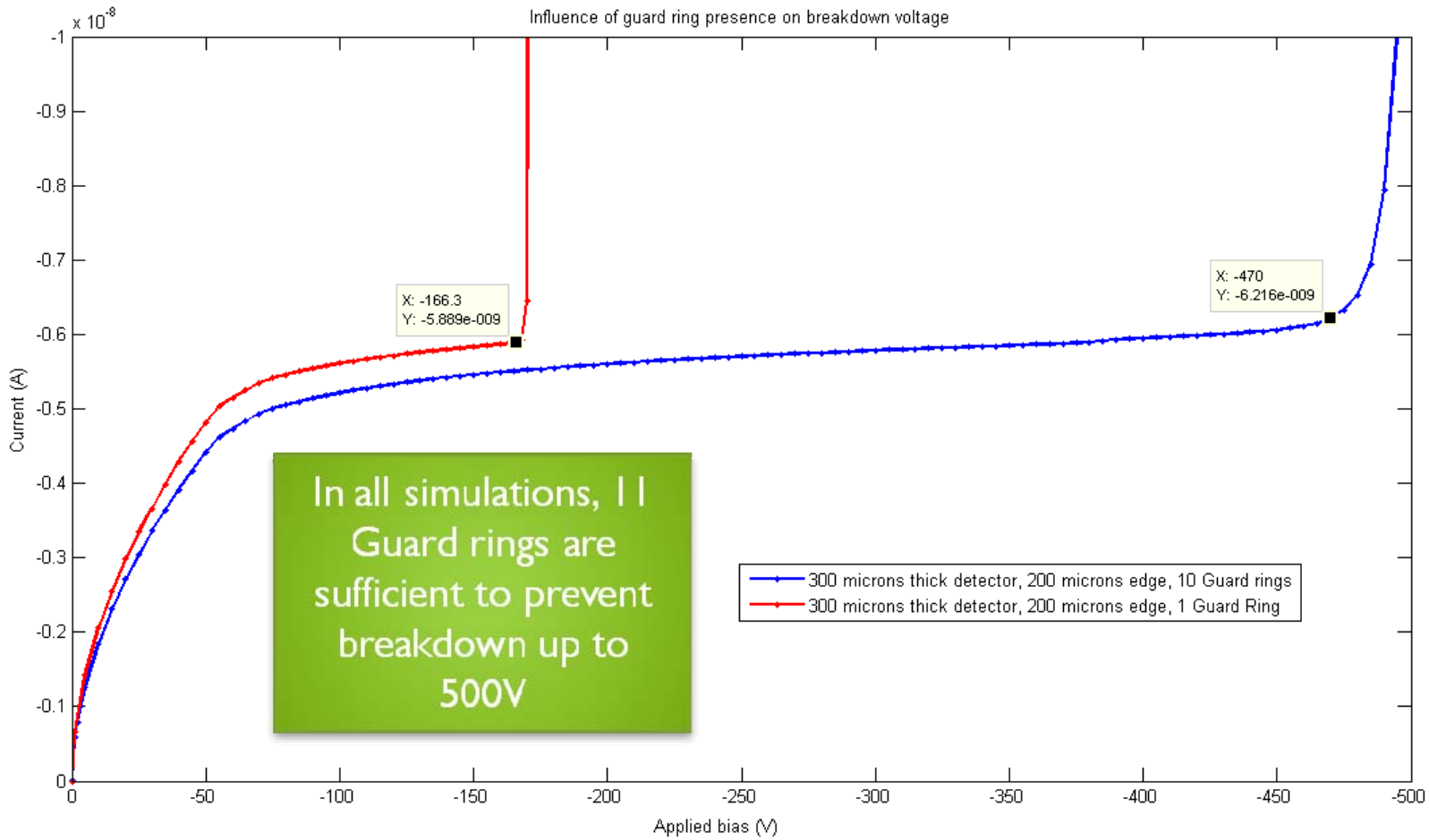




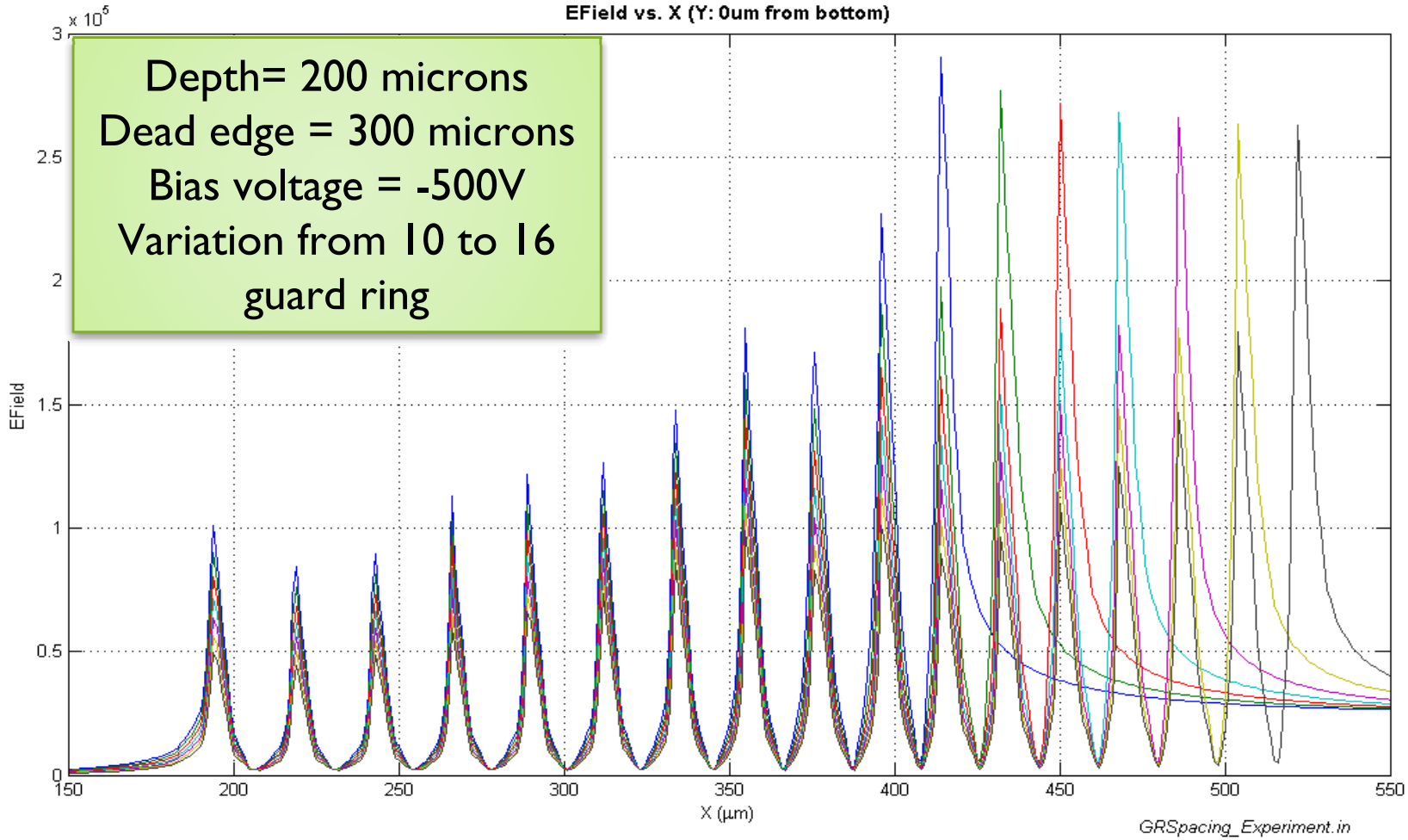
Inflexion in the guard potential curve is correlated to breakdown formation

Potential distribution

- Guard ring are essential for HV operation



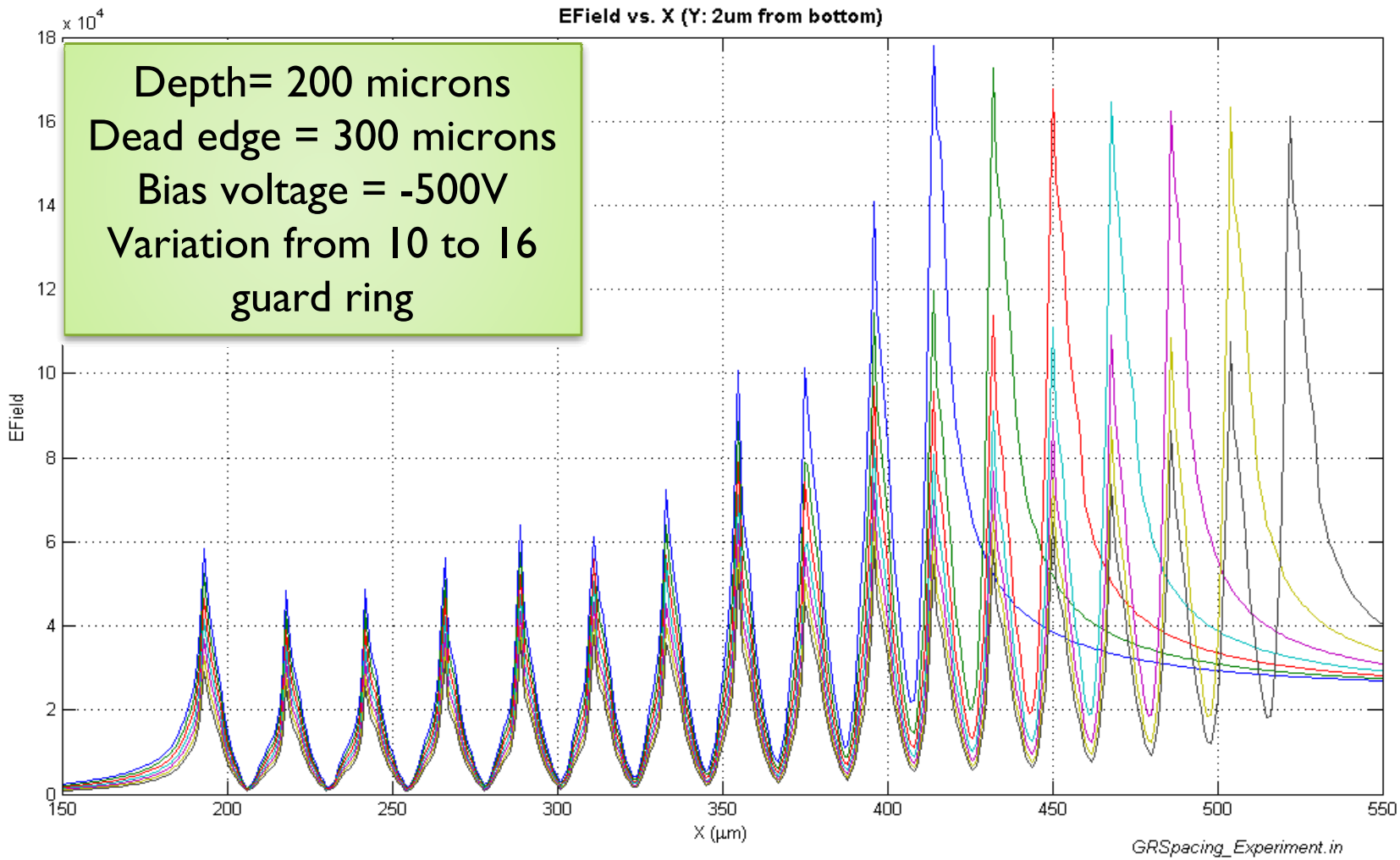
Electric Field in oxide



Depth= 200 microns
Dead edge = 300 microns
Bias voltage = -500V
Variation from 10 to 16 guard ring

Breakdown field in Oxide ≅ 5-6MV/cm

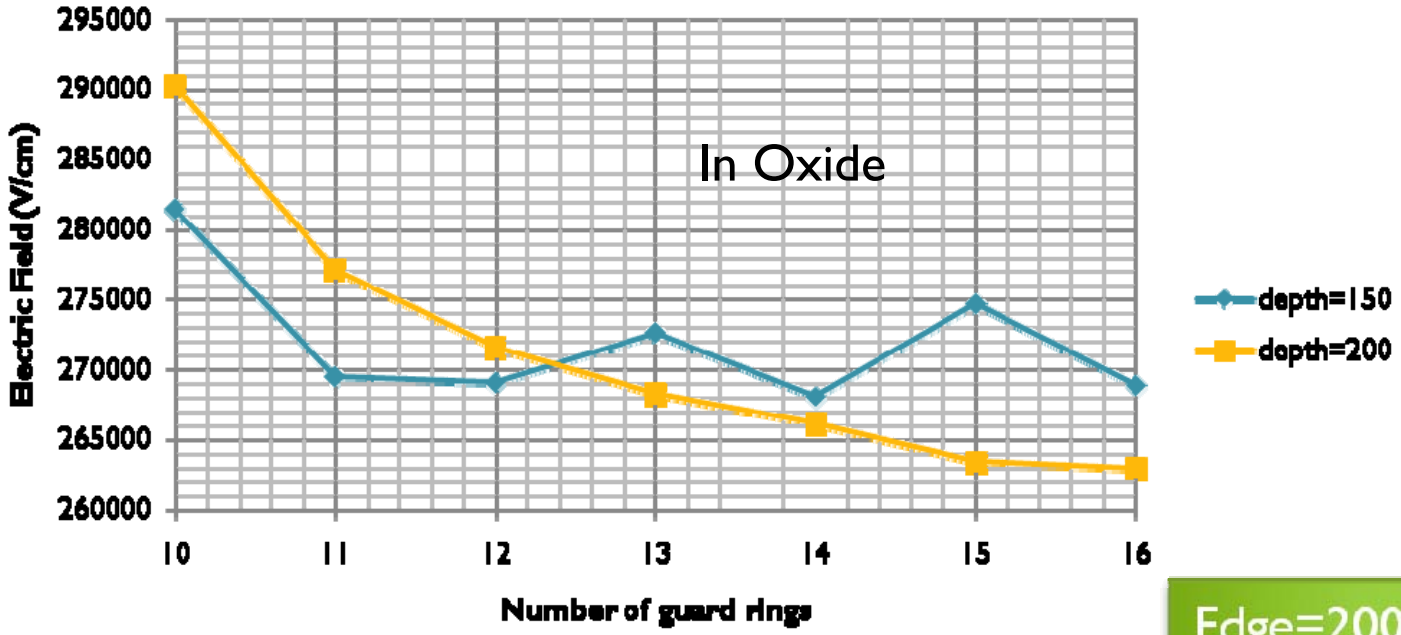
Electric Field in Silicon



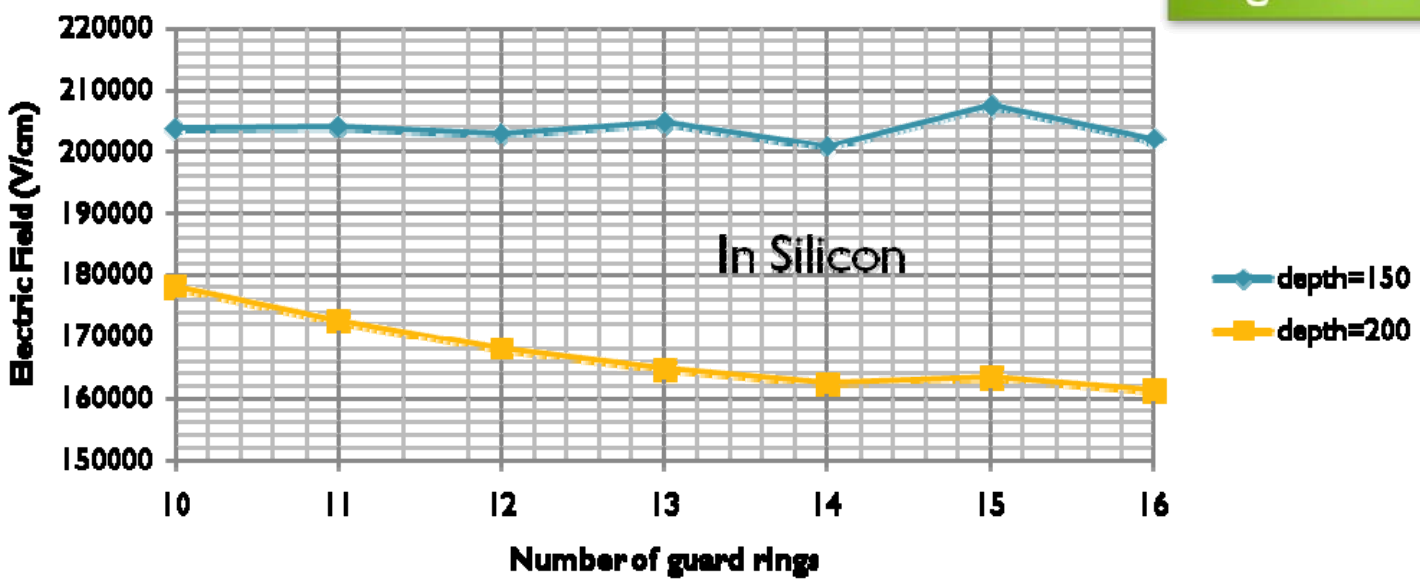
Depth= 200 microns
Dead edge = 300 microns
Bias voltage = -500V
Variation from 10 to 16 guard ring

Breakdown field in silicon≅ 0.3 MV/cm

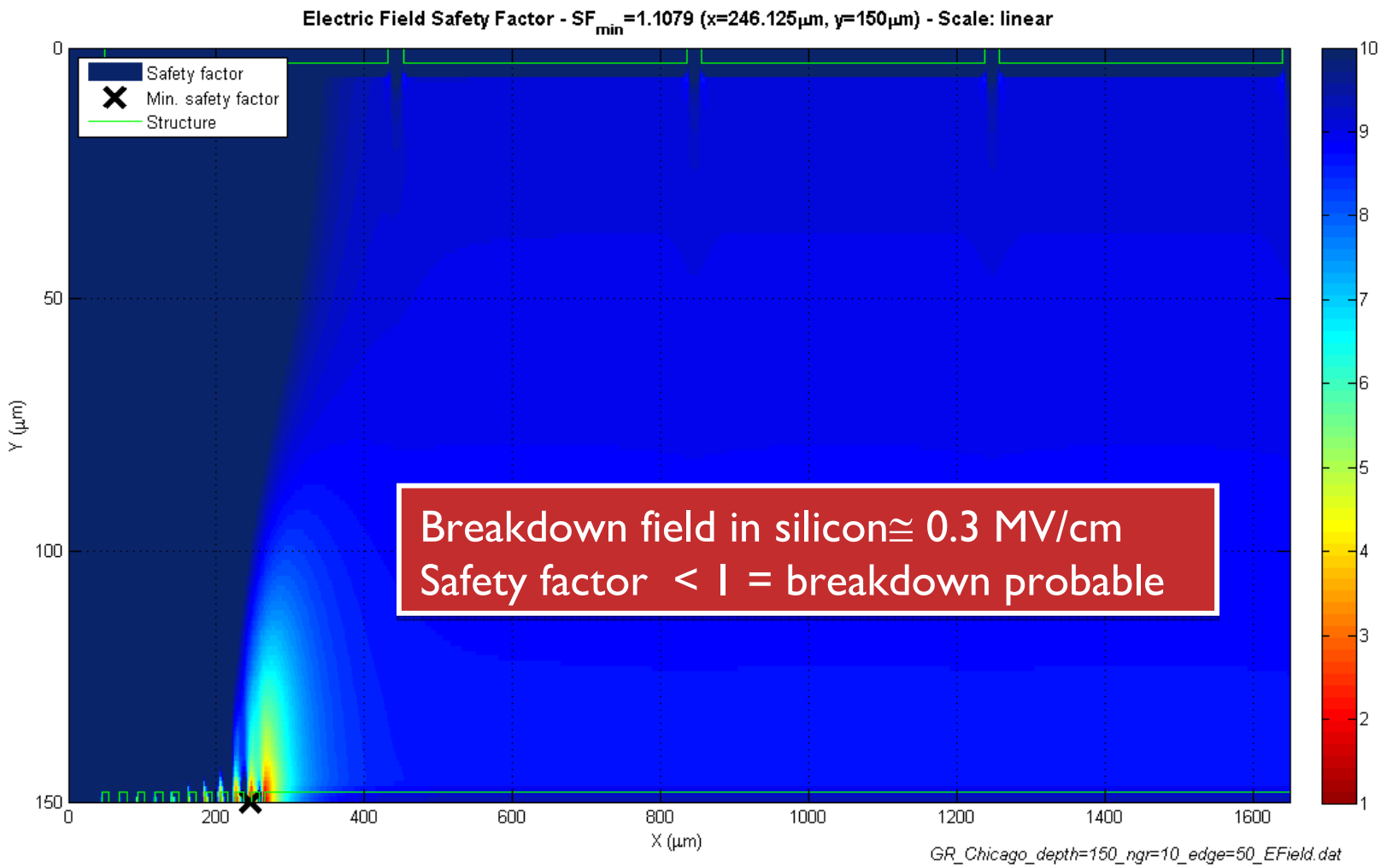
Electric field and breakdown



Edge=200 microns

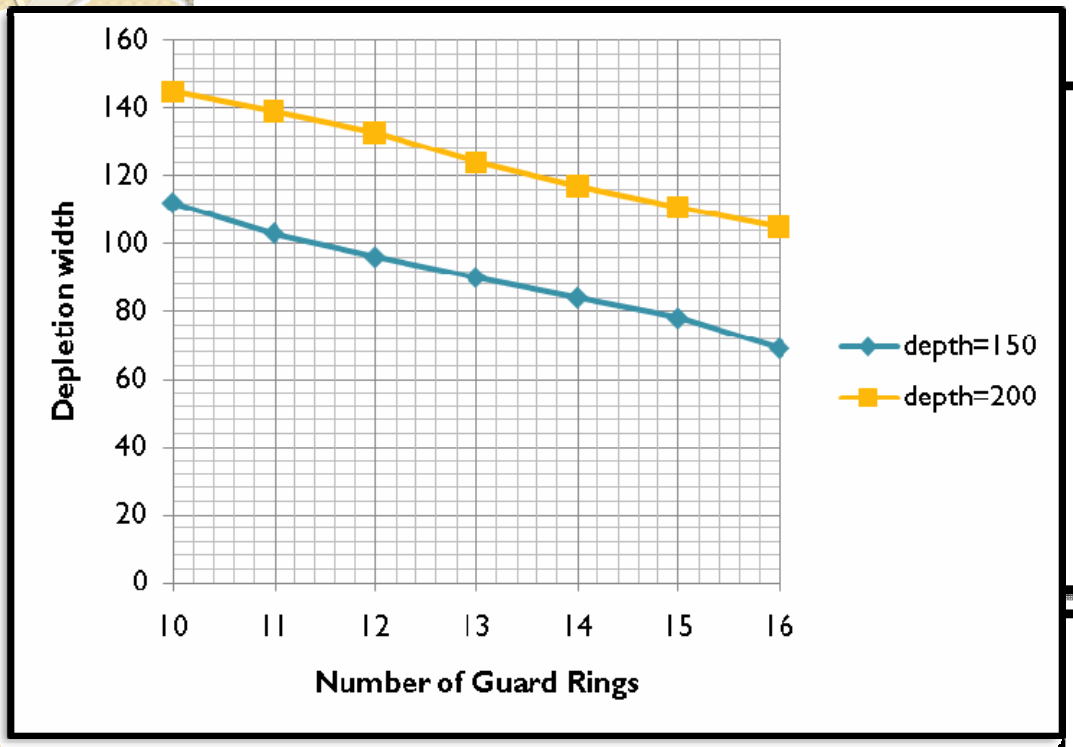


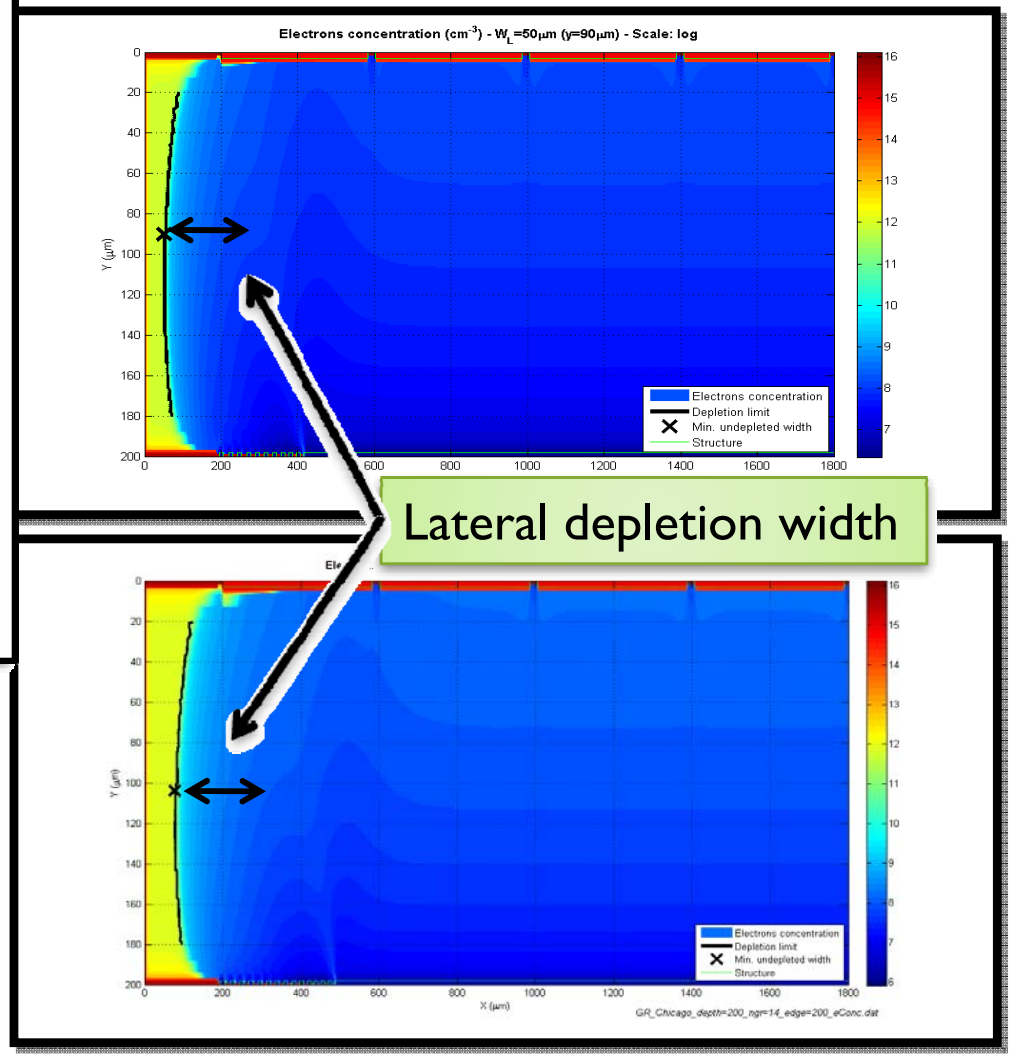
Electric Field and breakdown



Breakdown field in silicon≅ 0.3 MV/cm
Safety factor < 1 = breakdown probable

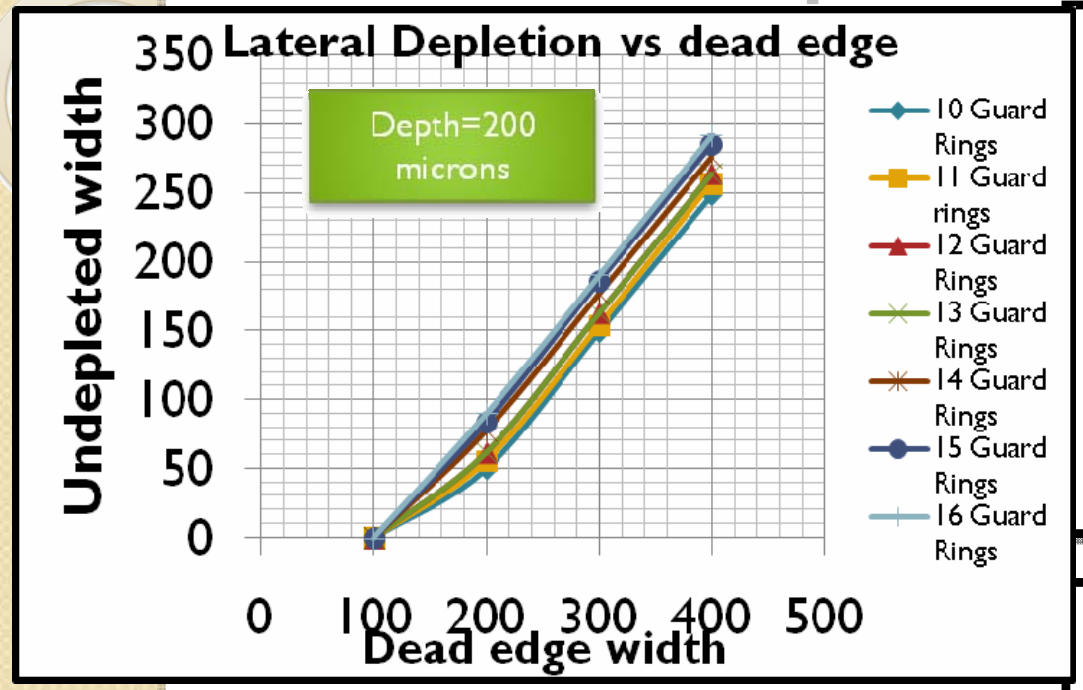
Lateral depletion

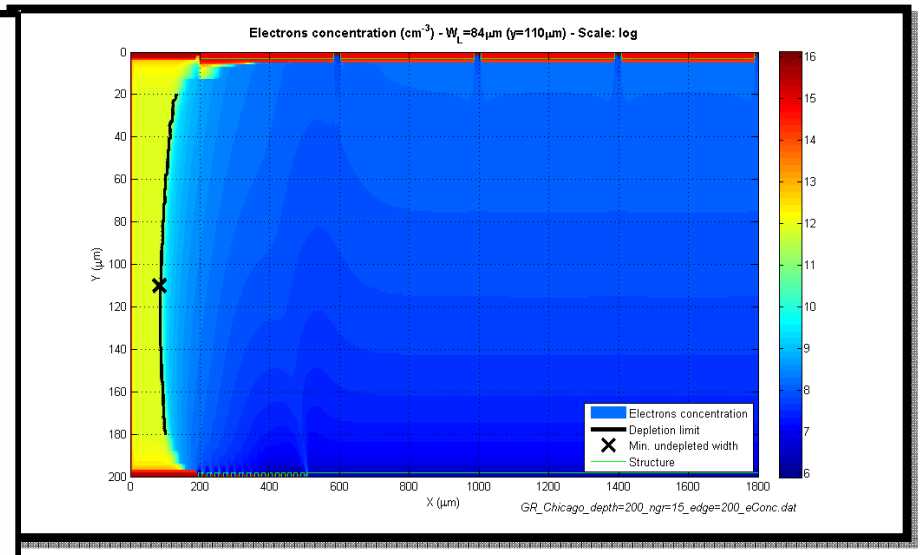


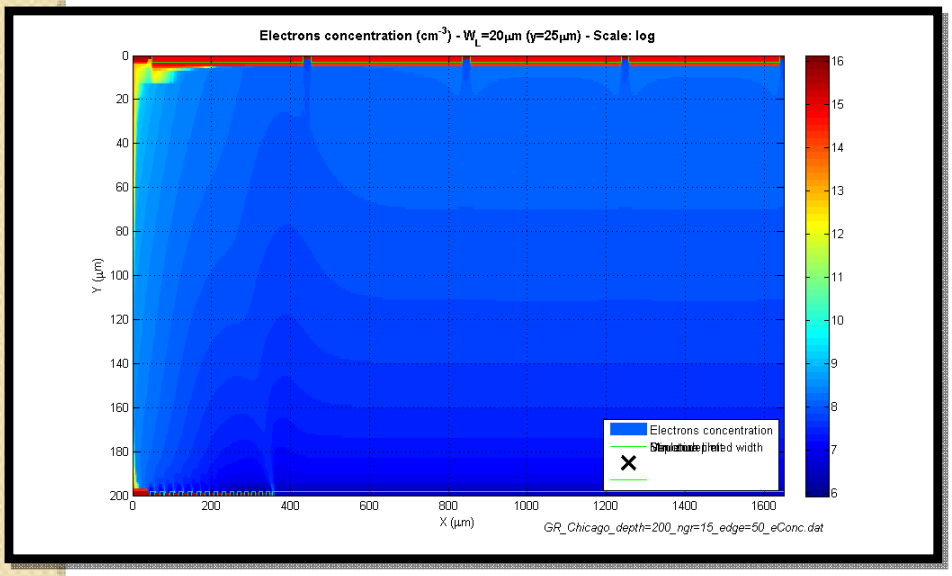


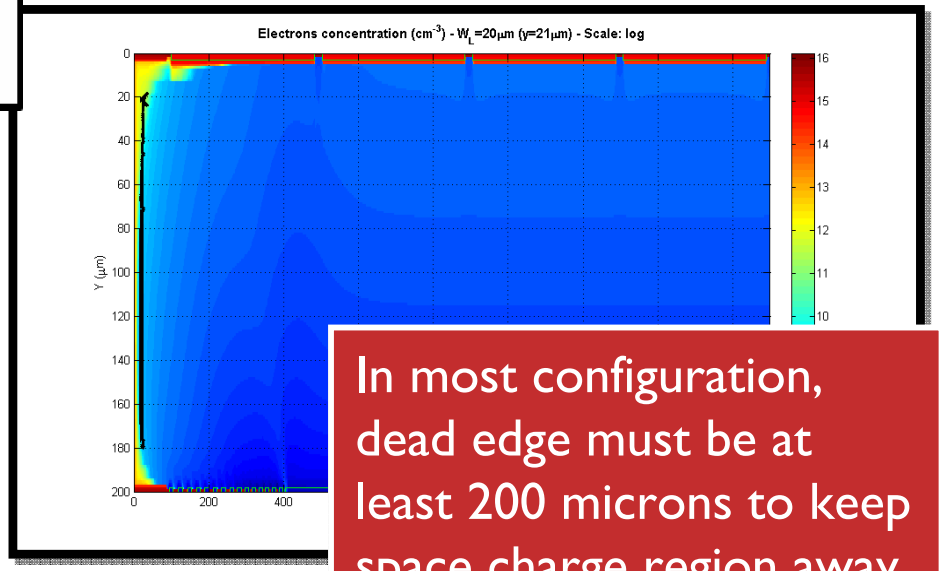
- Only depleted volume is sensible to particle passage
- Space charge region must not reach cutting edge, to prevent lateral breakdown

Lateral depletion







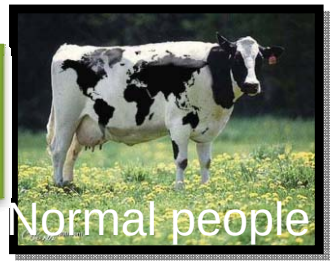


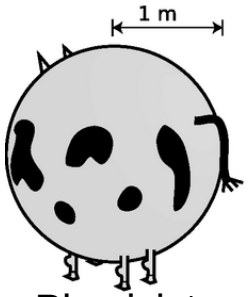
In most configuration, dead edge must be at least 200 microns to keep space charge region away from the edge.

Conclusion

- We simulated potential distribution, electric field and depletion for many variation of the ATLAS planar pixel sensor
- We show that reducing the number of Guard rings down to 11 could still provide breakdown protection up 500V bias
- We show that a 200 microns dead edge is minimal in this configuration to avoid lateral breakdown
- Test structure must be produced to verify and fine tune our simulation
- We will explore how spacing influence breakdown and will explore how radiation damage affect the guard ring behavior.

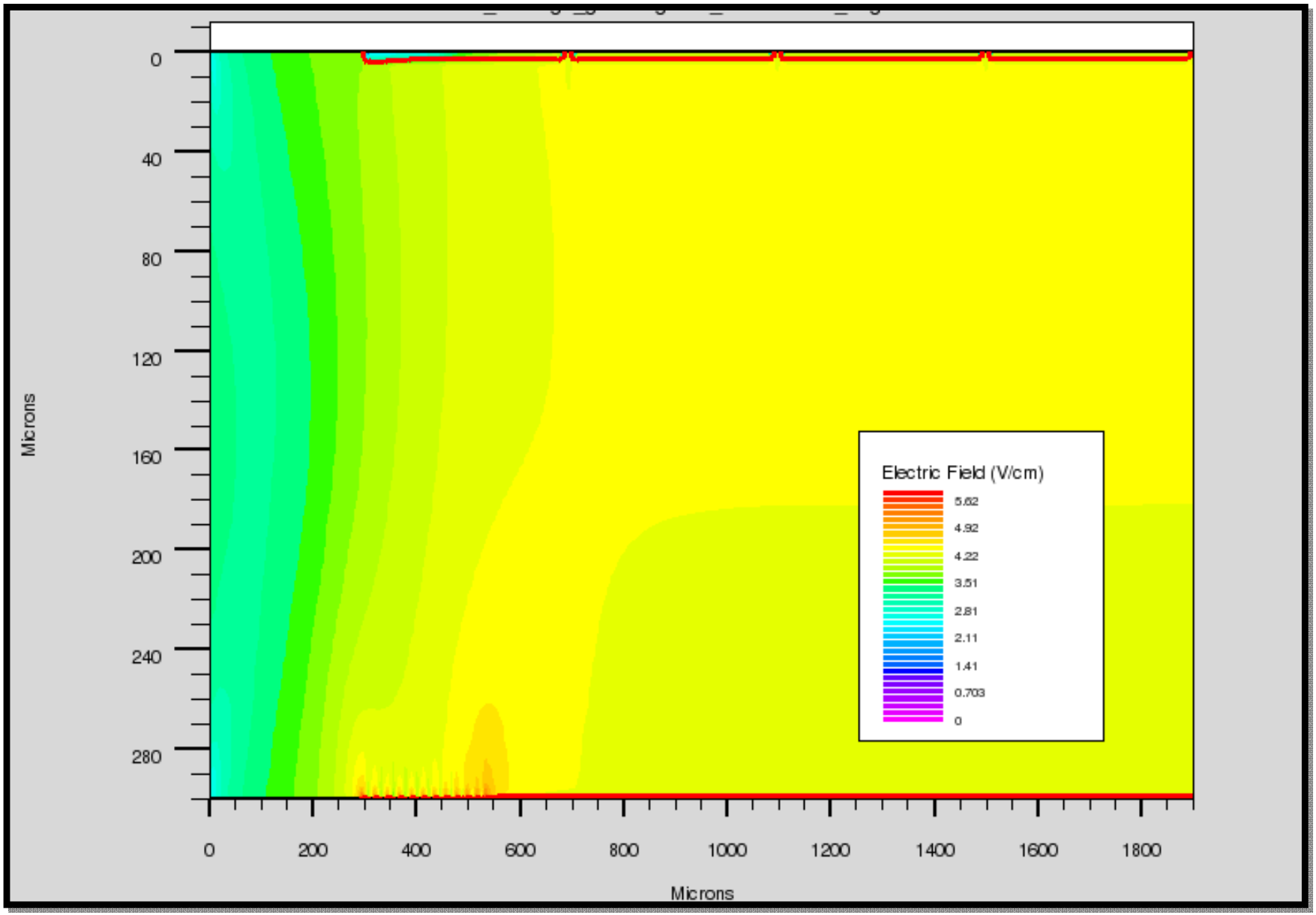
A cow seen by:



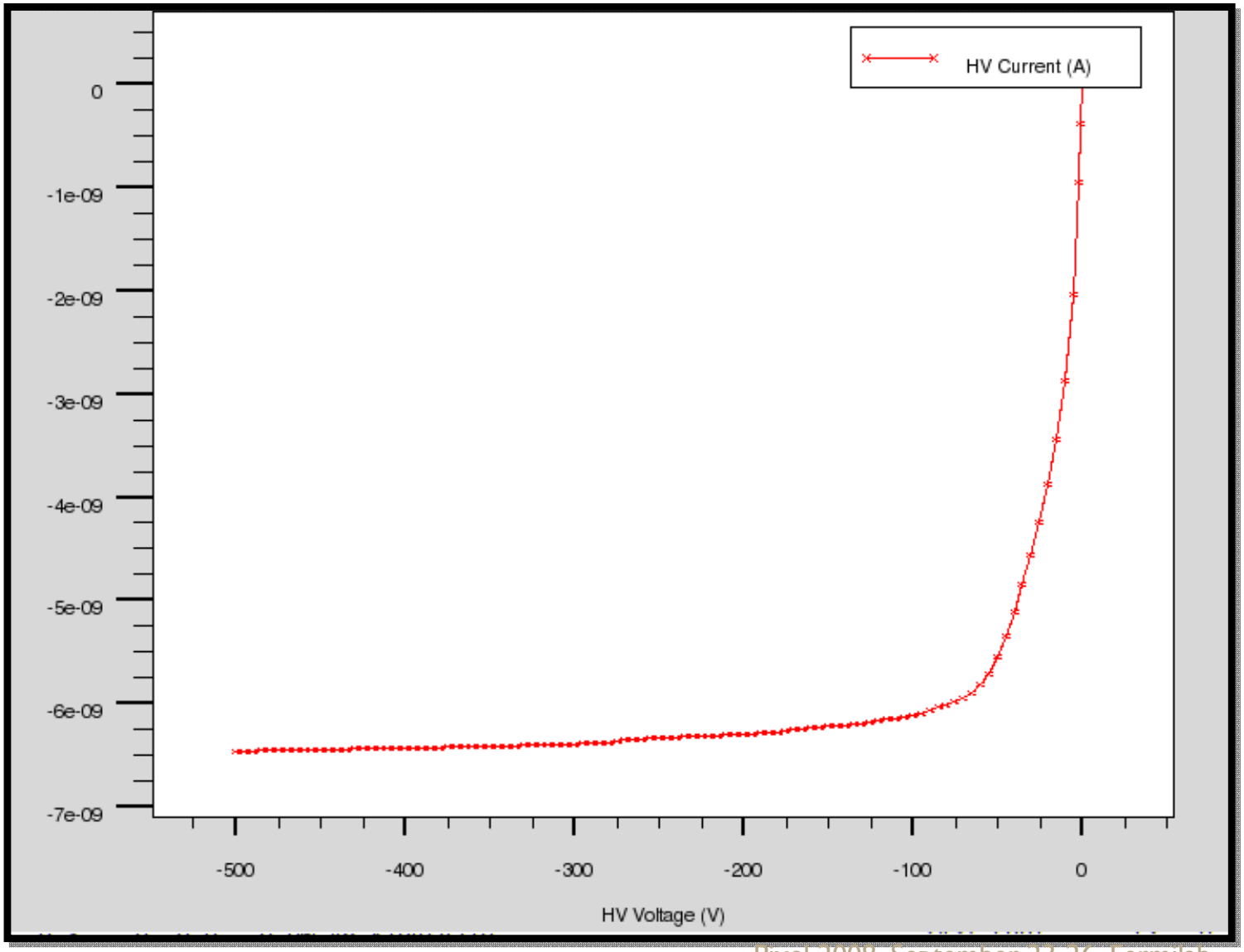


Thank you !

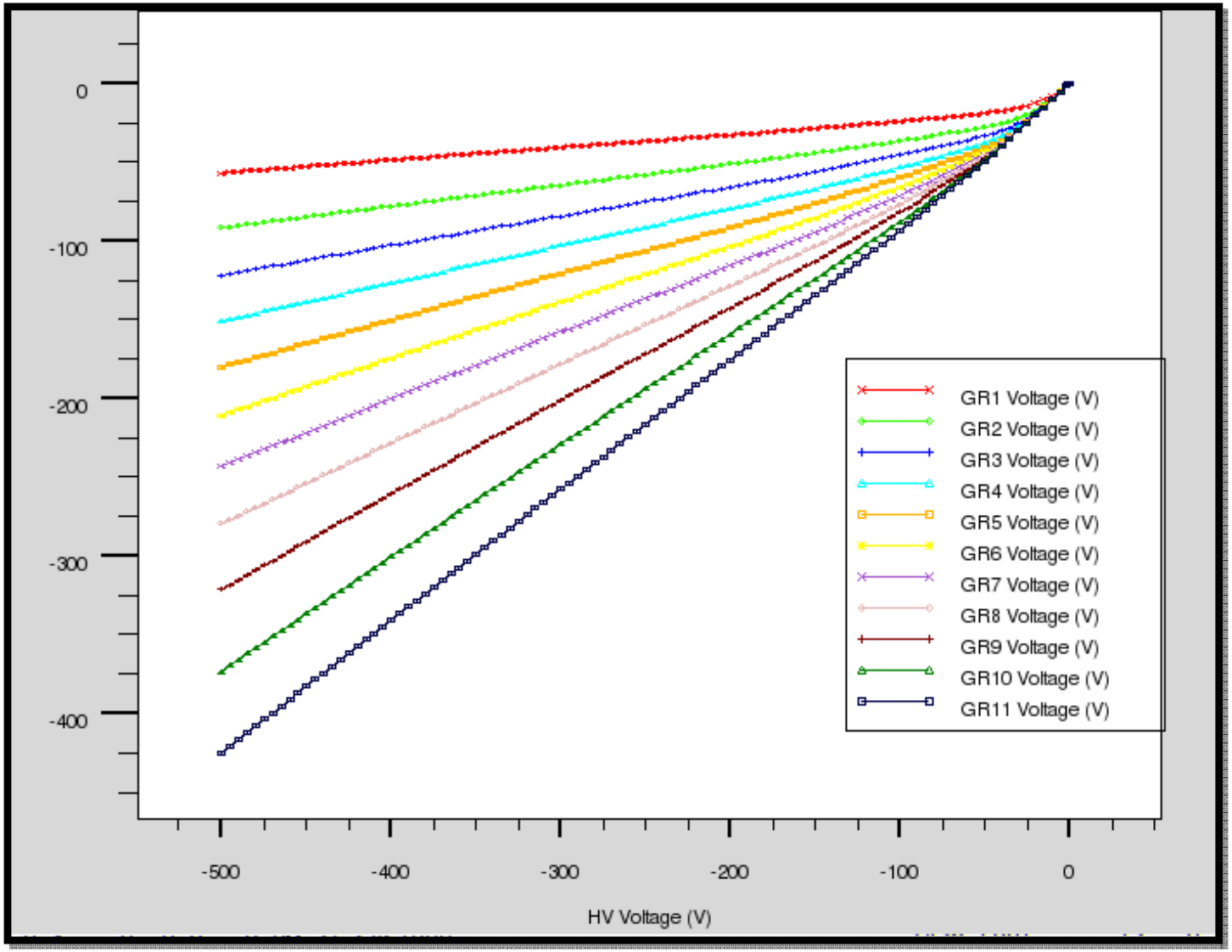
Backup


Electric Field (V/cm)
5.62
4.92
4.22
3.51
2.81
2.11
1.41
0.703
0
Microns
0
40
80
120
160
200
240
280
Microns
0
200
400
600
800
1000
1200
1400
1600
1800

Backup


HV Current (A)
0
-1e-09
-2e-09
-3e-09
-4e-09
-5e-09
-6e-09
-7e-09
-500
-400
-300
-200
-100
0
HV Voltage (V)

Backup


0
-100
-200
-300
-400
-500
-400
-300
-200
-100
0
HV Voltage (V)
GR1 Voltage (V)
GR2 Voltage (V)
GR3 Voltage (V)
GR4 Voltage (V)
GR5 Voltage (V)
GR6 Voltage (V)
GR7 Voltage (V)
GR8 Voltage (V)
GR9 Voltage (V)
GR10 Voltage (V)
GR11 Voltage (V)