Radiation Damage to DØ Silicon Microstrip Tracker and Micro-Discharge Effect

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for DØ Silicon Group

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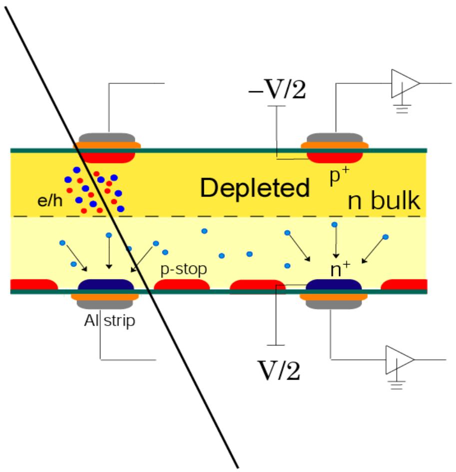
- DØ Silicon Microstrip Tracker

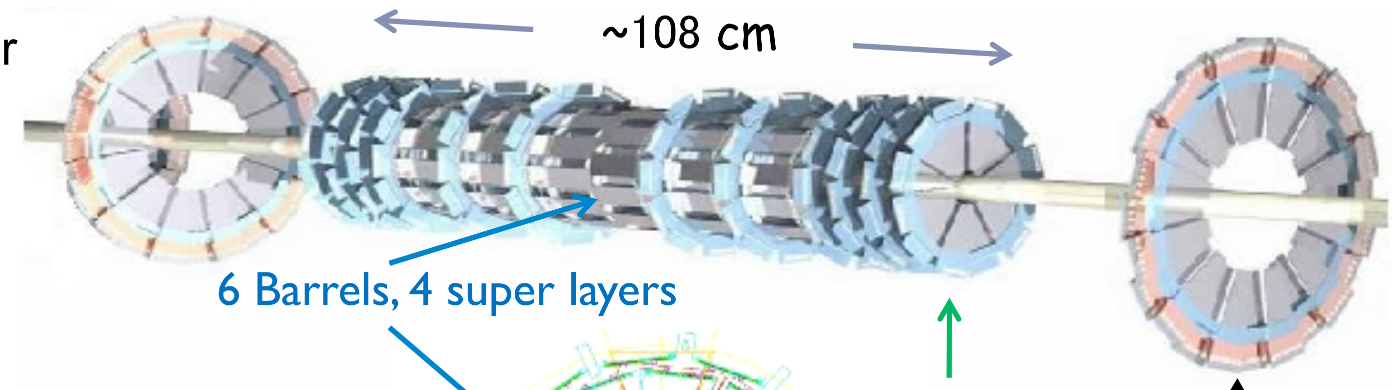
  Operational experiences by A. Jung in the poster session
- Radiation Damage to Silicon Sensors
  - Leakage Current
  - Full depletion voltage
  - Signal and Noise
- Micro-discharge Effect in Silicon Sensors
  - Sensitivity to humidity
  - Sensitivity to magnetic field
- Summary

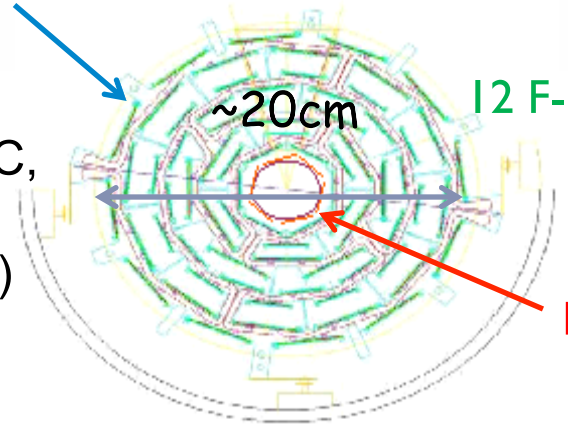
DØ Silicon Microstrip Tracker

NIMA634, 8
NIMA622, 298

AC-coupled Si Sensor

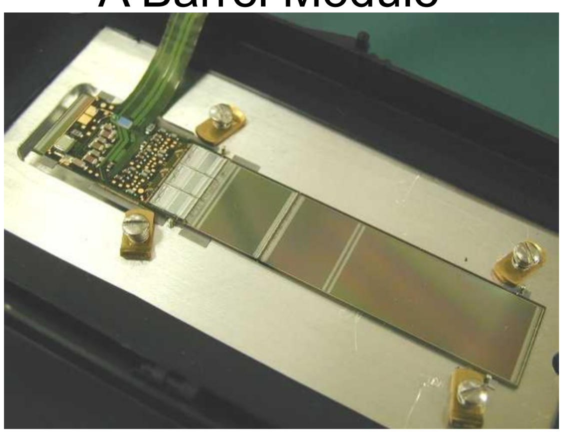






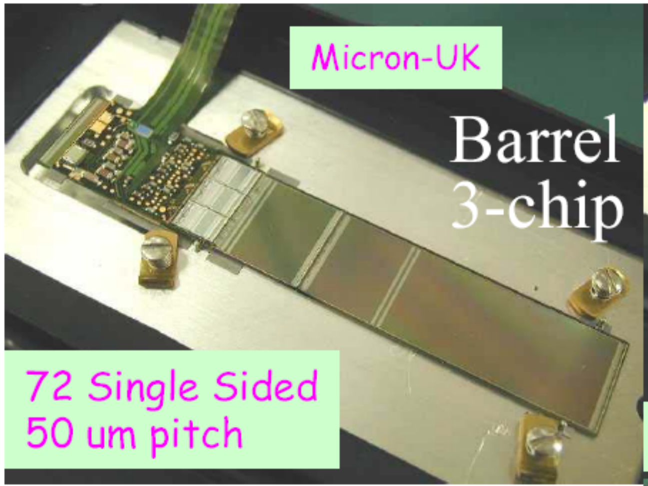
Operated at ~0°C,
Installed in 2001
(Layer 0 in 2006)

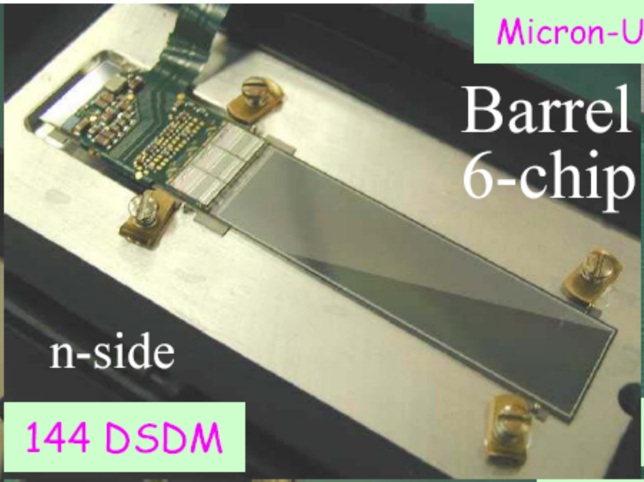
A Barrel Module

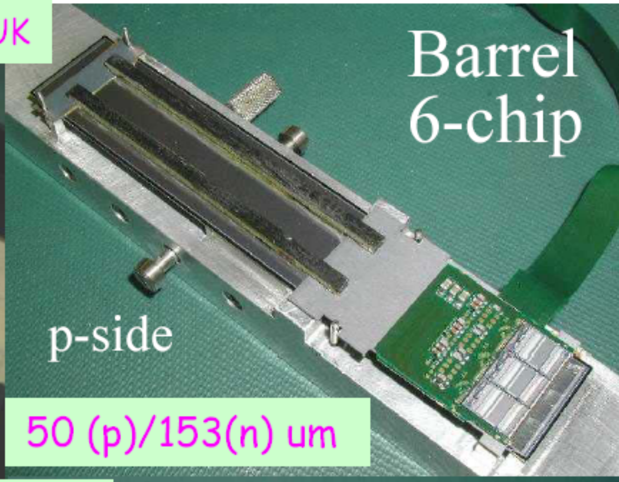


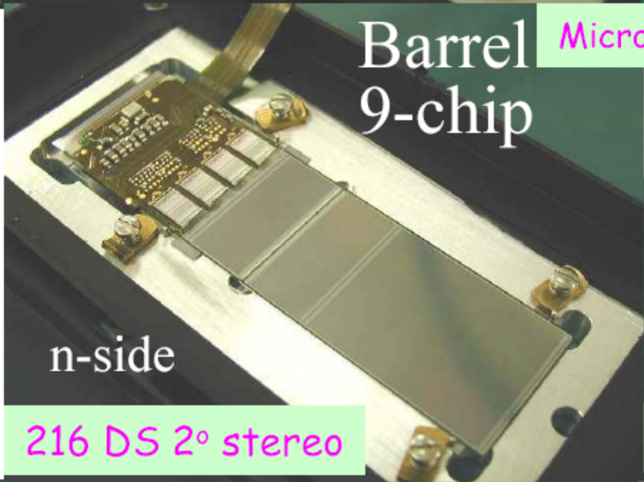
	Layer 0	Barrel	F Disk	H Disk
Sensor	Hamamatsu SS	Micron SS and DS	Micron and Eurysis DS	Elma SS
Inner R	1.61 cm	2.7 cm	2.6 cm	9.5 cm
Outer R	1.77 cm	10.1 cm	10.5 cm	26 cm

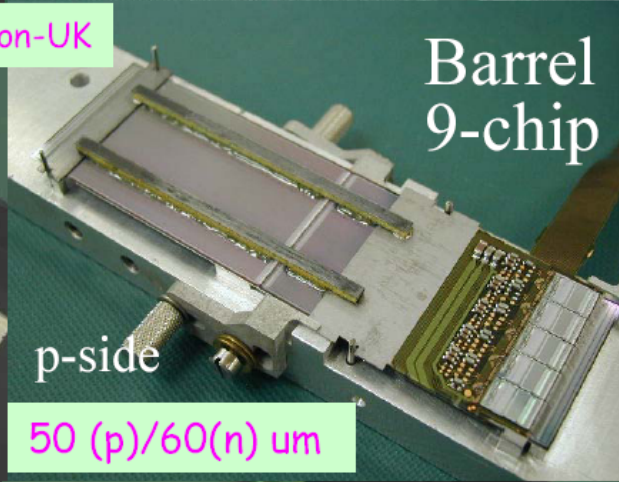
Various types of detectors (all AC coupled)

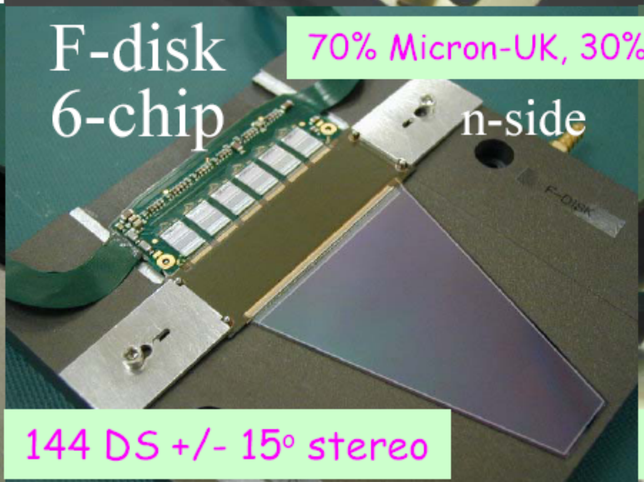


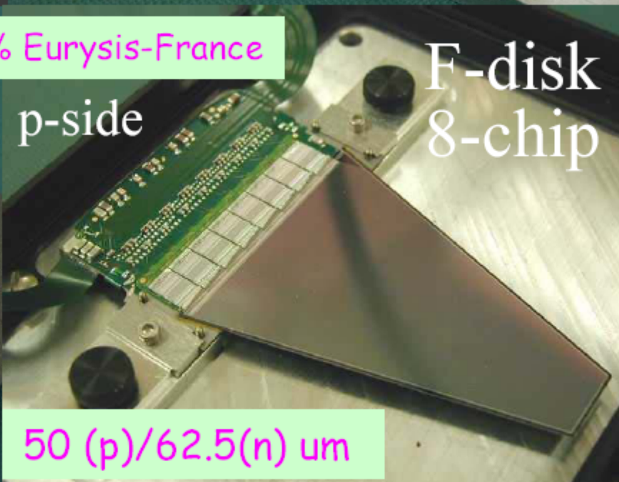












Radiation Damage

- Bulk damage due to non-ionizing energy loss

  - displacement damage, built up of crystal defects -

  I. increase of leakage current (shot noise, thermal runaway)

  II. change in effective doping concentration (higher full depletion voltage)

  III. increase of charge carrier trapping (loss of signal charge)

- Surface damage due to ionizing energy loss

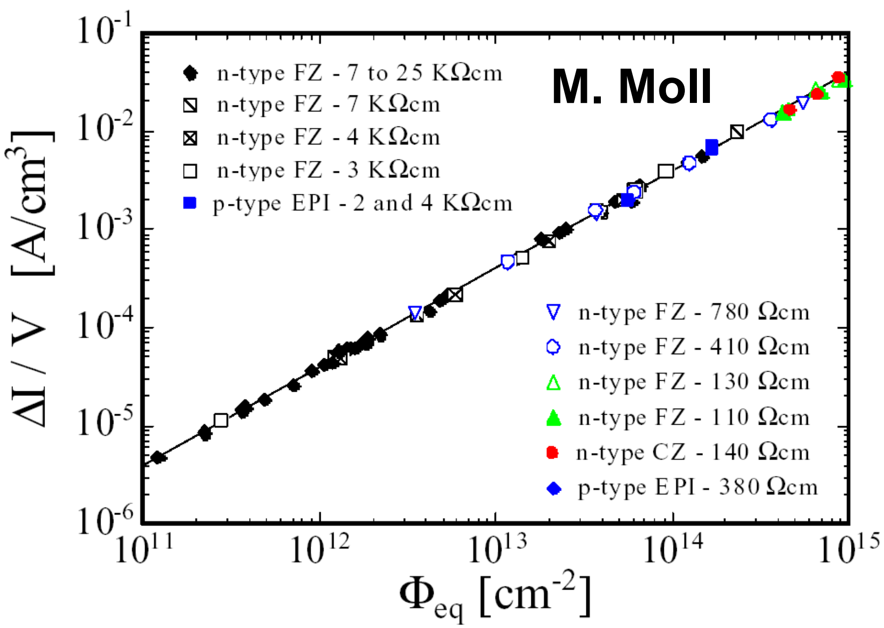
  - charge accumulation in the oxide (SiO2) and at the Si/SiO2 interface -

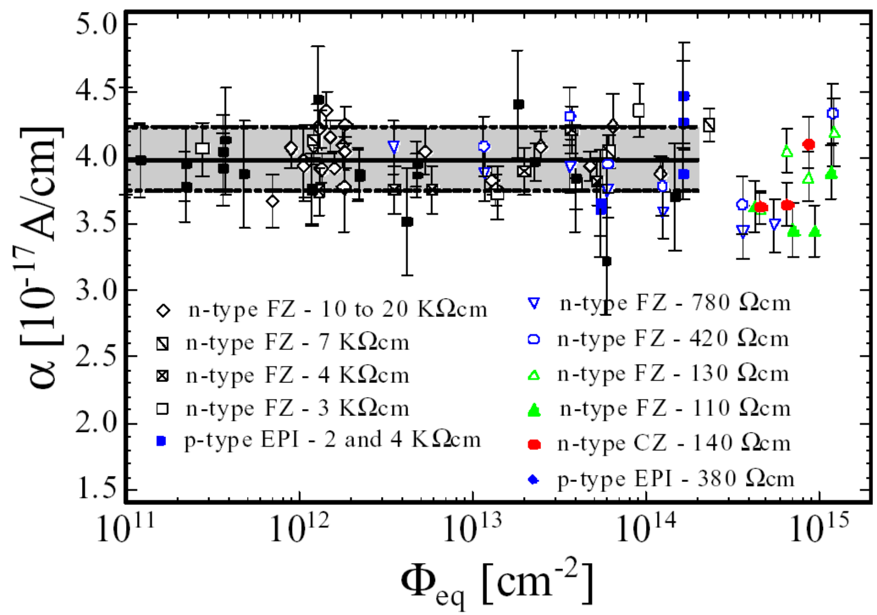
  affects: inter-strip capacitance (noise), breakdown behavior, …

- Largest concern for DØ SMT has been the bulk damage to the inner layers since the detector was originally designed for 2 fb^{-1}:
  - increase of leakage current
  - AC coupling capacitor breakdown and micro-discharge effects

    limit the bias voltage below 150V -> under-depleted inner sensors
  - noise increase, signal loss -> degraded signal-to-noise ratio

Increase of Bias Current

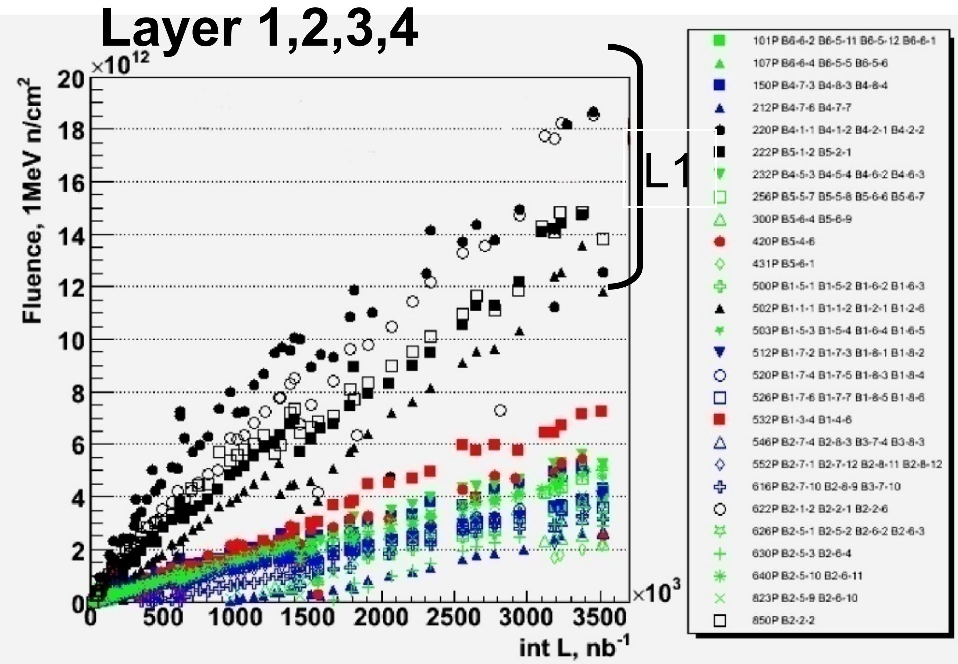


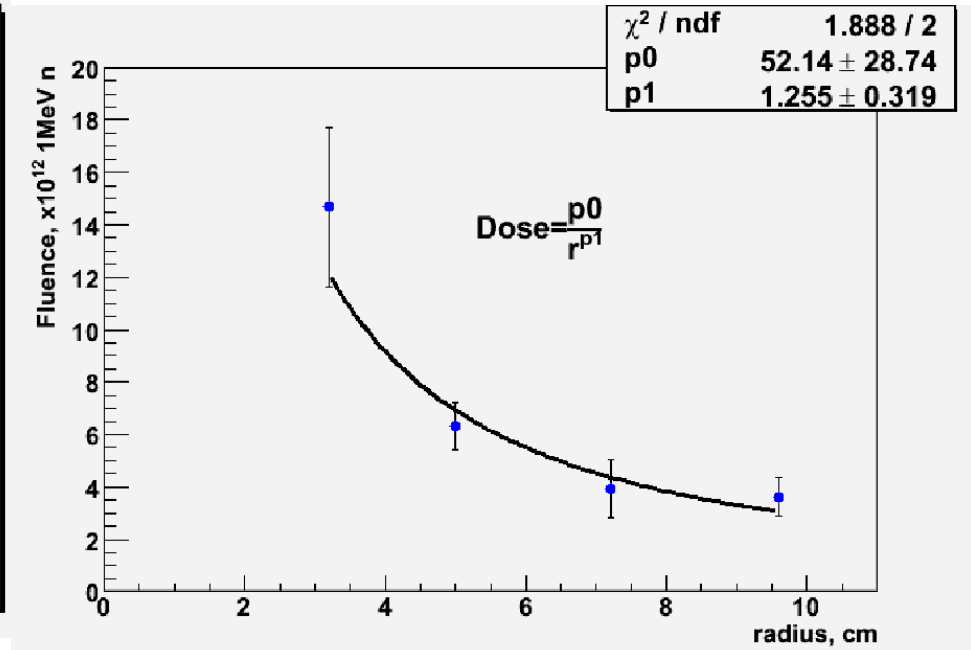


Φ_{eq} : 1MeV neutron equivalent fluence

$\alpha=\Delta I/(V\Phi_{eq})$: damage constant, depends on time and temperature, independent on sensor type

Fluence vs Delivered Luminosity

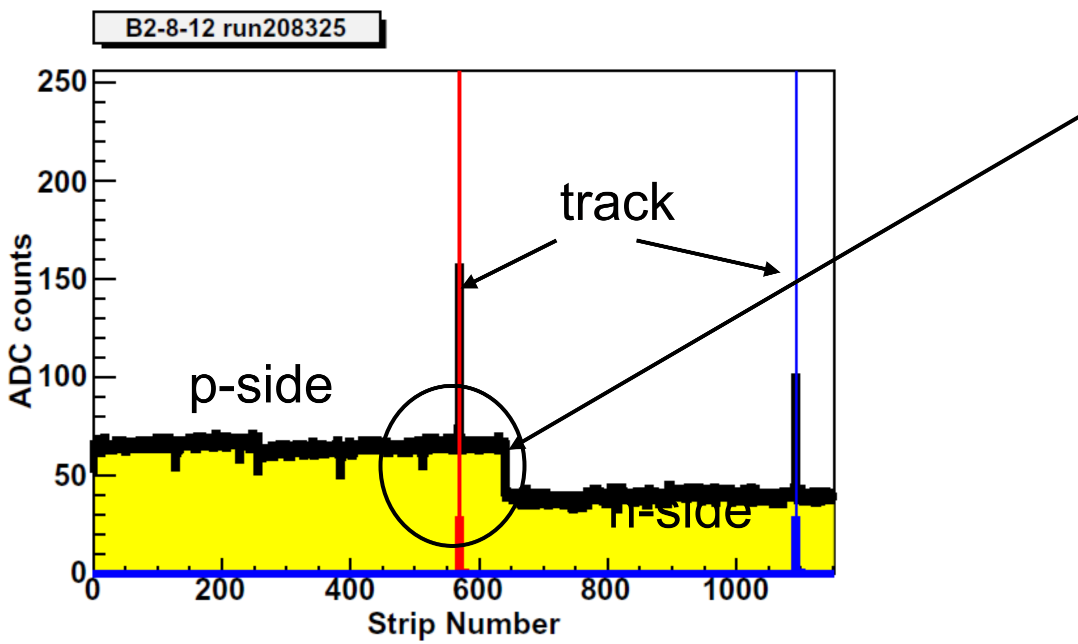


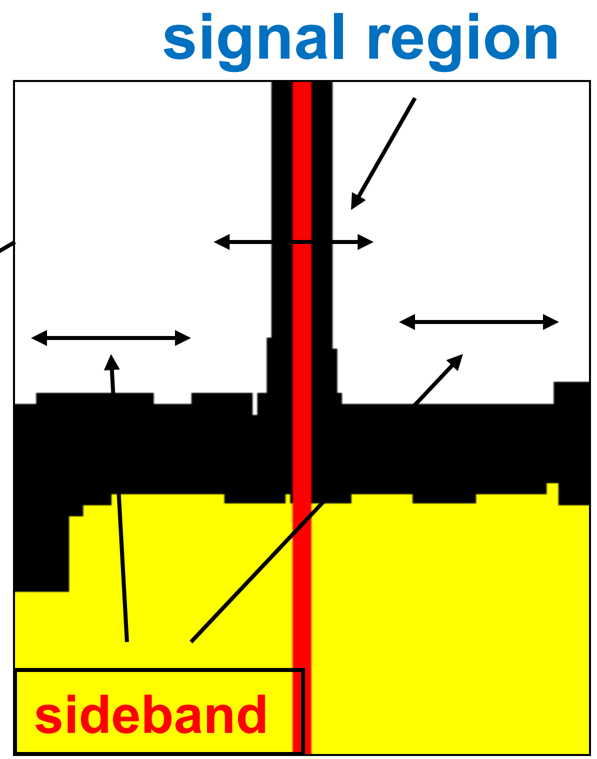


- Estimate the fluence from the leakage current
  $\mathbf{\Phi_{eq} = \Delta I / V\alpha}$ [V:volume, α: damage constant taking into account temperature and time dependence]
- Dependence of Fluence on integrated luminosity and radius
  $\mathbf{\Phi_{eq}/L = 1.5 \pm 0.8 \times 10^{13}\ cm^{-2}/fb^{-1} \times (r/1cm)^{-1.3 \pm 0.3}}$

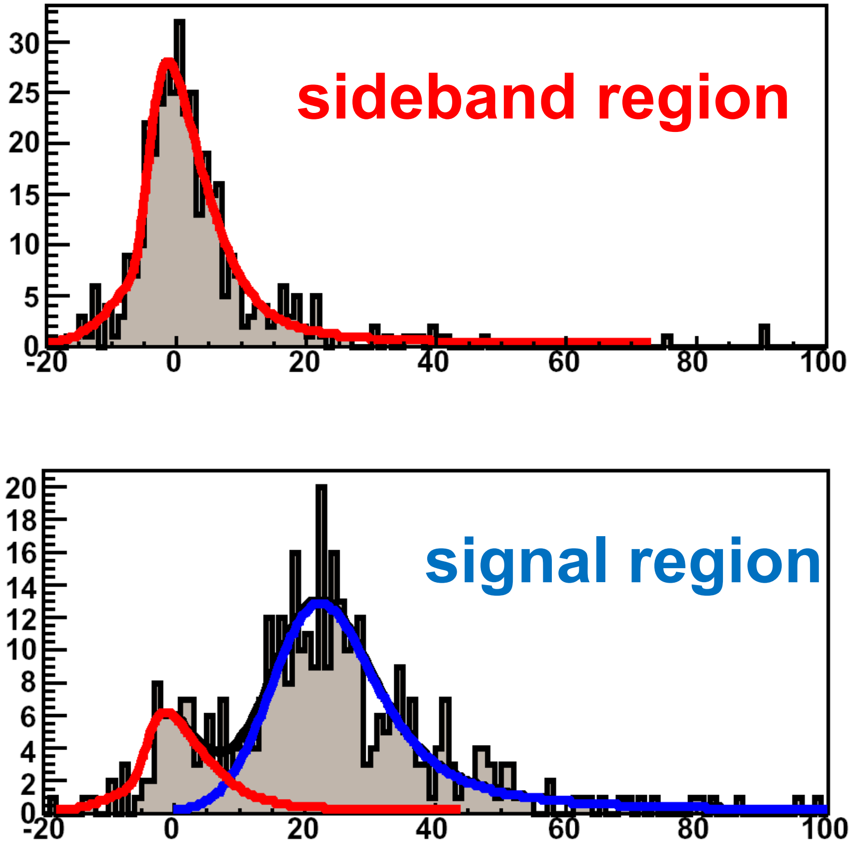
Charge Collection Efficiency Study

1. take special runs with all the channels read out
2. find where a track passes through the sensor
3. determine an average pedestal for the chip for the event
4. determine the signal and noise
5. correct for the track incident angle





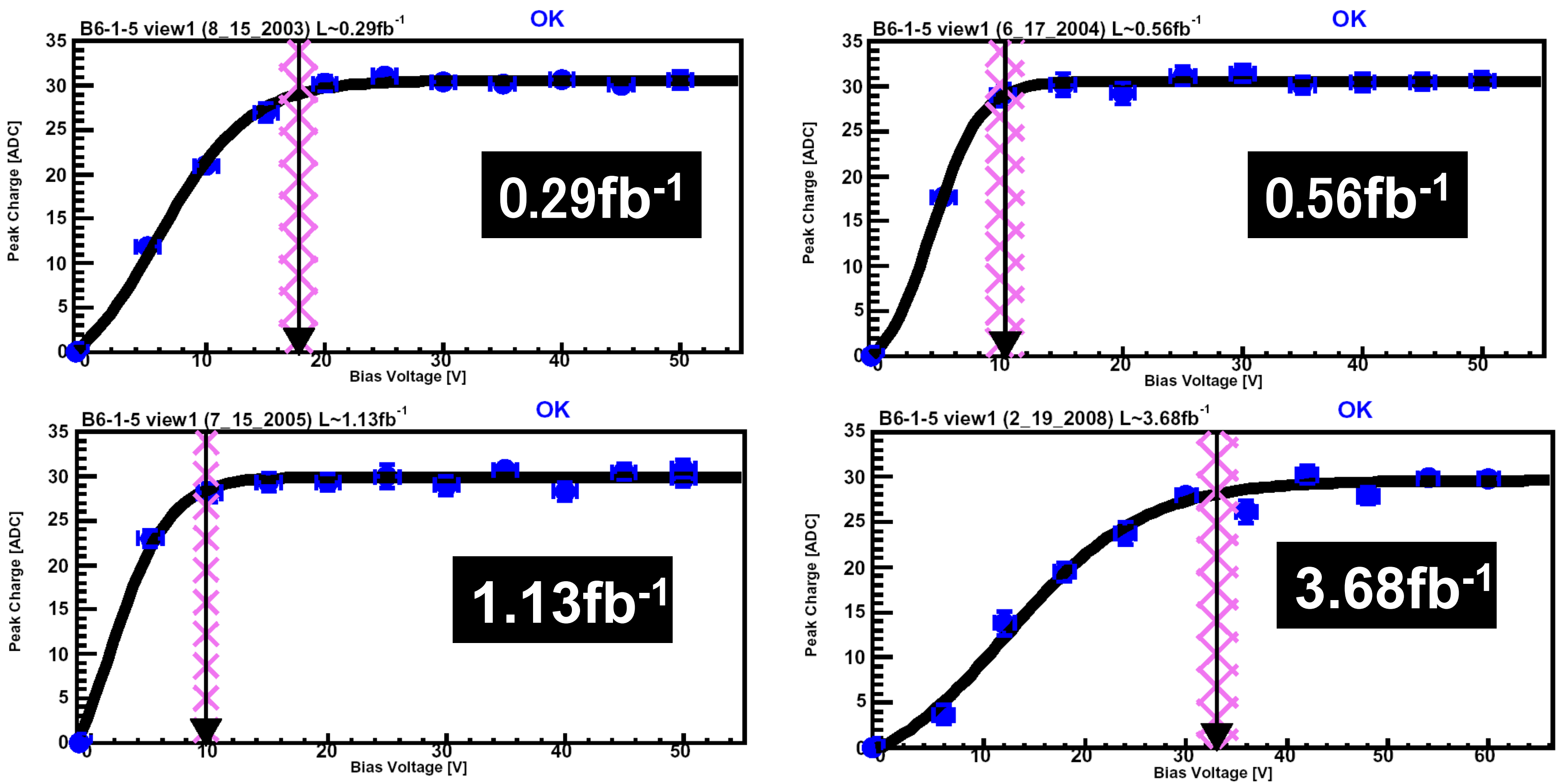
Determine Signal and Noise



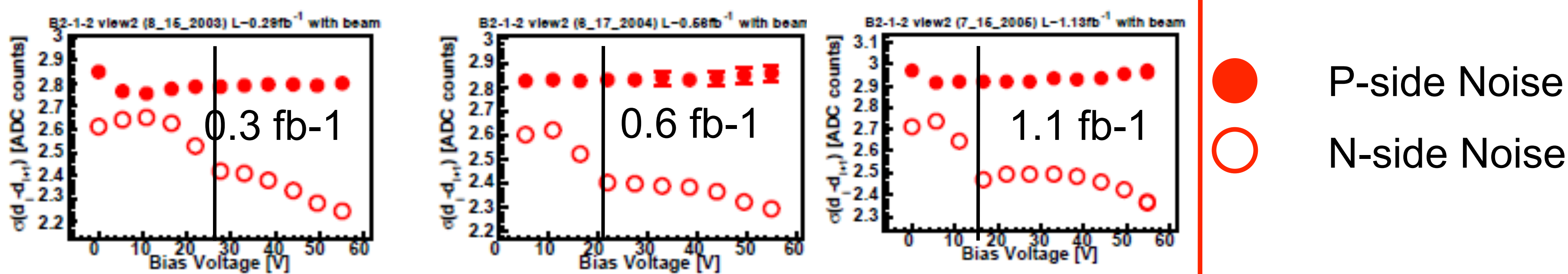
- Fit charge distribution
  - sideband events : landau+gaussian
    noise: Gaussian sigma
  - signal region : landau⊗gaussian
    signal: landau peak

Charge Collection Efficiency vs Bias Voltage

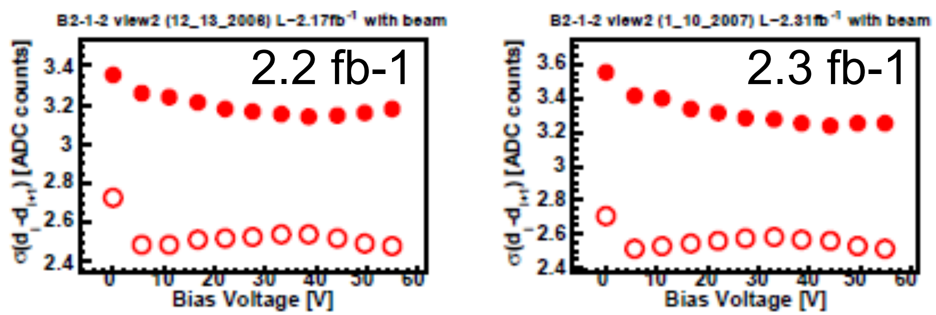
- Fit signal vs bias voltage with a sigmoid function
- 95% charge collection efficiency as the full depletion



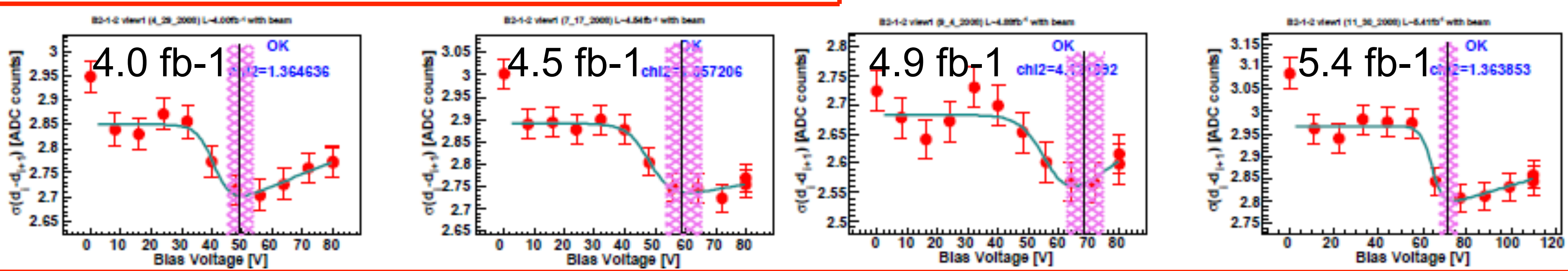
Noise vs Bias Voltage



find the kink→ full depletion



fit→ full depletion voltage



Fit to Hamburg Model

[M.Moll thesis, Uni Hamburg]

$$V_{dep} = \frac{|N_{eff}| \cdot e \cdot d^2}{2 \cdot \varepsilon}$$

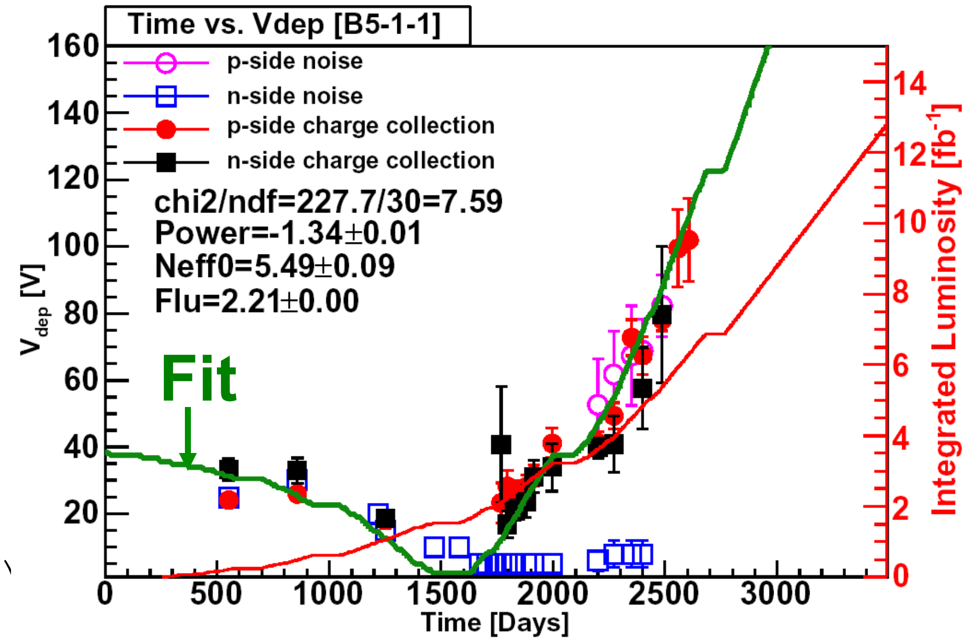
$$N_{eff} = N_{eff\,0} - (N_c + N_a + N_y)$$

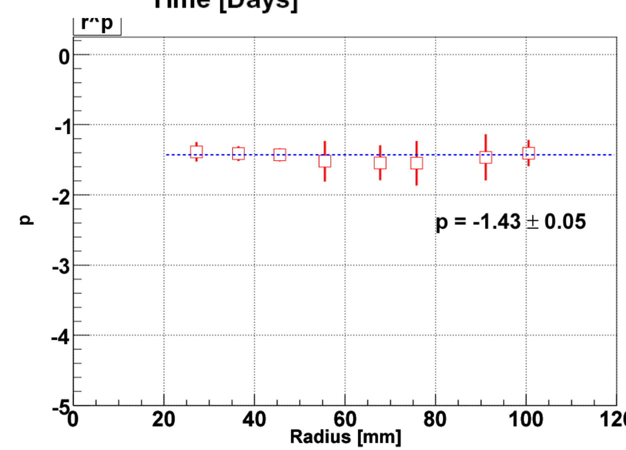
$$N_c(\Phi) = N_{c0} \cdot (1 - e^{-c \cdot \Phi}) + g_c \cdot \Phi$$

$$N_a(\Phi, t, T) = g_a \cdot \Phi \cdot e^{-k_{a0} \cdot e^{-E_{aa}/k_B T} \cdot t}$$

$$N_y(\Phi, t, T) = g_y \cdot \Phi \cdot \left(1 - \frac{1}{1 + k_{y10} e^{-E_{ay}/k_B T} \cdot t}\right)$$

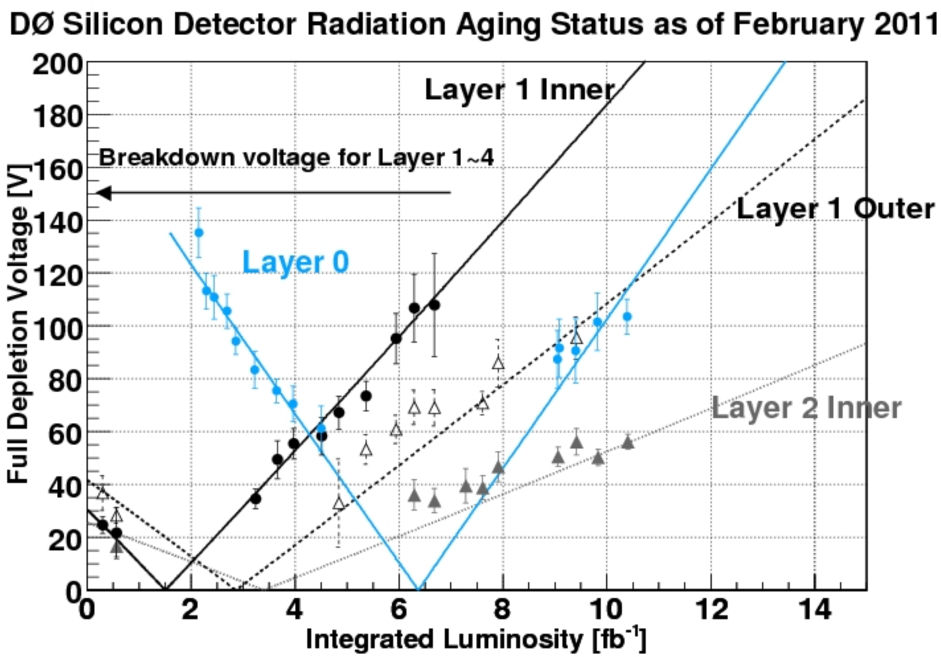
$$\Phi = \Phi_{1cm} \cdot r^p = \beta \cdot L_{\text{int}} \cdot r^p$$

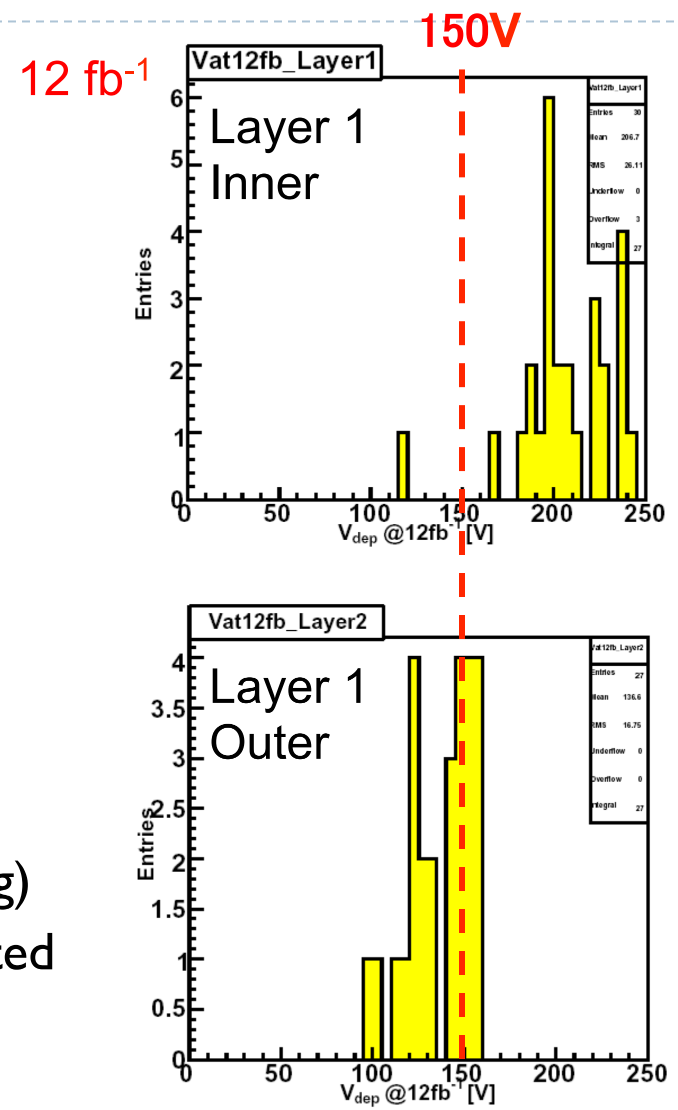




Assume CDF RunI β value 2.2×10^{13} cm^{-2}/fb^{-1} at r=1 cm and fit two parameters: **N_{eff0}, *p***

Projection Result

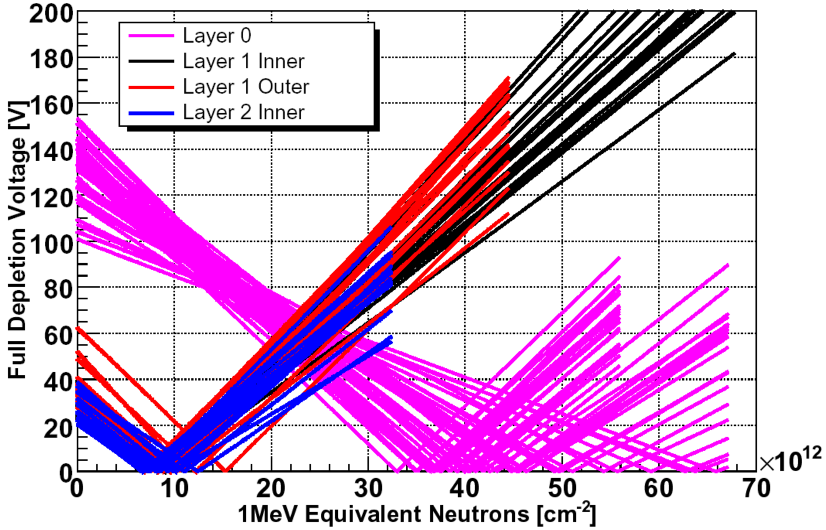


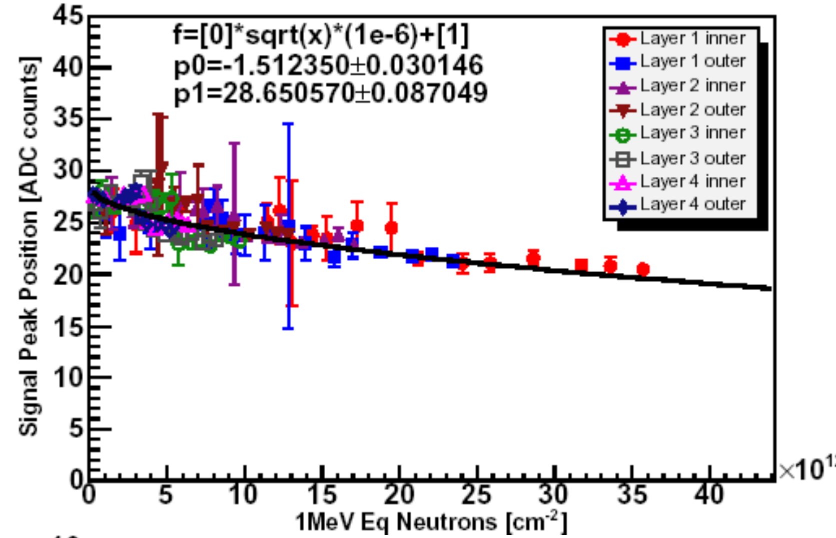


- ↑ Only showing data points from p-side charge collection study (all data are included in the fitting)
- →Layer 1 sensors might no longer be fully depleted by the end of the Tevatron RunII

Anticipated and compensated by Layer0

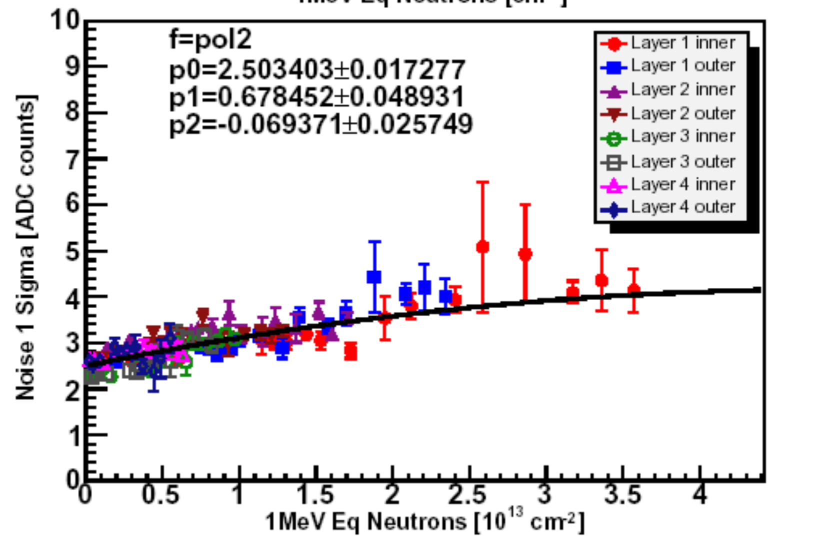
SMT Performance Evolutoin





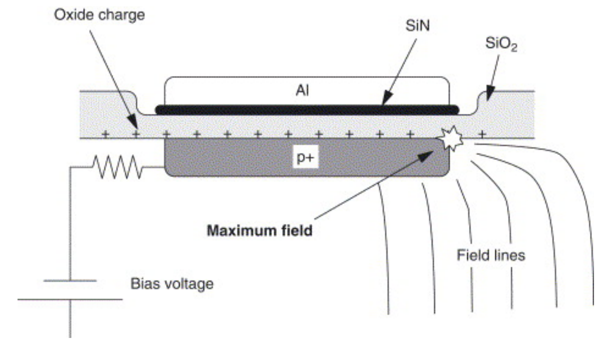
$$\Phi = \beta \cdot L_{int} \cdot r^{p}$$

$\beta = 2.2 \times 10^{13}$ cm^{-2}/fb^{-1} at r=1 cm

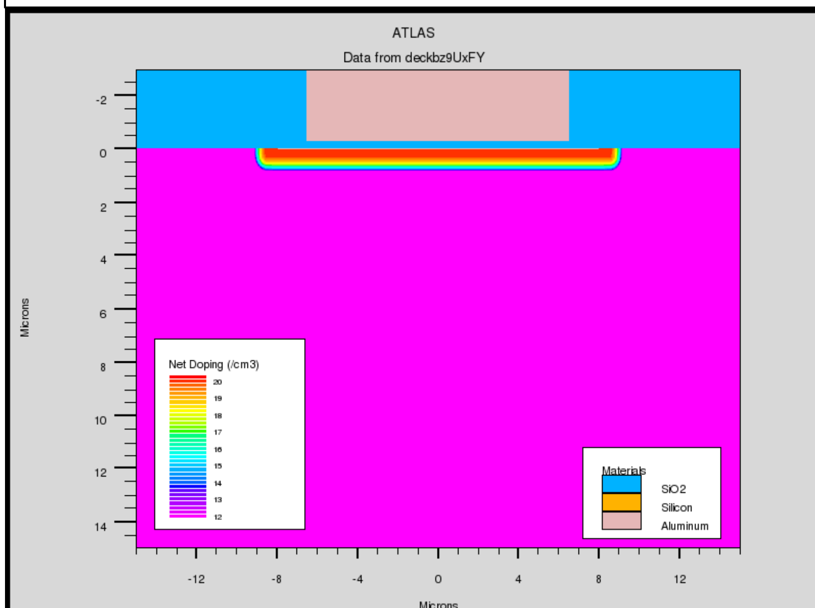


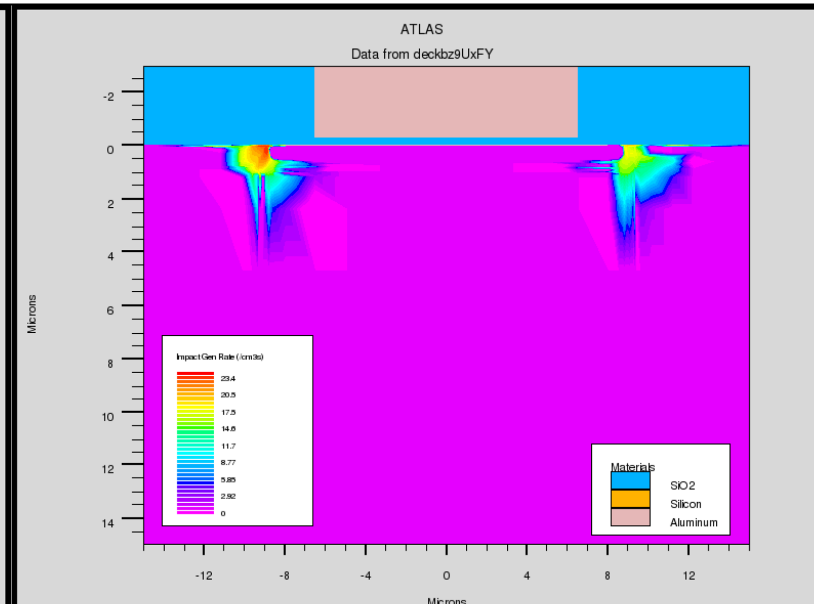
Micro-Discharge Effect

- Maximum bias voltage for DS sensors110-150V:
  - AC-coupling capacitor breakdown
  - Micro-discharge effect: local avalanches near implant edges.

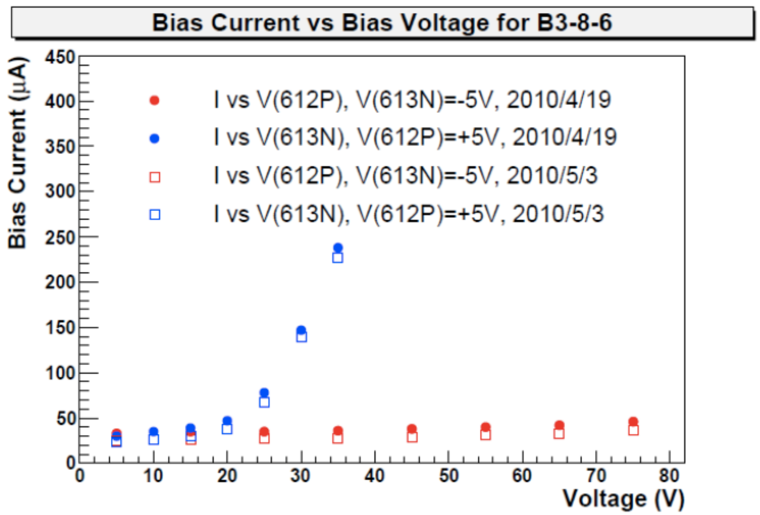


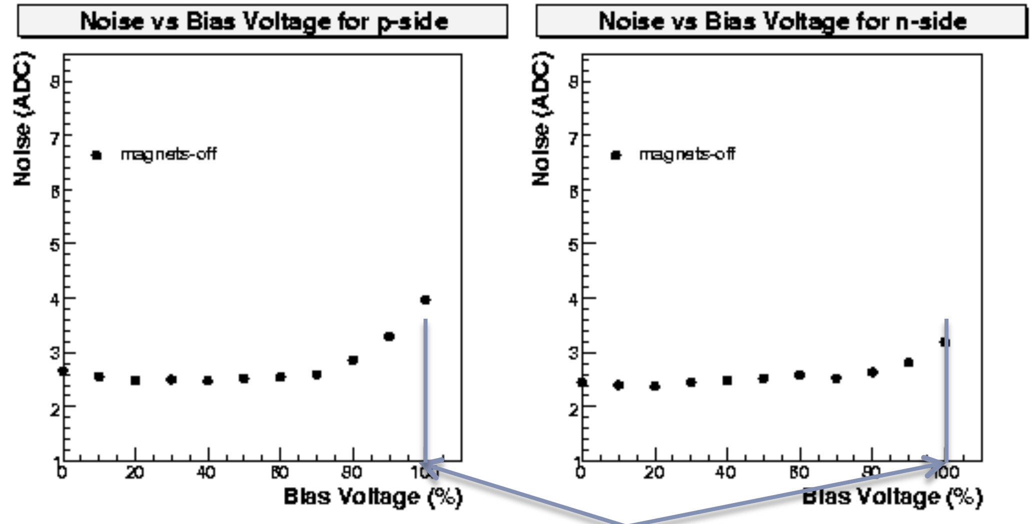
Simulation Using Silvaco TCAD





Micro-Discharge Effect





Full depletion

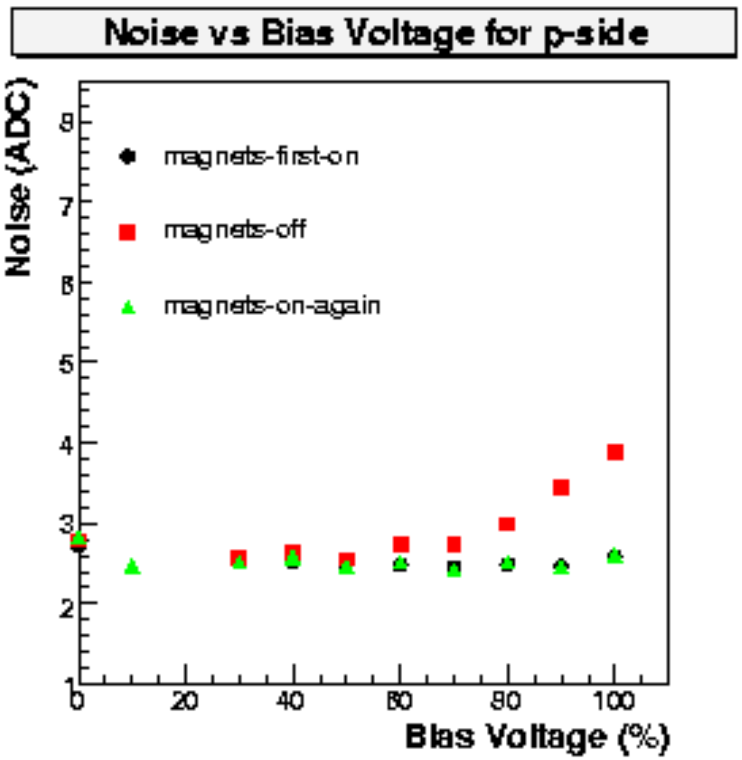
- Maximum bias voltage for DS sensors <(110-150) V:

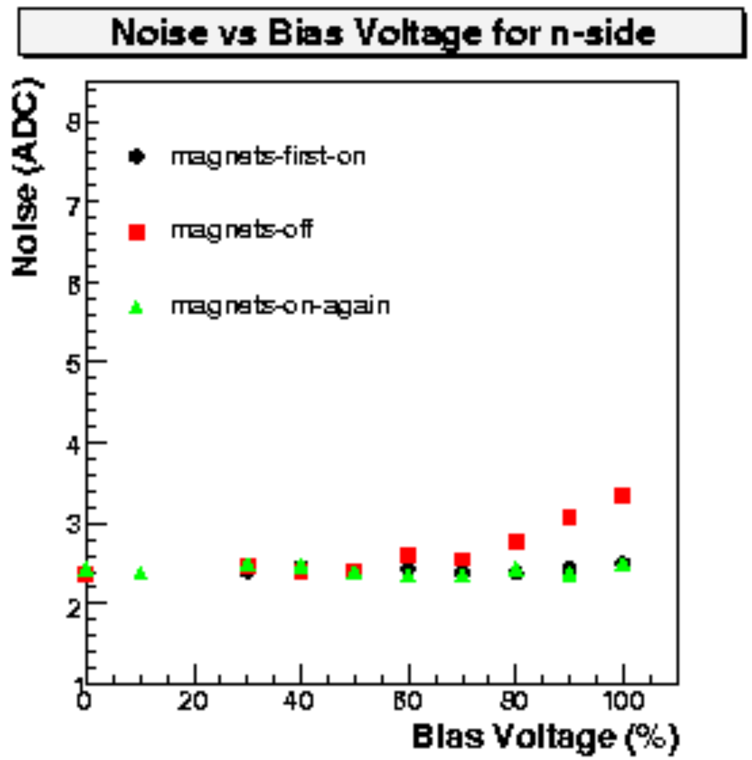
V(n side)<+(90-120)V by breakdown of AC coupling capacitor breakdown.

V(p side)>-(20-30)V by micro-discharge effect. Same before/after type inversion.

- Simulation suggests that asymmetric behavior between p and n side is due to the positive charge accumulated in SiO_2.
- We studied whether varying the humidity has an influence on p side breakdown voltage and thus the maximum bias voltage.

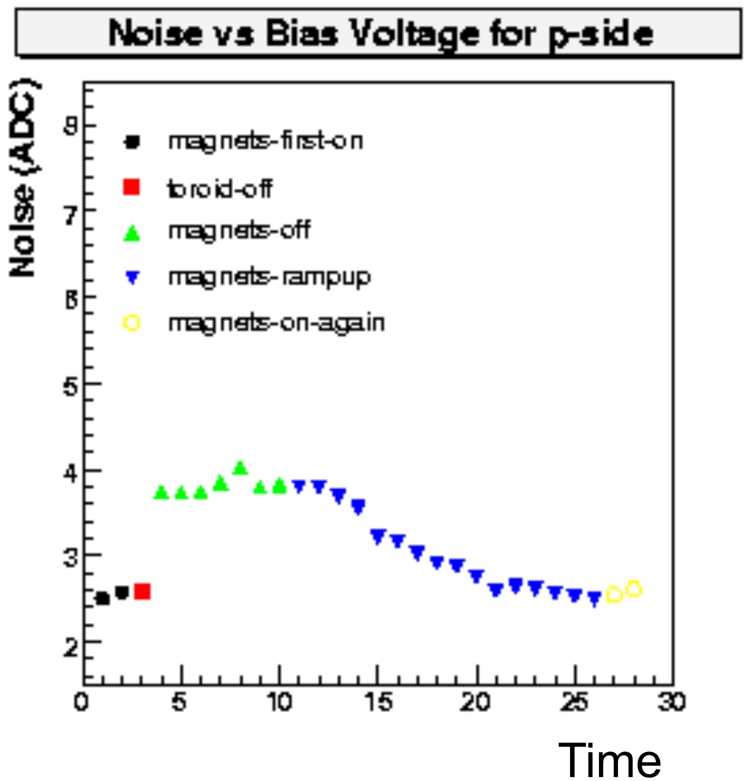
Sensitivity to Magnetic Field

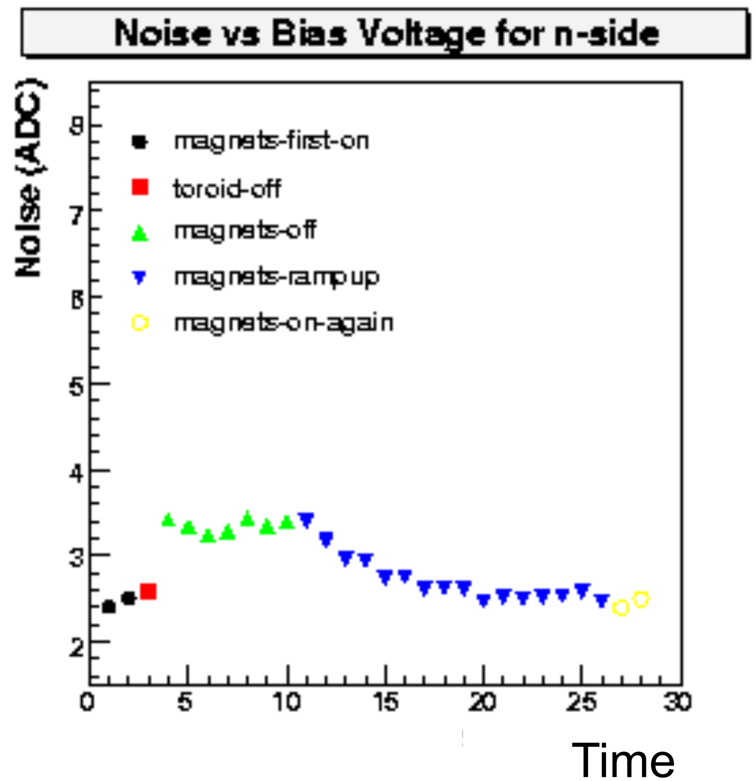




We observed sensitivity of the micro-discharge effect to solenoid magnetic field (~2 Tesla).

Sensitivity to Magnetic Field





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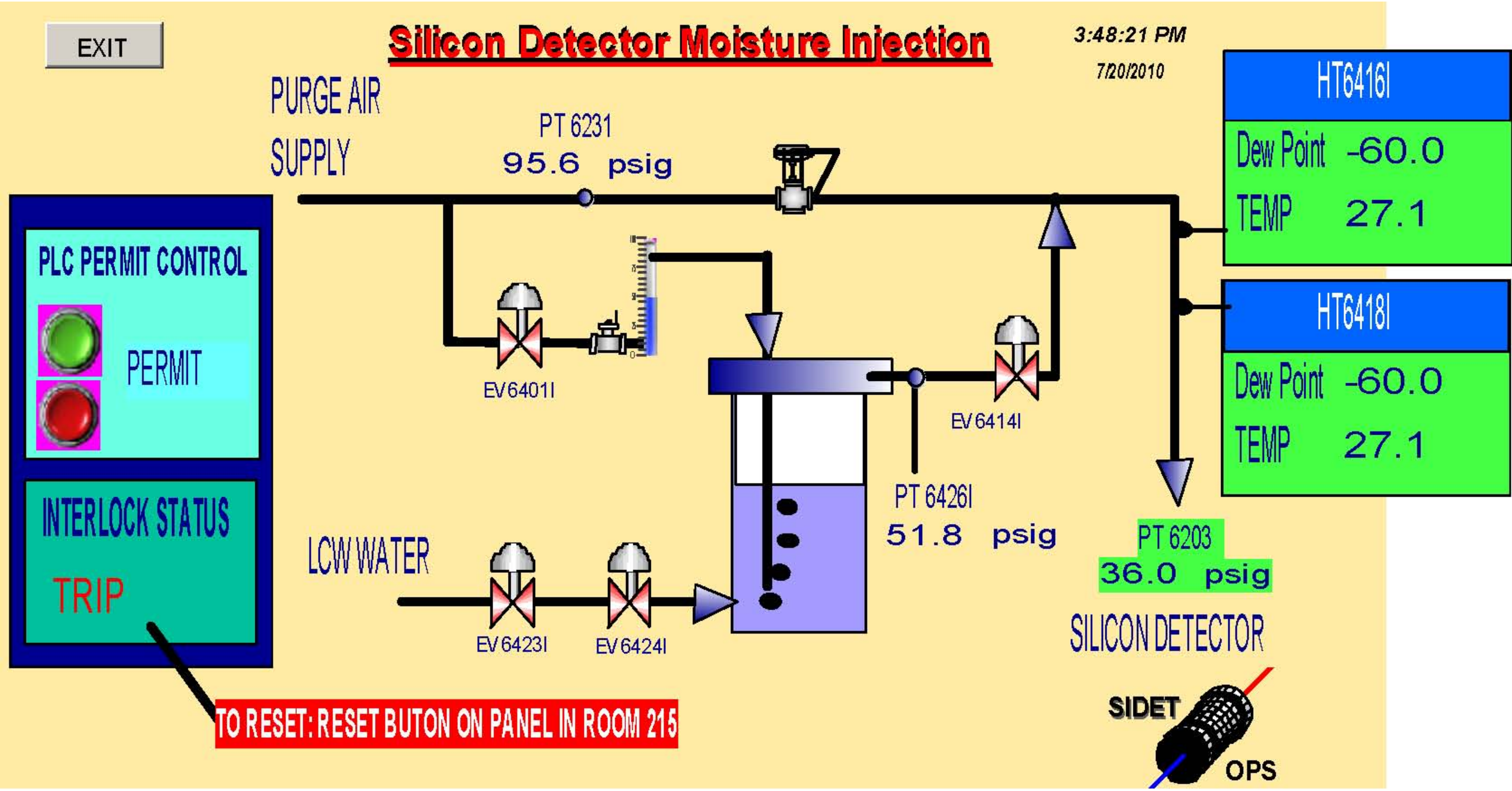
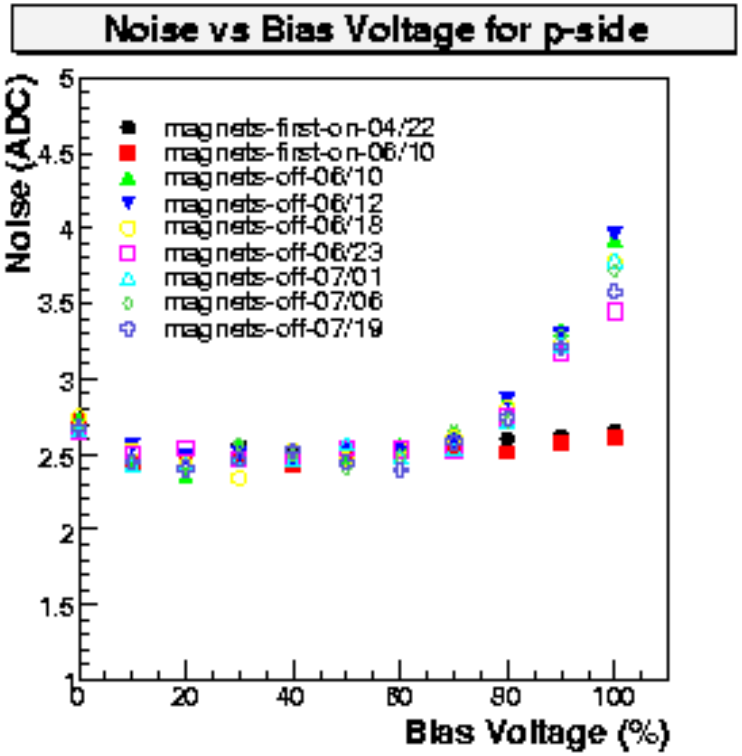
Moisture Injection System

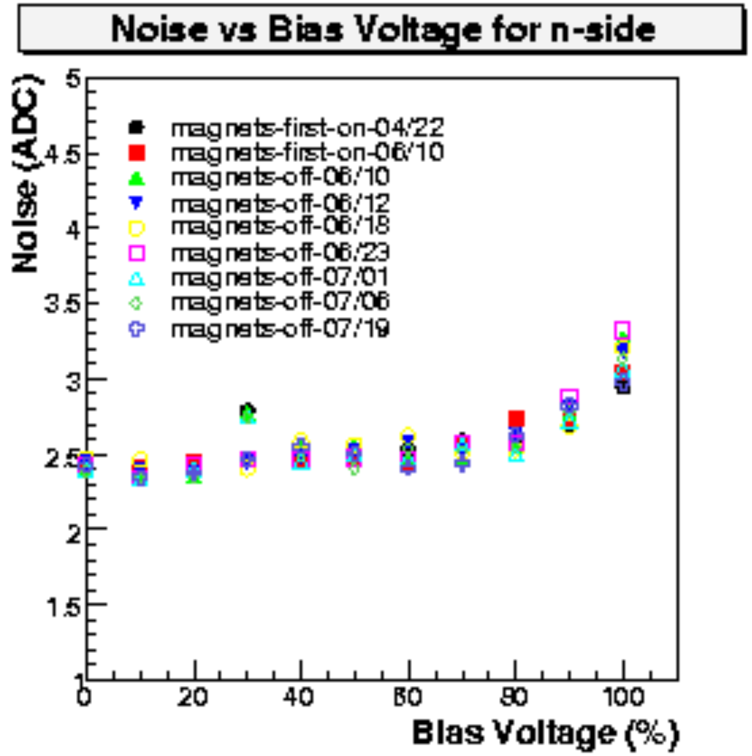


Sensitivity to Humidity

Moisture in silicon region (preliminary)		
	Dew point Degrees C	Water fraction ppm
Prior to injection	-49.5	21.6
After 6/8 initial step	-46.7	31.9
After 6/9 correction	-45.0	40.0
After 6/29 increase	-41.8	61.5
After 7/14 increase	-38.2	93.6
After 7/19 end	-48.3	25.6
Please recall that measured dew point in the silicon region is still decreasing when the system steps to the next location. No correction has been made for that.		

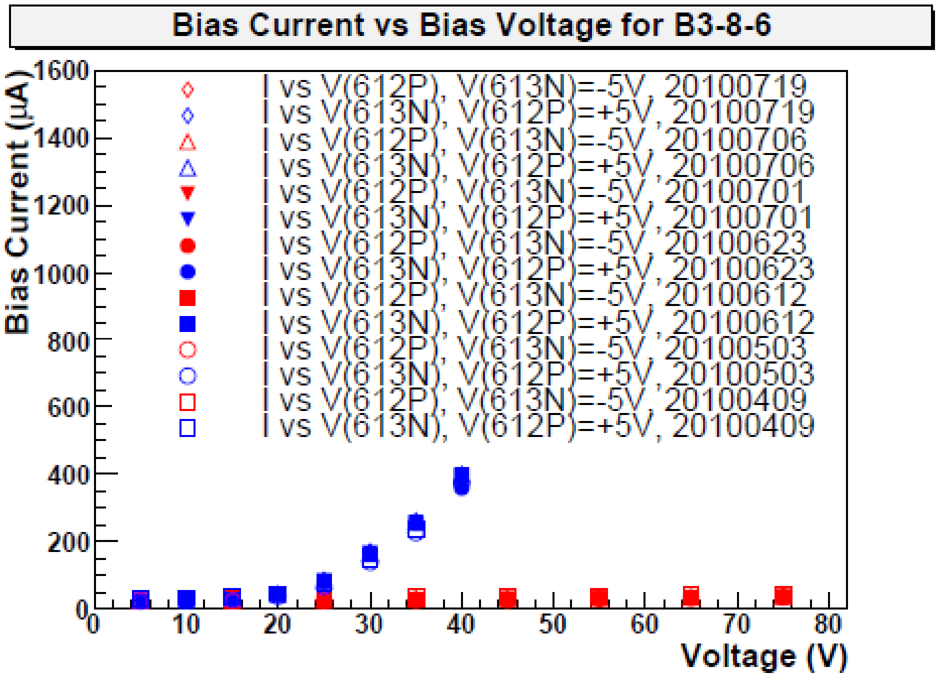
Sensitivity to Humidity

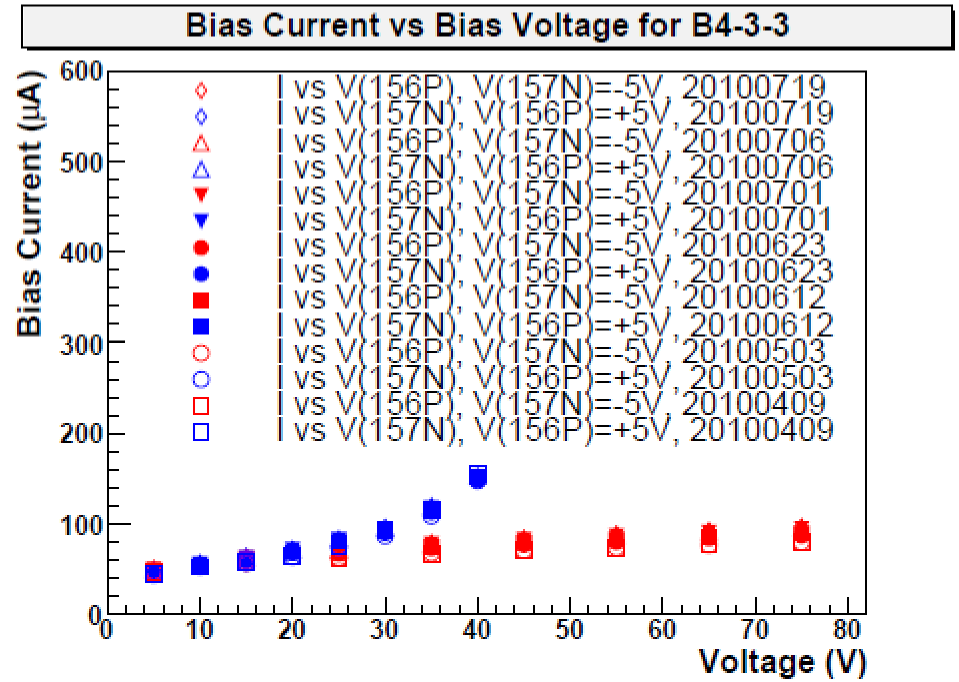




Using sensor readout noise with solenoid magnet in the off state, and the sensor bias current as an probe of the micro-discharge effect, we did not observe significant change in micro-discharge effect w.r.t. change in the humidity.

Sensitivity to Humidity



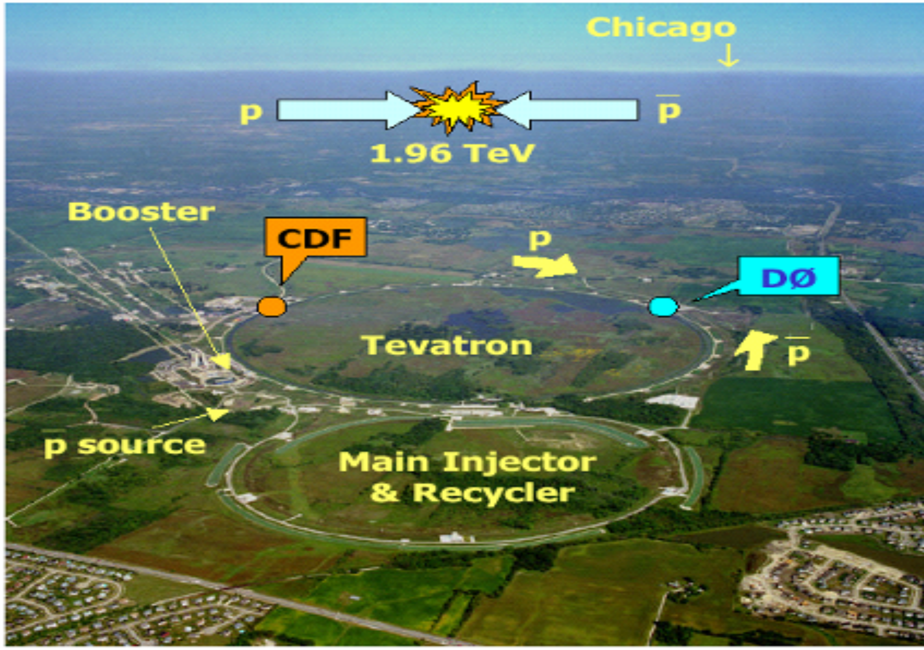


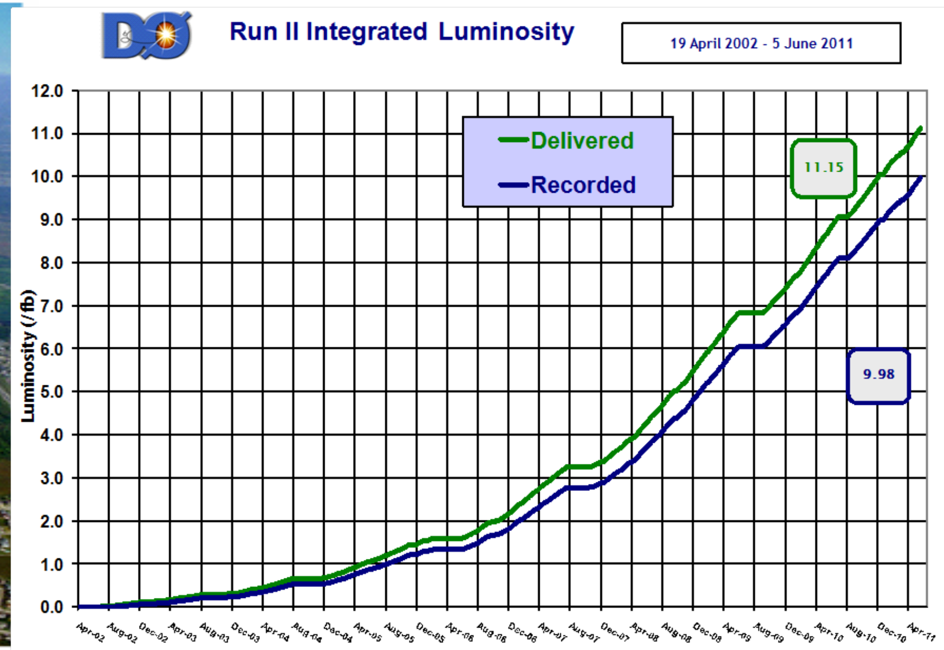
Using sensor readout noise with solenoid magnet in the off state, and the sensor bias current as an probe of the micro-discharge effect, we did not observe significant change in micro-discharge effect w.r.t. change in the humidity.

Summary

- Changes in the bias current, full depletion voltage, signal and noise due to radiation damage to the D0 silicon tracker have been closely monitored over the past 10 years. Measurement results are consistent with phenomenological models.
- Micro-discharge effect limits the maximum bias voltage that can be applied to double sided sensors, especially p side of D0 double sided sensors. The effect is studied with the D0 Silicon tracker and TCAD simulation. We did not observe significant change in the micro-discharge onset voltages before and after sensor type-inversion. We discovered that micro-discharge effect is sensitive to magnetic field. Its sensitivity to humidity was also explored and no significant change was observed with humidity increased from 20 ppm to 95 ppm.

Tevatron Collider at Fermilab

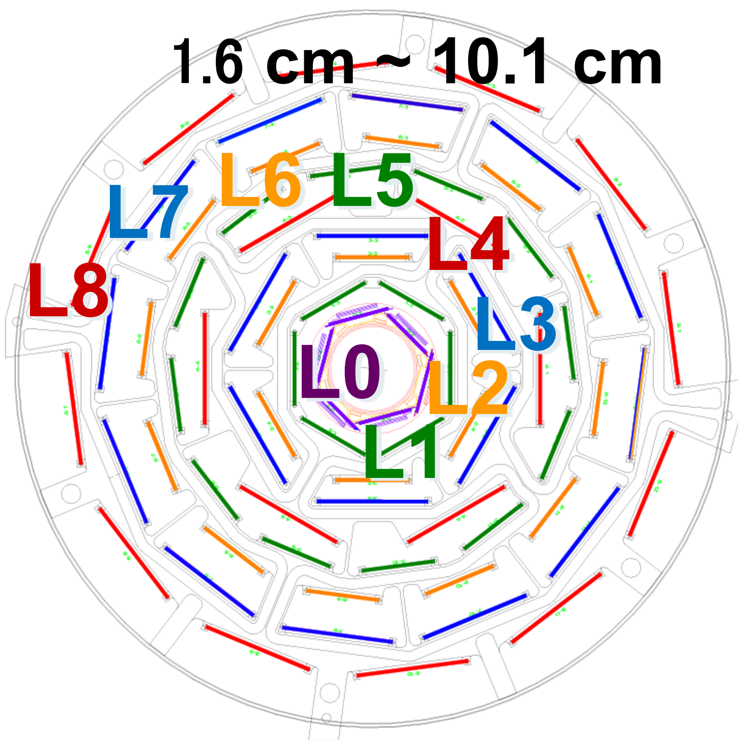




- Proton-antiproton colliding at $\sqrt{s}$=1.96TeV
- Peak luminosity record ~4.2x10^{32} cm^{-2} s^{-1}

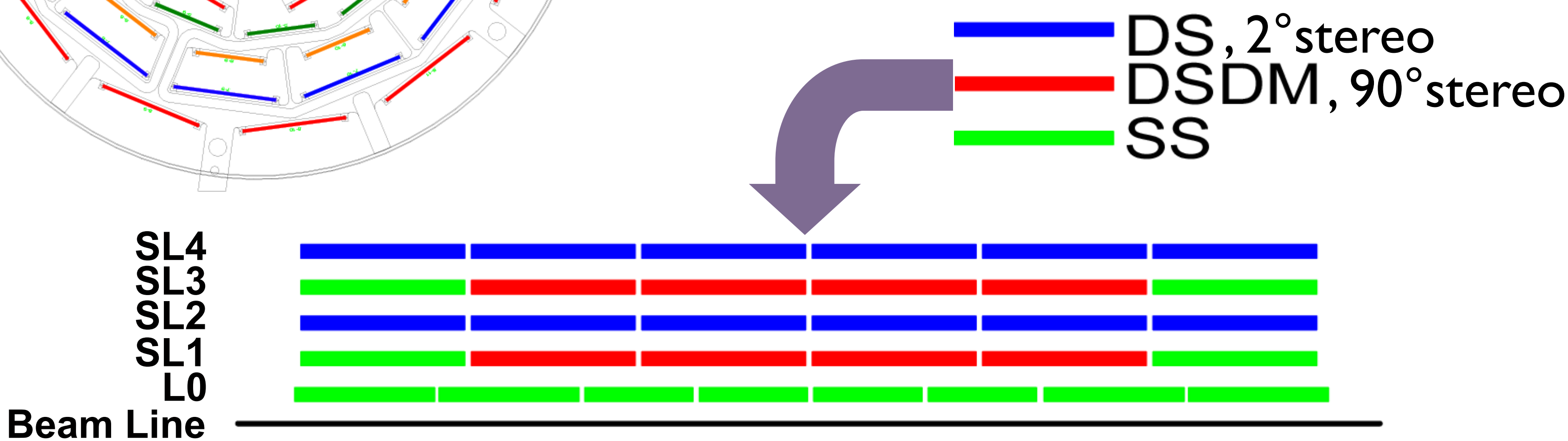
  Delivered integrated Luminosity >11 fb^{-1}
- Original DØ Silicon tracker installed in 2001, designed for 2 fb^{-1}. Layer 0 installed in 2006 in an effort to compensate for anticipated degradation in charge collection efficiency in original innermost layer.

SMT Layer0 and Barrel

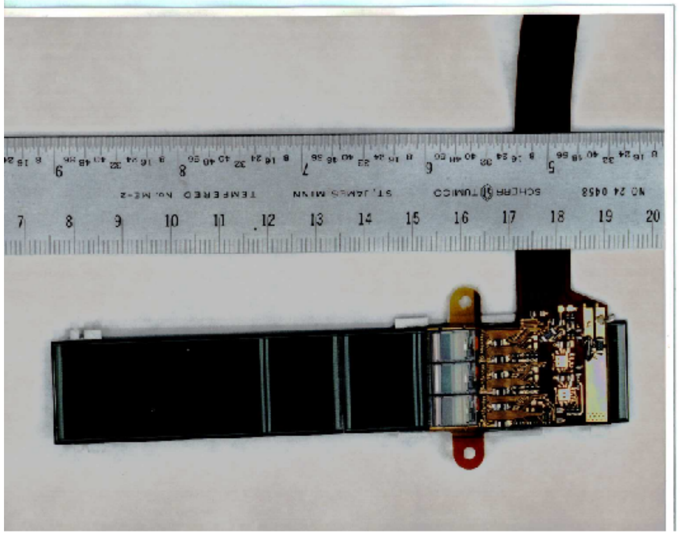


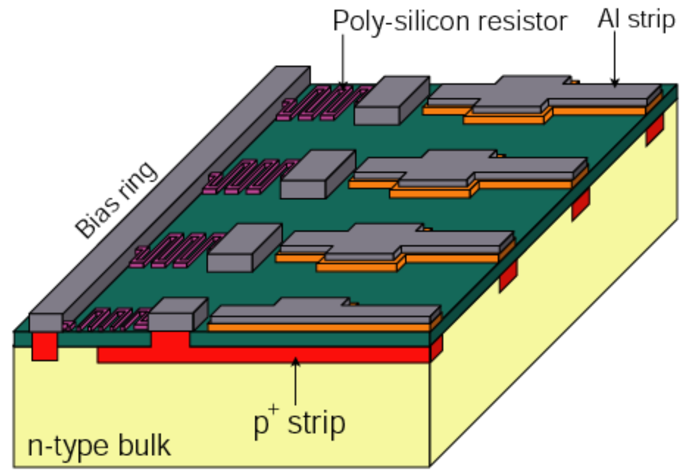
L1L2 → Super Layer 1
L3L4 → Super Layer 2
L5L6 → Super Layer 3
L7L8 → Super Layer 4
} Micron-UK

Layer 0 } HPK



Silicon Microstrip Detector



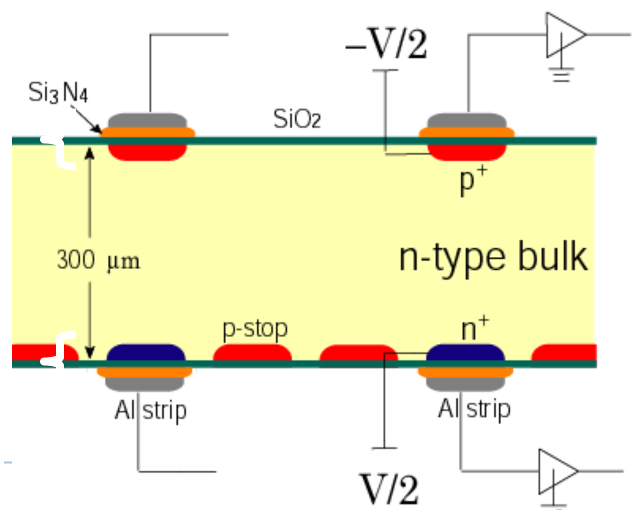


- HV limitation on sensors
  - Double-sided

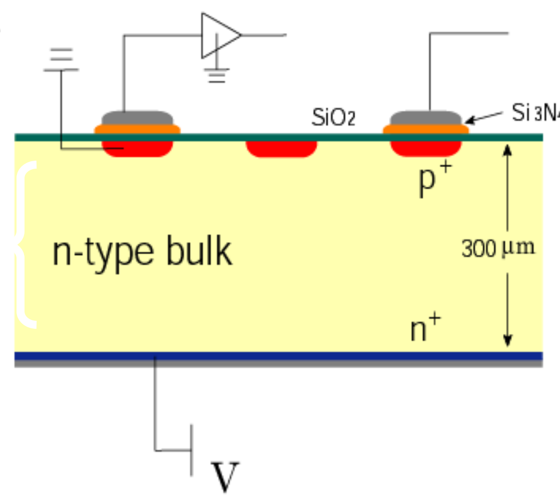
    : ~150V
  - Single sided

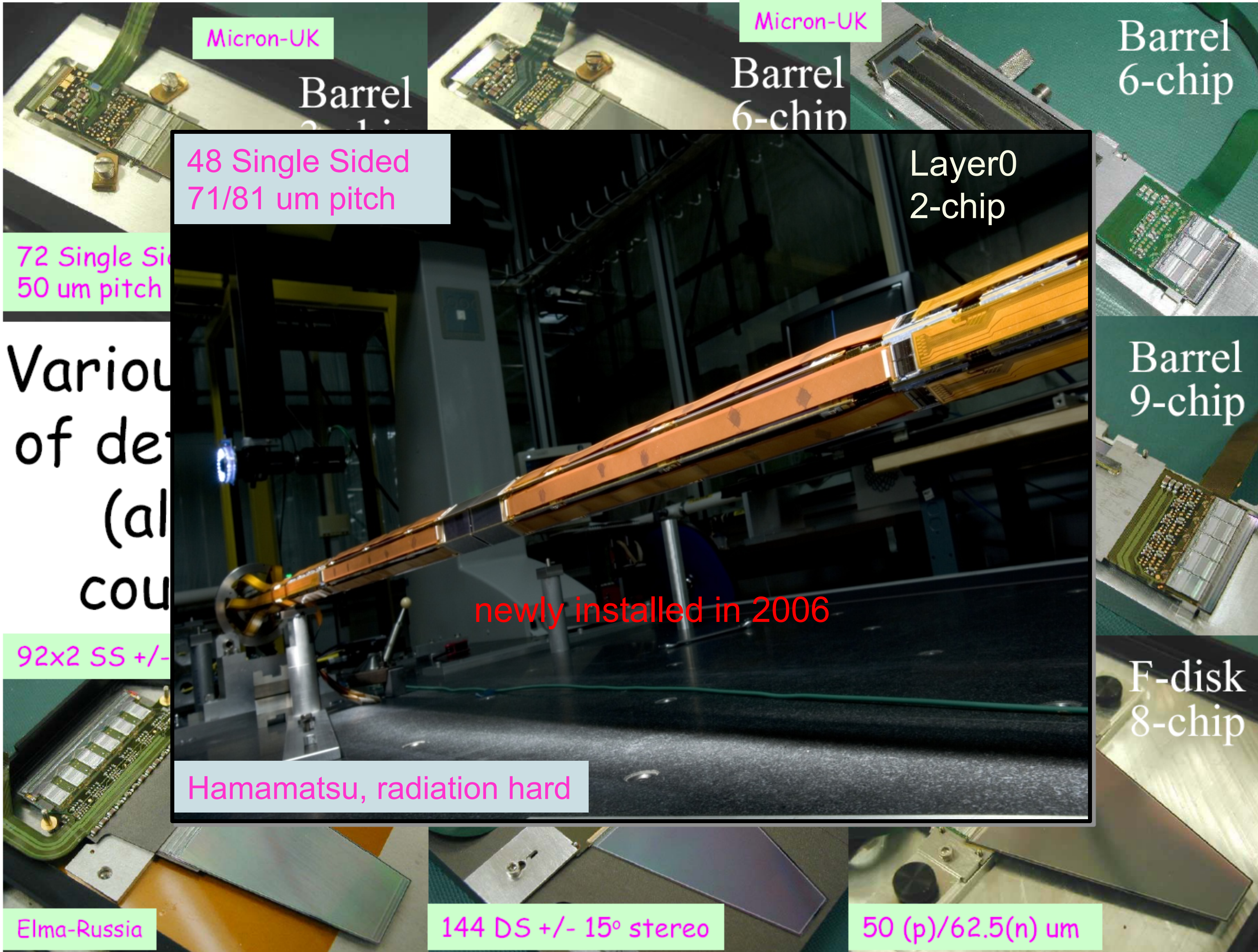
    : 500V or more

Double-Sided Sensor



Single-Sided Sensor

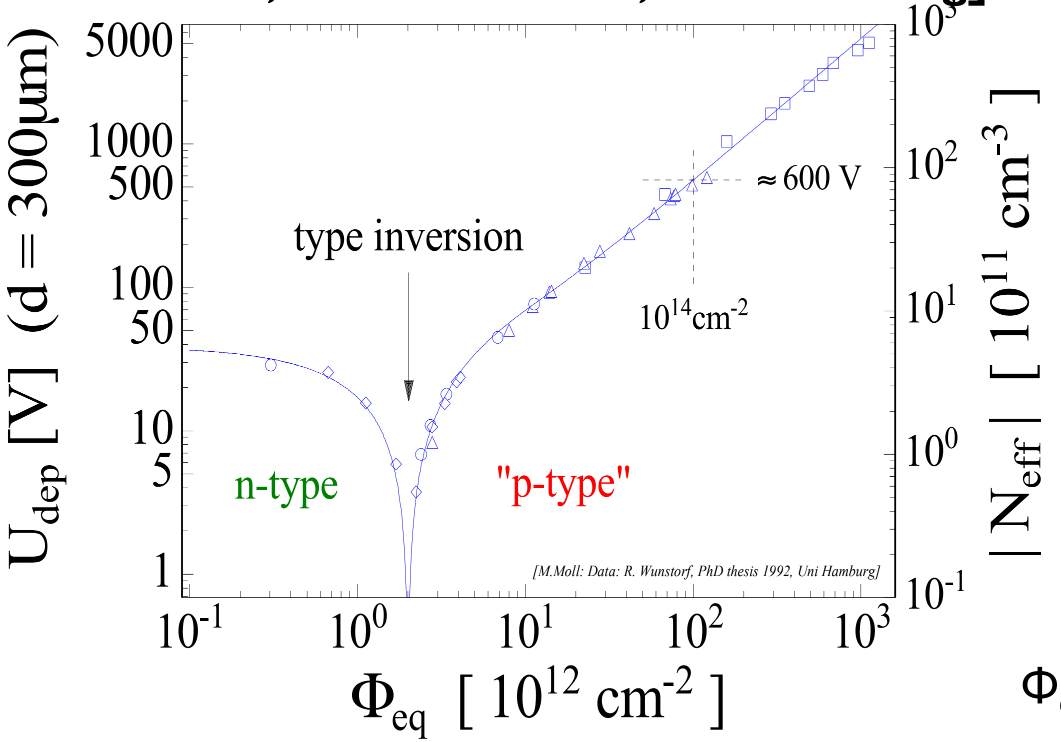




Micron-UK
Barrel
Micron-UK
Barrel
Barrel
6-chip
48 Single Sided
71/81 um pitch
Layer0
2-chip
50 um pitch
Barrel
9-chip
newly installed in 2006
F-disk
8-chip
Hamamatsu, radiation hard
Elma-Russia
144 DS +/- 15° stereo
50 (p)/62.5(n) um

Full Depletion Voltage and Type Inversion

[M.Moll: Data R.Wunstorf, PhD thesis 1992, Uni Hamburg]



Full Depletion Voltage :

$$V_{dep} = \frac{|N_{eff}| \cdot e \cdot d^2}{2 \cdot \varepsilon}$$

= depleting the full depth of the sensors from free charge carriers

Effective Doping Concentration :

$$N_{eff} = N_{eff\,0} - (N_c + N_a + N_y)$$

Φ_{eq} : 1MeV neutron equivalent fluence

- Stable damage : N_c
- Beneficial annealing : N_a
- Reverse annealing : N_y

Estimation of Damage Parameter

- The evolution of α with time after irradiation

$$\alpha = \sum_i a_i e^{-\frac{\Theta(T)t}{\tau_i}}$$

- The τ_i depends on temperature
  - Scaling time with

$$\Theta(T) = \exp\left(\frac{E_I}{k_B}\left(\frac{1}{T_R} - \frac{1}{T}\right)\right)$$

  - E_I=1.09 eV and T_R=20°C

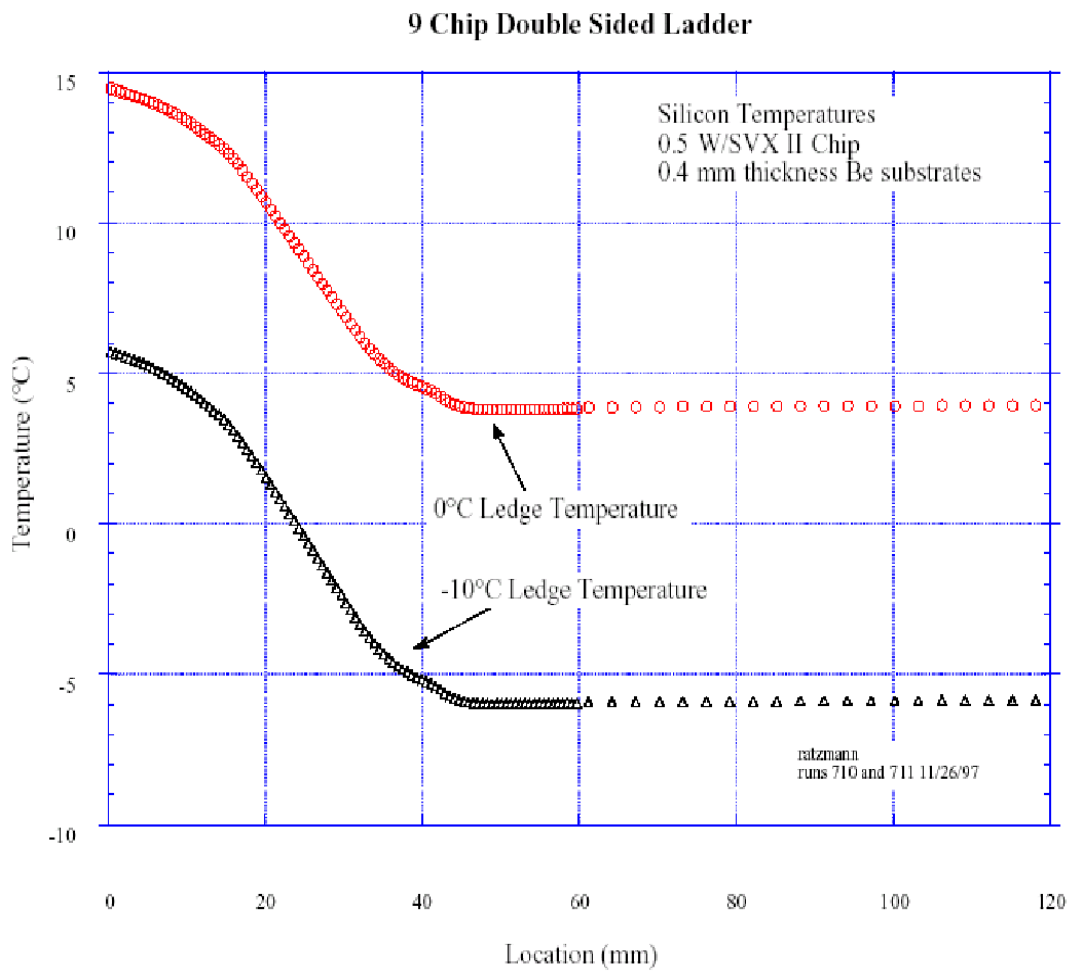
R. Wunstorf

Table 1: Annealing parameter of the damage induced bulk generation current [1]

Time constant τ_i [min]	Relative amplitude a_i
$(1.78 \pm 0.17) \cdot 10^1$	0.156 ± 0.038
$(1.19 \pm 0.03) \cdot 10^2$	0.116 ± 0.003
$(1.09 \pm 0.01) \cdot 10^3$	0.131 ± 0.002
$(1.48 \pm 0.01) \cdot 10^4$	0.201 ± 0.002
$(8.92 \pm 0.59) \cdot 10^4$	0.093 ± 0.007
∞	0.303 ± 0.006

Temperature Corrections

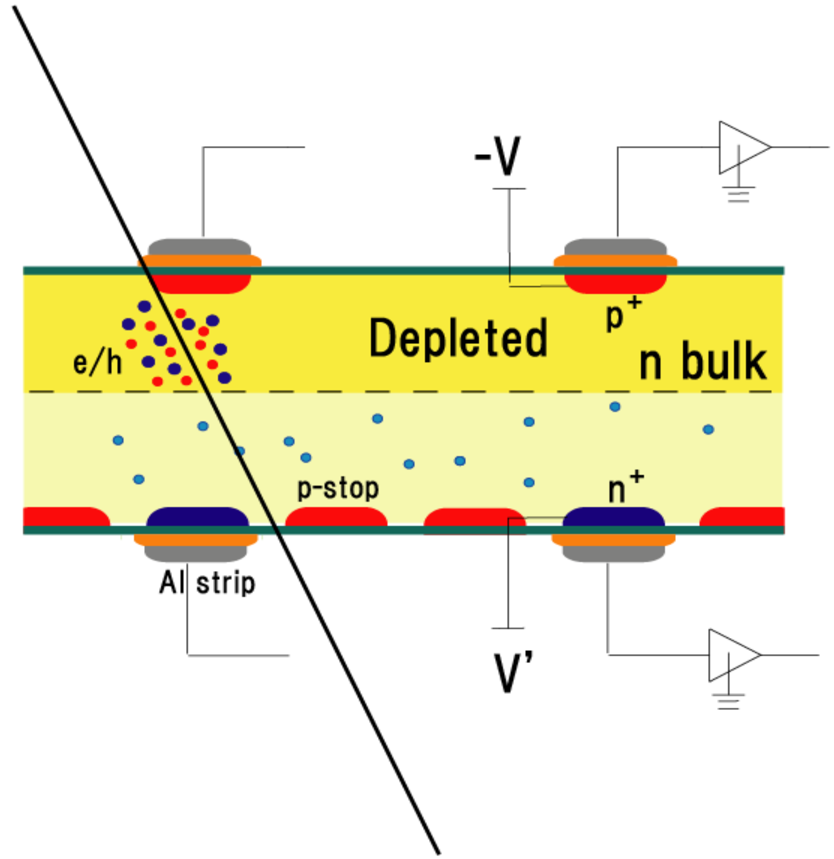
- Temperature profile is complicated
  - Silicon sensors warm-up during read-out
- Include the profile into the temperature dependence instead of finding an average temperature



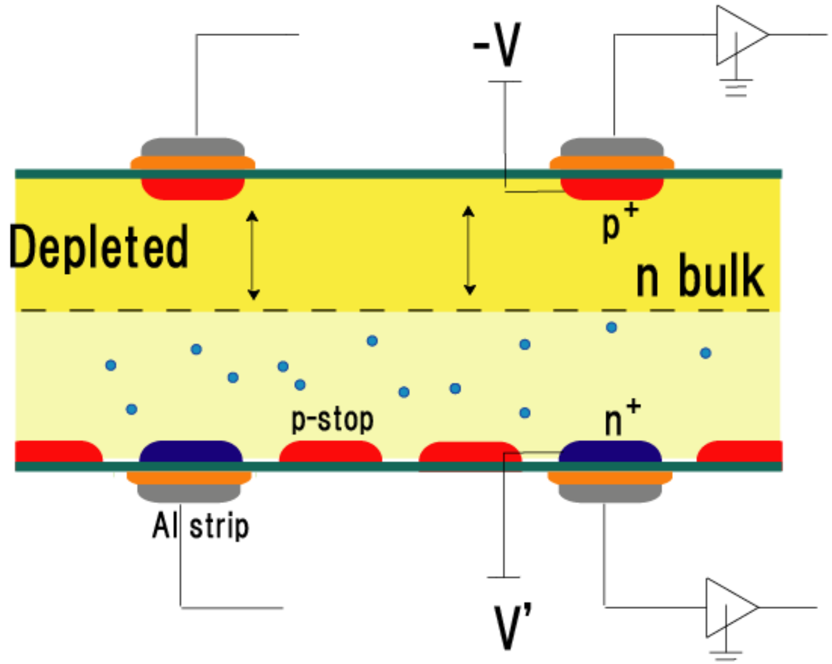
Zhenyu Ye (Fermilab)

Full Depletion Voltage from Charge Collection

- Amount of collected charge depends on the depleted volume
- If sensor is fully depleted, charge collection efficiency becomes high and stable

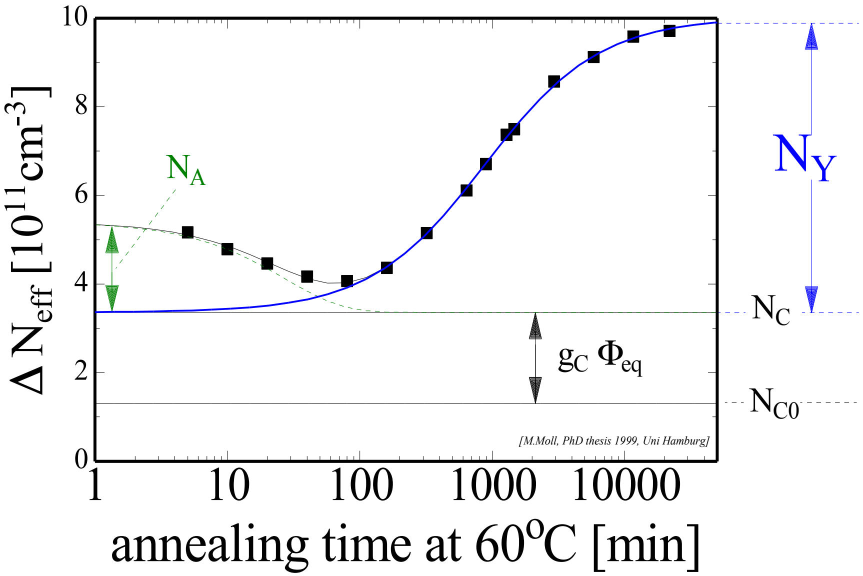


Full Depletion Voltage from Noise



- Thermal noise from free charge carriers
  - charge carriers removed by applying bias voltage
  - **ohmic side noise** strong decrease at full depletion

Annealing



$$N_c(\Phi) = N_{c0} \cdot (1 - e^{-c\cdot\Phi}) + g_c \cdot \Phi$$

$$N_a(\Phi, t, T) = g_a \cdot \Phi \cdot e^{-k_{a0} \cdot e^{-E_{aa}/k_B T} \cdot t}$$

$$N_y(\Phi, t, T) = g_y \cdot \Phi \cdot \left(1 - \frac{1}{1 + k_{y10} e^{-E_{ay}/k_B T} \cdot t}\right)$$

- Three components
  - Stable damage : N_c
  - Beneficial annealing : N_a
  - Reverse annealing : N_y
- Reverse annealing time constant depends on temperature:

  ~500 years (-10°C)

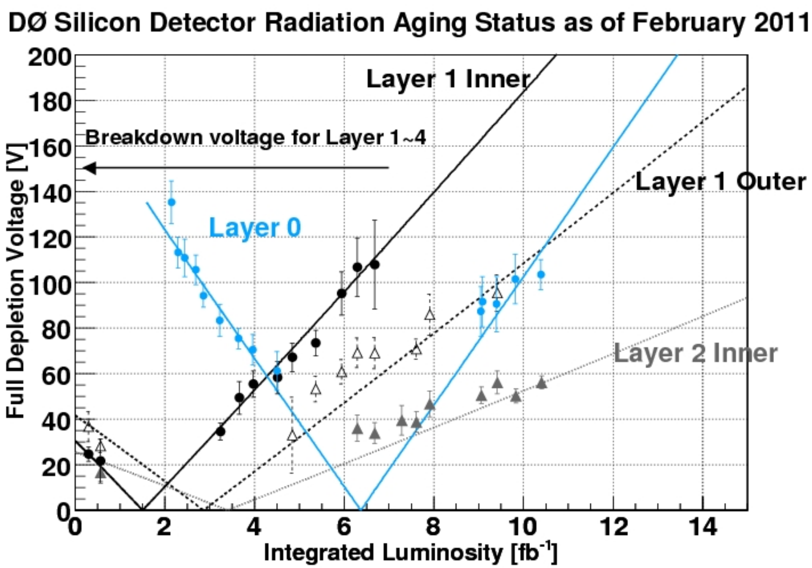
  ~500 days (20°C)

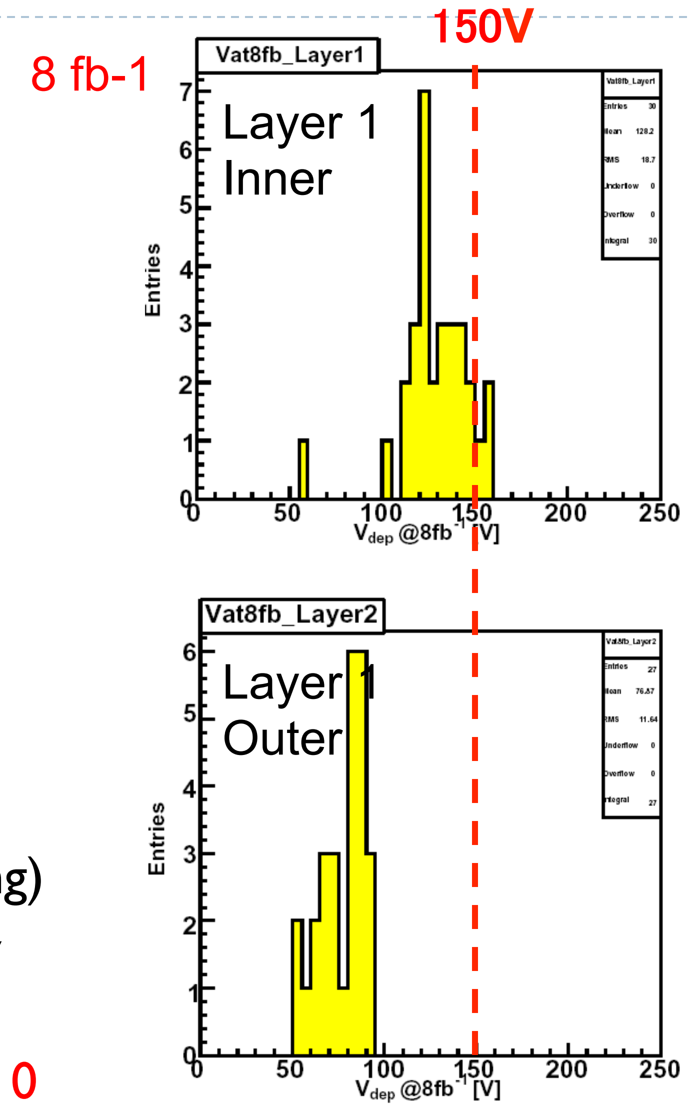
  ~21 hours (60°C)

Parameters

- kB = 8.617343e-5 [eV*K^-1]
- Nc0 = 0.65 * Neff0 [cm^-3]
- c = 1.1e-13 [cm^2]
- gc = 1.49e-2 [cm^-1]
- ka0 = 2.4e13 [s^-1]
- Eaa = 1.09 [eV]
- ga = 1.81e-2 [cm^-1]
- ky10 = 1.5e+15 [s^-1]
- Eay = 1.33 [eV]
- gy = 5.16e-2 [cm^-1]

Projection Result

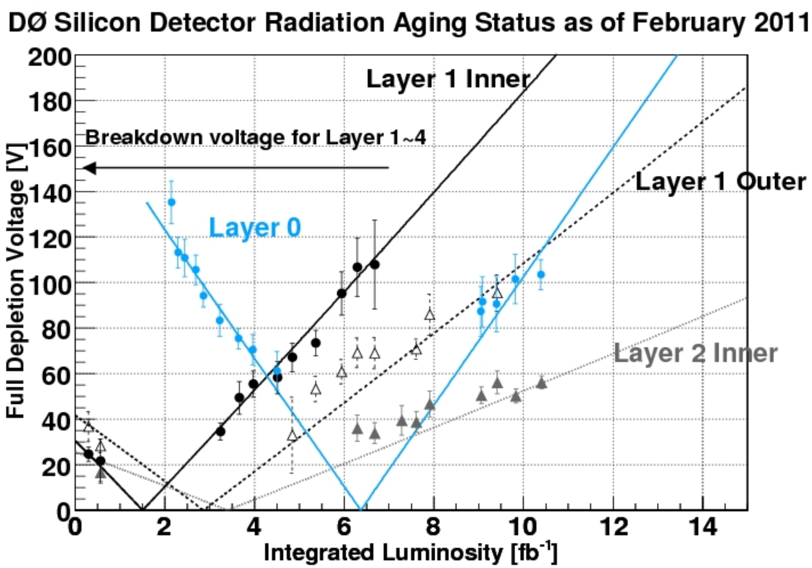


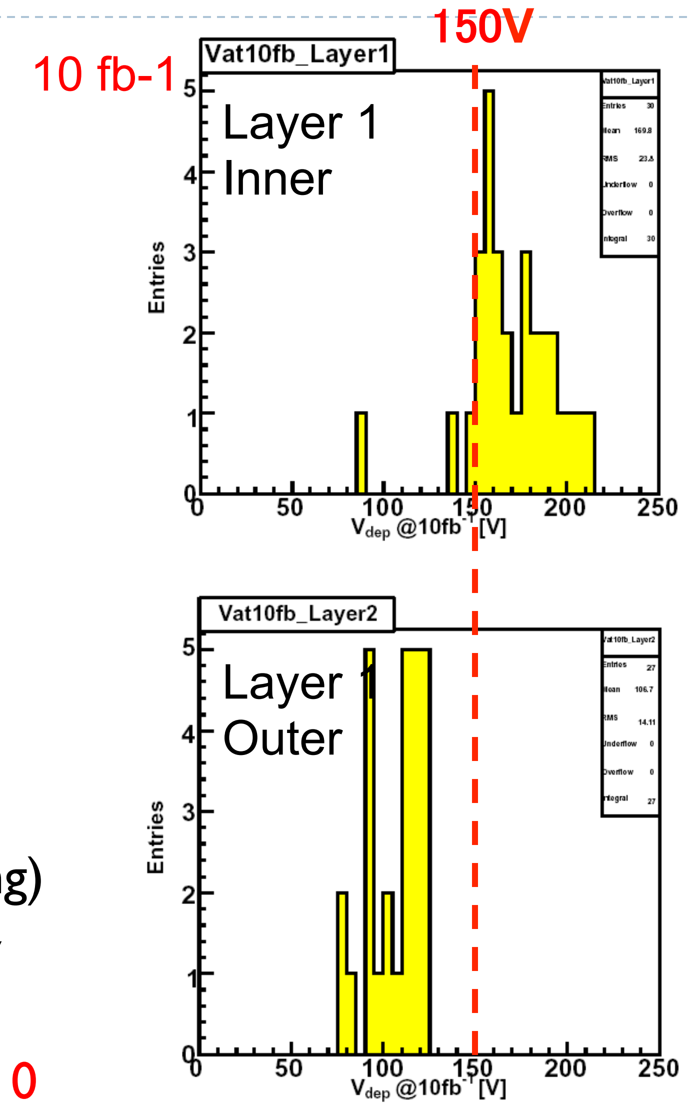


- ↑ Time is projected to integrated luminosity
- ↑ Only showing data points from p-side charge collection study (all data are included in the fitting)
- →Some Layer 1 sensors might no longer be fully depleted by the end of the Tevatron Run2

Anticipated and compensated by installing Layer 0

Projection Result

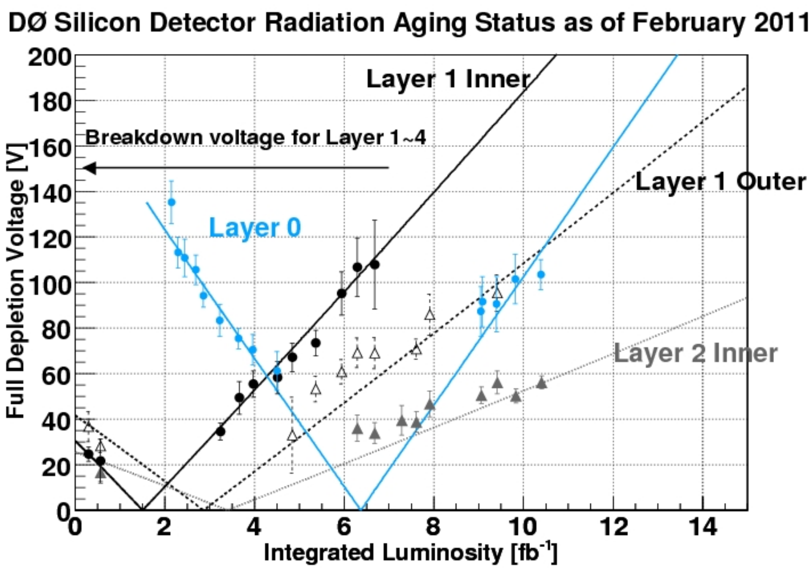


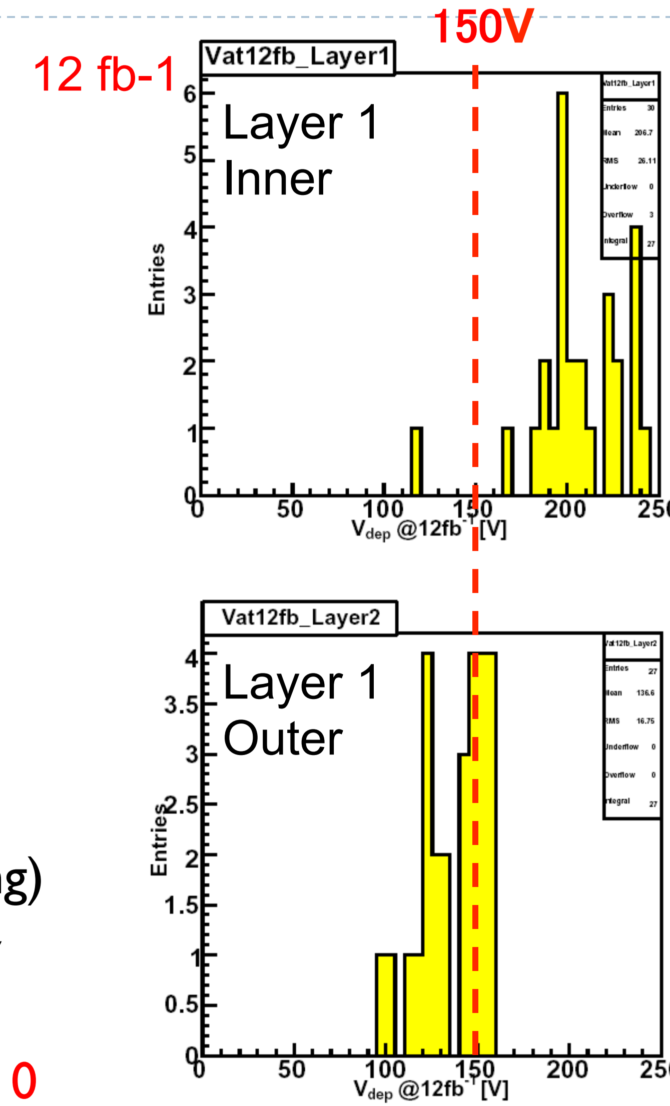


- ↑ Time is projected to integrated luminosity
- ↑ Only showing data points from p-side charge collection study (all data are included in the fitting)
- →Some Layer 1 sensors might no longer be fully depleted by the end of the Tevatron Run2

Anticipated and compensated by installing Layer 0

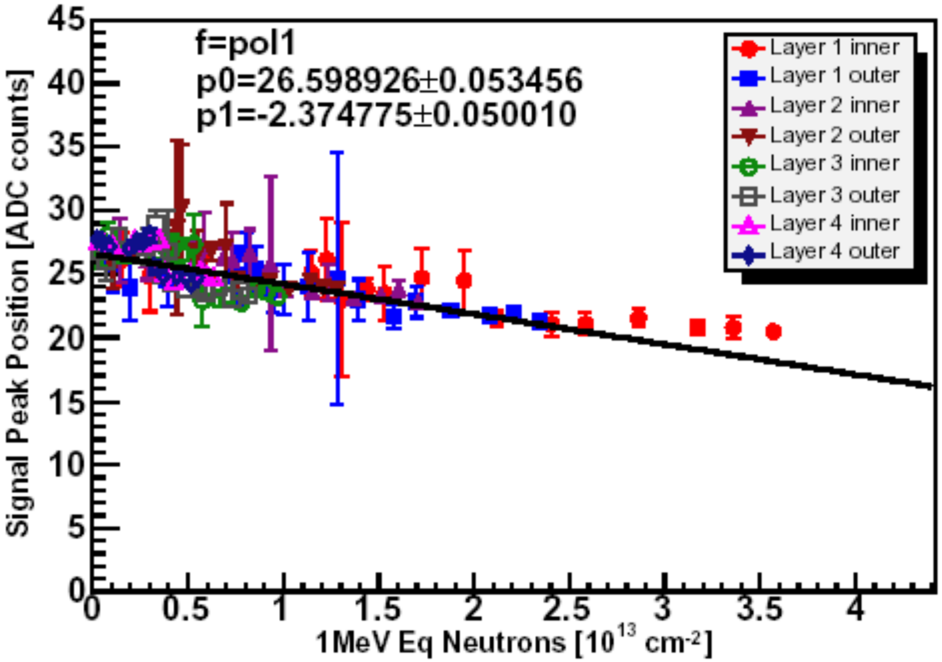
Projection Result



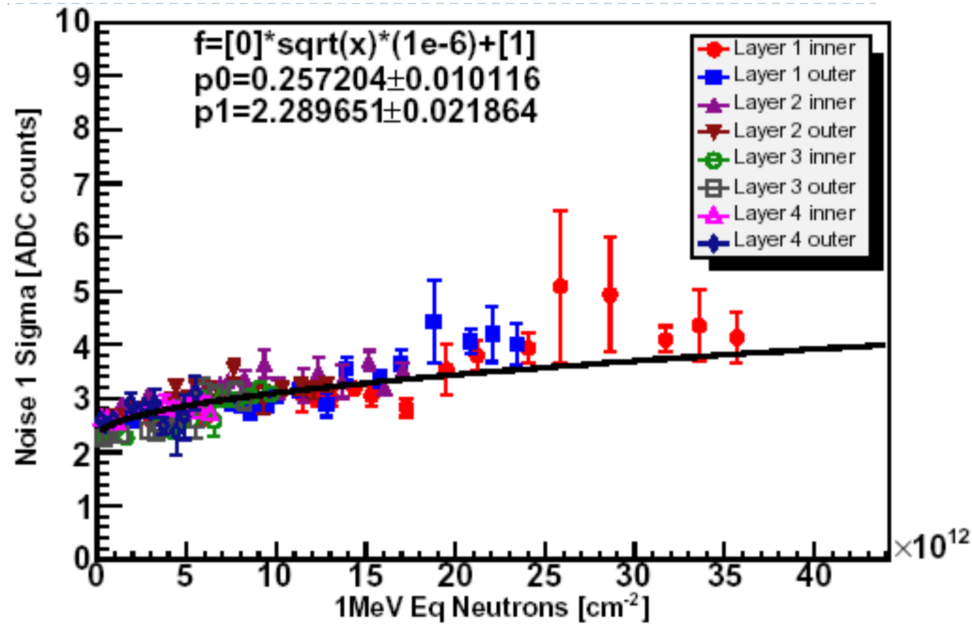


- ↑ Time is projected to integrated luminosity
- ↑ Only showing data points from p-side charge collection study (all data are included in the fitting)
- →Some Layer 1 sensors might no longer be fully depleted by the end of the Tevatron Run2

Anticipated and compensated by installing Layer 0



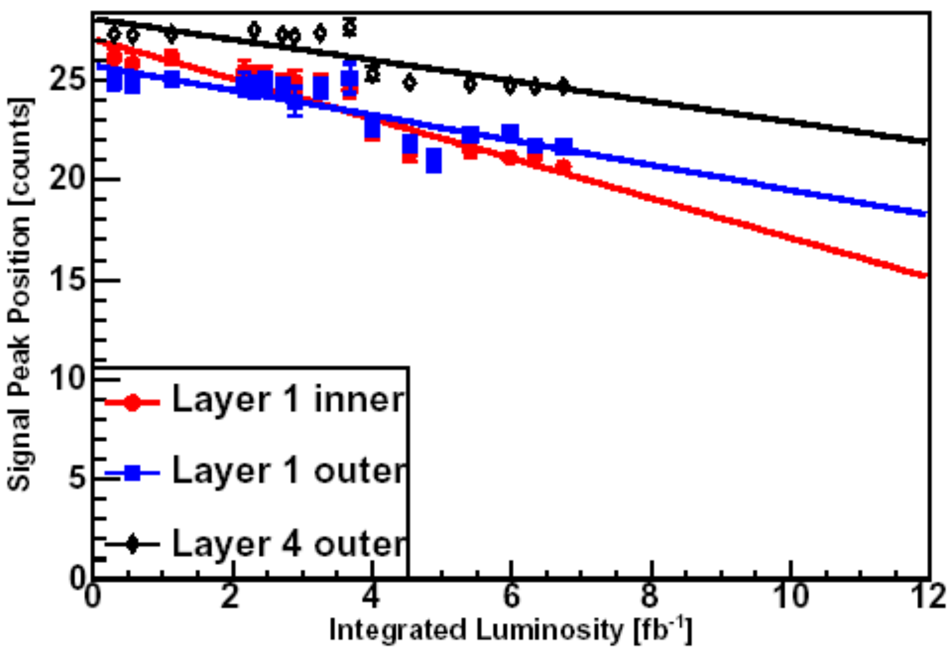
f=pol1
p0=26.598926±0.053456
p1=-2.374775±0.050010
Layer 1 inner
Layer 1 outer
Layer 2 inner
Layer 2 outer
Layer 3 inner
Layer 3 outer
Layer 4 inner
Layer 4 outer
Signal Peak Position [ADC counts]
1MeV Eq Neutrons [10^13 cm^-2]



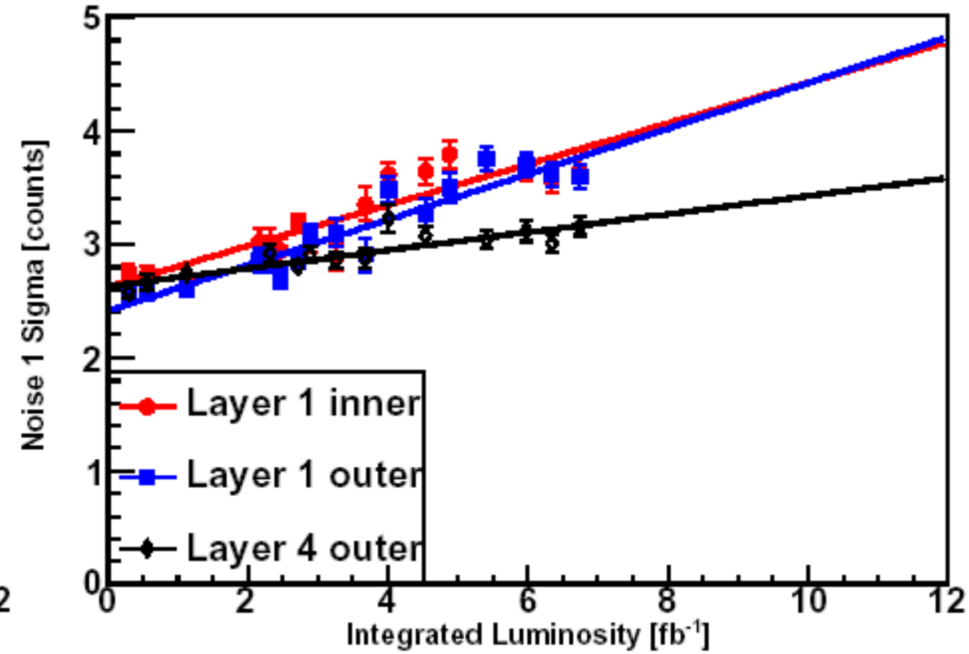
f=[0]*sqrt(x)*(1e-6)+[1]
p0=0.257204±0.010116
p1=2.289651±0.021864
Layer 1 inner
Layer 1 outer
Layer 2 inner
Layer 2 outer
Layer 3 inner
Layer 3 outer
Layer 4 inner
Layer 4 outer
Noise 1 Sigma [ADC counts]
×10^12
1MeV Eq Neutrons [cm^-2]

Signal and Noise

Signal



Noise



- signal peak position goes down
- noise increases
- S/N decreased from about 10 to 4-5 (7) for innermost (outer) layer at 12 fb-1.

Micro-Discharge Effect

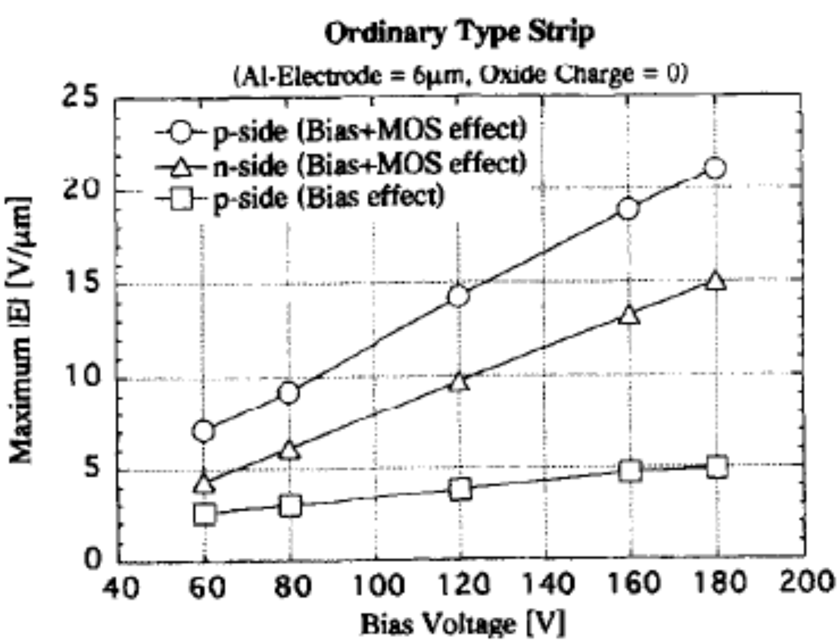


Fig. 4. The maximum field strength around the implant-strip in the Si bulk as a function of bias voltage for the ordinary type strip. The squares are the contribution from bias only on the junction side. The circles and triangles show the maximum field from the bias and the MOS effect (full potential across the coupling capacitor) for the p-side and the n-side, respectively.

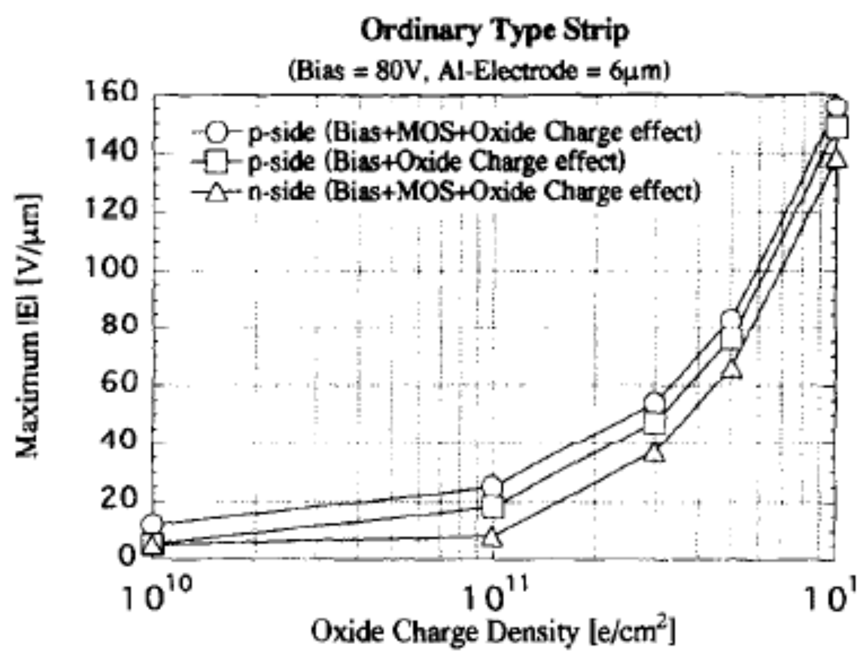


Fig. 6. The maximum field around the implant-strip of the ordinary type is shown as a function of the oxide charge density trapped in the Si-SiO_2 interface. The circles, squares and triangles show the maximum field around the p^+ implant-strip with full bias potential across the capacitor, the p^+ implant-strip without potential across, and the n^+ implant-strip with full potential across, respectively.

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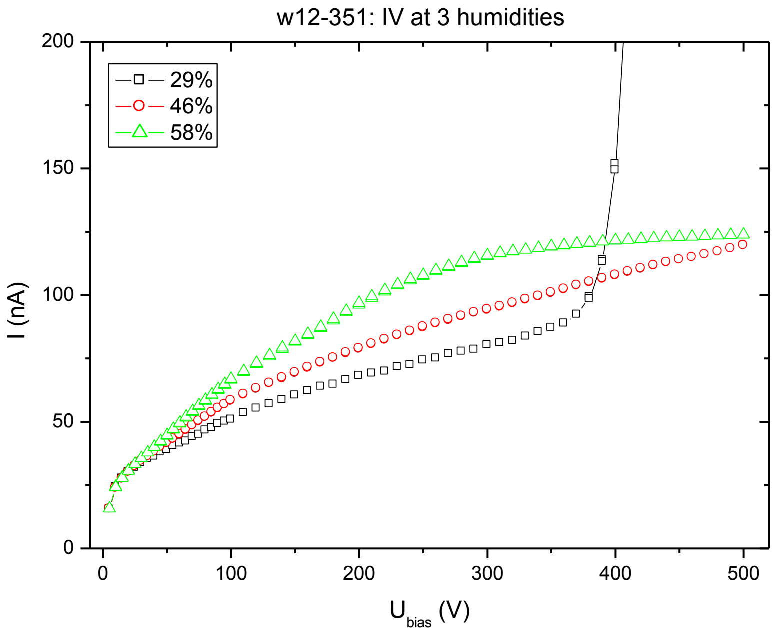

Simulations by Rainer Richter and Graham Beck show that the surface charging leads also to a decrease of the electric field near the strip edge. Thus a faster depletion at higher humidity should be accompanied by a suppression of breakdown if it develops near the strip edge. This is indeed observed in some cases.

By the same reason keeping detector at 150V for ~45 min helps to suppress breakdowns at higher voltages as was reported by Rainer Richter on 16.04.03.