# Charge Collection in irradiated Si Sensors

- **Monitoring the health of the Charge Collection System**
- **New Parameter: Efficiency Voltage**
- **Correlation between efficiency and cluster size**

C. Betancourt, B. Colby, N. Dawson, V. Fadeyev M. Gerling, F. Hurley,
S. Lindgren, P. Maddock, H. F.-W. Sadrozinski, S. Sattari, J. v. Wilpert, J. Wright
*SCIPP, UC Santa Cruz*

# Charge Collection and C-V Measurements in irradiated Si Sensors

- **Monitoring the health of the Charge Collection System**
- **New Parameter: Efficiency Voltage**
- **Correlation between efficiency and cluster size**
- **Admittance Measurement**

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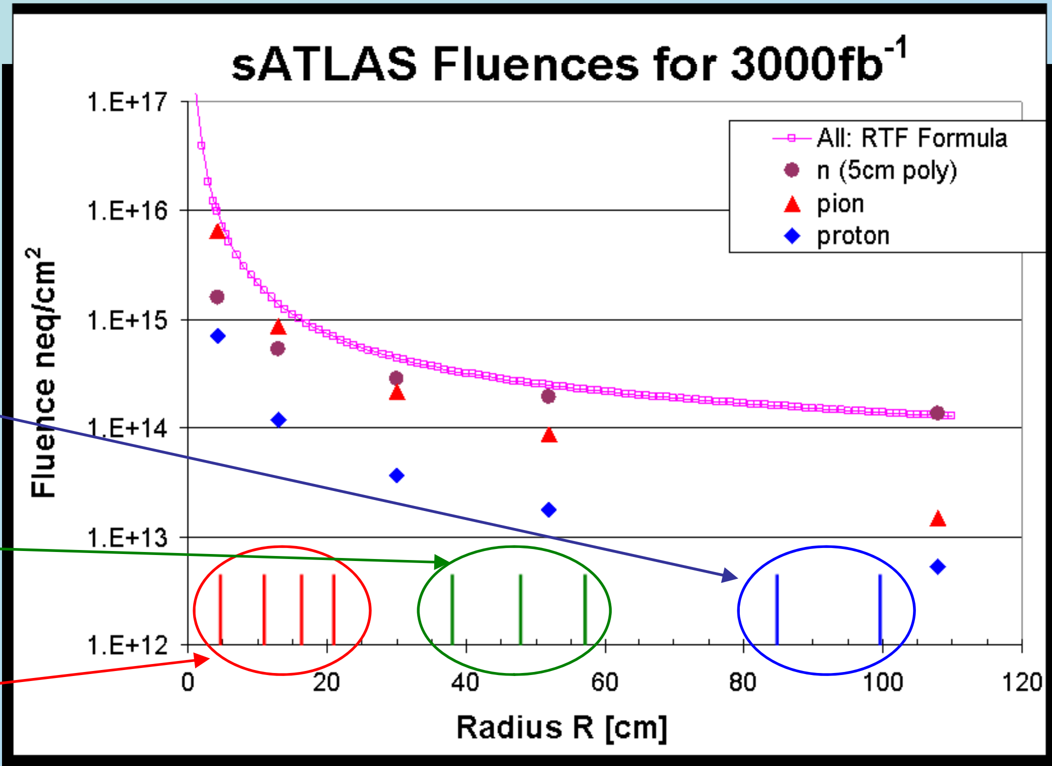
# Fluence in the sATLAS Tracker "du jour"

Radial Distribution of Sensors determined by Occupancy < 2%, still emerging

Long Strips

Short Strips

Pixels



ATLAS Radiation Taskforce http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/RADIATION/RadiationTF_document.html

**5 - 10 x LHC Fluence**

**Mix of n, p, π depending on radius R**

**Strips damage largely due to neutrons**

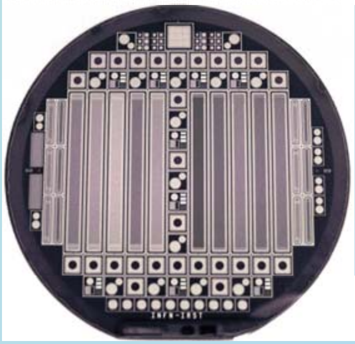
**Pixels Damage due to neutrons+pions**

**Design fluences for sensors** (includes 2x safety factor) **:**

| | | |
|---|---|---|
| B layer (r=3.7 cm) | 2.5*10$^{16}$ neq/cm$^2$ | 1140 MRad |
| Innermost Pixel Layer (r=5cm): | 1.4*10$^{16}$ neq/cm$^2$ | 712 MRad |
| 2nd Pixel Layer (r=7cm): | 7.8*10$^{15}$ neq/cm$^2$ | 420 MRad |
| Outer Pixel Layers (r=11cm): | 3.6*10$^{15}$ neq/cm$^2$ | 207 MRad |
| Short strips (r=38cm): | 6.8*10$^{14}$ neq/cm$^2$ | 30 MRad |
| Long strips (r=85cm): | 3.2*10$^{14}$ neq/cm$^2$ | 8.4 MRad |

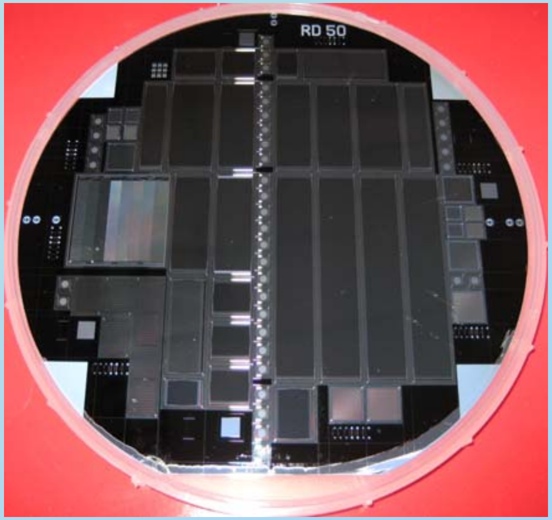
# Towards Commercialization of P-type

**4" : IRST (SMART)**



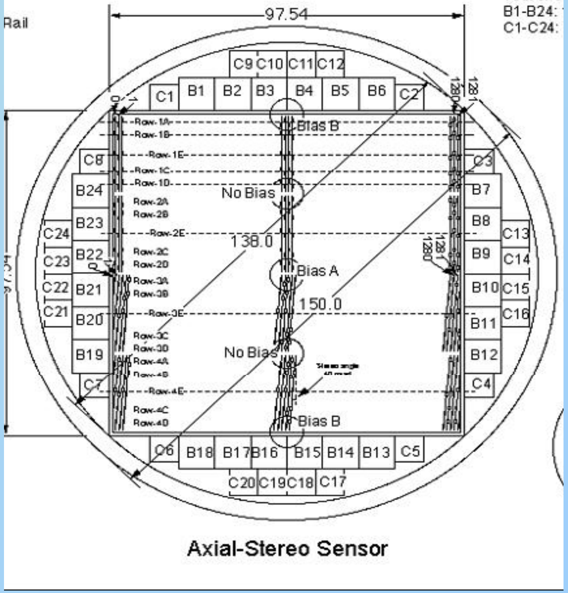
n-on-n, p-on-n, n-on-p
FZ and Mcz

**6" : Micron (RD50)**



n-on-n, p-on-n, n-on-p
FZ and Mcz

**HPK: (ATLAS07)**



Axial-Stereo Sensor

n-on-p, FZ

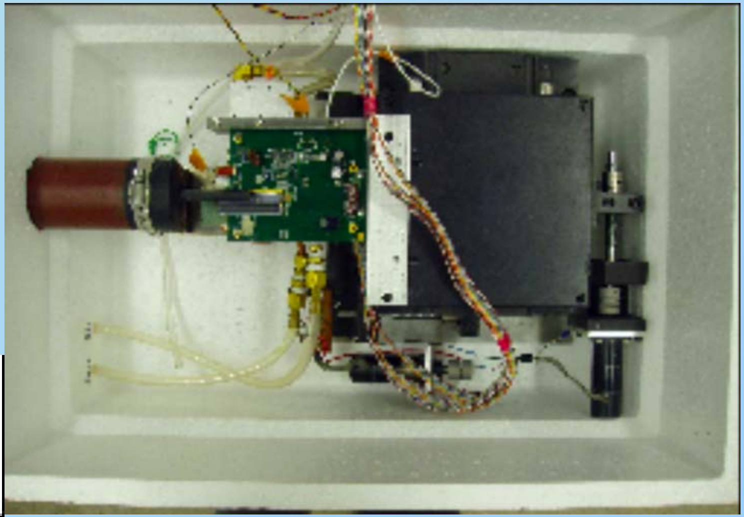
Testing: UC Santa Cruz, Liverpool U. , Ljubljana

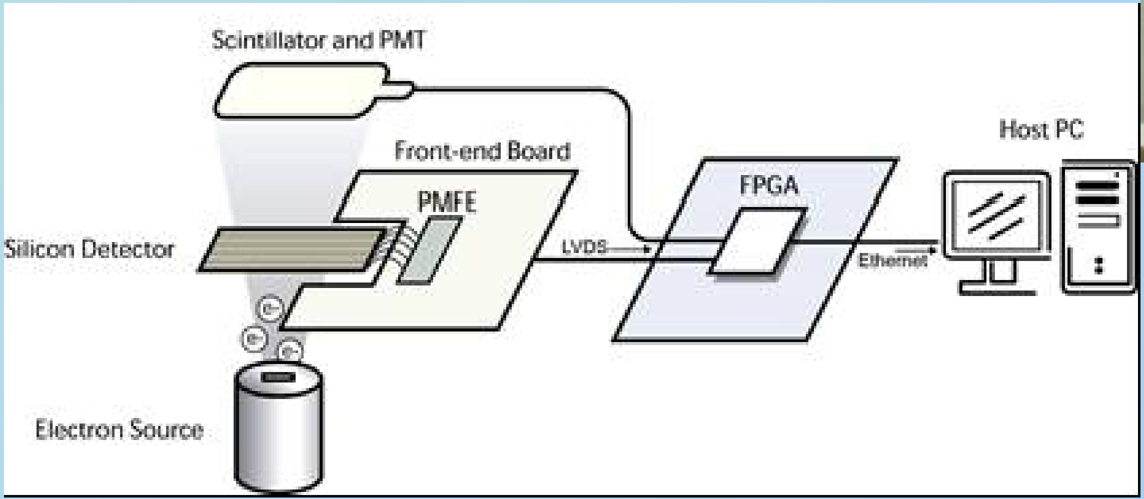
[redacted]

# Charge Collection System

Measurement of collected charge with min. ion. particles (MIPs) combines all effects of radiation damage: depletion voltage increase, inversion, trapping…

CCE System is beta source ($^{90}$Sr)
with trigger from single thick scintillation counter.
Measurements carried out in freezer
at low temperature (-30 $^{o}$C)

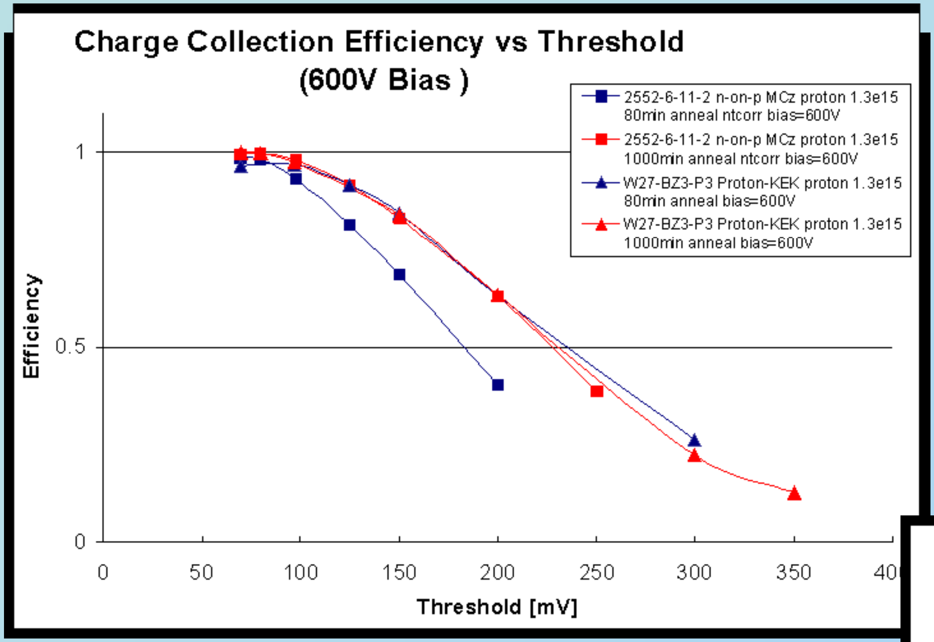




Binary readout
with 100 ns shaping time
Positive and negative
charge readout

**Accelerated Annealing at elevated temperature (60$^{o}$C):**
**about 440 times faster than at RT: 1000 min @ 60$^{o}$C = 305 days at RT**
**Activation energy E = 1.28 eV (Ziock et al. 1994)**
**Annealing important for thermal management.**

# Collected Charge: CCE



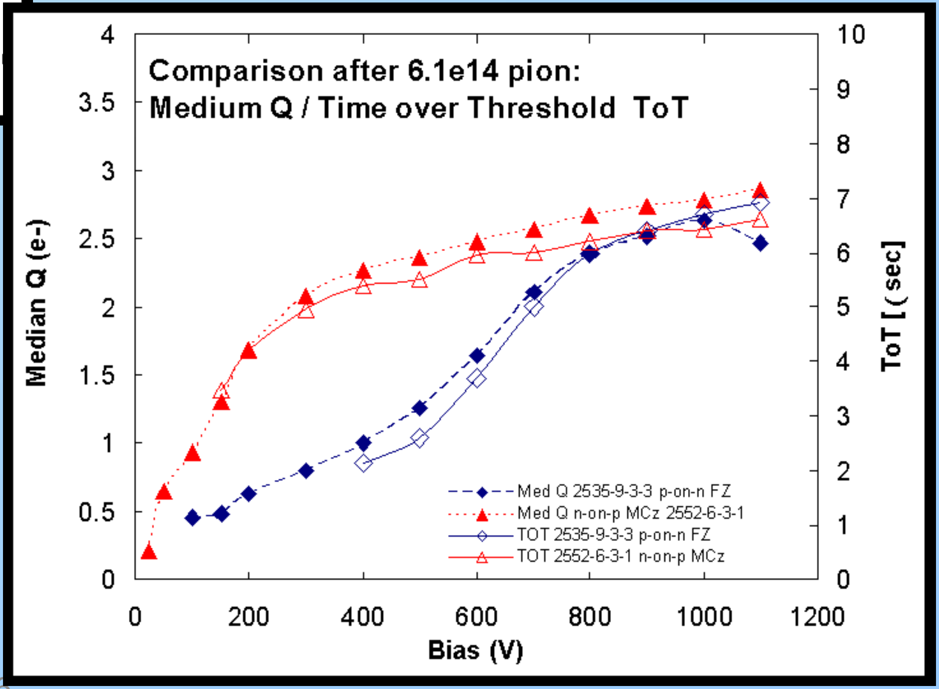
**Determination of collected charge**

**1. statistical: binary**
Threshold curves -> Efficiency
-> **Median Q** (50% efficiency point)

**2. event-by-event: analog**
Time-over-Threshold ToT
-> peak of distribution -> **ToT Q**

**Good agreement between MedQ and ToT**
**Accuracy: ~10% sample-to-sample**
**few % within one sample during anneal.**

**N.B. Complicated bias dependence!!**

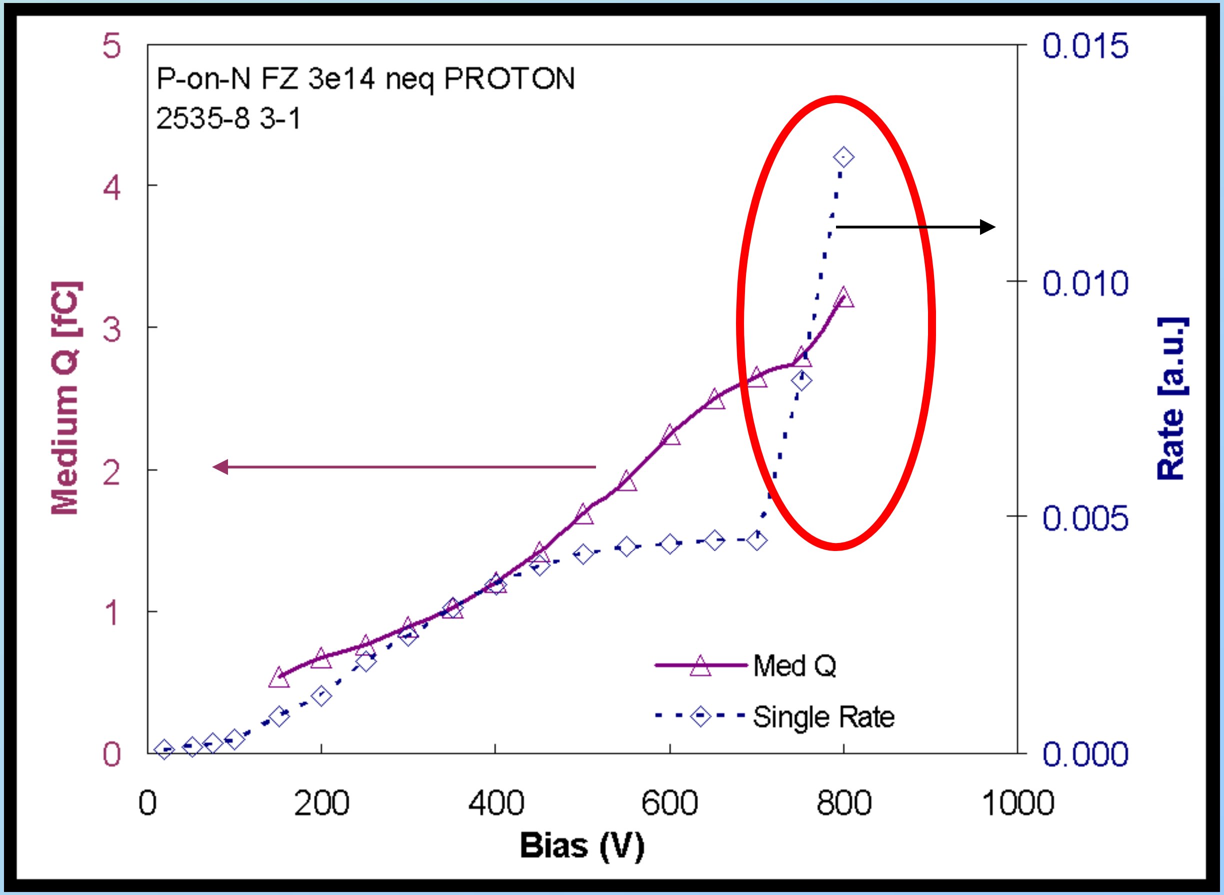


# Collected Charge and Single Rate

**Sensor single rate** is crucial for health of apparatus.

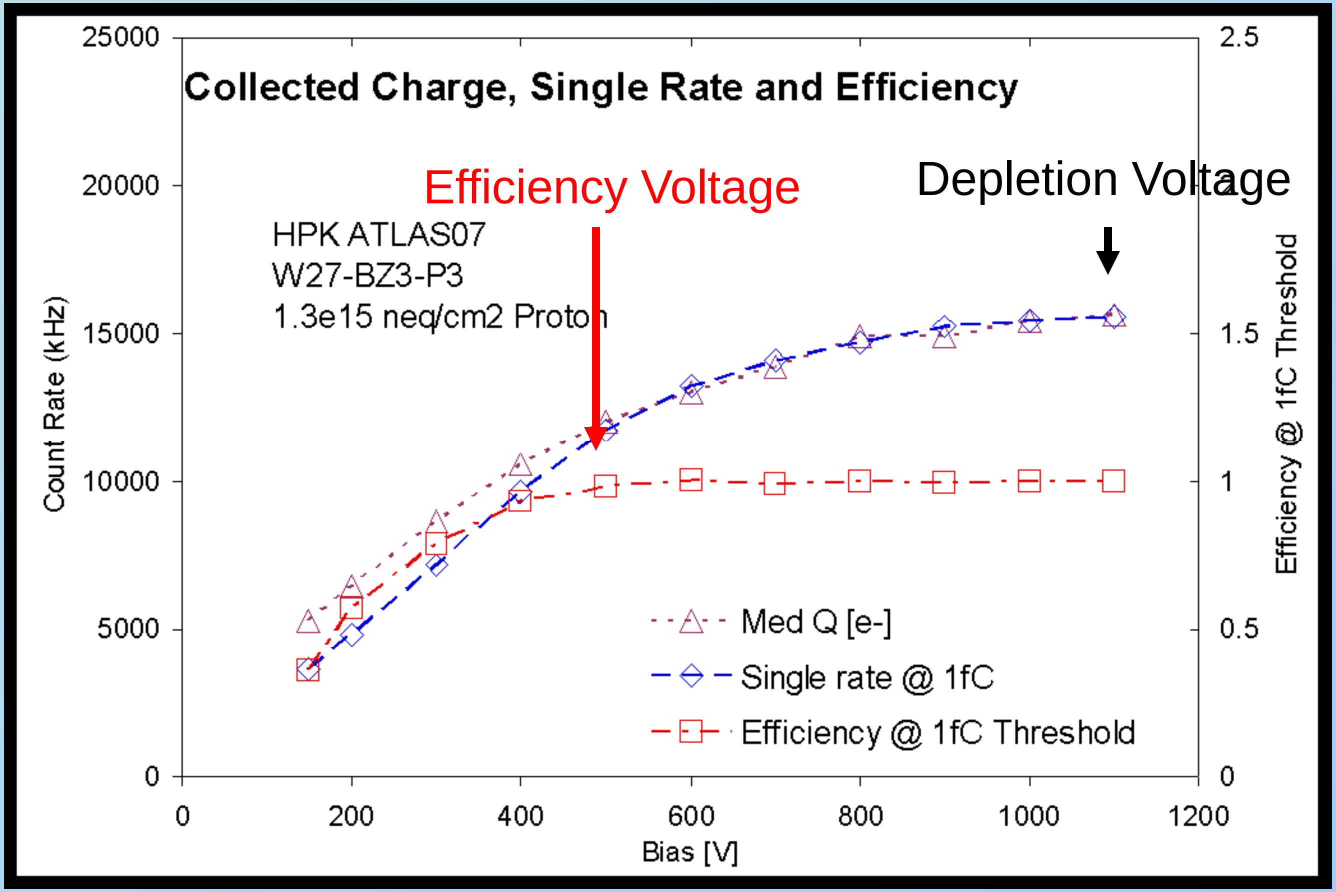
Single rate can foretell problems in charge collection measurement, which can't be detected

efficiency or
collected charge or
leakage current



# Collected Charge, Single Rates and Efficiency

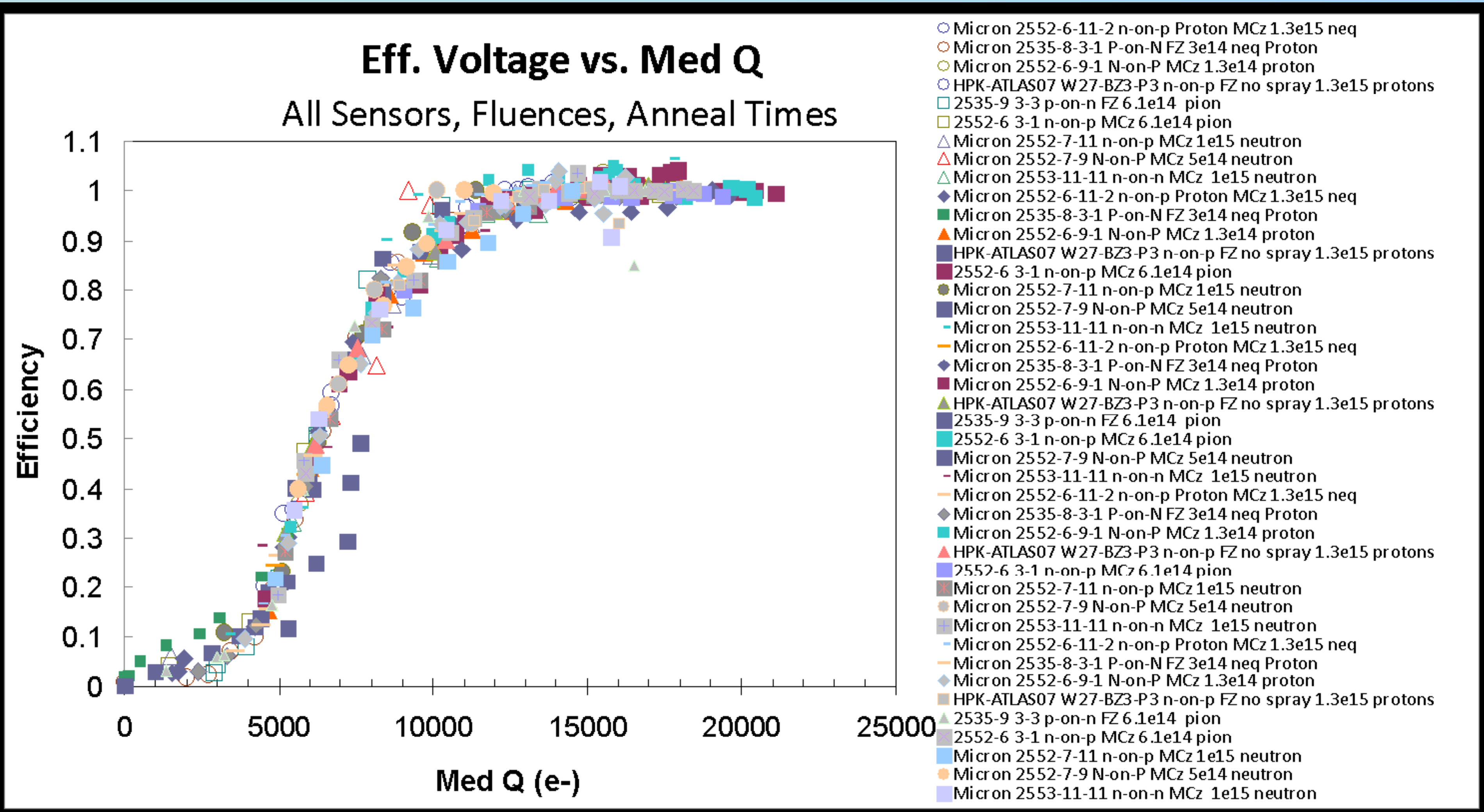
**Sensor single rate** at 1 fC threshold is tracking the **median collected charge** well.
**Efficiency** at 1fC threshold saturates at much lower voltage and reaches 100% if
signal/threshold S / T > 2,2
Signal/Noise > 9 in the experiment



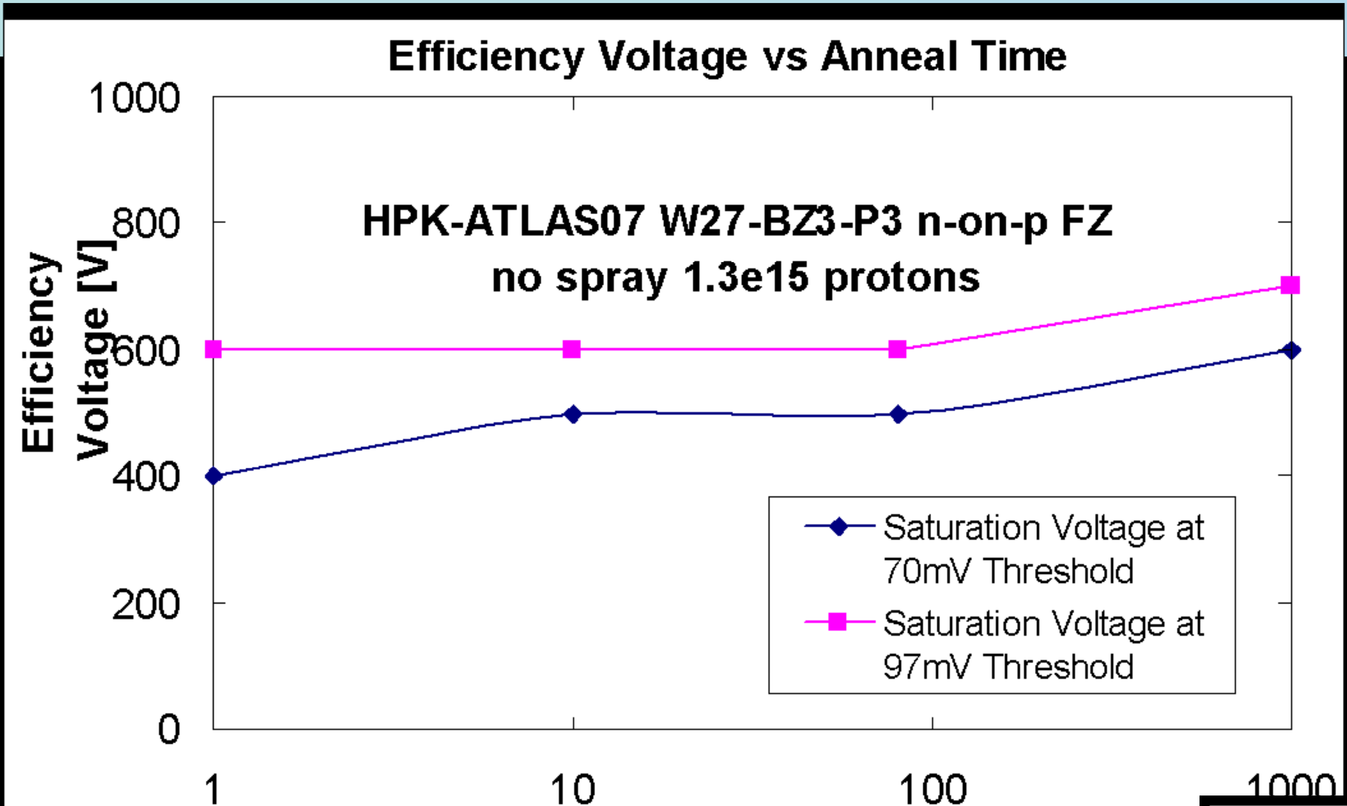
Determine the required voltage for 98.5% efficiency: “Efficiency Voltage” (e.g. 1 fC threshold)

# Collected Charge and Efficiency

**Complete universal correlation between collected charge and efficiency**



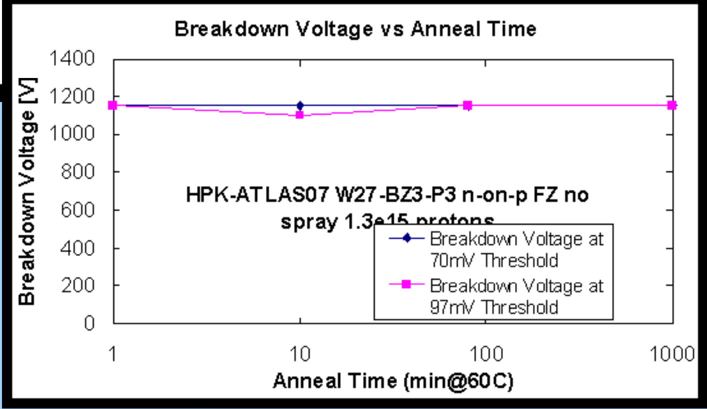
# Efficiency Voltage (Threshold Dependence)



**Efficiency Voltage is threshold dependent.**

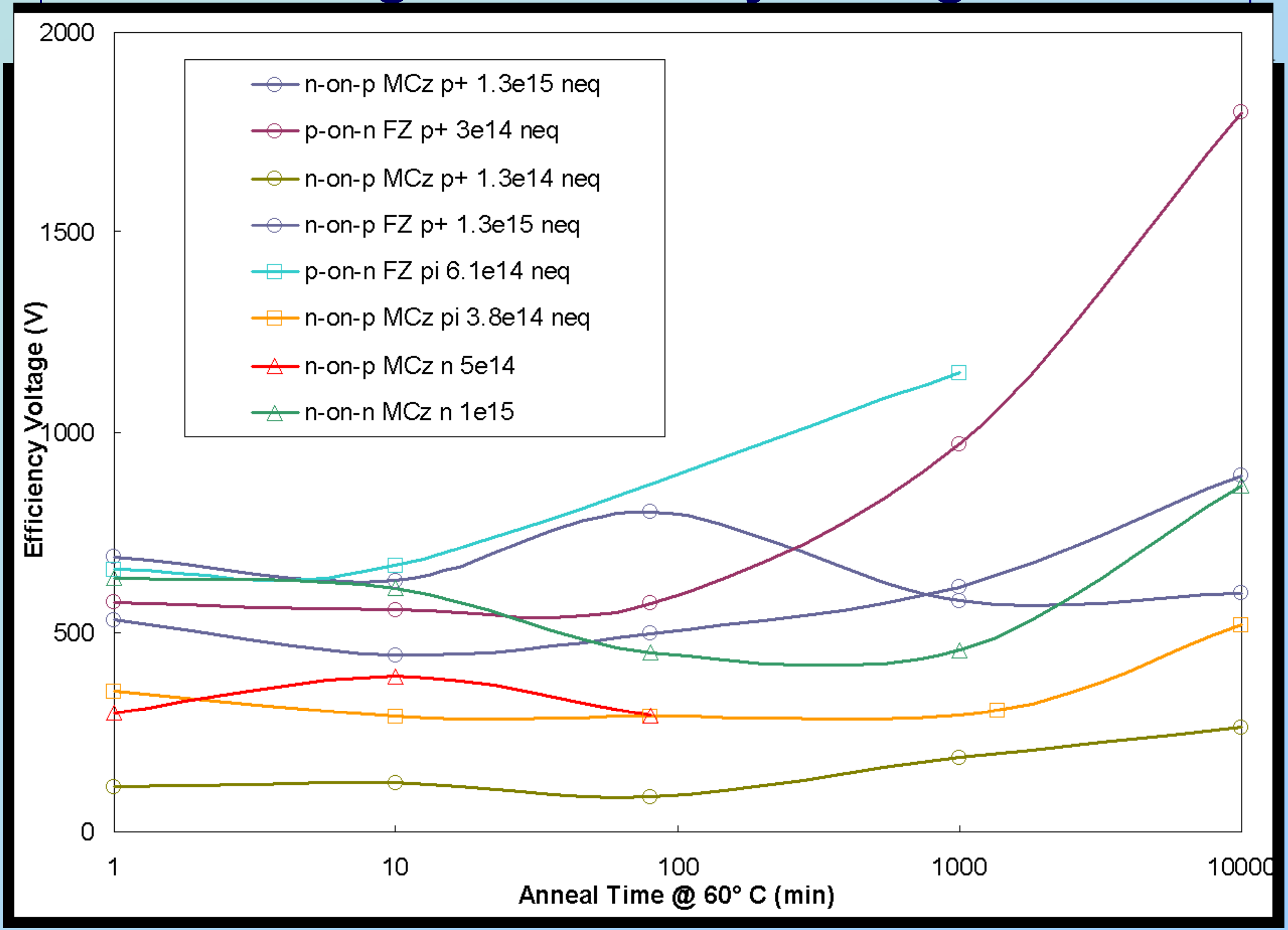
**Threshold**
**1 fC -> 0.7 fC:**

**gives reduction of Efficiency Voltage of 100-200 V.**



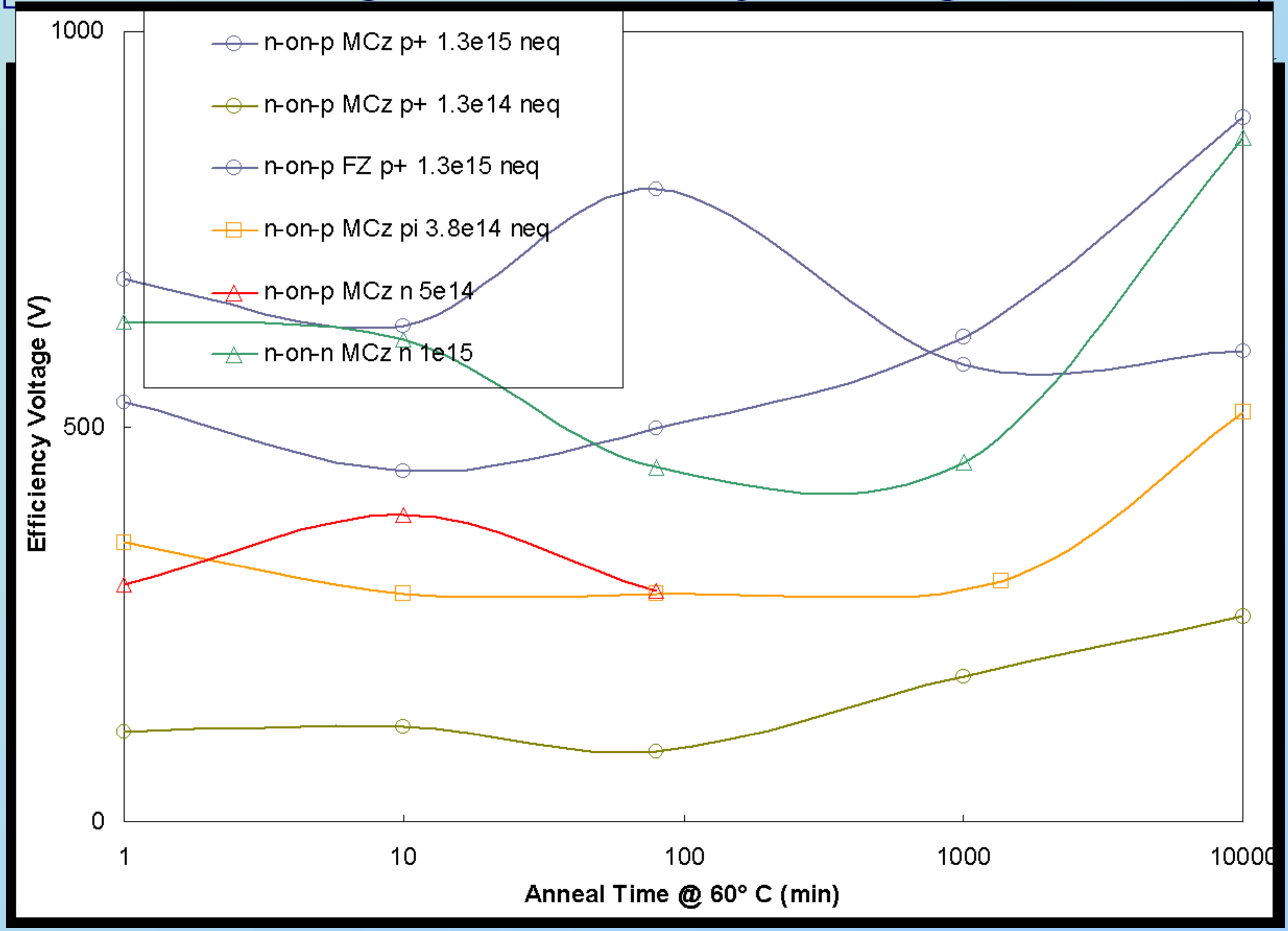
For stable operation:
Breakdown Voltage >> Efficiency Voltage

# Annealing of Efficiency Voltage (@ 1fC)



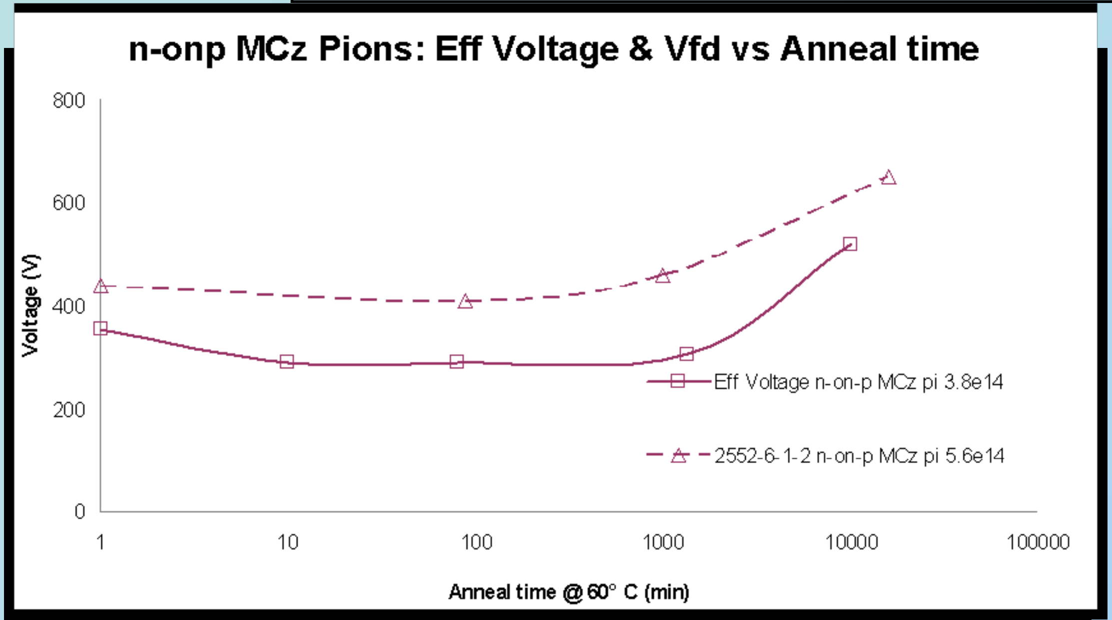
**Annealing benign** for all but p-on-n FZ

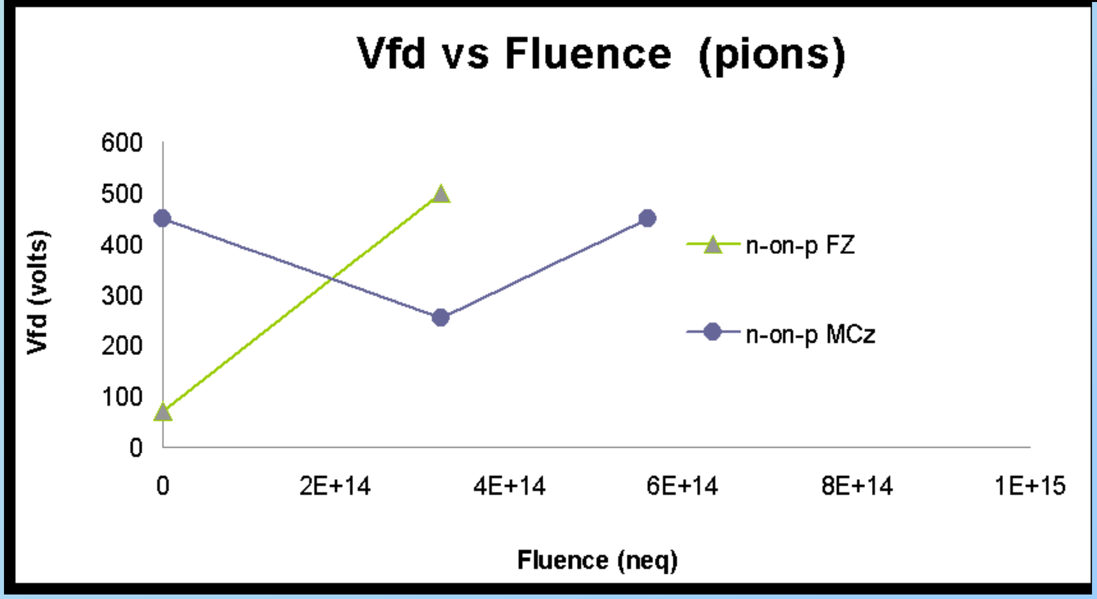
# Annealing of Efficiency Voltage (@ 1fC)



**No big difference between proton/pion and neutron irradiation**
**N-on-n MCz shows "typical n-type" annealing, but on a small scale.**

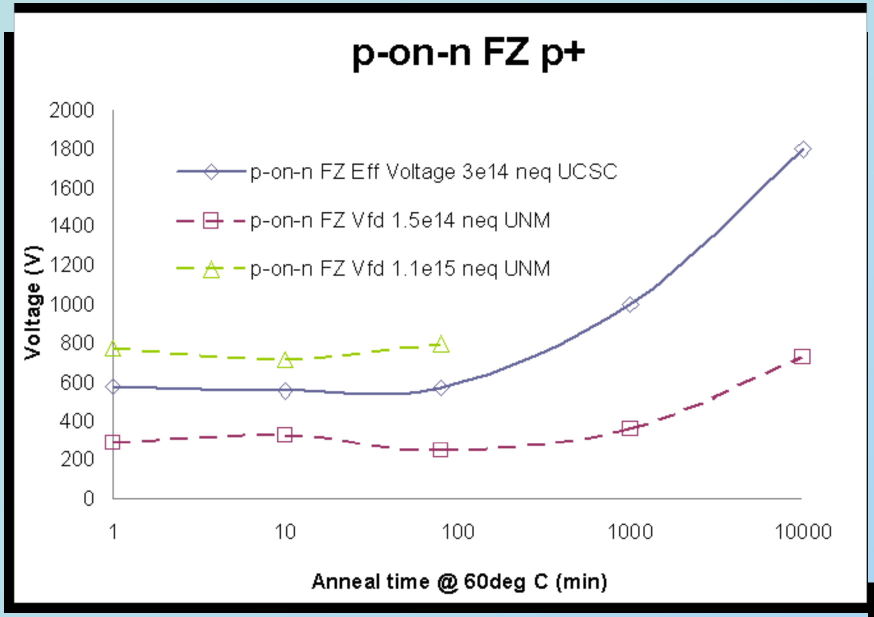
# Comparison Efficiency Voltage - Vfd


n-onp MCz Pions: Eff Voltage & Vfd vs Anneal time


Vfd vs Fluence (pions)

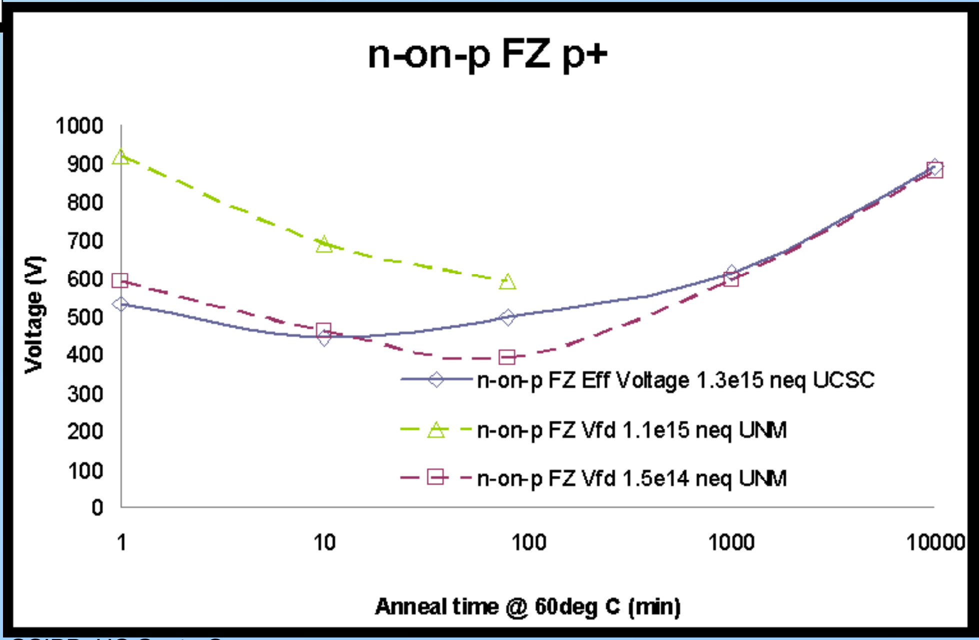
If one adjust the Efficiency voltage with difference in fluence, the Eff Voltage vs. Anneal curve will be above the Vfd curve, indicating that n-on-p MCz inverts with pion (also proton) irradiation. This is also seen in the Vfd as a function of fluence curve.

# Comparison Efficiency Voltage - Vfd



Once the Efficiency voltage is scaled with the fluence, it would clearly be much larger than the Vfd for either Vfd fluence, indicating strong inversion of p-on-n FZ after proton irradiation

For n-on-p FZ, it can be seen that at a given fluence, the efficiency voltage will be lower than Vfd, indicating no inversion after prtoton irradiation. This is consistent with the p-on-n FZ being inverted (bulk becomes more p-type)



# What to do with C-V Measurements?

**“C-V”**

**means here “ learn something about the depletion of the sensor, to be used to predict CCE or learn something about the state of the sensor when compared to CCE”**

**At least 4 diferent approaches:**

1. Measure C-V at 10 kHz and low temperature: **wrong**
2. Measure C-V at R.T and 10 kHzless **less wrong**, **good convention**
   (Gregor showed is ~ ok for diodes: Vdep(CEE) =Vdep(CV) within 200V)
3. Measure C-V at lower temperature, adjust frequency C-V(f,T) **better**
4. Measure Admittance, extract the width of the space charge region **best ?**

# C-V(f,T)

## 3. Measure C-V at lower temperature, adjust frequency

**Measure C-V at lower temperature,**
**adjust frequency**
**to match according**
**to the emission coefficicnt C-V(f,T).**
**(usual current temperature**
**dependence)**

M.K. Petterson, et al., RRESMDD06,
Nucl. Inst. Meth. A 583, 189(2007)

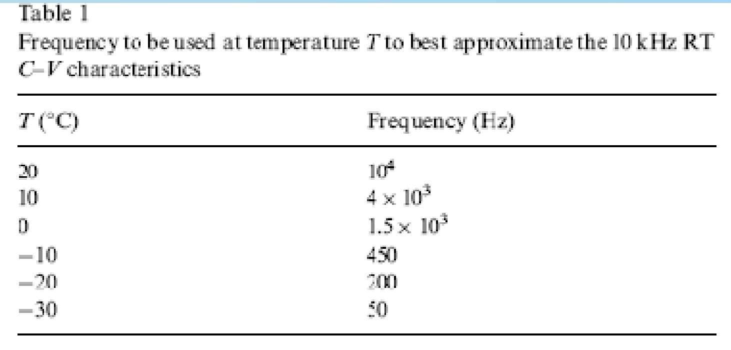


Table 1
Frequency to be used at temperature *T* to best approximate the 10 kHz RT *C–V* characteristics

| *T* (°C) | Frequency (Hz) |
|---|---|
| 20 | $10^4$ |
| 10 | $4 \times 10^3$ |
| 0 | $1.5 \times 10^3$ |
| −10 | 450 |
| −20 | 200 |
| −30 | 50 |

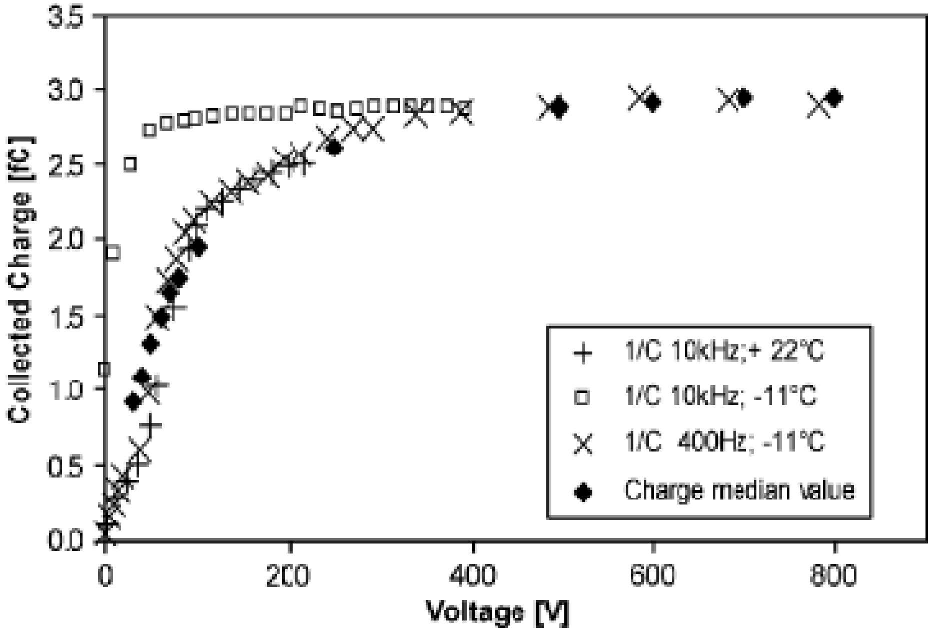


Fig. 4. Median value of the collected charge in an irradiated n-type MCz Si microstrip detector W187-S2 (Fluence of irradiation $1.7 \times 10^{14}\,\mathrm{cm}^{-2}$ 1 MeV $n_{eq}$), after 5 min annealing at 60 °C, compared to the reciprocal capacitance normalised on the collected charge measured at different temperatures with test signal of different frequencies.

# Admittance

4. **Measure Admittance, extract the width of the space charge region**

$$Y = Z^{-1} = G_p + j\omega C_p$$

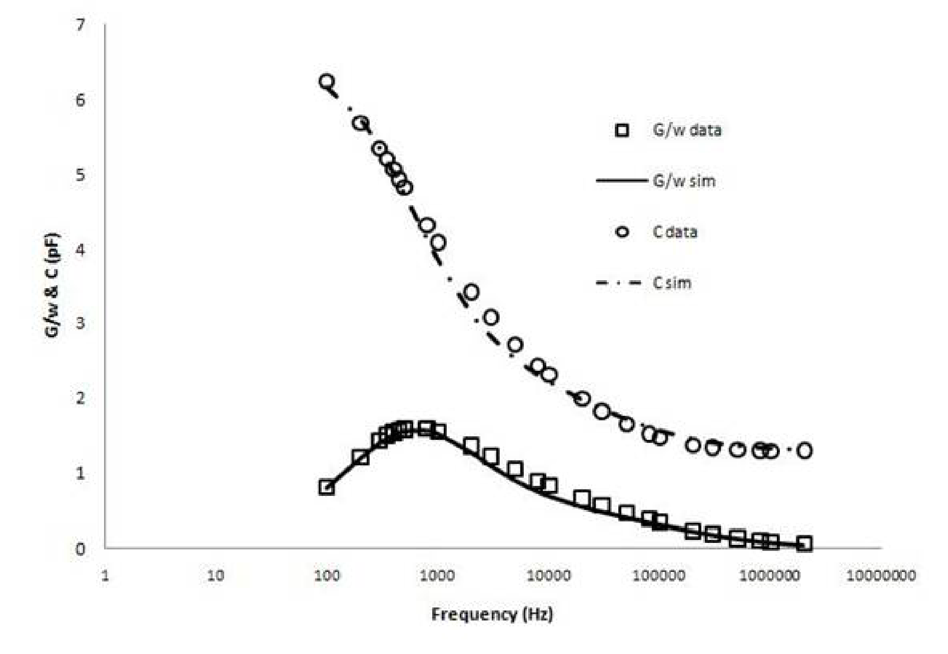
**Introduce Debye length to characterize non-abrupt junction(s)**
**Since trapping and de-trapping is important, measure both Capacitance C and Conductance G as a function of temperature T and frequency ω**

$$C_d(V_{dep}) = \varepsilon A / (W - L_D)$$

**Frequency dependence of conductance reveals dynamics of trapping**

C, Betancourt , et al.,
RRESMDD08,
IEEE 2009,
Senior Thesis

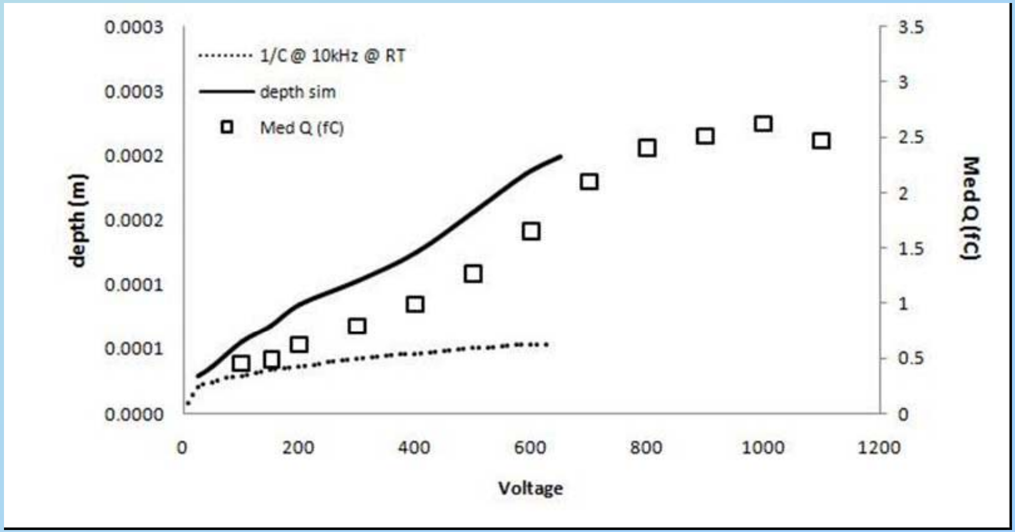
**Measured and simulated C and G/ω as a function of frequency for a pion irradiated n-type FZ detector taken at 100V and 22 degrees C**



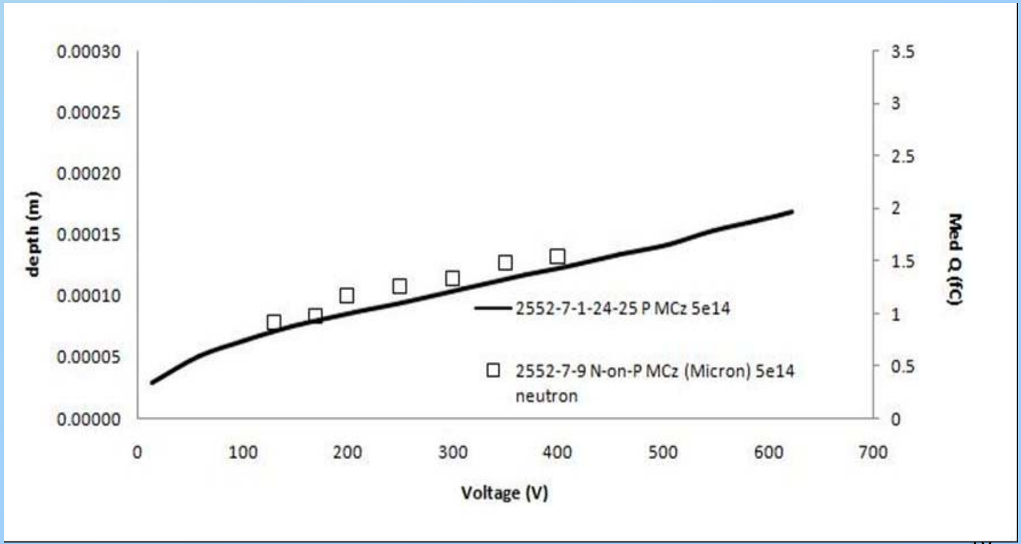
# Results of Admittance Measurement

## Extracted depth of the space charge region from CCE andAdmittance

**p-on-n FZ pion irradiated sensor and diode**

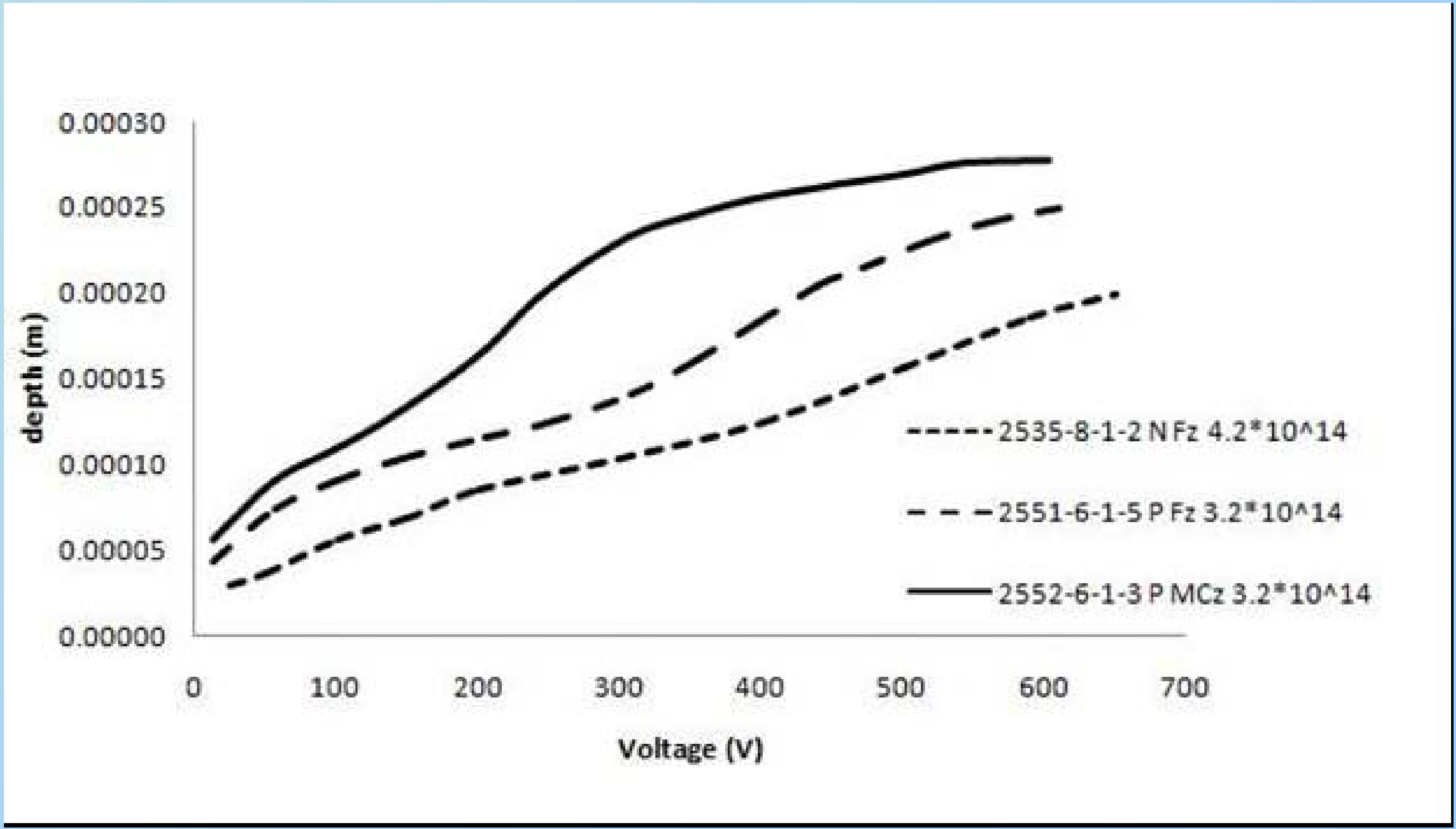


**n-on-p MCz neutron irradiated Sensor and diode**



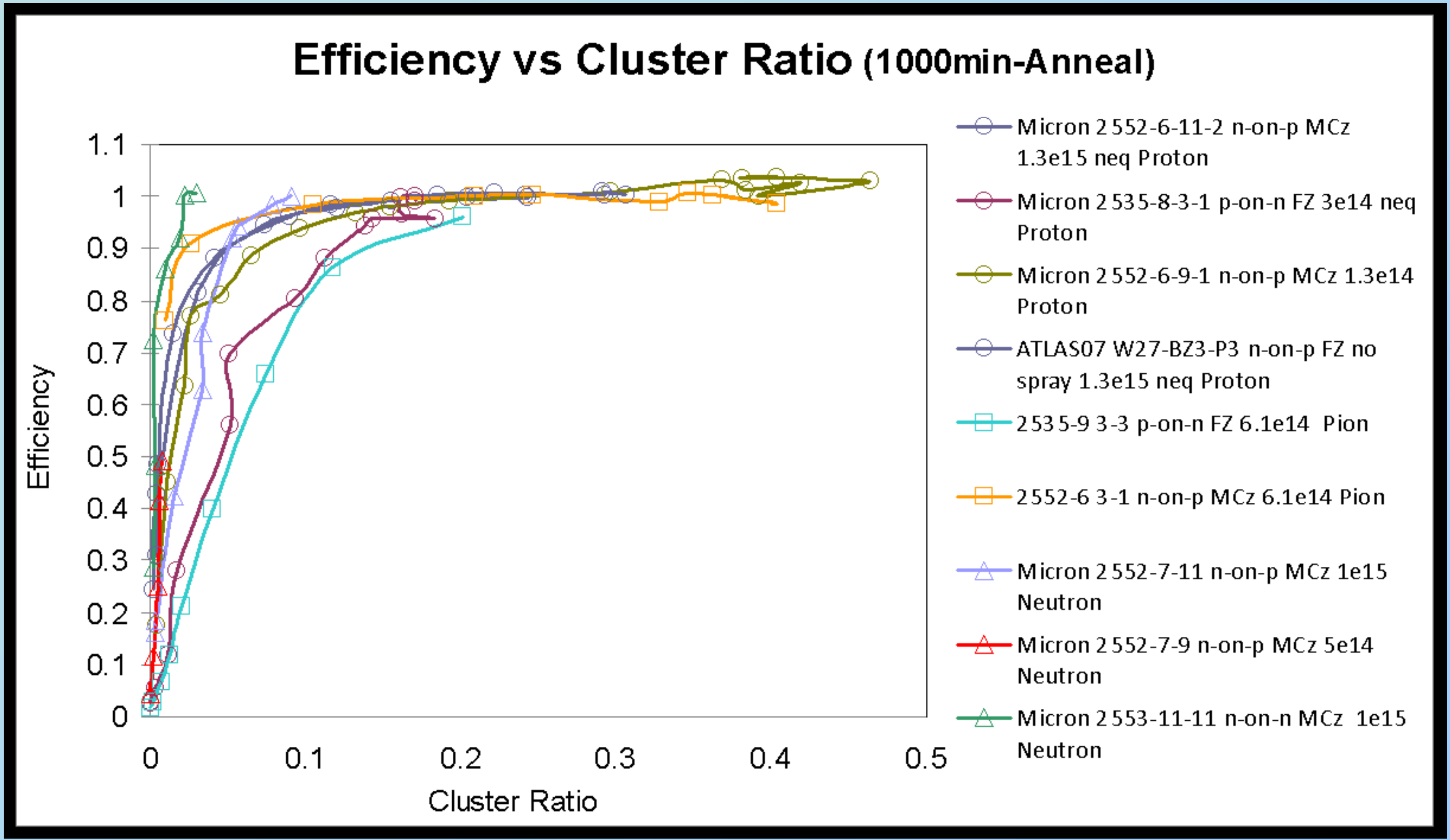
# Results of Admittance Measurement

**Depleted depth of the space chare region for various pion detectors Extracted from Admittance measurements**



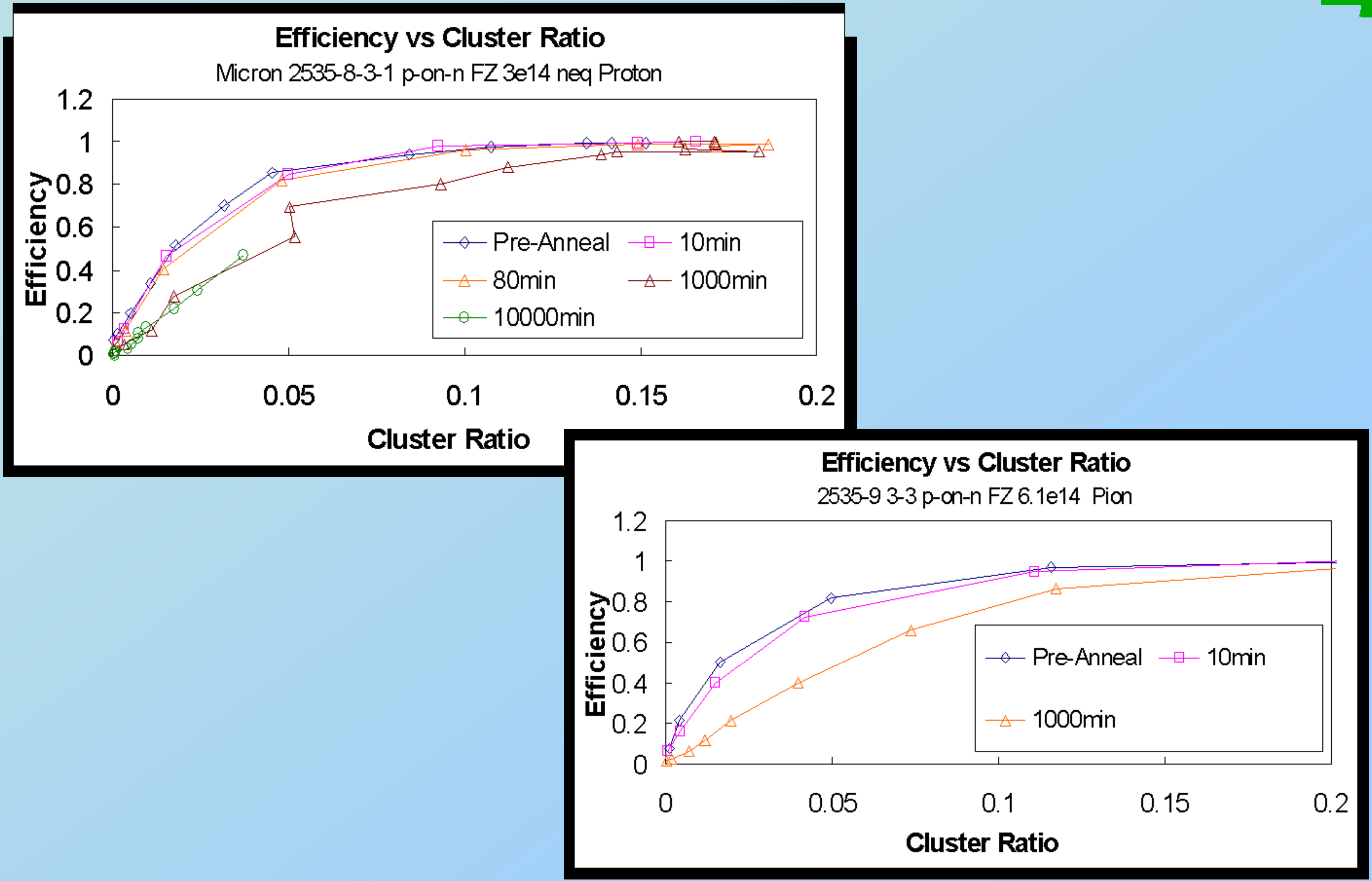
# Clustersize and Efficiency

**Cluster size is given by the “Cluster Ratio”**
**= # of clusters with multiple strips / # of clusters with one strips**



**Good Correlation, p-on-n FZ inverted.**

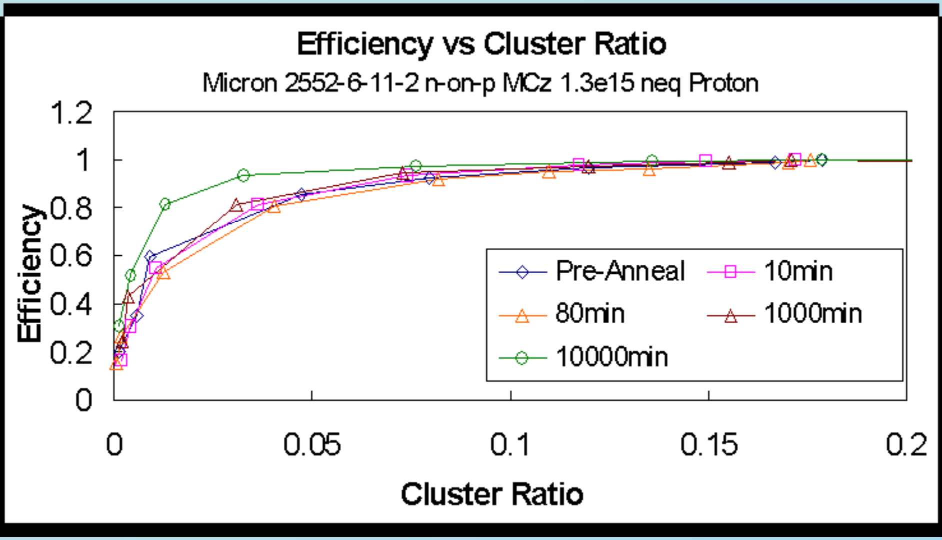
# Clustersize and Efficiency

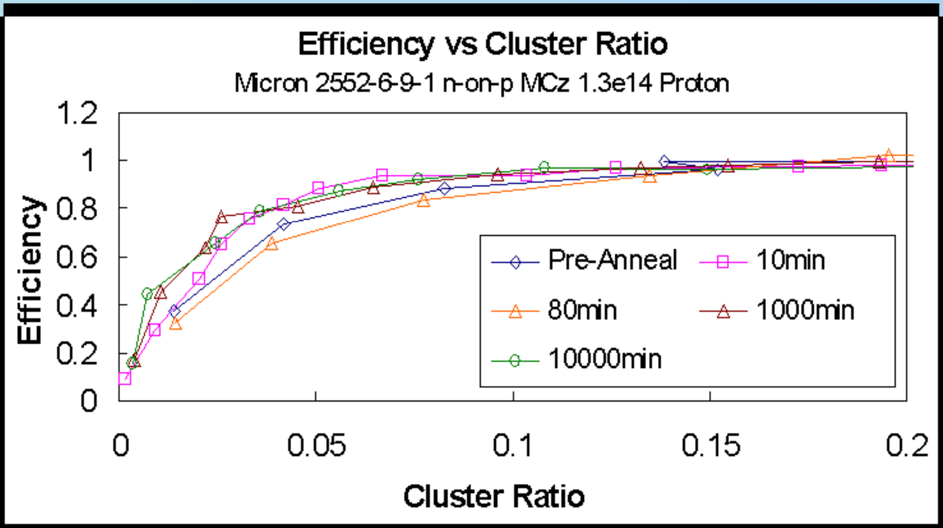


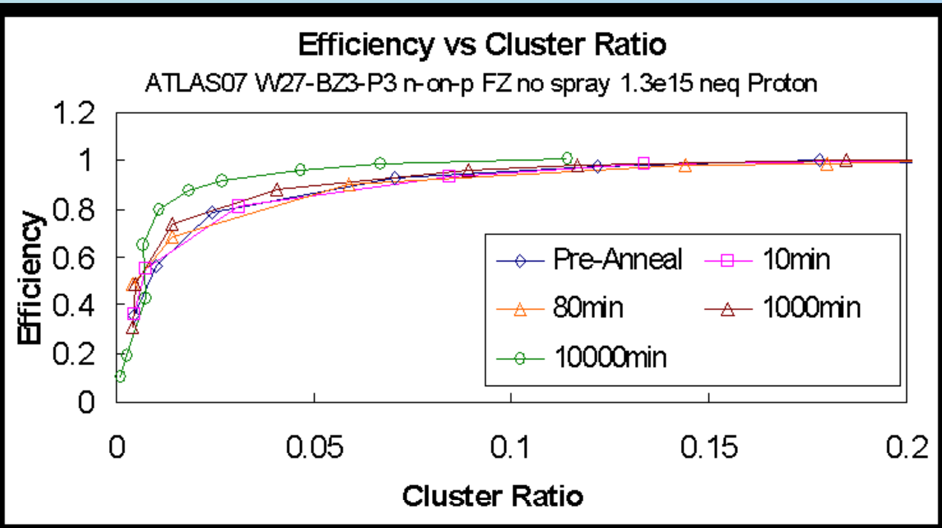
**Cluster size changes during annealing for n-type FZ**

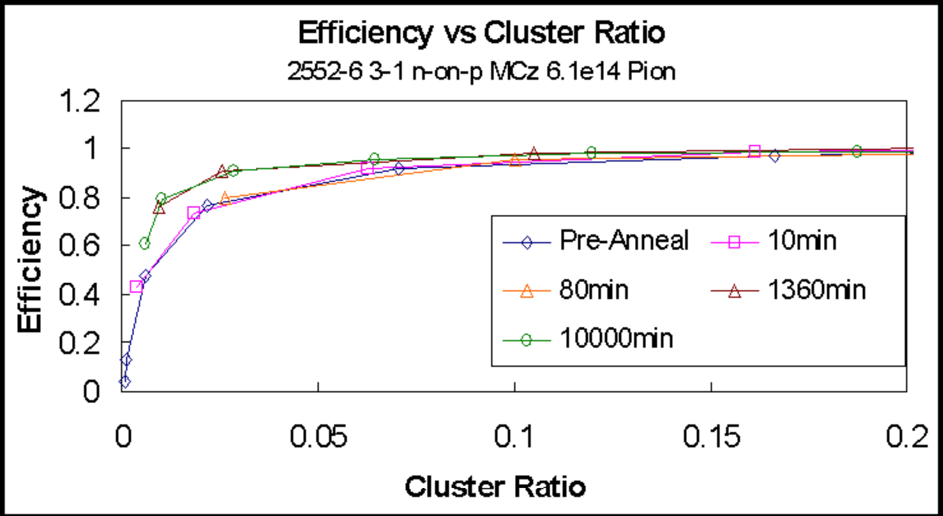
# Clustersize and Efficiency

**All p-type ~ same ?**









# Conclusions

For charge collection studies, the health of the system can be determined by monitoring the singles rate. It signals breakdown and thus unphysical behavior even before the leakage current or the collected charge do it.

In order to quantify the performance, we introduce the “efficiency voltage” as the bias voltage at which the efficiency reaches 100%. Very little annealing is observed, with the exception in p-on-n FZ.

The efficiency voltage for p-type material is about the same for FZ and MCz in this fluence range.

Comparison between efficiency voltage for SSD and full depletion voltage Vfd of diodes permits insight into the fact of “inversion”.

The correlation of the efficiency with the clustersize is uniform across many different sensor types, particle species during irradiation, and anneal steps (with the exception of the p-on-n FZ sensors,)

Admittance allows extraction the depth of the depleted region of irradiated sensors

# Acknowledgments

Thanks to

the foundries and institutes who supplied sensors in a collaborative manner

staff in Ljubljana, Louvain, CERN, Karlsruhe, PSI, BNL, LANL, UCSC for carrying out the irradiations.

RD50 and ATLAS07 collaborators and the many students who spend their evenings and nights taking and analyzing the data.