Modeling, simulation and data fitting of the new charge-injected -diodes (CID) for SLHC tracking applications

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Outline

1. Effect of Trapping on CCE in SLHC
2. The CID Concept and Principle
3. The Model of CID Strip/Pixel Detectors
4. Simulation Results and Data Fitting
5. Summary

Trapping effect on CCE in S-LHC

$$Q = Q_0 \cdot CCE = Q_0 \cdot CCE_{GF} \cdot CCE_t = Q_0 \cdot \frac{w}{d} \cdot \frac{\tau_t}{t_{dr}} (1 - e^{-t_{dr}/\tau_t})$$

Trapping term

Depletion term

CCE_{GF} is a geometrical factor

CCE_t is related with trapping

For fluence less than 10^{15} n/cm², the trapping term CCE_t is insignificant

For fluence 10^{16} n/cm², the trapping term CCE_t is a limiting factor of detector operation !

$$Q \cong 80\ \text{e's}/\mu\text{m} \cdot v_{dr} \cdot \tau_t \equiv 80 \cdot d_t\ \text{(e's) (for SLHC fluences)}$$

$d_t = v_{dr} \cdot \tau_t$ is the trapping distance

Effect of Trapping on CCE in SLHC

TRAPPING

$$\tau_t = \frac{1}{\sigma v_{th} N_{t,empty}}$$

The thermal velocity $v_{th} \approx 10^7$cm/s

10^{16}cm^{-2} irradiation produces $N_{t,empty} \approx 3\text{-}5 \times 10^{16}$ cm^{-3} with $\sigma \approx 10^{-14}$cm^2

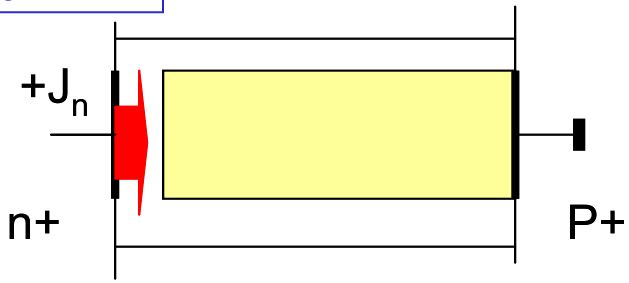
On average (e and h) it gives a $\tau_t \approx 0.2$ ns!

Even in highest E-field (Saturation velocity, 10^7 cm/s), carrier drifts only 20-30 μm before it gets trapped regardless whether the detector is fully depleted or not !

In S-LHC conditions, about 90% of the volume of d=300μm detector is dead space if $N_{t,empty}$ is not reduced!

The CID Concept and Principle (CERN RD 39 Collaboration)

Carrier injection

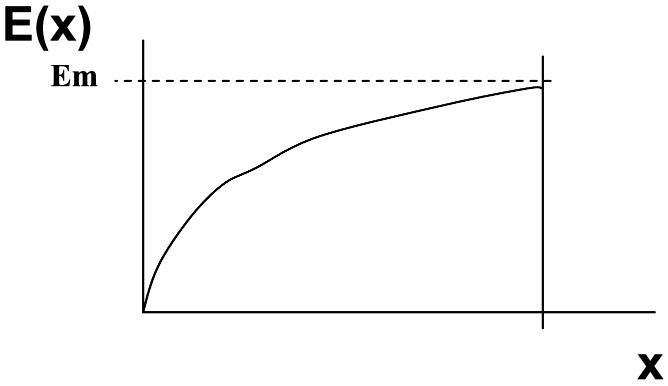


$J_n = en\mu E$

divJ=0

divE=n_{tr}

E(x=0) = 0 (SCLC: Space Charge Limited Current mode)



$$E(x) = \frac{3}{2}\frac{V}{d}\cdot\sqrt{\frac{x}{d}} \qquad E_m = \frac{3}{2}\cdot\frac{V}{d}$$

The key advantage:

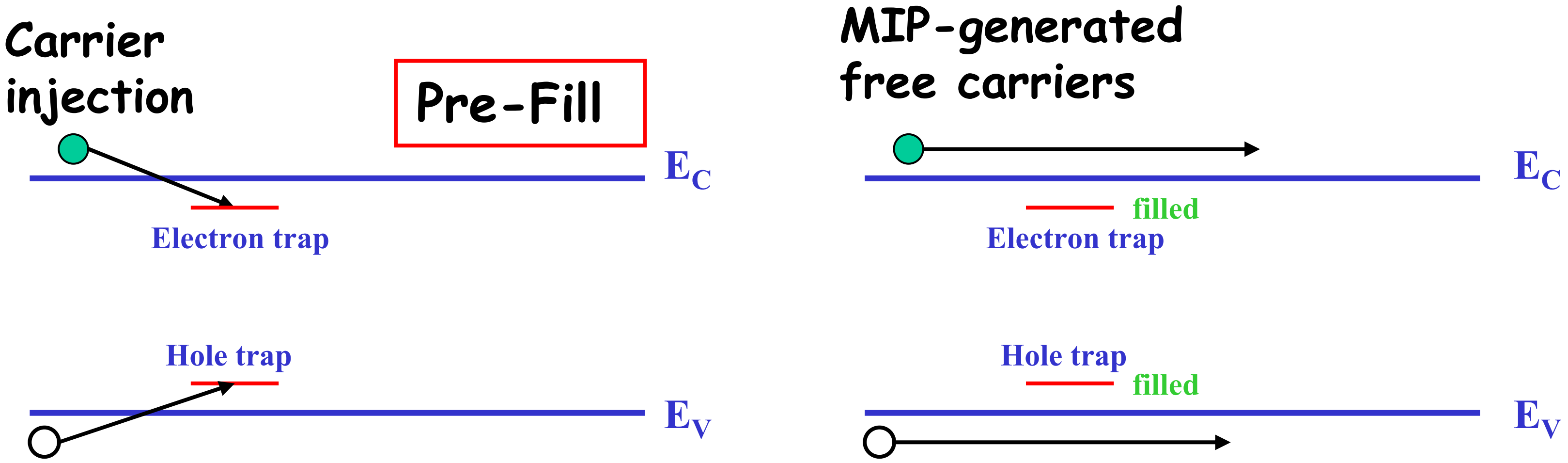
The shape of E(x) is ***not affected*** by fluence, **and virtual full depletion**

V. Eremin, RD39, CERN, November 11, 2005

The CID Concept and Principle

Pre-filling of traps by carrier injection

Carrier injection can also pre-fill the traps to make them inactive



Carrier injection

Pre-Fill

E_C

Electron trap

Hole trap

E_V

MIP-generated free carriers

E_C

filled

Electron trap

Hole trap

filled

E_V

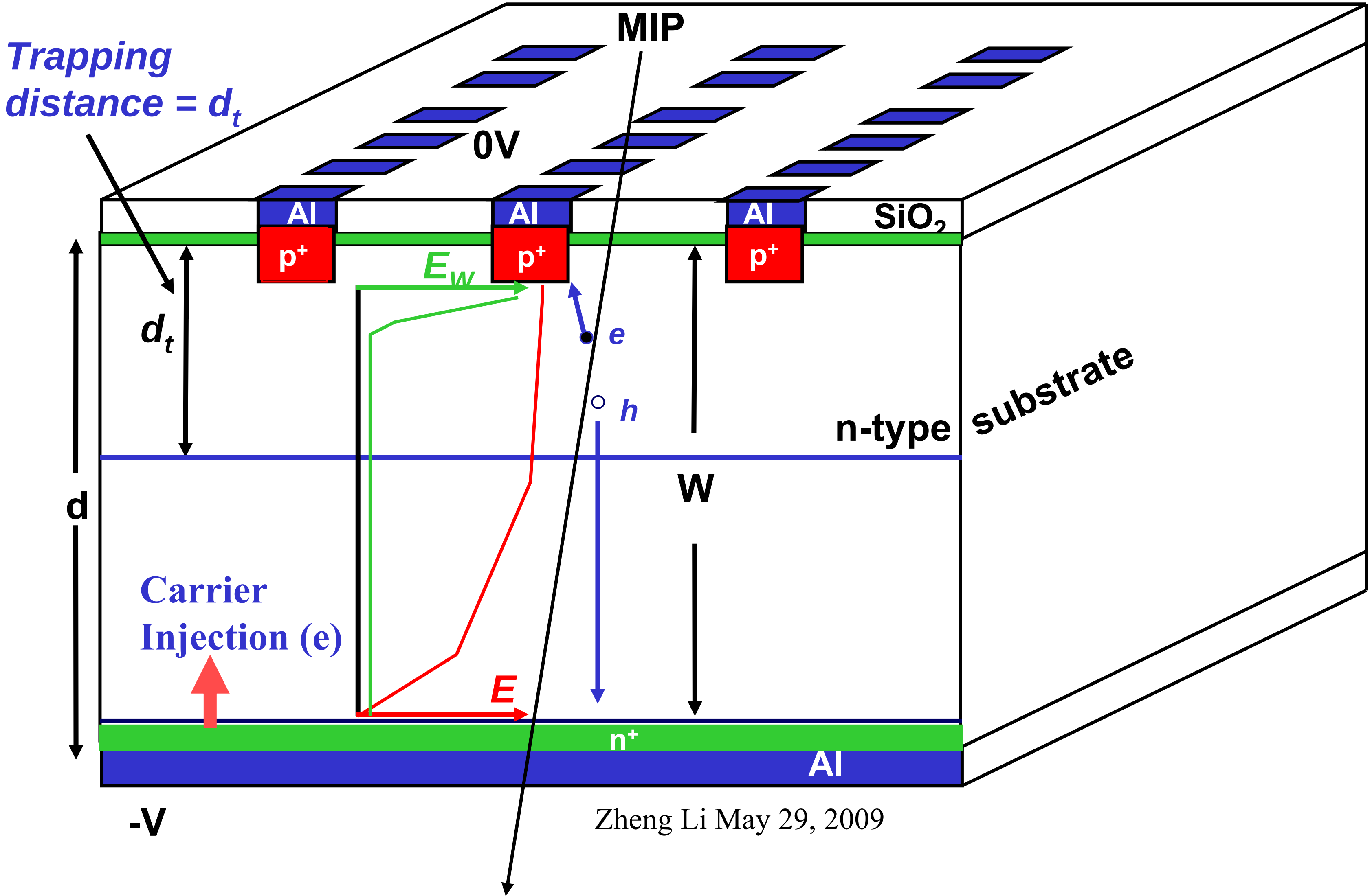
$$N_{t,empty} \searrow \longrightarrow \tau_t \nearrow \longrightarrow Q \nearrow$$

The Model of CID Strip/Pixel Detectors

d : thickness (200- 300 μm)

w: depletion depth (≤ d)

d_t: trapping distance

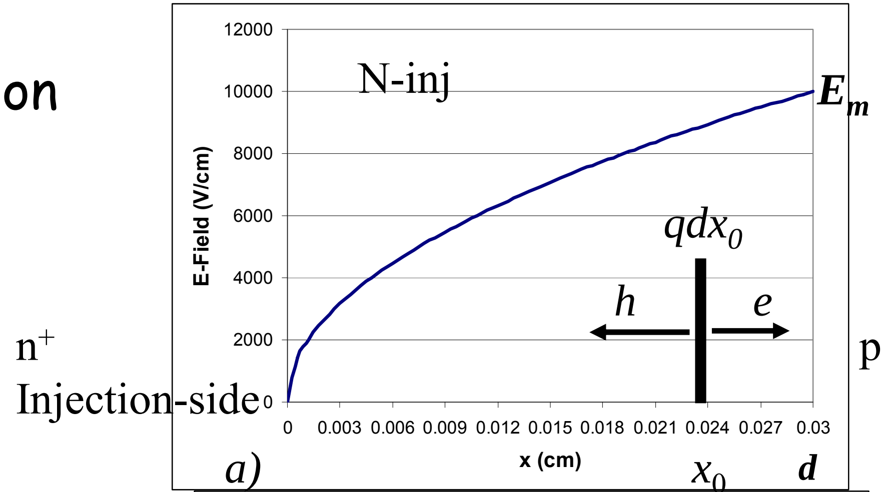


The Model of CID Strip/Pixel Detectors

Ninj-Pstrip

Electric field in a CID for N-injection

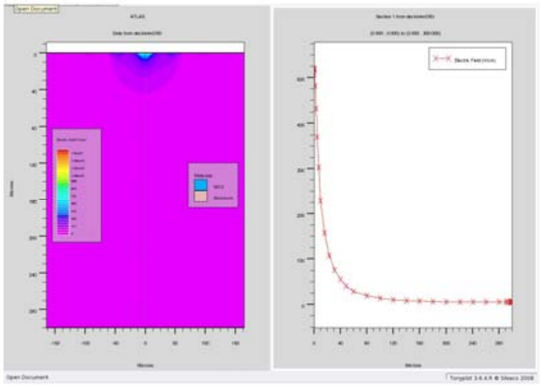
$$E(x) = E_m \cdot \sqrt{\frac{x}{d}} \quad ; \quad E_m = \frac{3}{2} \cdot \frac{V}{d}$$



Weighting field in a CID for P-strips

2D simulated weighting field

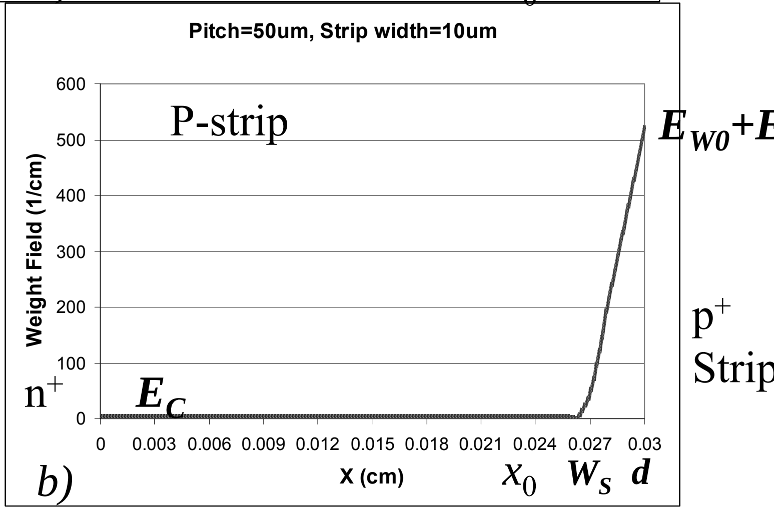
Weighting field (50 um pitch, 10 um strip, 300 um thick



1D approximation

$$E_W(x) = \begin{cases} E_C & x \le d - W_S \\ E_C + E_{W0}\left(1 - \dfrac{d-x}{W_S}\right) & x \ge d - W_S \end{cases}$$

$$W_S = \frac{2(1 - d \cdot E_C)}{E_{W0}}$$



The Model of CID Strip/Pixel Detectors

Carrier drift velocity

$$v_{dr}(x(t)) = \frac{dx(t)}{dt} = \frac{\mu E(x(t)}{1+\mu E(x(t)/v_s}$$

Carrier mobility temperature dependence

$$\mu_e = \mu_{e0}\left(\frac{T}{300}\right)^{-2.26} \qquad \mu_{e0} = 1590 cm^2/s/V$$

,

$$\mu_h = \mu_{h0}\left(\frac{T}{300}\right)^{-2.21} \qquad \mu_{h0} = 507 cm^2/s/V$$

Trapping time constant

$$\frac{1}{\tau_t} = \eta \cdot \Phi_{n_{eq}} = 5\times 10^{-7} cm^2/s \cdot \Phi_{n_{eq}}$$

Total collected charge:

$$Q = Q_e + Q_h$$

$$= q_{MIP}\int_0^d \Delta x_0 \left[\int_0^{t_{edr}-t_{edr}(x_0)} v_{edr}(t)\cdot E_W(x(t))\cdot e^{-t/\tau_t}\,\Delta t + \int_0^{t_{hdr}(x_0)} v_{hdr}(t)\cdot E_W(x(t))\cdot e^{-t/\tau_t}\,\Delta t \right]$$

The Model of CID Strip/Pixel Detectors

For electrons:

$x_0 \longrightarrow d$

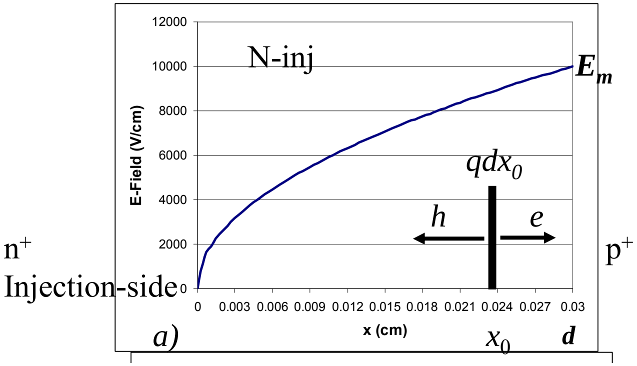
$$x(t) = d\left[\sqrt{\frac{v_{es}^{\;2}}{\mu_e^{\;2} E_m^{\;2}} + \frac{v_{es} t}{d}} - \frac{v_{es}}{\mu_e E_m}\right]^2$$

$$t_{edr}(x_0) = \frac{x_0}{v_{es}} + \frac{2d}{\mu_e E_m}\sqrt{\frac{x_0}{d}}$$

$$t_{edr} = \frac{d}{v_{es}} + \frac{2d}{\mu_e E_m}$$

,

$$v_{edr}(x(t)) = v_{es}\left[1 - \frac{v_{es}}{\mu_e E_m}\frac{1}{\sqrt{\frac{v_{es}^{\;2}}{\mu_e^{\;2} E_m^{\;2}} + \frac{v_{es} t}{d}}}\right]$$



For holes:

$x_0 \longrightarrow 0$

$$x(t) = d\left[\sqrt{\frac{v_{hs}^{\;2}}{\mu_h^{\;2} E_m^{\;2}} + \frac{v_{hs}(t_{hdr} - t)}{d}} - \frac{v_{hs}}{\mu_h E_m}\right]^2$$

$$t_{hdr} = \frac{d}{v_{hs}} + \frac{2d}{\mu_h E_m}$$

$$v_{hdr}(x(t)) = -v_{hs}\left[1 - \frac{v_{hs}}{\mu_h E_m}\frac{1}{\sqrt{\frac{v_{hs}^{\;2}}{\mu_h^{\;2} E_m^{\;2}} + \frac{v_{hs}(t_{hdr} - t)}{d}}}\right]$$

Simulation Results and Data Fitting

Simulation results

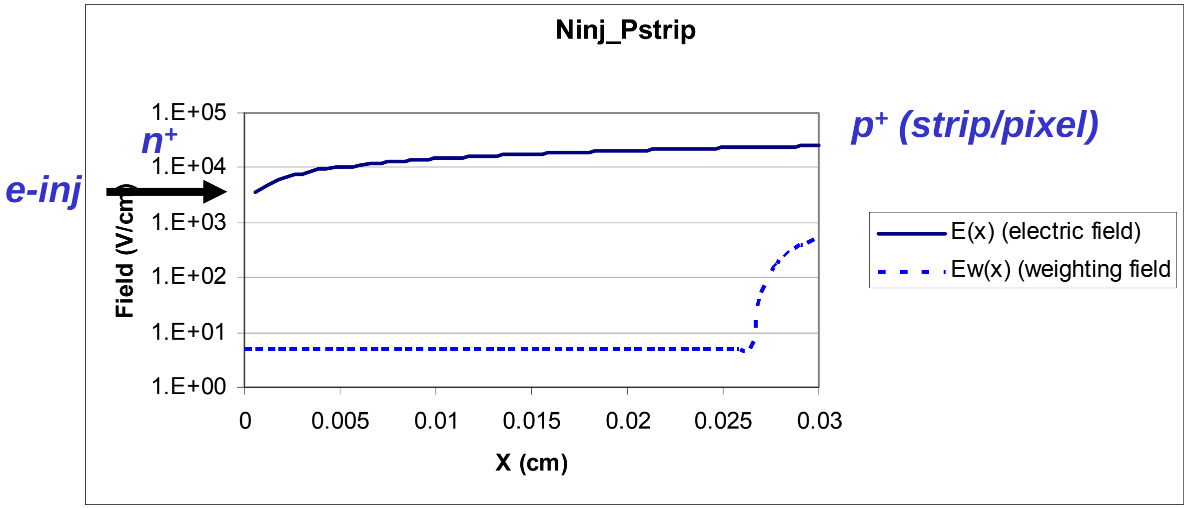
N-injection (e's), P-strip

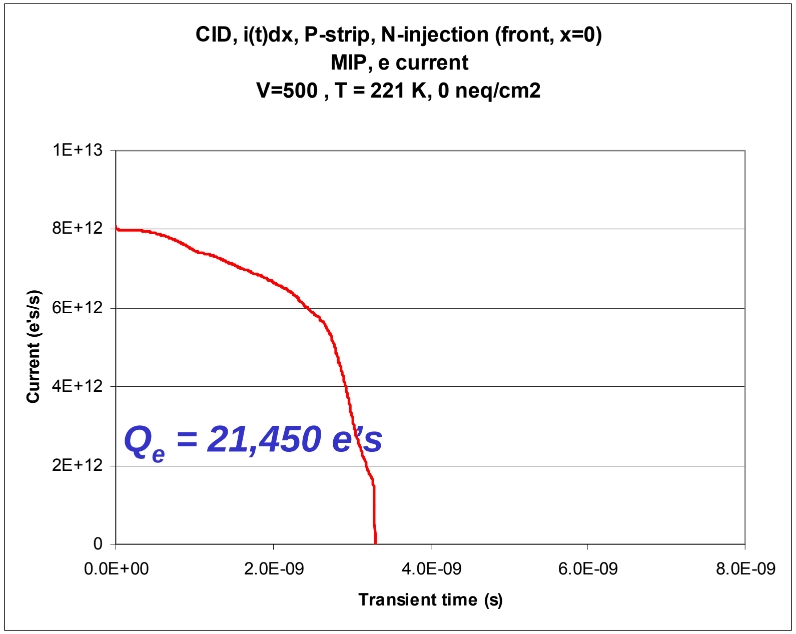
V = 500 V, T = 221 K

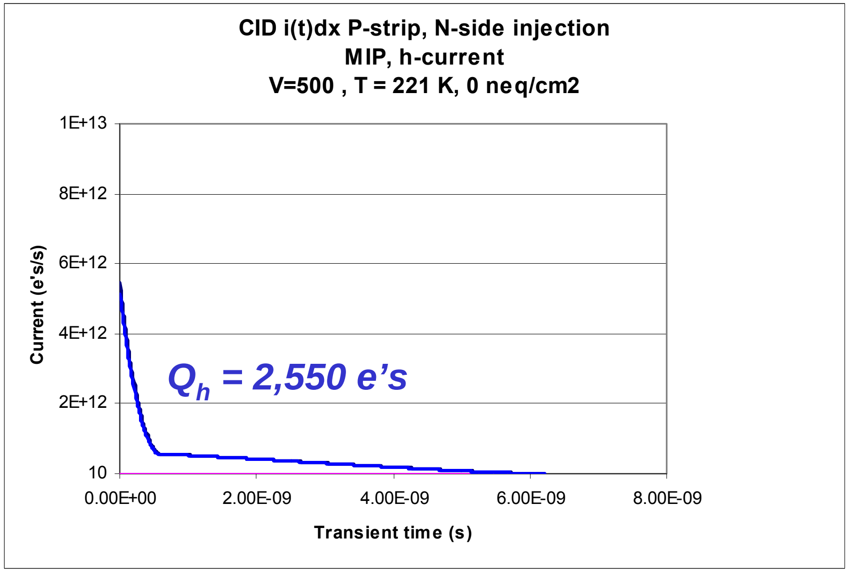
No radiation

Q = 24,000 e's

(89.4% by electrons)







Simulation Results and Data Fitting

Simulation results

N-injection (e's), P-strip

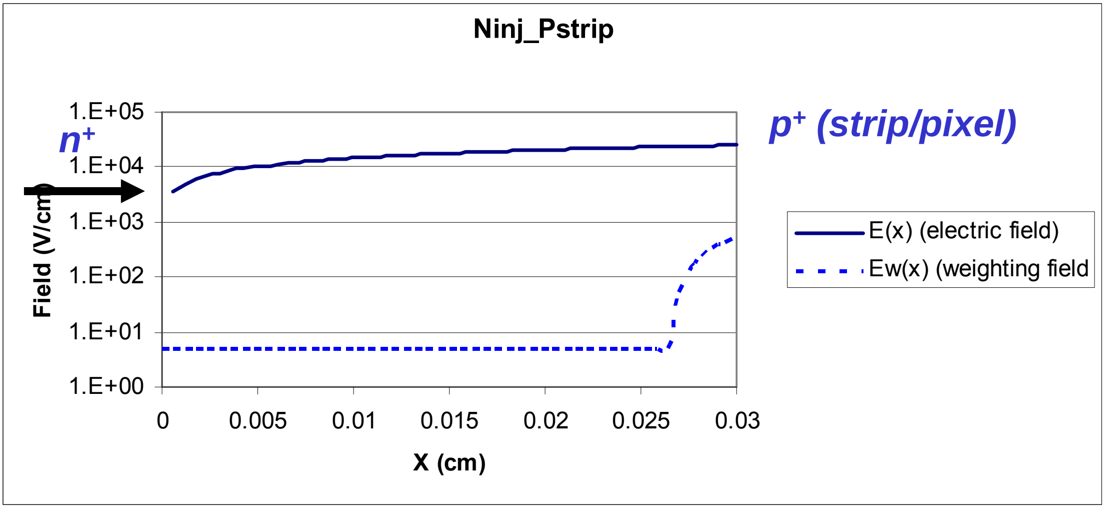
$V = 500$ V, $T = 221$ K

$3\times10^{15}\ n_{eq}/cm^2$

$Q = 6110$ e's (Pad: 6470e's)

(83% by electrons)

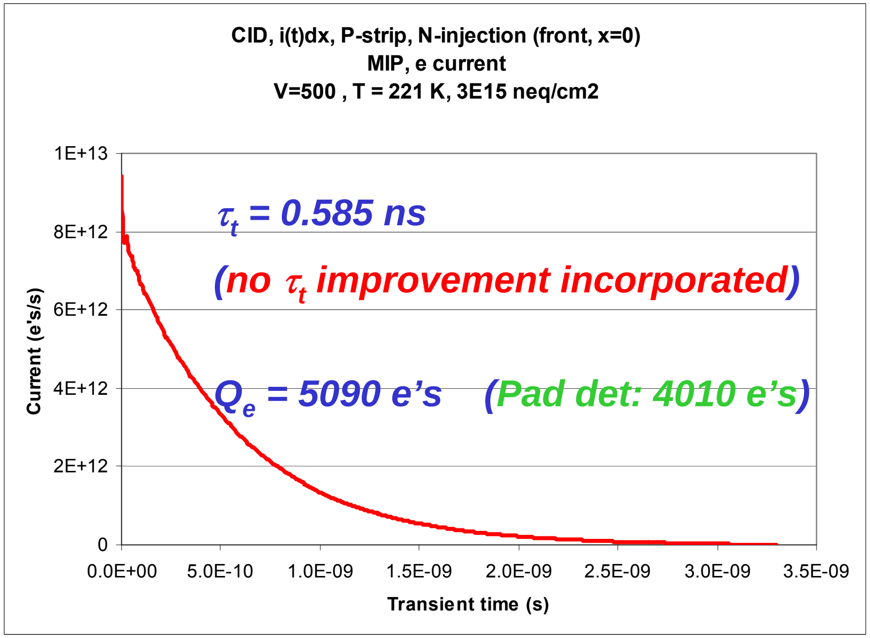
(62% for pad det.)



e-inj

n^+

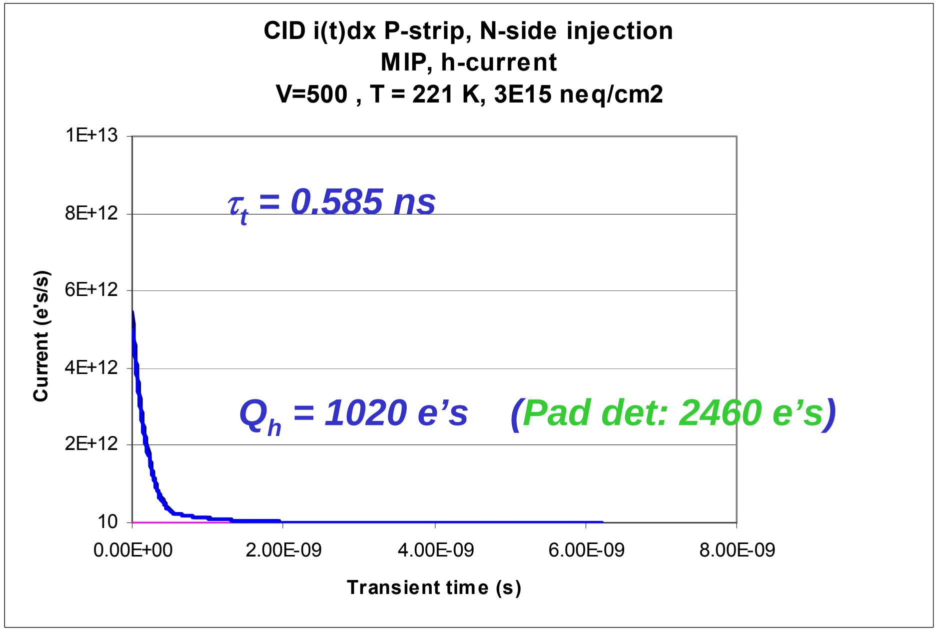
p^+ (strip/pixel)



$\tau_t = 0.585$ ns

(no τ_t improvement incorporated)

$Q_e = 5090$ e's (Pad det: 4010 e's)



$\tau_t = 0.585$ ns

$Q_h = 1020$ e's (Pad det: 2460 e's)

Simulation Results and Data Fitting

Simulation results

N-injection (e's), P-strip

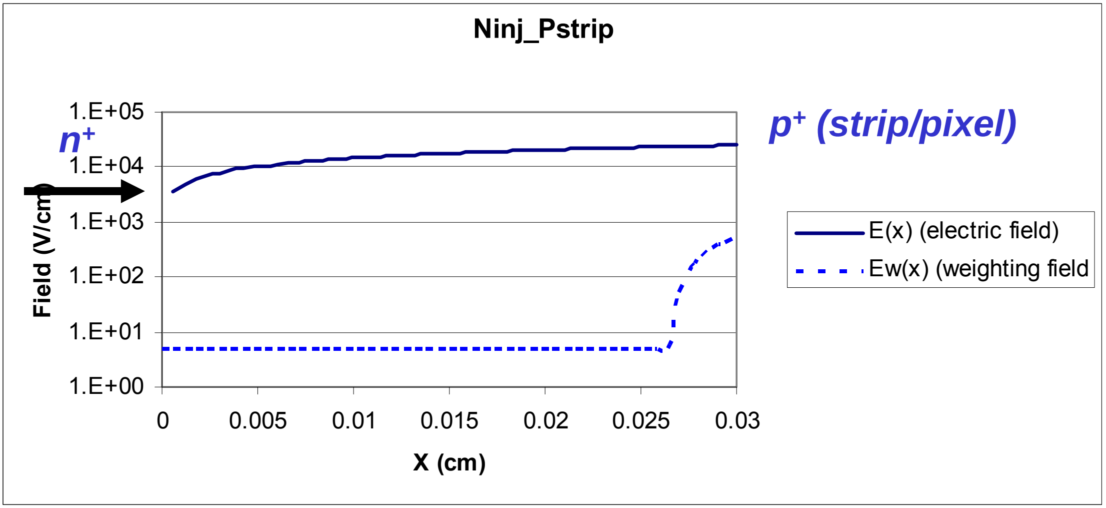
V = 500 V, T = 221 K

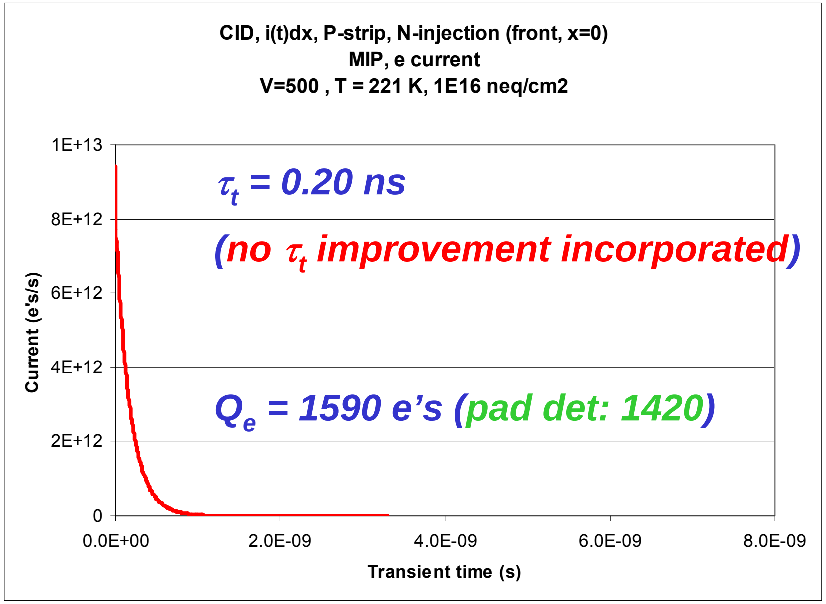
$1\times10^{16}\ n_{eq}/cm^2$

Q = 2140 e's (pad: 2220e's)

(74% by electrons)

(pad: 64%)

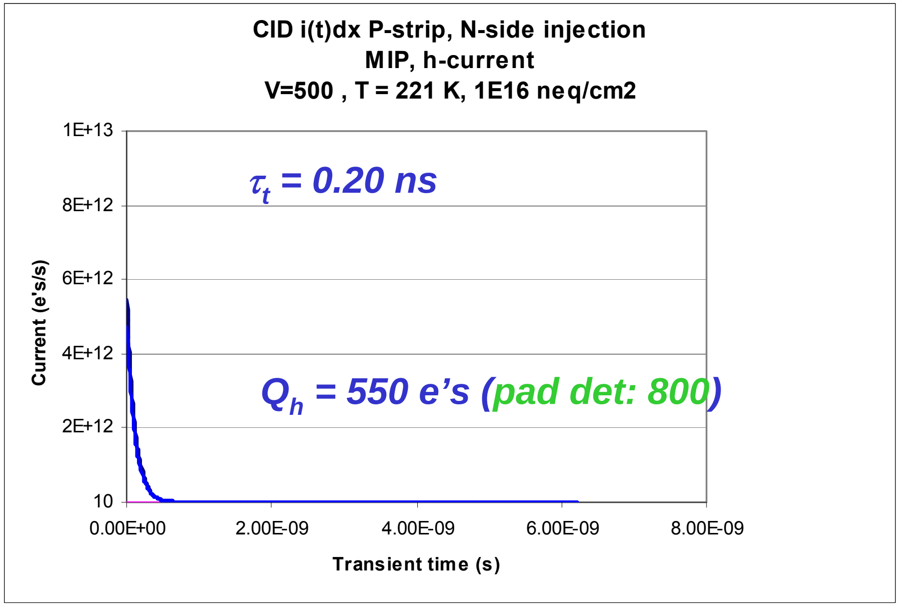




τ_t = 0.20 ns

(no τ_t improvement incorporated)

Q_e = 1590 e's (pad det: 1420)



τ_t = 0.20 ns

Q_h = 550 e's (pad det: 800)

Simulation Results and Data Fitting

Simulation results

τ_t = 5.85 ns

(τ_t improvement incorporated)

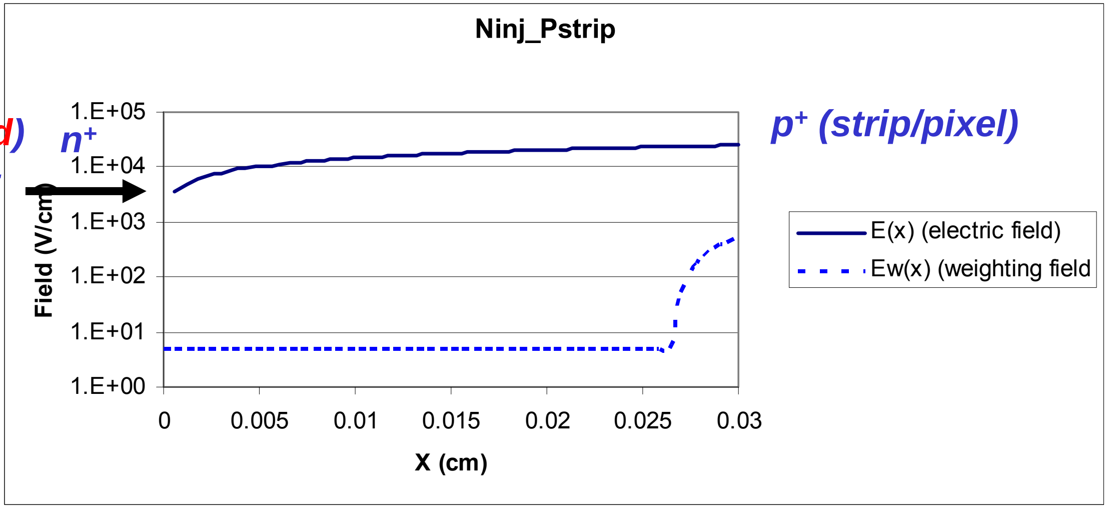
N-injection (e's), P-strip e-inj

V = 500 V, T = 221 K

3×10^{15} n_{eq}/cm^2

Q = 18360 e's

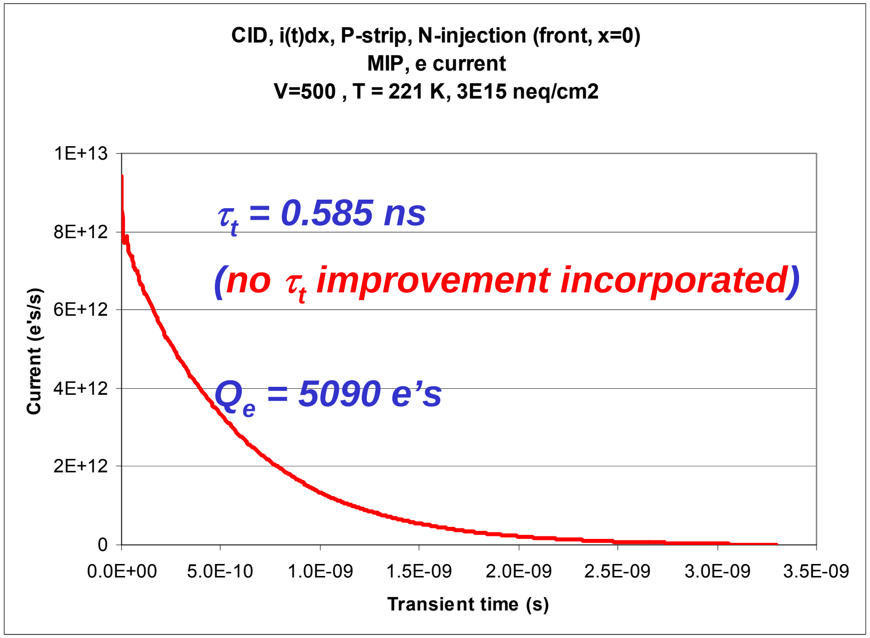
(94% by electrons)



Ninj_Pstrip

n^+

p^+ (strip/pixel)

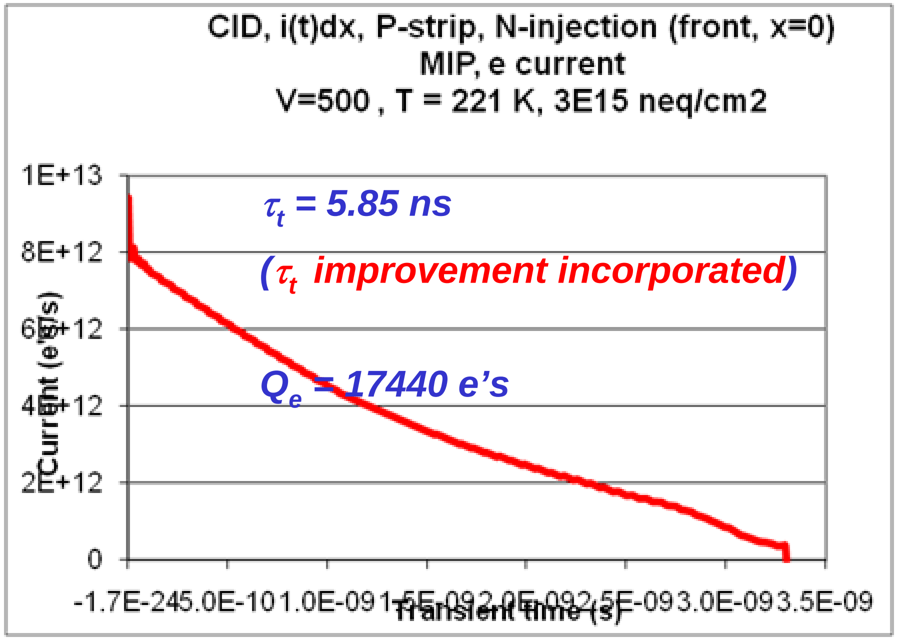


CID, i(t)dx, P-strip, N-injection (front, x=0)
MIP, e current
V=500 , T = 221 K, 3E15 neq/cm2

τ_t = 0.585 ns

(no τ_t improvement incorporated)

Q_e = 5090 e's



CID, i(t)dx, P-strip, N-injection (front, x=0)
MIP, e current
V=500 , T = 221 K, 3E15 neq/cm2

τ_t = 5.85 ns

(τ_t improvement incorporated)

Q_e = 17440 e's

Simulation Results and Data Fitting

Simulation results

τ_t *= 5.85 ns*

(τ_t *improvement incorporated)*

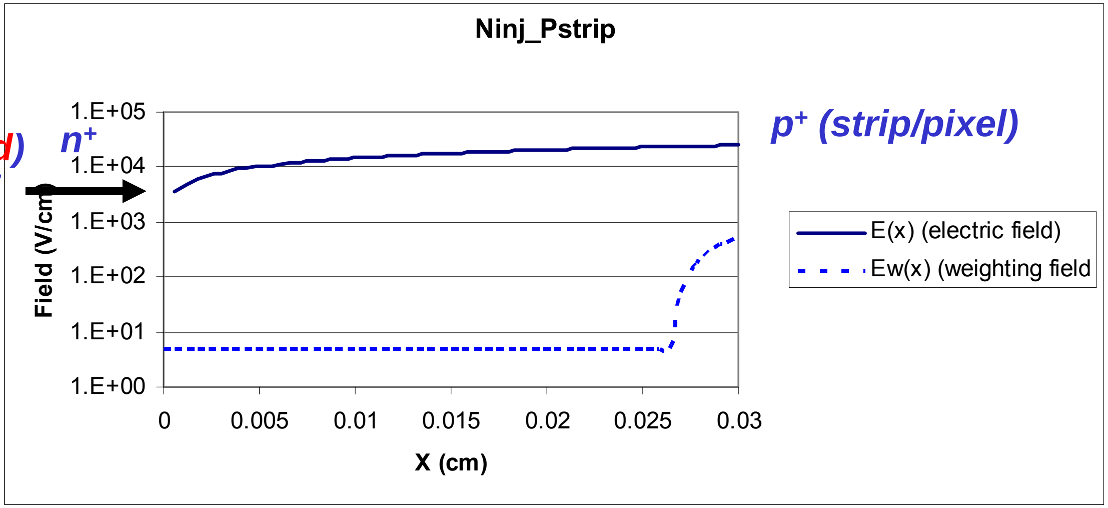
N-injection (e's), P-strip

V = 500 V, T = 221 K

1x10^{16} *n*$_{eq}$*/cm*^{2}

Q = 12020 e's

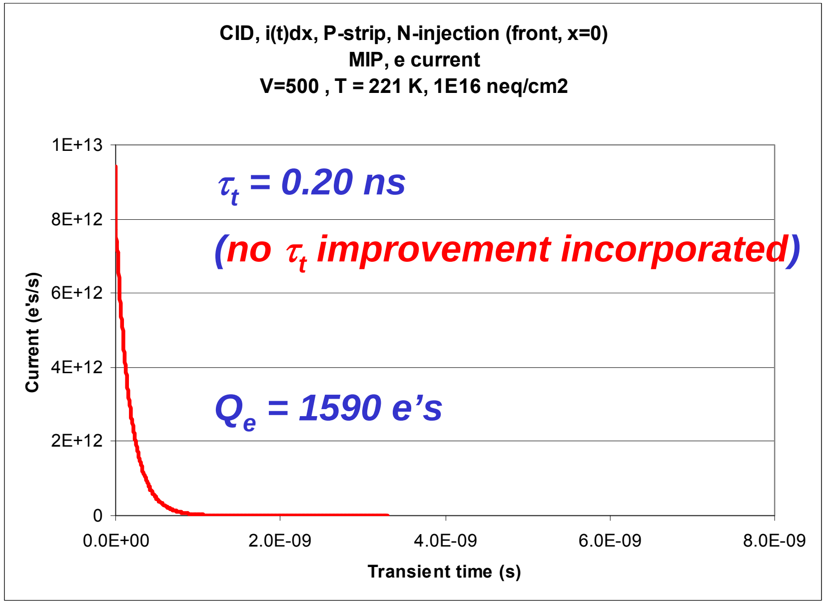
(95% by electrons)



e-inj

n$^+$

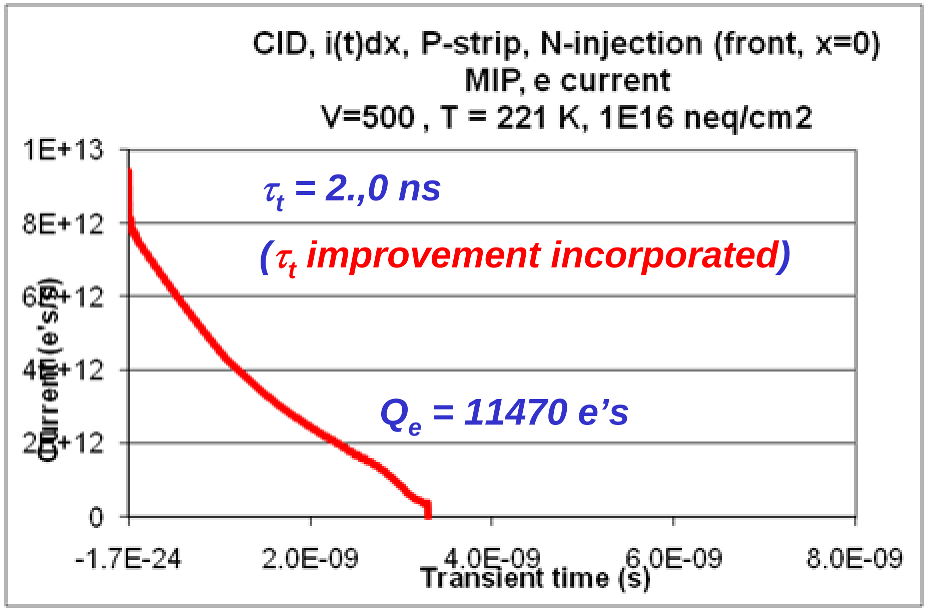
p$^+$ *(strip/pixel)*



τ_t *= 0.20 ns*

(no τ_t *improvement incorporated)*

Q$_e$ *= 1590 e's*



τ_t *= 2.,0 ns*

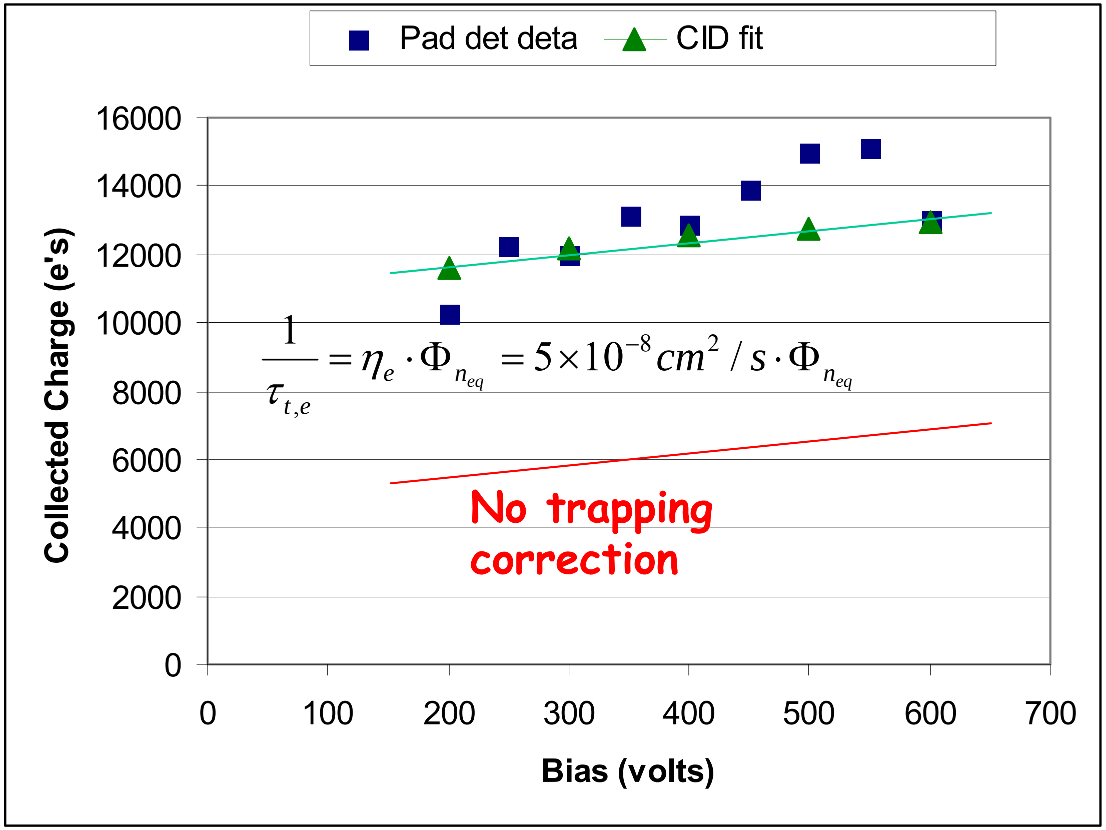
(τ_t *improvement incorporated)*

Q$_e$ *= 11470 e's*

Simulation Results and Data Fitting

CID pad detector IR laser test results (MIP charge) –CCE at -53 °C (220K)

$3\text{X}10^{15}\ n_{eq}/cm^2$



$$\frac{1}{\tau_{t,e}} = \eta_e \cdot \Phi_{n_{eq}} = 5\times10^{-8} cm^2 / s \cdot \Phi_{n_{eq}}$$

No trapping correction

Larger $\tau_{t,e}$ for electrons used to fit CID data $\tau_{t,e}$ = 6.67 ns as compared 0.667 ns with no injection (hole trapping stays the Same)

Much less charge trapping CID

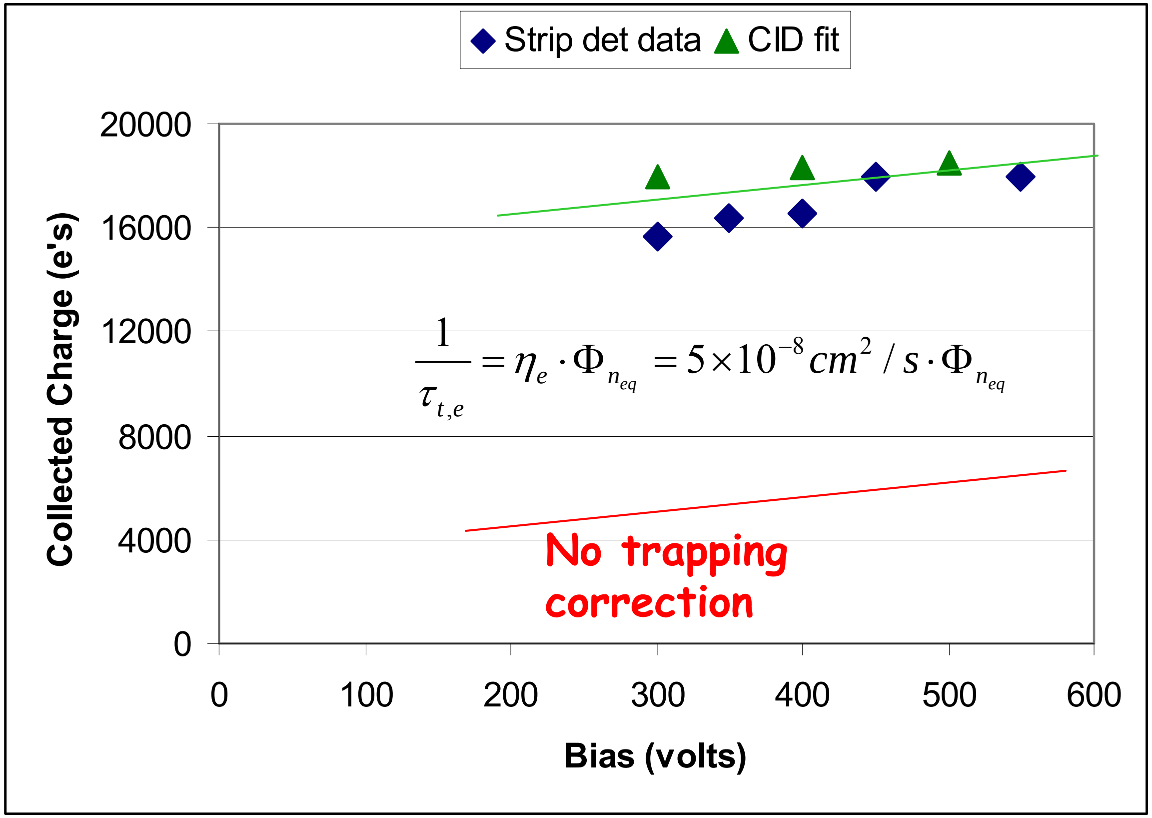
Election injection makes η_e 10 times smaller!

Data: Zheng Li, CERN RD39 Status Report, 94th LHCC open session, 19th November 2008, CERN

Simulation Results and Data Fitting

CID strip detector test beam results (MIP charge)
CERN H2 muon, 225 GeV/c (-52 °C (221K))

$3X10^{15}\ n_{eq}/cm^2$



$$\frac{1}{\tau_{t,e}} = \eta_e \cdot \Phi_{n_{eq}} = 5\times10^{-8} cm^2/s \cdot \Phi_{n_{eq}}$$

No trapping correction

Larger $\tau_{t,e}$ for electrons used to fit CID data $\tau_{t,e}$ = 6.67 ns as compared 0.667 ns with no injection (hole trapping stays the Same)

Even much less charge trapping CID strip detectors

Election injection makes η_e 10 times smaller!

Data: Zheng Li, CERN RD39 Status Report, 94th LHCC open session, 19th November 2008, CERN

Simulation Results and Data Fitting

Predictions of collected charge for CID with various configurations (-52 °C (221K), 500V, 1x10^{16} n_{eq}/cm^2 (Q_0 = 24000 e's)

CID Type	Junction side	Injection side/of	Segment -ed side	High field side	Reduced trapping of	Q_e (# of e's)	Q_h (# of e's)	Q (# of e's)
N_{inj}-P_{strip} ($p^+/n/n^+$)	n^+ (SCSI)	n^+ electrons	p^+	p^+	electron	11470	550	12020
N_{inj}-N_{strip} ($n^+/n\ (p)/p^+$)	n^+ (SCSI)	n^+ electrons	n^+	p^+	electron	1840	2070	3910
P_{inj}-P_{strip} ($p^+/n/n^+$)	p^+ (no SCSI)	p^+ holes	p^+	n^+	hole	1200	1500	2700
P_{inj}-N_{strip} ($n^+/n\ /p^+$)	p^+ (no SCSI)	p^+ holes	n^+	n^+	hole	740	7940	8680

SCSI: space charge sign inversion

Summary

1. A mode has been developed to simulate CID with segmentation

2. Inaddition to the virtual full depeltion at any fluenece, fitting of the model to experimental data indicating a increase in carrier trappiing time due to charge injection → reduction of carrier trapping → increase in CCE by > 3 times

3. For high charge collection, the segmented side of the detector should be opposite of injection side

4. The best configuration is the simple $p^+/n/n^+$ CID with n^+ side injection and segmentaed p+ side after SCSI

Backup slides

Effect of Trapping on CCE in SLHC

- Trapping time: τ_t
- $1/\ \tau_t = \gamma\ \Phi_n$
- $\gamma_e = 7.50\times10^{-7}\ \mathrm{cm}^2/\mathrm{s}$
- $\gamma_h = 3.75\times10^{-7}\ \mathrm{cm}^2/\mathrm{s}$
- for $10^{16}\ \mathrm{n}_{eq}/\mathrm{cm}^2$:

H.W. Kraner et al., Nuclear Instruments and Methods in Physics Research A326 (1993) 350-356

$\tau_{te} = 0.13$ ns

$\tau_{th} = 0.26$ ns

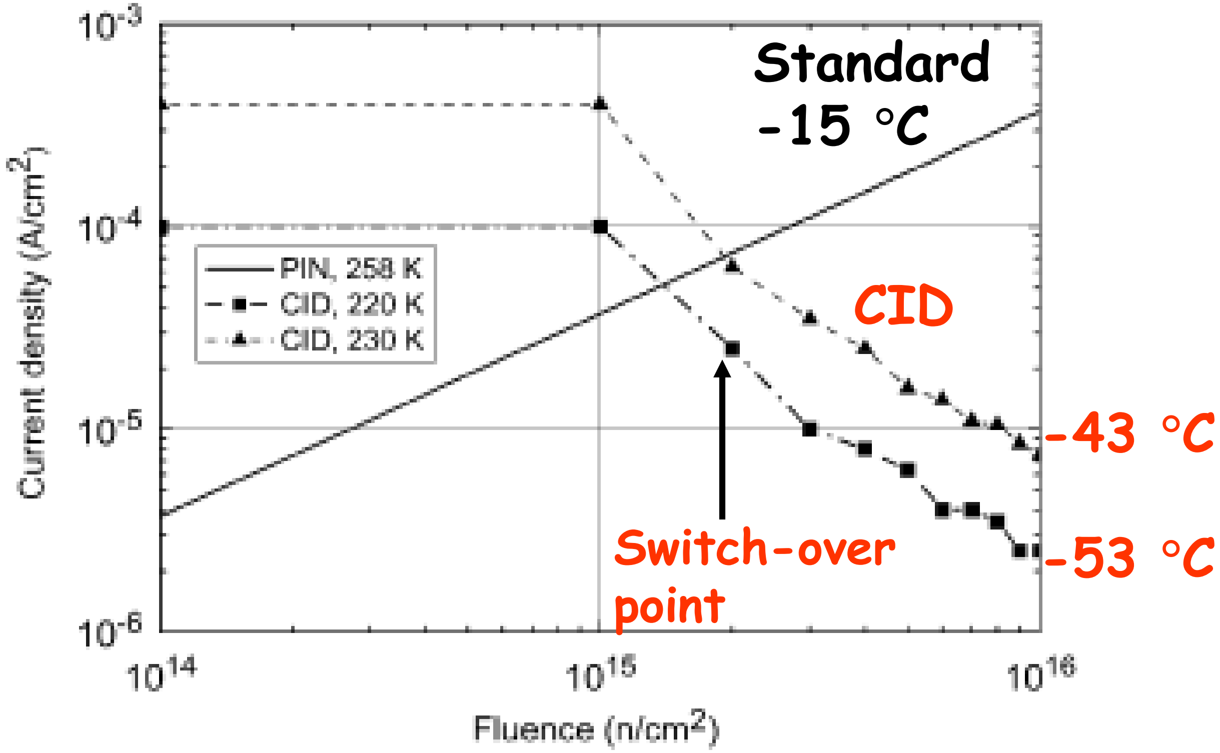
$\tau_t = 0.20$ ns as average for SLHC (no pre-filling)

Trapping distance (or effective charge collection distance) is:

$d_t \leq \tau_t \times V_s = 20\ \mu\mathrm{m} \ll d$, the detector thickness or depletion depth

Current comparisons

Switch over point from standard reverse bias to CID (forward) is $2x10^{15}$ n_{eq}/cm^2



Standard -15 °C

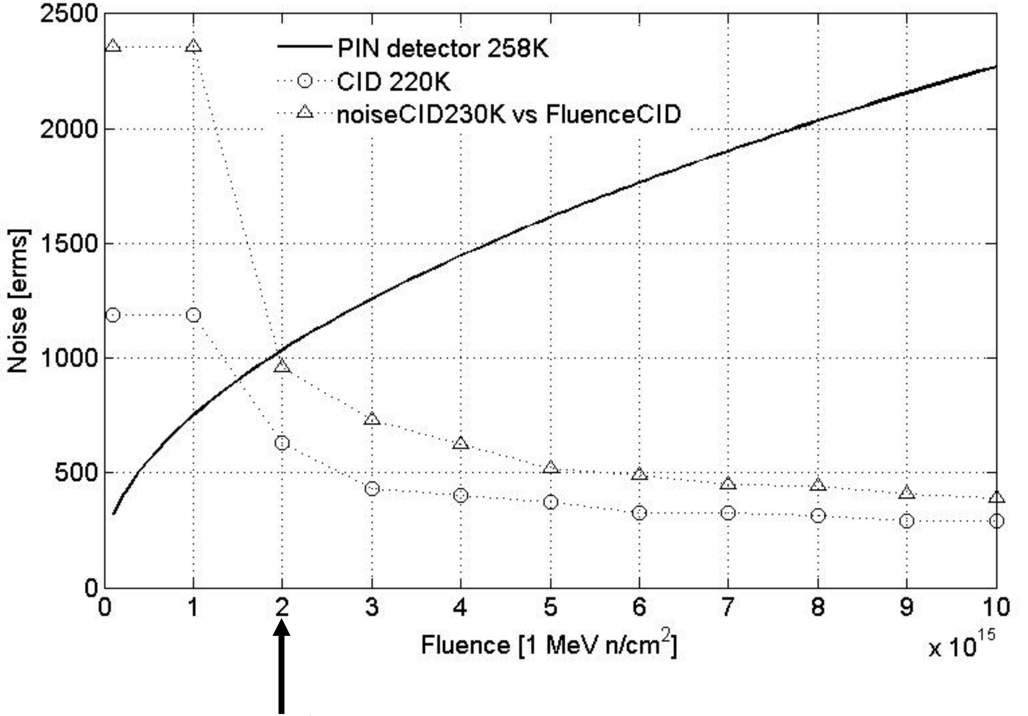
CID

-43 °C

-53 °C

Switch-over point

Simulation of noise performance of CID detector versus normal detector operation.



Switch-over point

The simulation has been made according to the strip detector design of CERN ATLAS experiment: pitch 80 μm, strip length 6 cm and read-out shaping time 25 ns , PIN is biased to the full depletion and the temperature is 258 K. The bias for CID is 200V. As it can be seen, at fluence 2×10^{15} n_{eq}/cm^2 the CID noise becomes lower than in PIN detector.

Conclusions

- Increase of detector thickness leads to the increase of signal and reduction of current

- Reduction of current allows to increase the operational temperature
-35 C is a reasonable operational temperature for CID of 400um thick

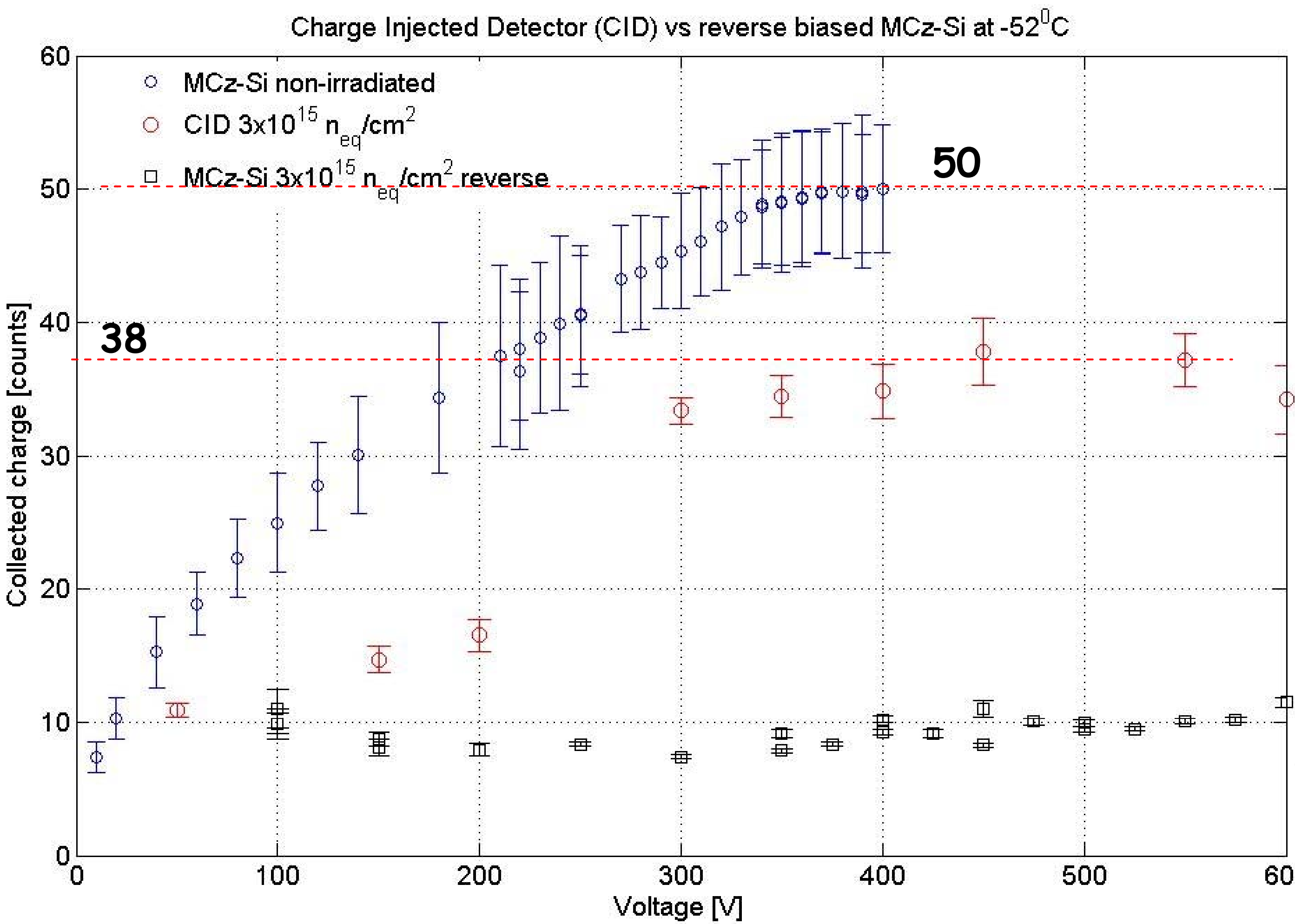
- Range of operational bias voltage 200 – 400V

- No breakdown effect at any bias voltage

- The operational current < 100 nA/pixel (80 x 250 um, 1 mA/cm2)

- Power dissipation < 300 mW/cm2

CID strip detector test beam results –CCE at -52 ^{0}C (221K)



n fluence (n_{eq}/cm^2)

$3x10^{15}$ → $1x10^{16}$

75% → 22.5%

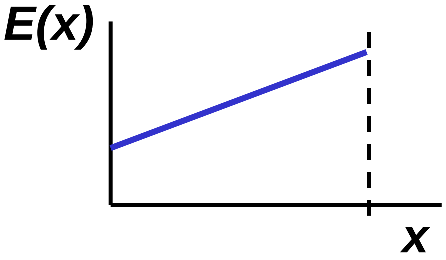
(18,000e's) (5400 e's)

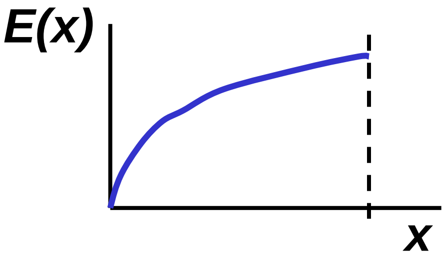
20% → 6%

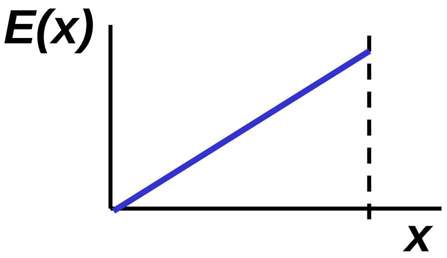
(4800 e's) (1440 e's)

Zheng Li, CERN RD39 Status Report, 94th LHCC open session, 19th November 2008, CERN

Evolution of E(x) in CID with the injected current







“Diode” mode

$p>p_{tr}$
$E(x) \sim E(0) + ax$

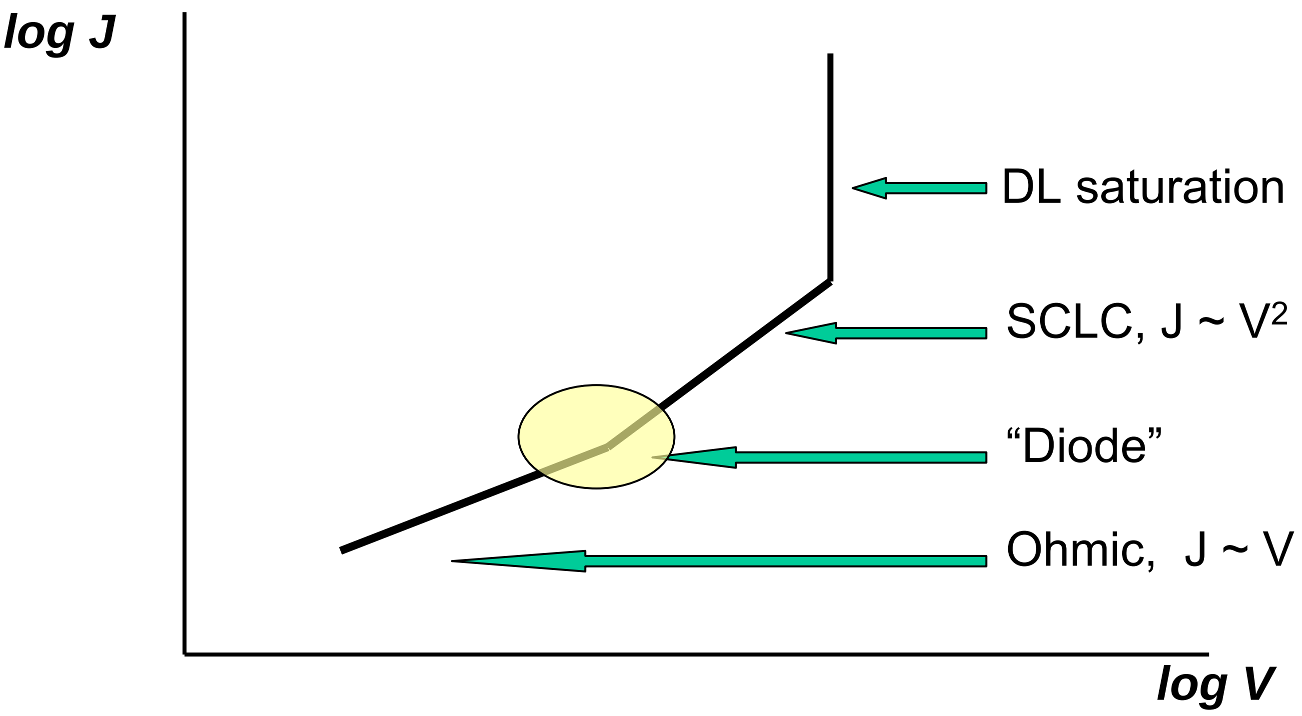
SCLC mode

$N_{dl}>p_{tr}$
$E(x) \sim SQR(x)$
$J \sim V^2$

Deep Level saturation

$p >> p_{tr}$
$E(x) = ax$

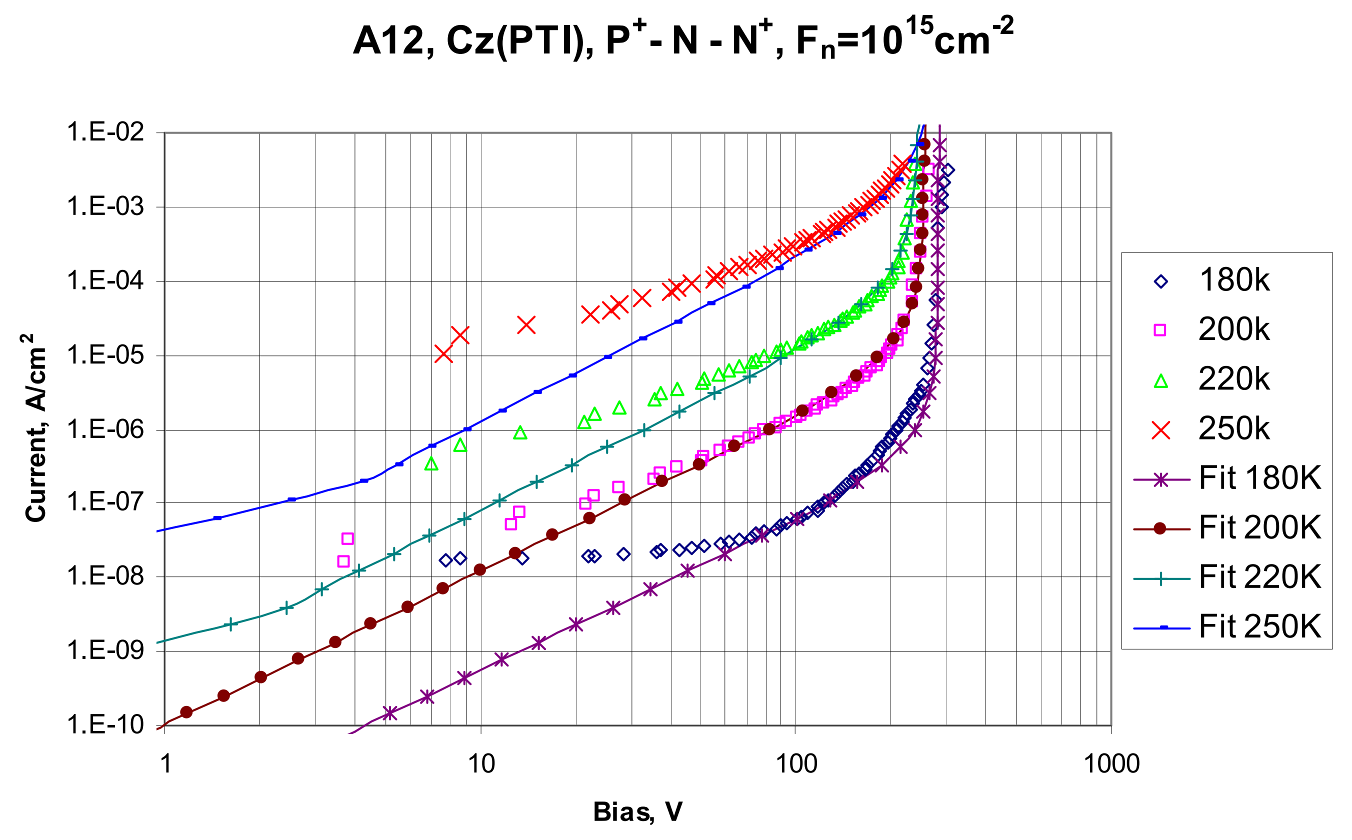
I-V characteristic of CID



Proof of CID concept: – ***observation of SCLC and DL saturation behavior***

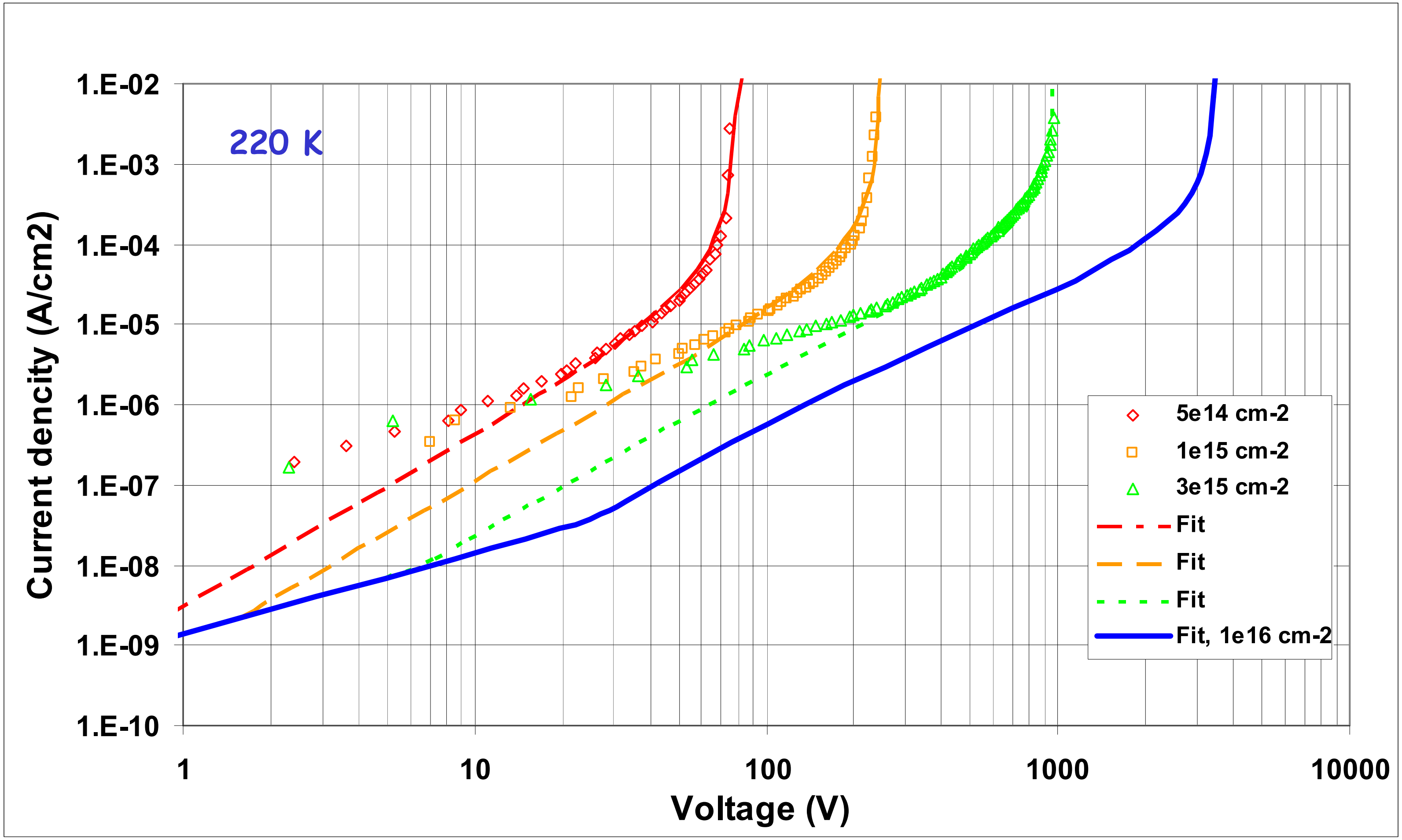
Problem: - ***optimal range of V for CID operation***

I-V characteristics of CID

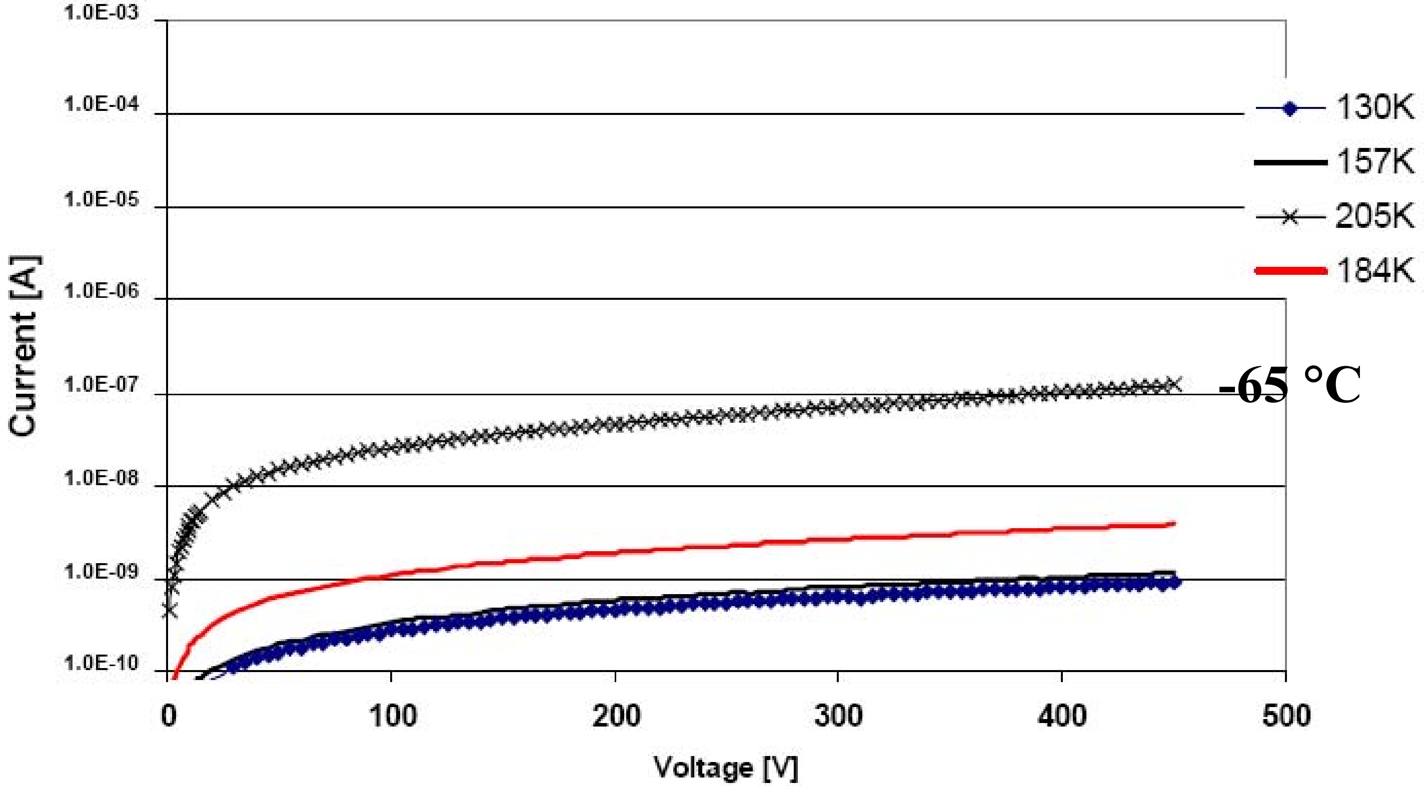


Zheng Li May 29, 2009

I-V characteristics of CID



SLHC fluencec



MCz-Si 9MeV proton irradiated 7×10^{15} 1MeV n_{eq}/cm^2

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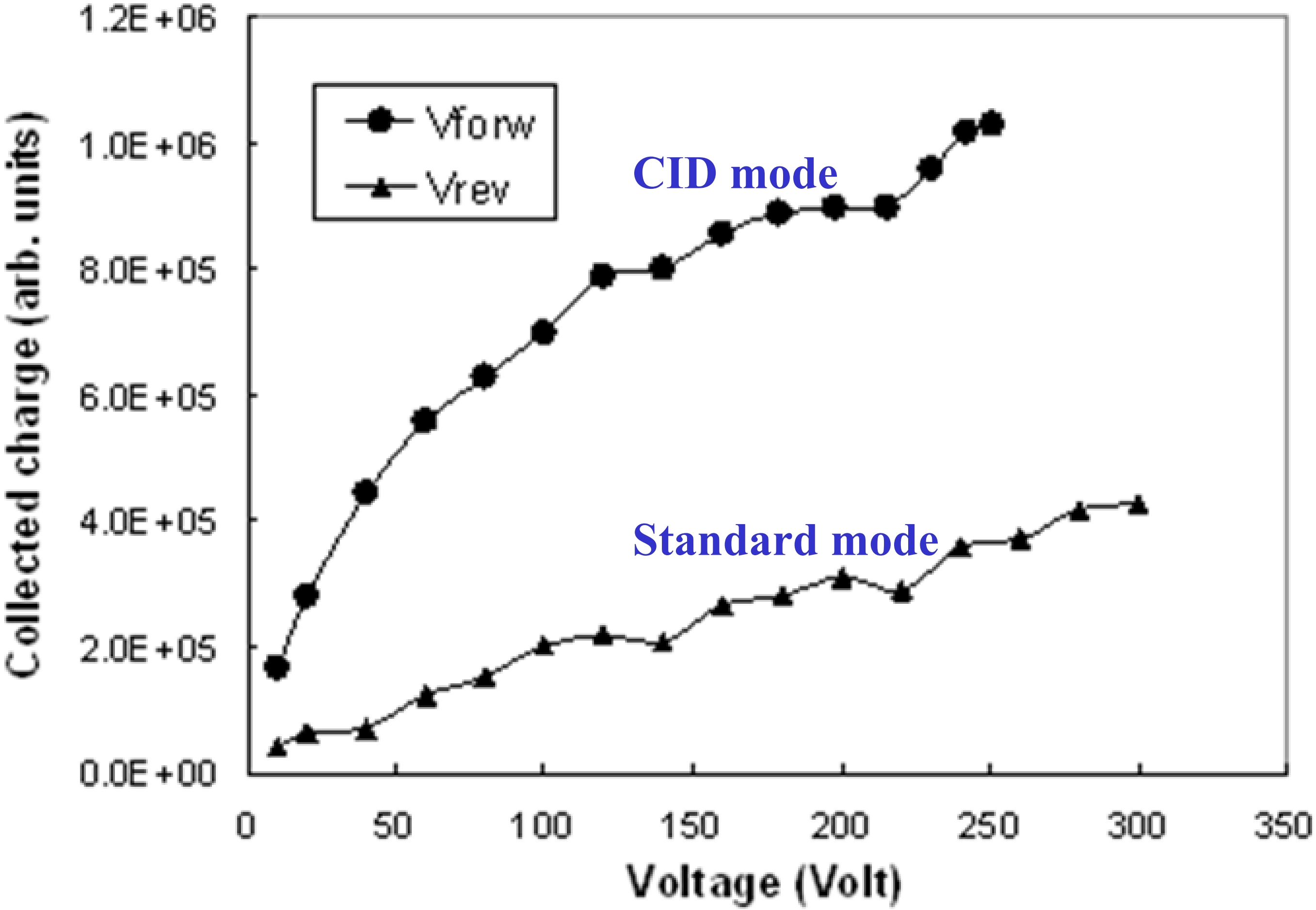
Main advantages CID over standard PN detectors

1. **The detectors are always fully depleted**
2. **The electric field profile does not change with fluence**
3. **Much lower bias voltage is needed**
4. **The higher the radiation fluence, the lower the operation current at given bias and temperature**
5. **The operation bias range increases with fluence**
6. **No breakdown problem due to self-adjusted electric field by space charge limited current feedback effect**
7. **Simple detector processing technology (single-sided planar technology)**
8. **Injection can also be used to deactivate trapping centers --- CCE ↑**

$\Phi_n = 1\times10^{15}$ cm^{-2}, T = 180 K, MIPs (1050 nm laser)

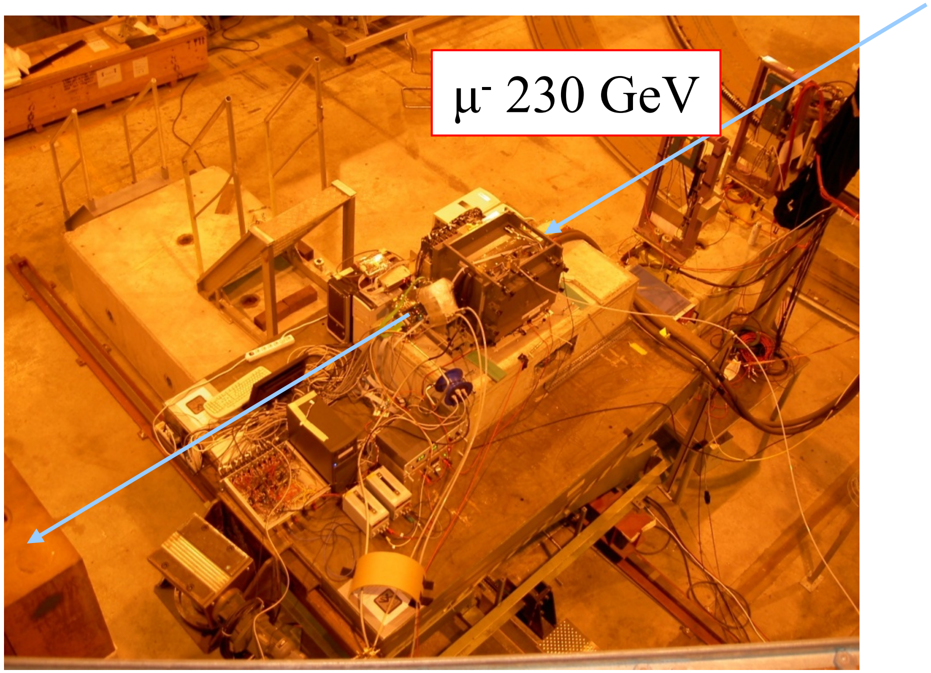


Possible Si detector solutions for SLHC's most inner region

Solution	**CCE improvement due to**	**Technology/ implementation difficulties**
Replacement every 1-2 years	**New detectors**	**Hard to access the inner region**
3D Si detectors	**Small V_{fd}** **Small drift distance *t***	**Complicated processing technology** **Column spacing *t* should be < 40 μm** **Possible surface damage problem to ionizing radiation**
Cryogenic Si detectors	**Fixed electric field (small bias)** **Freezing traps (low trapping)** **Low leakage current**	**Difficult to implement cryogenic system**
Elevated temp annealing (DRIVE) **(MCZ Si only, ≥ 400 °C)**	**Annealing out of defect levels related to:** **Leakage current, space charges** **And trapping**	**Difficult to implement annealing in a full detector system**

Characterization of CID strip detectors –Segmented detectors

- Test beam with 225 GeV/c muon beam at CERN H2.
- MCz-Si strip detector irradiated 3×$10^{15} n_{eq}/cm^2$.
- 768 channels attached to APV25 read-out
- CID detector placed in external cold box capable to cool down to -54°C while module is operational.
- Data acquisition with modified XDAQ. Analysis with CMSSW.



- 8 reference planes.
- Resolution ~4μm.
- About 25000 events in 20min.