The Sixth International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors

Cryogenic Si detectors for Ultra Radiation Hardness in SLHC Environment

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On behalf of CERN RD39 Collaboration

Outline

- Trapping effect on Charge Collection Efficiency (CCE) in SLHC

  LHe temperature TCT setup

  Operation of current-injected-detectors (CID)

  CCE measurements on CID

  Summary

Trapping effect on CCE in S-LHC

$$CCE = CCE_{GF} \cdot CCE_t = \underbrace{\frac{w}{d}}_{\text{Depletion term}} \cdot \overbrace{e^{-t_{dr}/\tau_t}}^{\text{Trapping term}}$$

CCE_{GF} is a geometrical factor

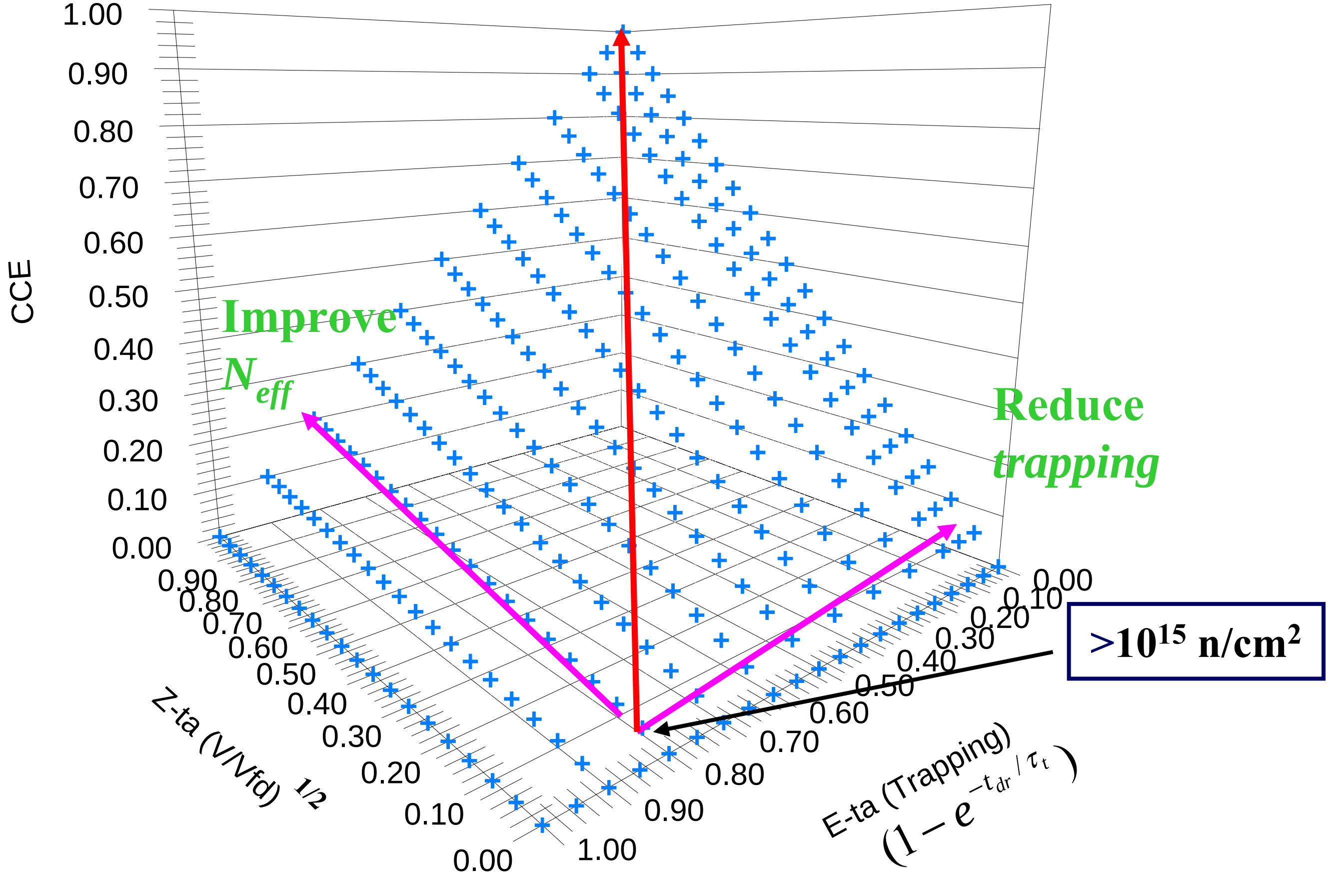
$$w = \sqrt{\frac{2\varepsilon\varepsilon_0 V}{eN_{eff}}} \text{ and } \frac{w}{d} = \sqrt{\frac{V}{V_{fd}}}$$

CCE_t is related with trapping

For fluence less than 10^{15} n/cm^2, the trapping term CCE_t is insignificant

For fluence 10^{16} n/cm^2, the trapping term CCE_t is a limiting factor of detector operation !

To get better CCE:



CCE=Zta*(1-Eta)

Combined effect (RD39)

TRAPPING

$$\tau_t = \frac{1}{\sigma v_{th} N_t}$$

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

10^{16} cm^{-2} irradiation produces $N_T \approx 3\text{-}5 \cdot 10^{16}$ 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 !

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

$\tau_{te} = 0.13$ ns

$\tau_{th} = 0.26$ ns

$\tau_t = 0.20$ ns as average

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

Trapping distance (or effective charge collection distance) is:

$d_{eff} \leq \tau_t \times V_s = 20$ µm << d, the detector thickness or depletion depth

The main limiting factor is trapping for SLHC!

Effective CCE thickness

d : thickness (200- 300 μm)

w: depletion depth (≤ d)

t: trapping distance (20-50 μm)

Thickness d

$Q(t) = Q(w) \cdot t/w$

$Q(w) = W/d \cdot Q_0$

$Q(t) = Q_0 \cdot t/d$

The same!

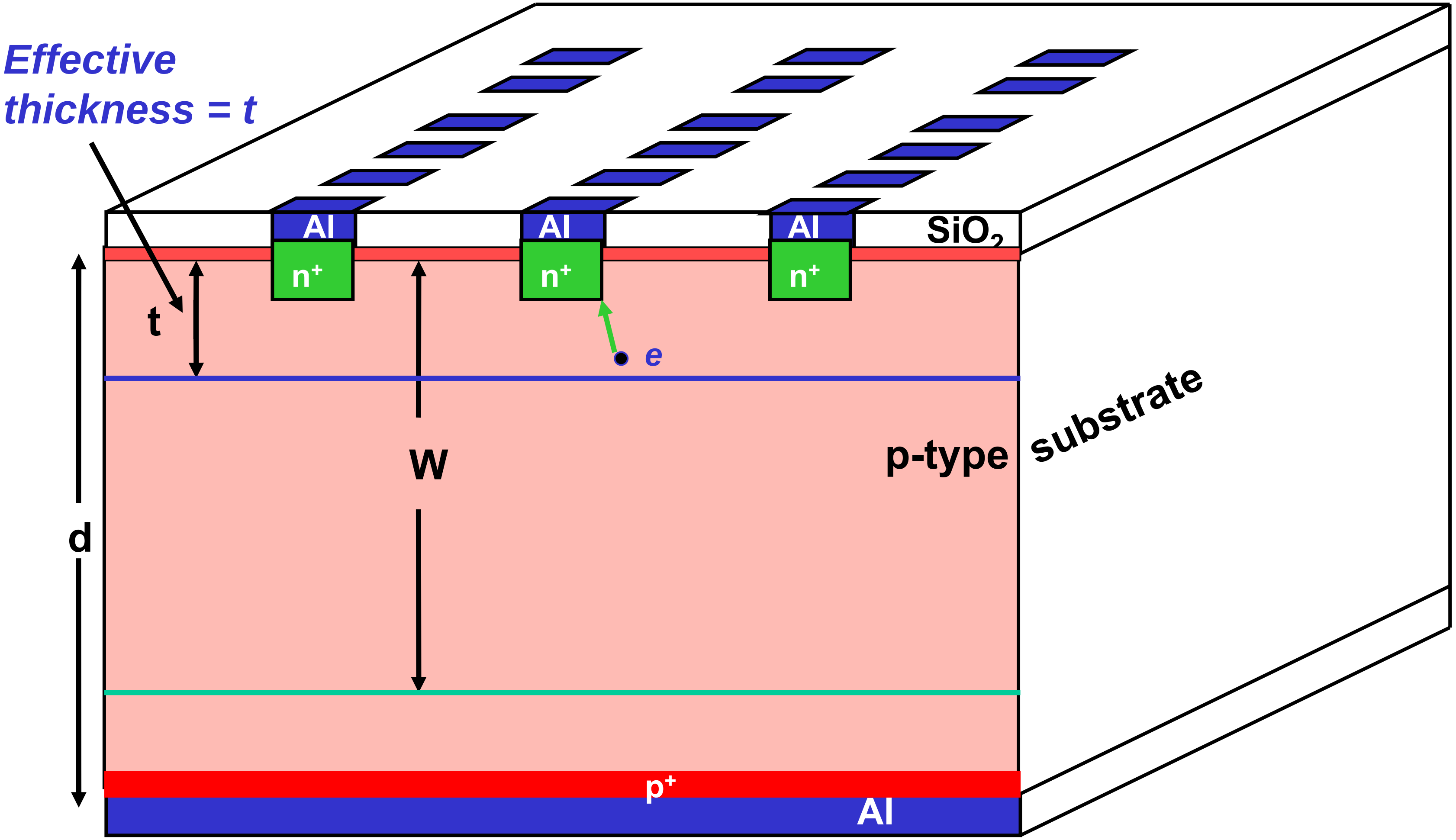
Thickness t (fully depleted, t = w)

$Q(t) = Q(w) \cdot t/w = Q(w)$

$Q(w) = w/d \cdot Q_0 = t/d \cdot Q_0$

$Q(t) = Q_0 \cdot t/d$

Effective thickness = t



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 ºC)	Annealing out of defect levels related to: Leakage current, space charges And trapping	Difficult to implement annealing in a full detector system

DETRAPPING

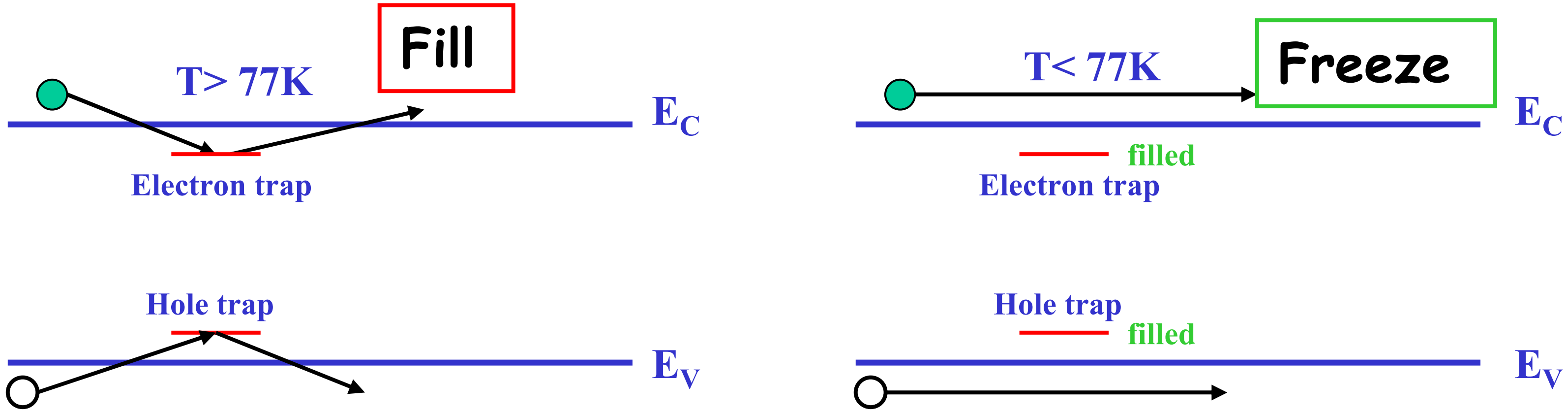
$$\tau_d = \frac{1}{\sigma v_{th} N_C e^{-E_t/kT}}$$

If a trap is filled (electrically non-active) the detrapping time-constant is crucial

The detrapping time-constant depends exponentially on T

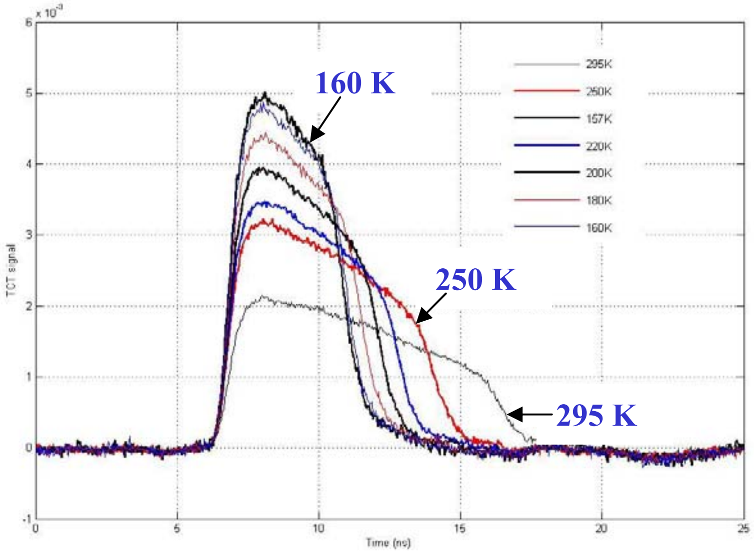
For A-center (O-V at E_c-0.18 eV with $\sigma \approx 10^{-15}$ cm^2)

T(K)	300	150	100	77	60	55	50	48	47	46
τ_d	3.7 ns	3.9 µs	4 ms	2 s	1.22 hrs	1.2 days	53 days	302 days	2.1 years	5.47 years

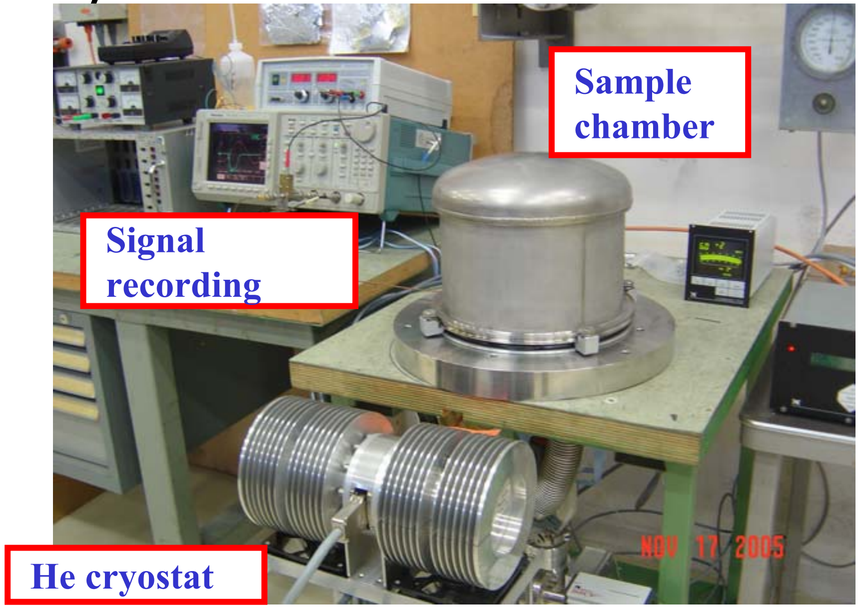


LHe Temp TCT Setup

- A fast TCT setup at CERN with sub-LN_2 temp for CCE measuements
- All components of the setup have been made
- The electical part (TCT with ps laser) and the He cryostat are now operational
- The final calibration and actual CCE measurements at sub-LN_2 temperatures are now underway

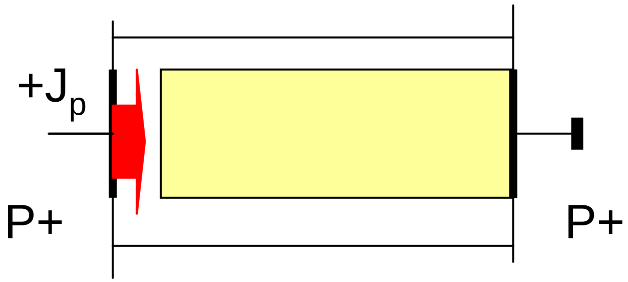


First TCT signal of a Si detector



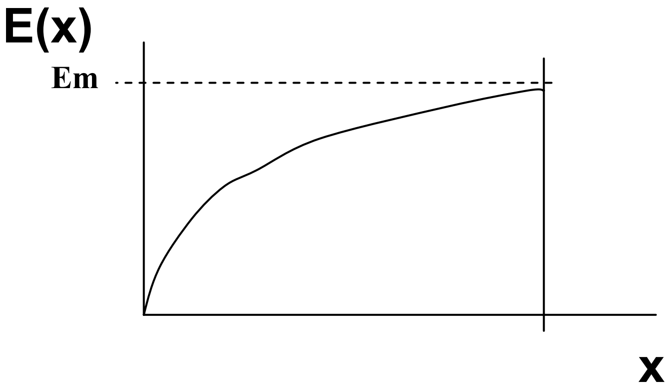
He cryostat, to 40 K in 2 hours

Current injected detector (principle of operation)



$$\left.\begin{array}{l} J_p = ep\mu E \\ \\ \mathrm{div}J=0 \\ \\ \mathrm{div}E=p_{tr} \\ \\ E(x=0) = 0 \end{array}\right\}$$

(SCLC: Space Charge Limited Current mode)

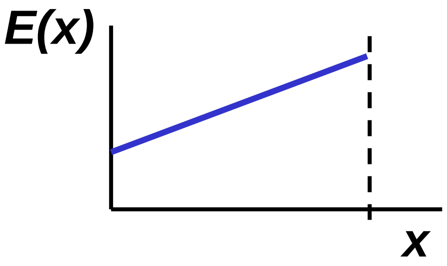


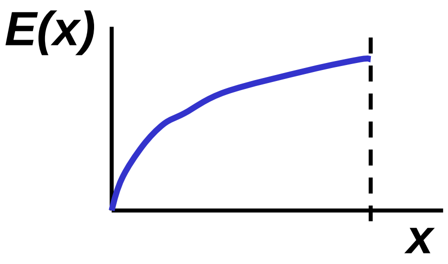
$$\boxed{E(x)=\frac{3}{2}\frac{V}{d}\cdot\sqrt{\frac{x}{d}} \qquad E_m=\frac{3}{2}\cdot\frac{V}{d}}$$

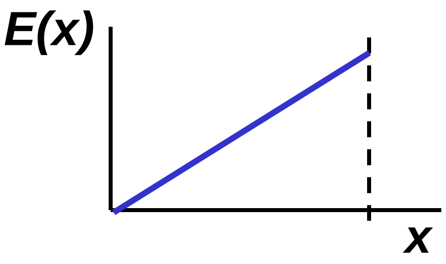
The key advantage:

The shape of E(x) is ***not affected*** by fluence

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







"Diode" mode

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

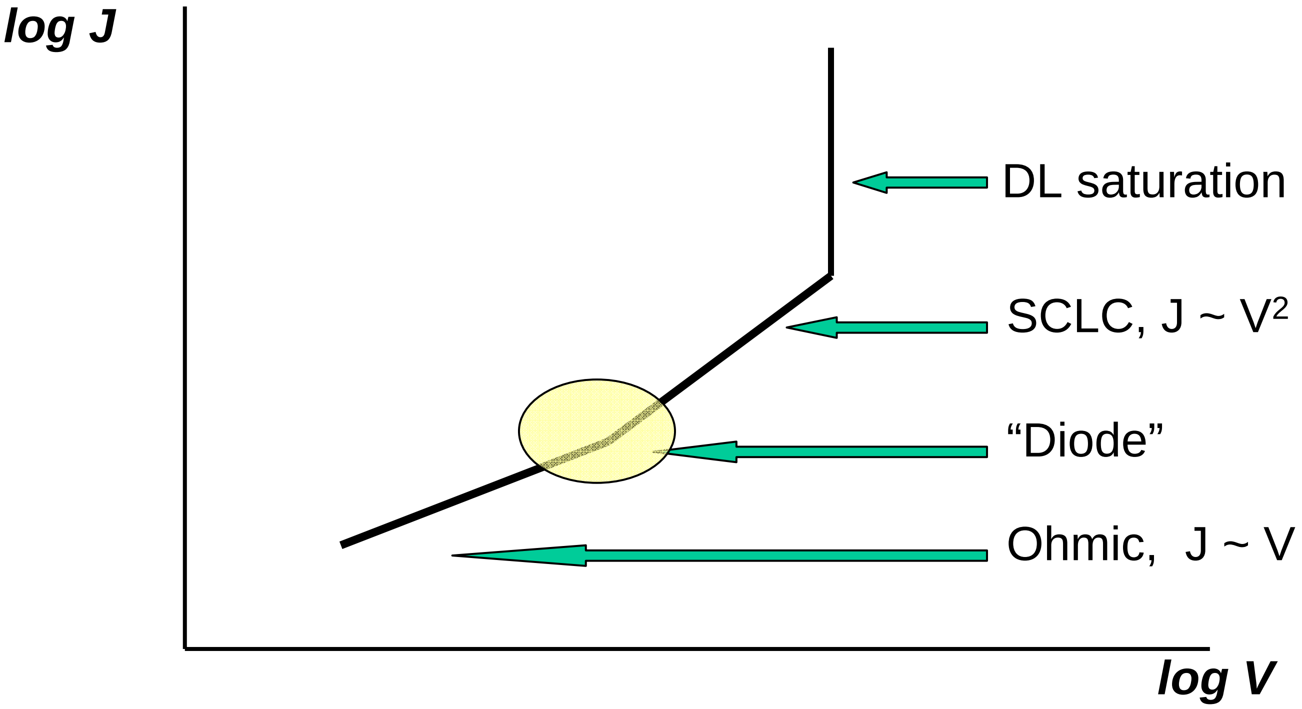
SCLC mode

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

Deep Level saturation

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

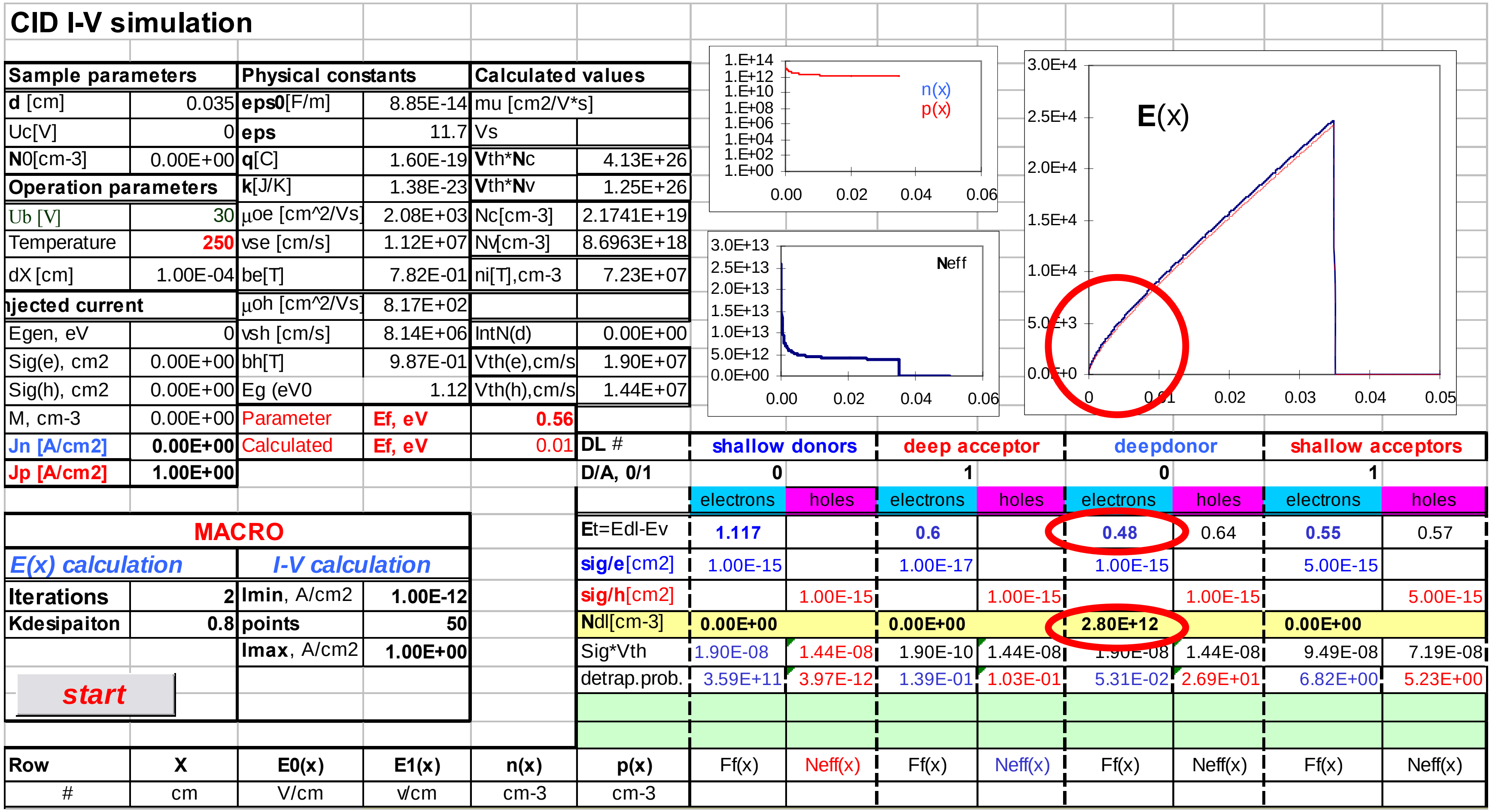
I-V characteristic of CID



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

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

CID I-V simulation software



CID I-V simulation

Sample parameters		Physical constants		Calculated values	
d [cm]	0.035	**eps0**[F/m]	8.85E-14	mu [cm2/V*s]	
Uc[V]	0	**eps**	11.7	Vs	
N0[cm-3]	0.00E+00	**q**[C]	1.60E-19	**V**th*__N__c	4.13E+26
Operation parameters		**k**[J/K]	1.38E-23	**V**th*__N__v	1.25E+26
Ub [V]	30	μoe [cm^2/Vs]	2.08E+03	Nc[cm-3]	2.1741E+19
Temperature	**250**	vse [cm/s]	1.12E+07	Nv[cm-3]	8.6963E+18
dX [cm]	1.00E-04	be[T]	7.82E-01	ni[T],cm-3	7.23E+07
jected current		μoh [cm^2/Vs]	8.17E+02		
Egen, eV	0	vsh [cm/s]	8.14E+06	IntN(d)	0.00E+00
Sig(e), cm2	0.00E+00	bh[T]	9.87E-01	Vth(e),cm/s	1.90E+07
Sig(h), cm2	0.00E+00	Eg (eV0	1.12	Vth(h),cm/s	1.44E+07
M, cm-3	0.00E+00	Parameter	**Ef, eV**	**0.56**	
Jn [A/cm2]	**0.00E+00**	Calculated	**Ef, eV**	0.01	
Jp [A/cm2]	**1.00E+00**				

MACRO			
E(x) calculation		***I-V calculation***	
Iterations	2	**Imin**, A/cm2	**1.00E-12**
Kdesipaiton	**0.8**	**points**	**50**
		Imax, A/cm2	**1.00E+00**

start

DL #	**shallow donors**		**deep acceptor**		**deepdonor**		**shallow acceptors**	
D/A, 0/1	**0**		**1**		**0**		**1**	
	electrons	holes	electrons	holes	electrons	holes	electrons	holes
Et=Edl-Ev	**1.117**		**0.6**		**0.48**	0.64	**0.55**	0.57
sig/e[cm2]	1.00E-15		1.00E-17		1.00E-15		5.00E-15	
sig/h[cm2]		1.00E-15		1.00E-15		1.00E-15		5.00E-15
Ndl[cm-3]	**0.00E+00**		**0.00E+00**		**2.80E+12**		**0.00E+00**	
Sig*Vth	1.90E-08	1.44E-08	1.90E-10	1.44E-08	1.90E-08	1.44E-08	9.49E-08	7.19E-08
detrap.prob.	3.59E+11	3.97E-12	1.39E-01	1.03E-01	5.31E-02	2.69E+01	6.82E+00	5.23E+00

Row	**X**	**E0(x)**	**E1(x)**	**n(x)**	**p(x)**	Ff(x)	Neff(x)	Ff(x)	Neff(x)	Ff(x)	Neff(x)	Ff(x)	Neff(x)
#	cm	V/cm	v/cm	cm-3	cm-3								

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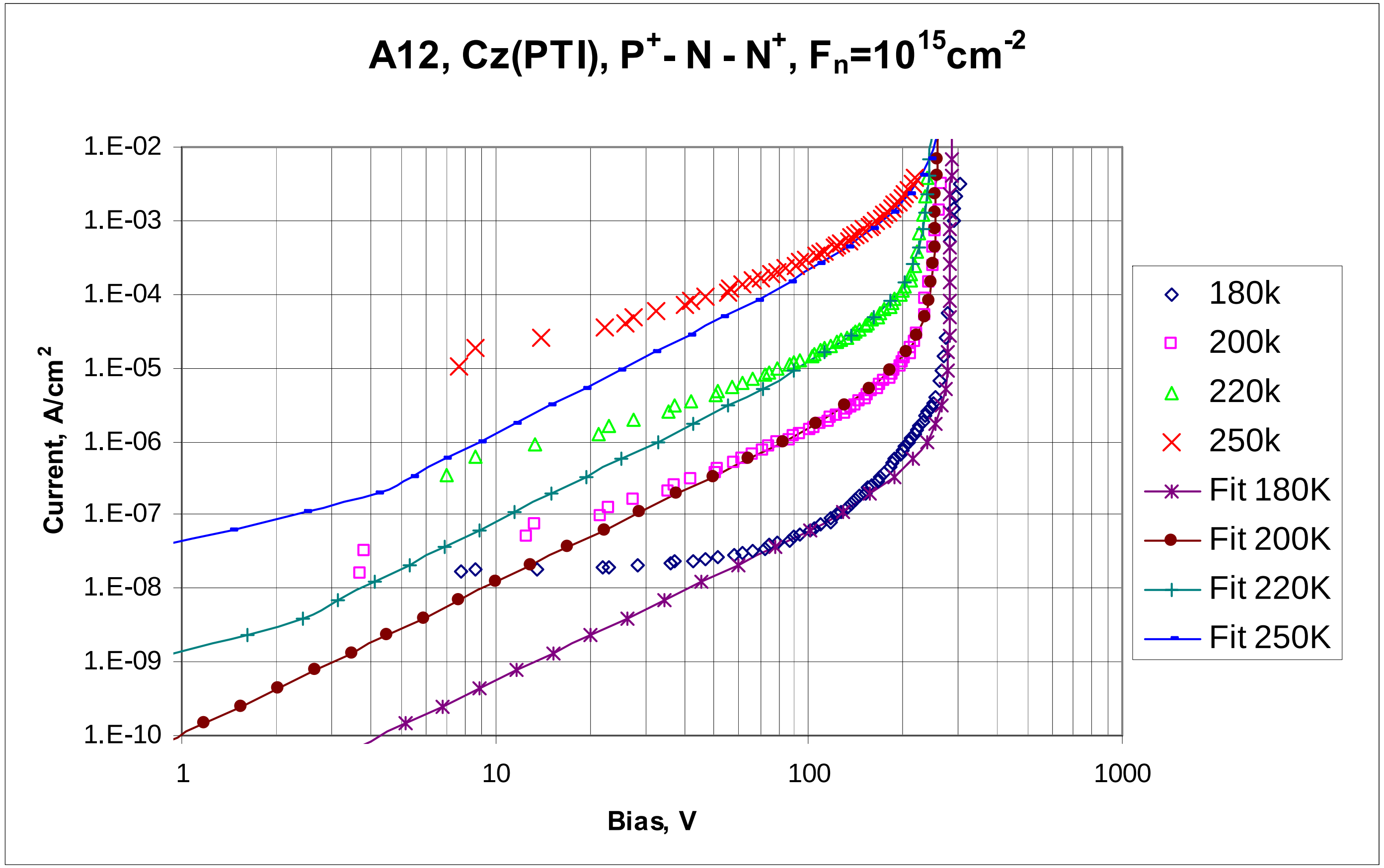
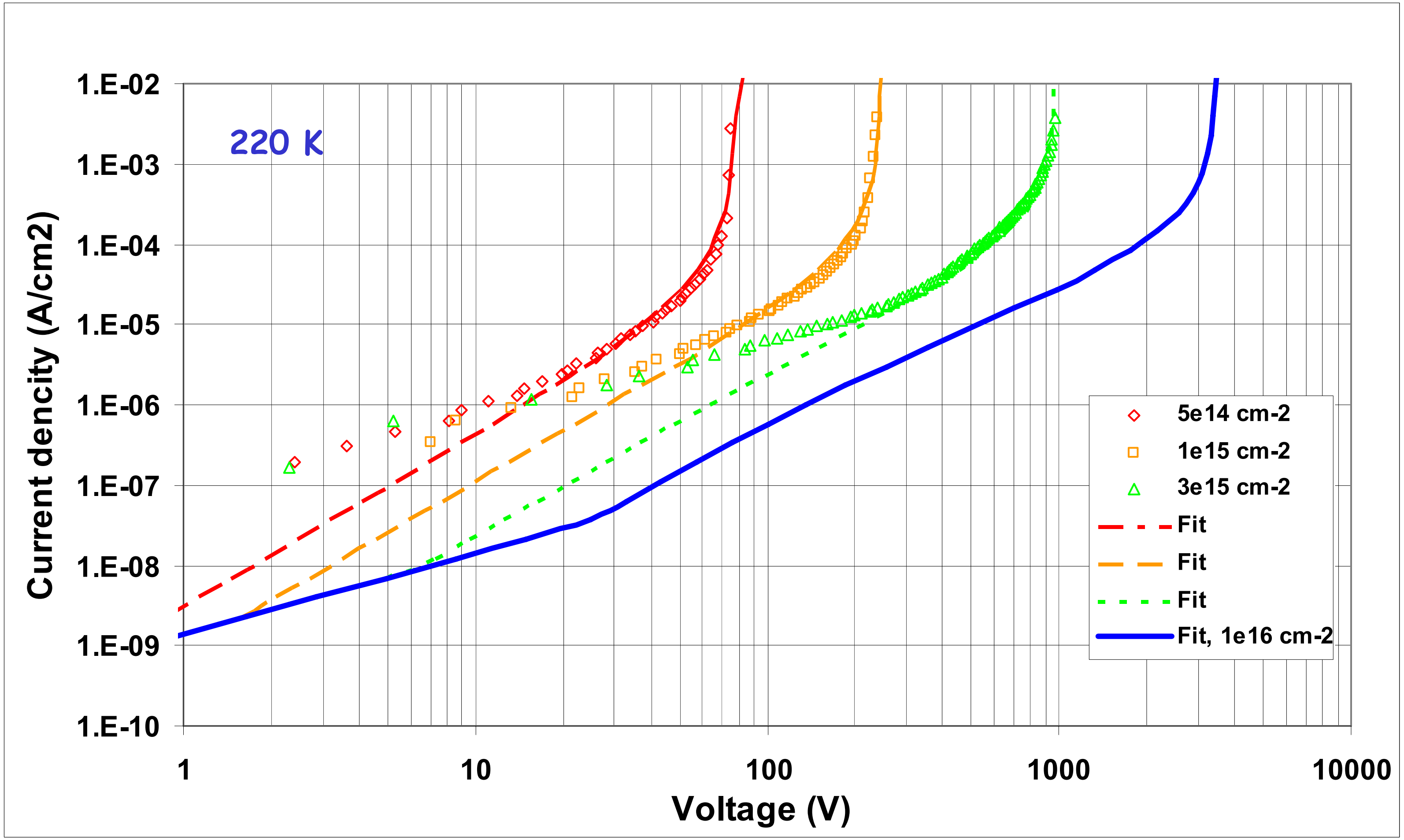
Collaboration, September 14, 2006

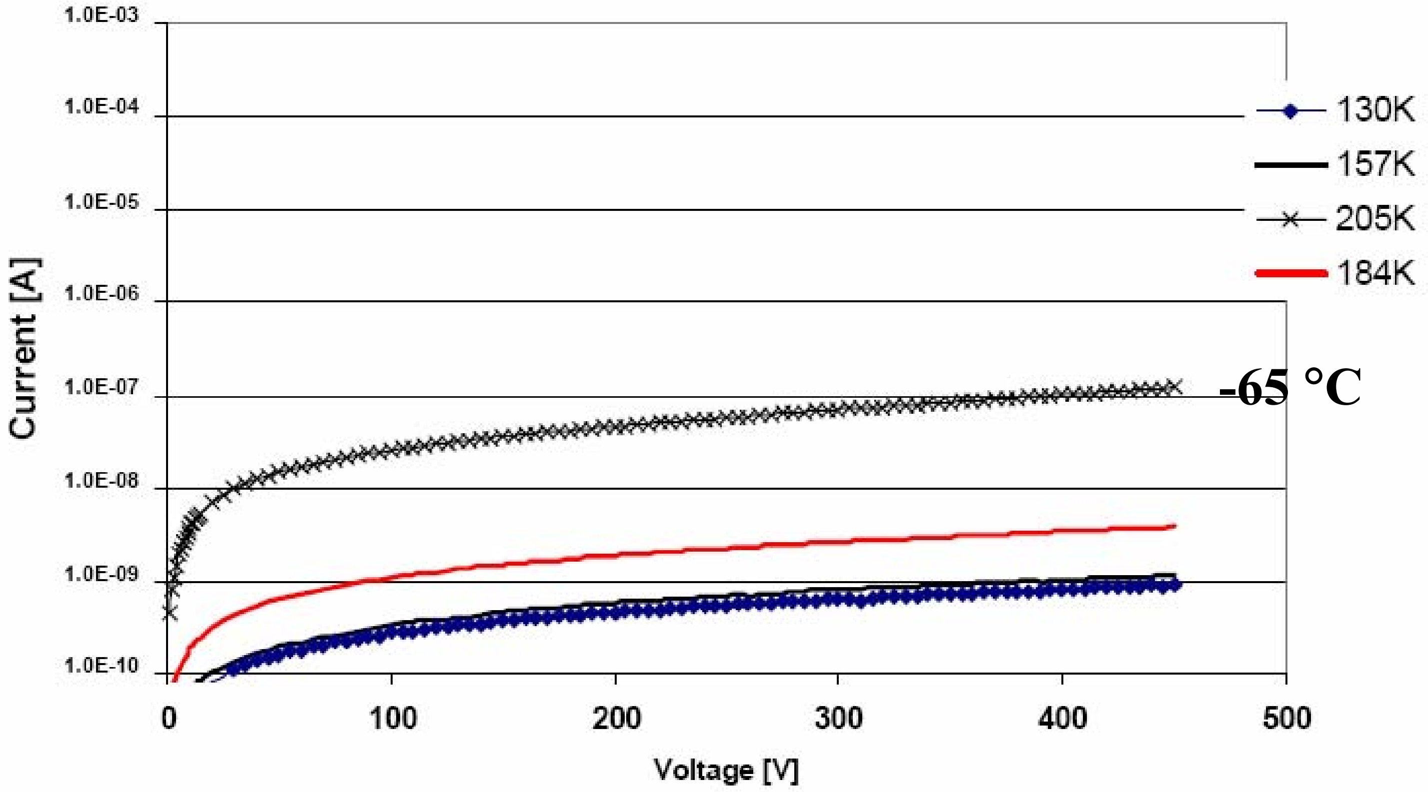
I-V characteristics of CID



I-V characteristics of CID



SLHC fluencec

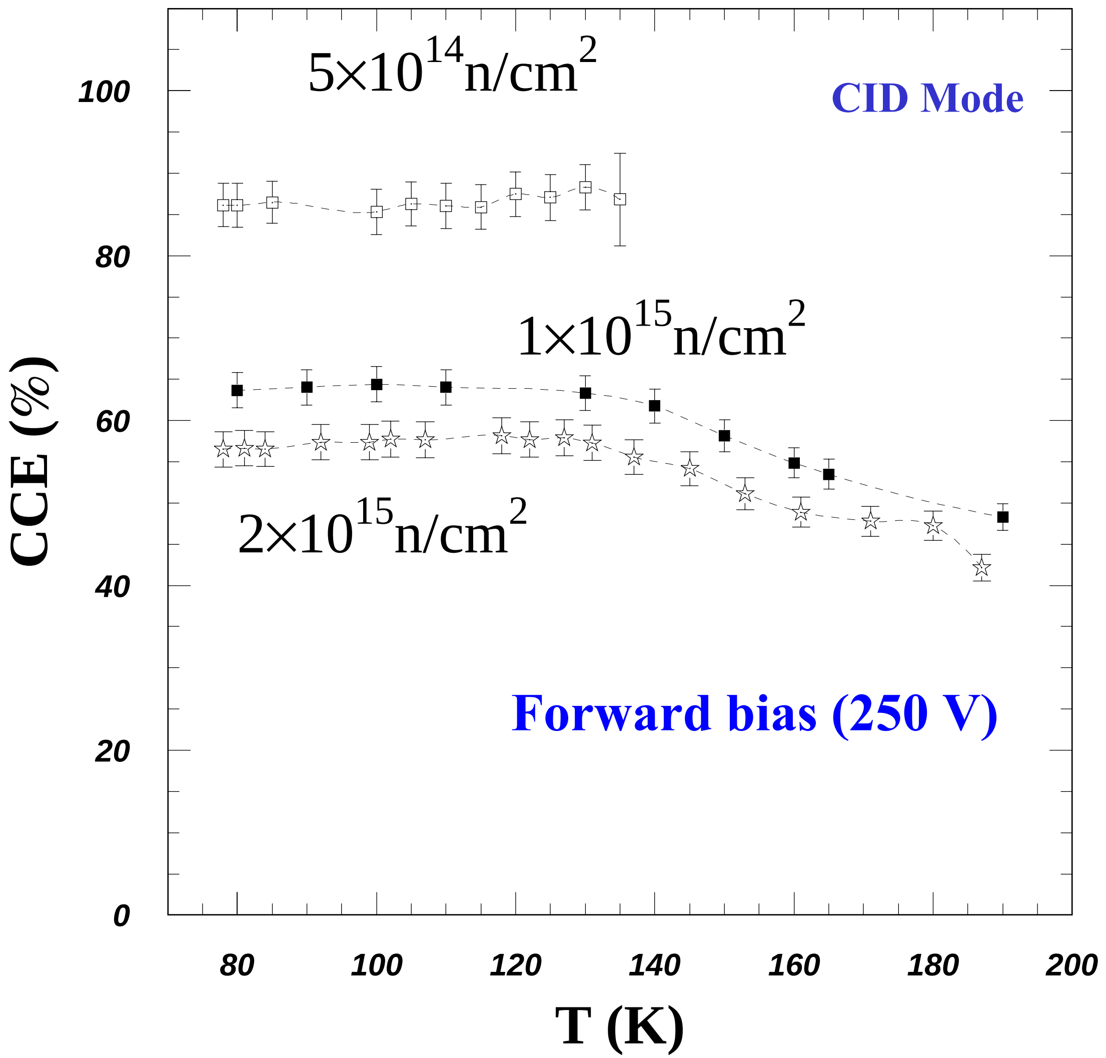


MCz-Si 9MeV proton irradiated 7×10^{15} 1MeV n_{eq}/cm^2

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 ↑**

CCE to 90Sr source at various temperatures for CID



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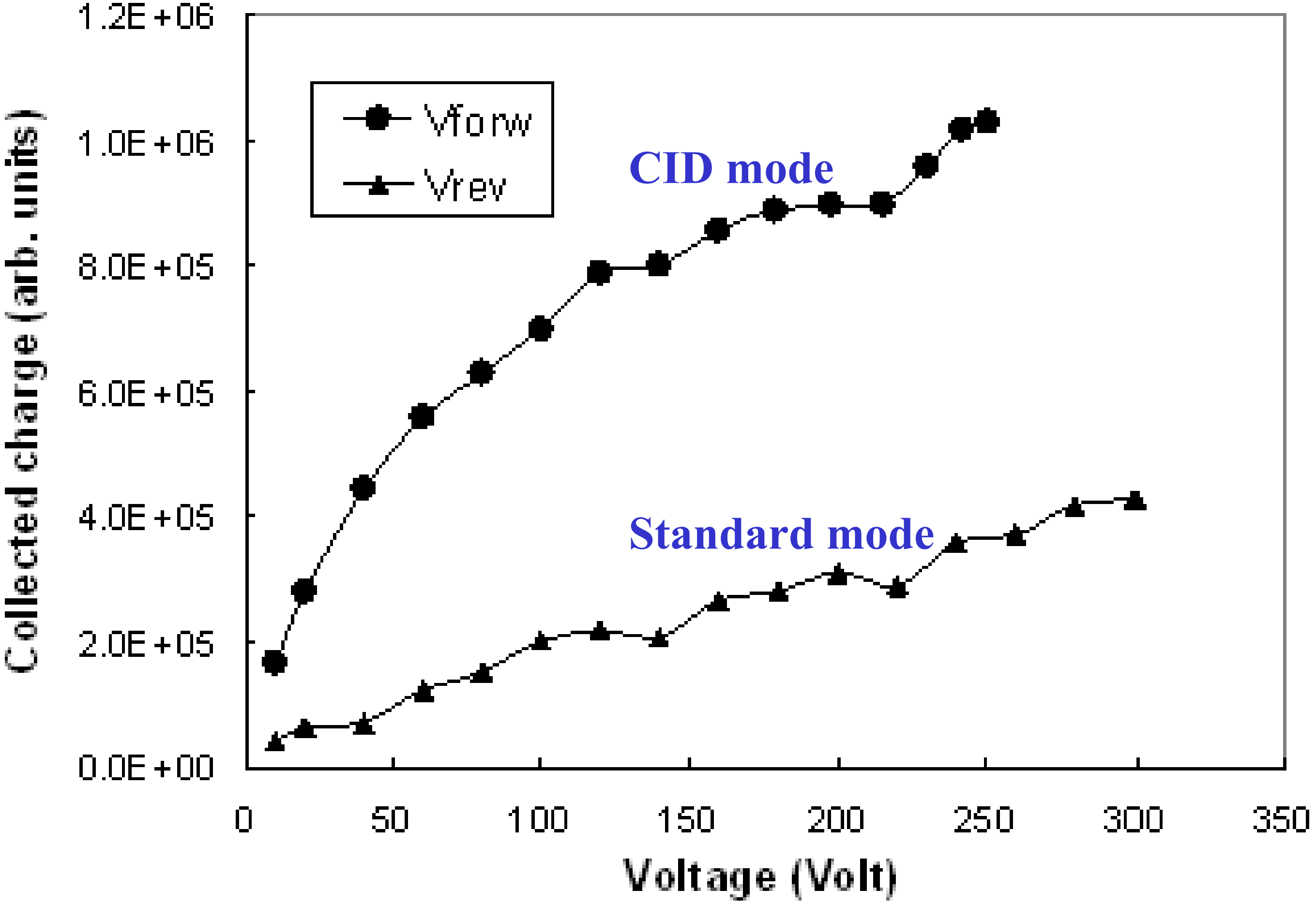
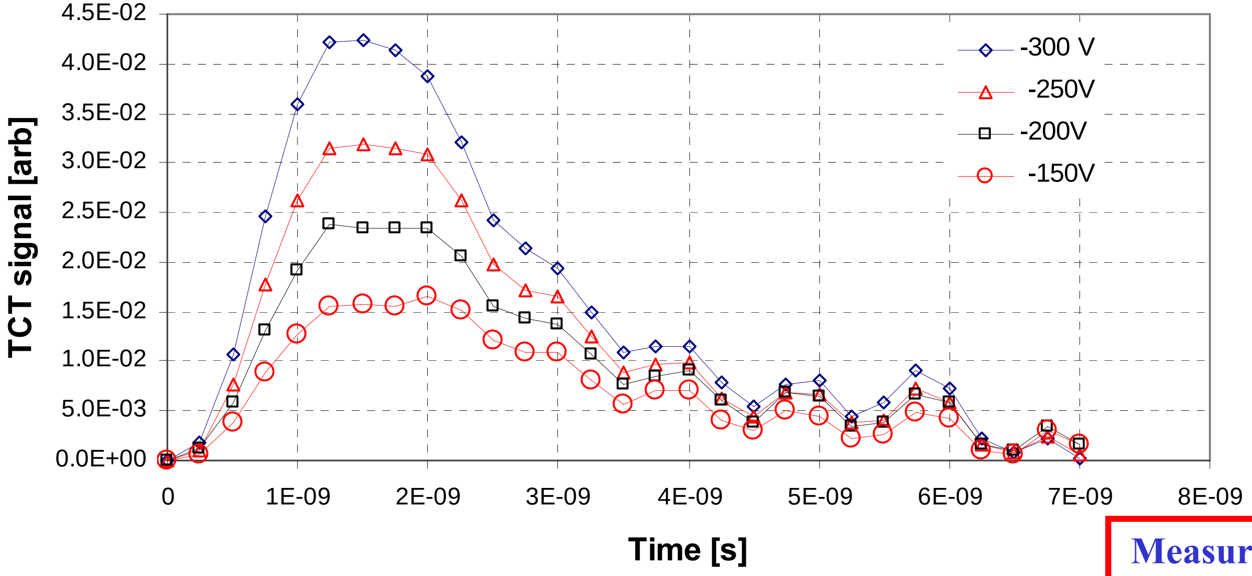
$\Phi_n = 1\times10^{15}$ cm^{-2}, T = 180 K, MIPs (1050 nm laser)

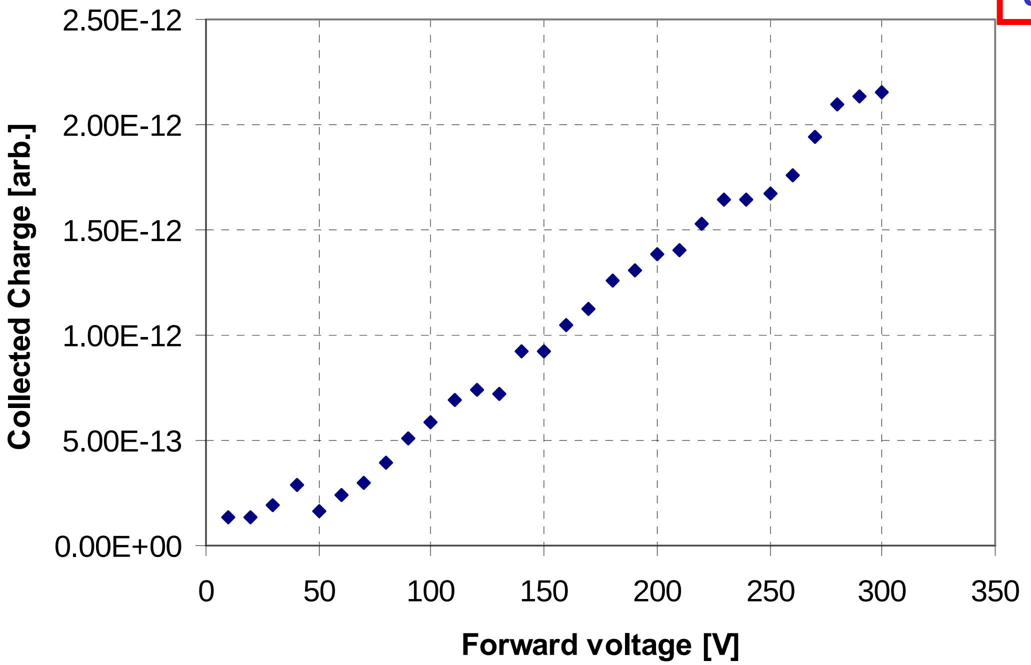


CID mode



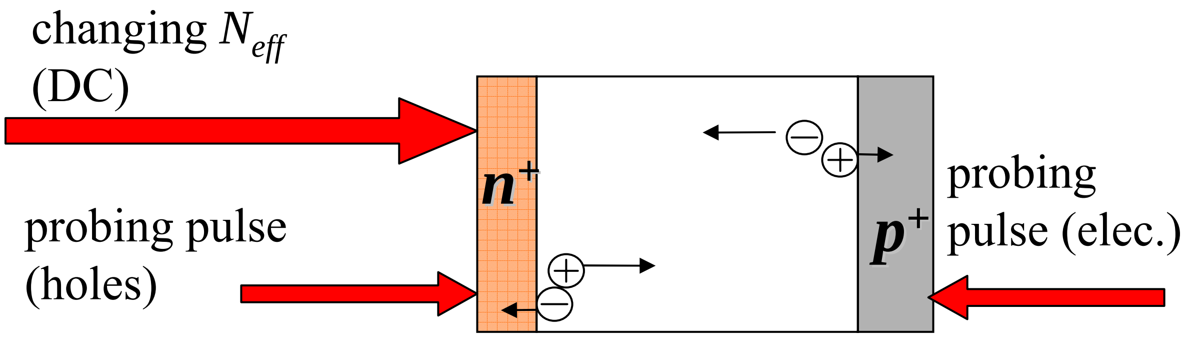
Measurements from He cryostat, at 60K

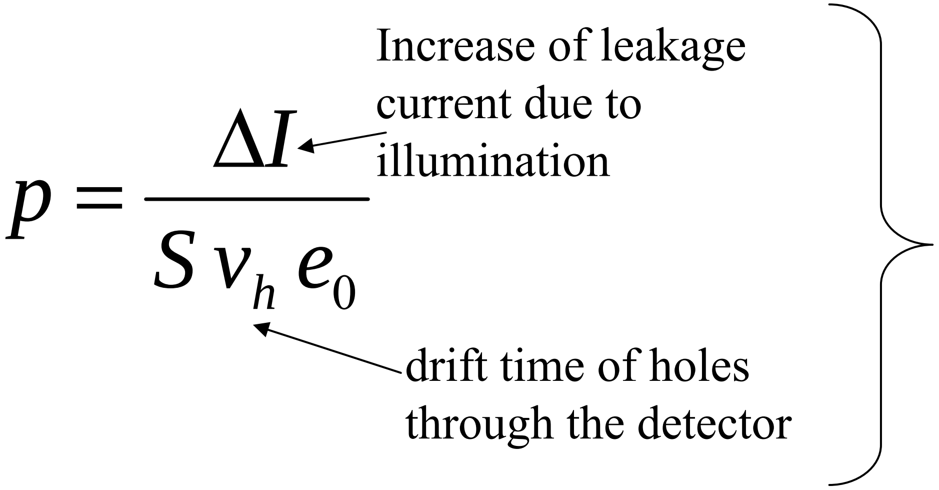
P-type MCZ,
red laser
$1x10^{15}/cm^2$



Charge Injected Diode

high *p* : continuous (DC) illumination of n+ side by red laser:



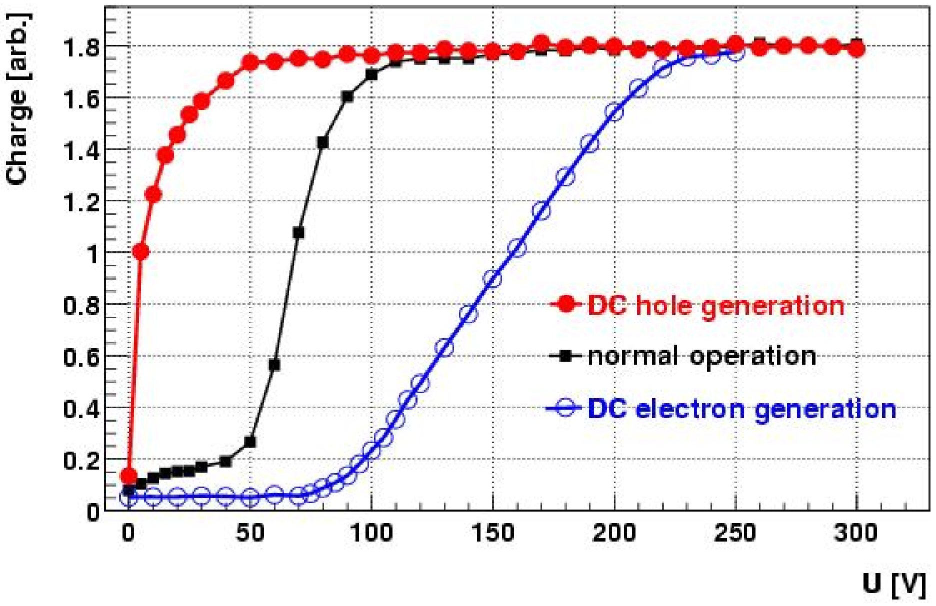


$$p = \frac{\Delta I}{S\, v_h\, e_0}$$

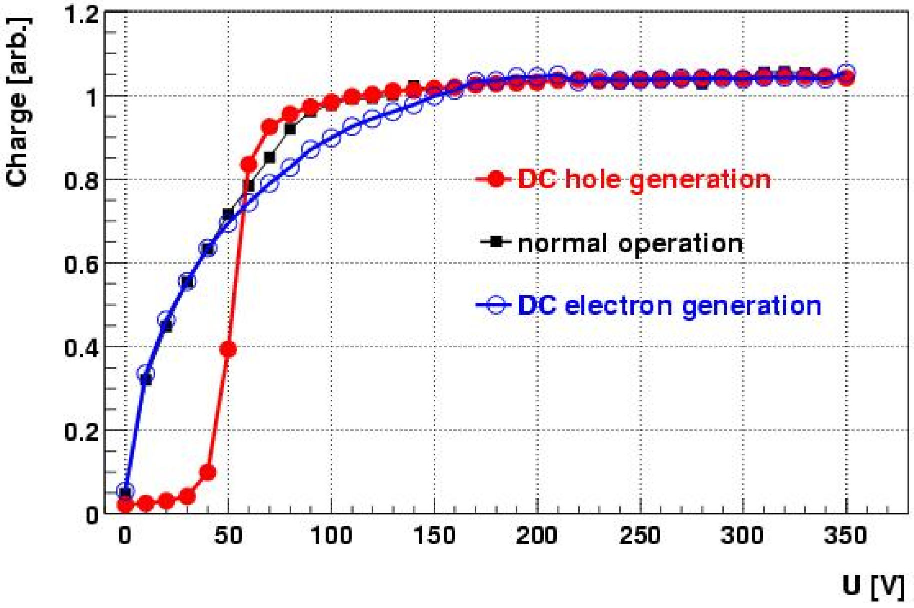
N_{eff} controlled by:

- illumination intensity (*p*)
- operation voltage (*p*)
- temperature
(trapping -detrapping process)

Charge Injected Diode



electron current pulse



hole current pulse

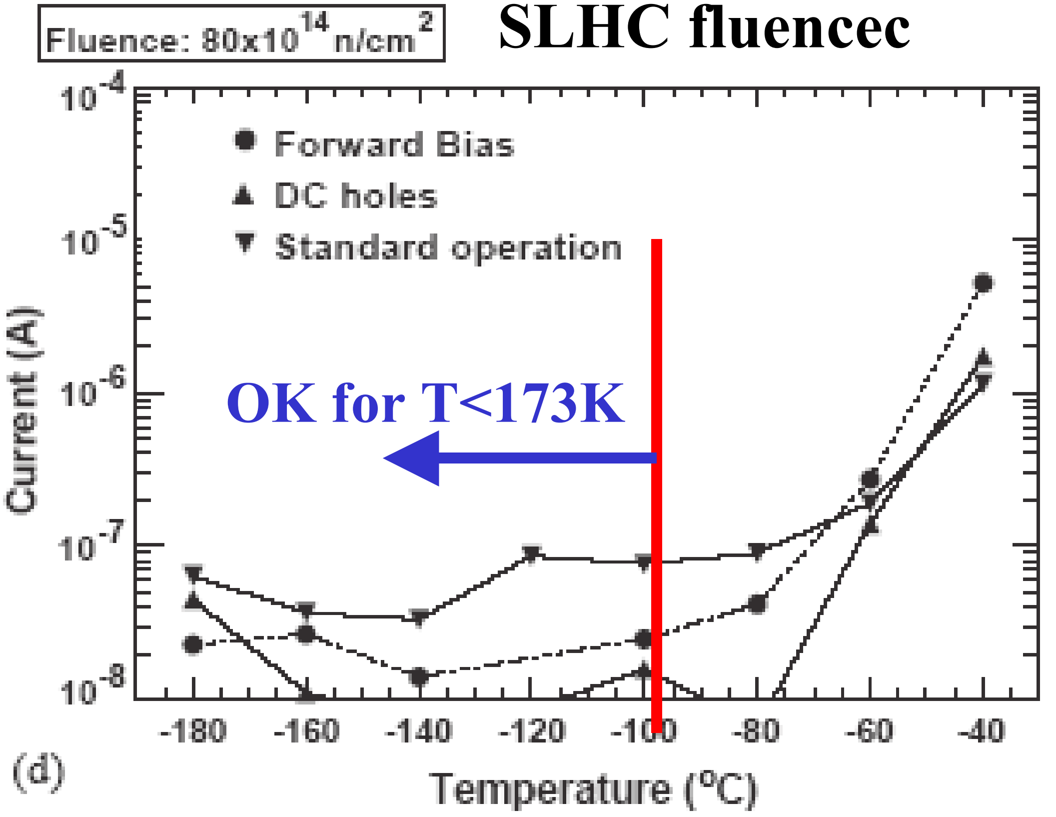
$\Phi_{eq}=5x10^{13}$ cm^{-3} (after ~10 days at 20^{o}C)

A significant reduction of V_{FD} in case of continuous hole injection!

CCE Measurements on CID

DC injection with a red laser (electrons or holes)

Or current injection (forward bias)



SLHC fluencec

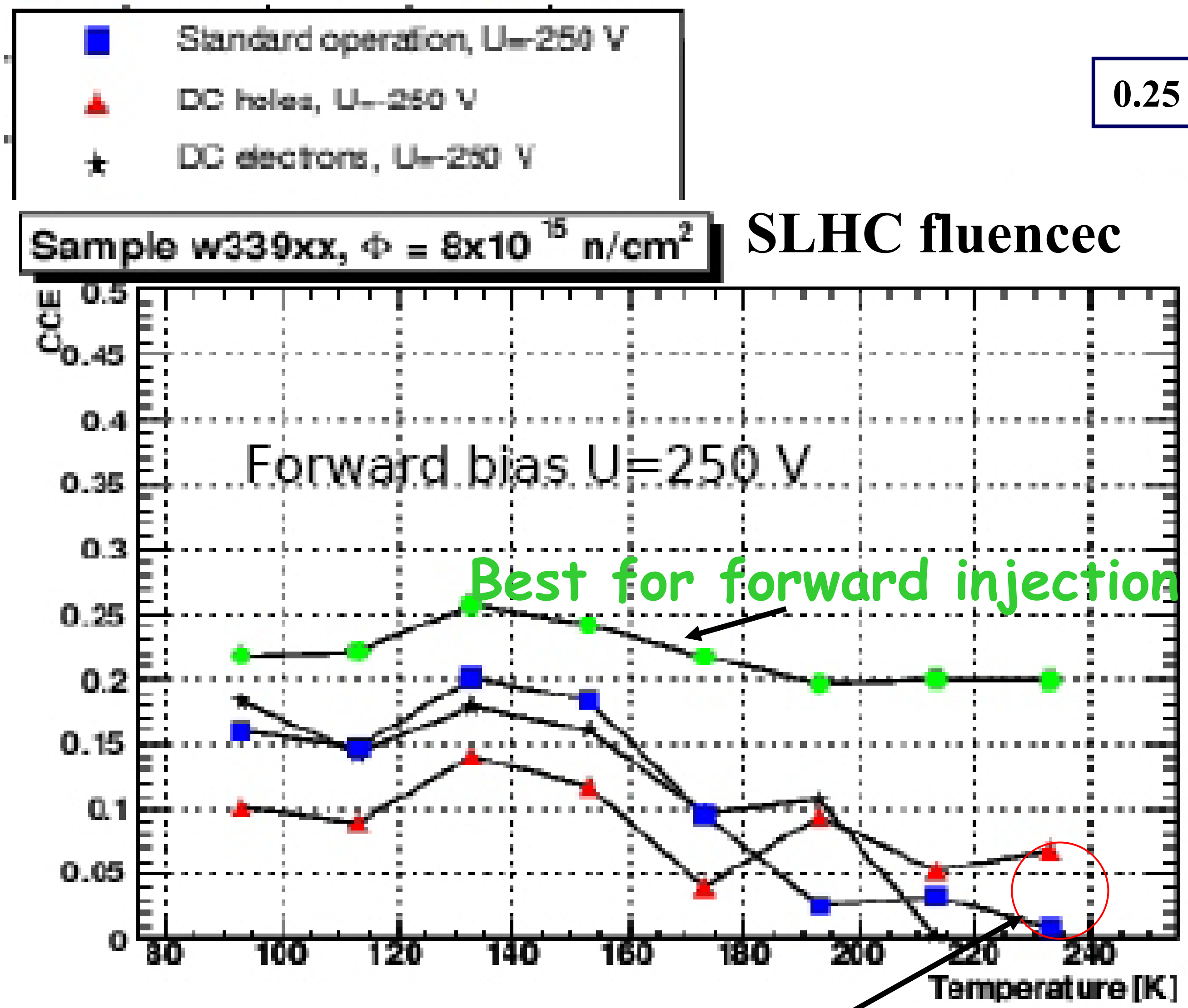
OK for T<173K

0.25 cm^2

CCE to ^{90}Sr source at various temperatures for CI

0.25 cm^2

SLHC fluencec



Best for forward injection

Close to 0 at RT!

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Summary

- To increase CCE for SLHC, cryogenic operation of Si detectors at cryogenic temps may be necessary

  Trapping can be frozen at such low temps

  CID can stablize the detector electric field and increase the detector CCE

  CCE measurements on CID at crogenic temperatures with laser and forward current injection have shown significant increase in CCE