CCE of heavily irradiated Si diodes operated with increased free carrier concentration and under forward bias

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Motivation:

- LHC upgrade ➔ relevant fluences: 10^{16} n/cm^2
- standard Si detectors operated in standard way will be very difficult if not impossible to use

  - check the alternative way of operation with heavily irradiated standard detectors:
    - ✓ forward bias

      A. Chilingarov et al., NIM A399 (1997) 35.
    - ✓ increased carrier concentration with DC light illumination

      V. Eremin et al., NIM A360 (1995) 458
      G. Lutz, NIM A377 (1996) 234.
      G. Kramberger et al., NIMA A497 (2003) 440.
    - ✓ cryogenic temperatures

      V. Palmieri et al., NIM A413 (1998) 475.
      K. Borer et al., NIM A440 (2000) 5.

  - measure CCE with ^{90}Sr source

Samples and Setup:

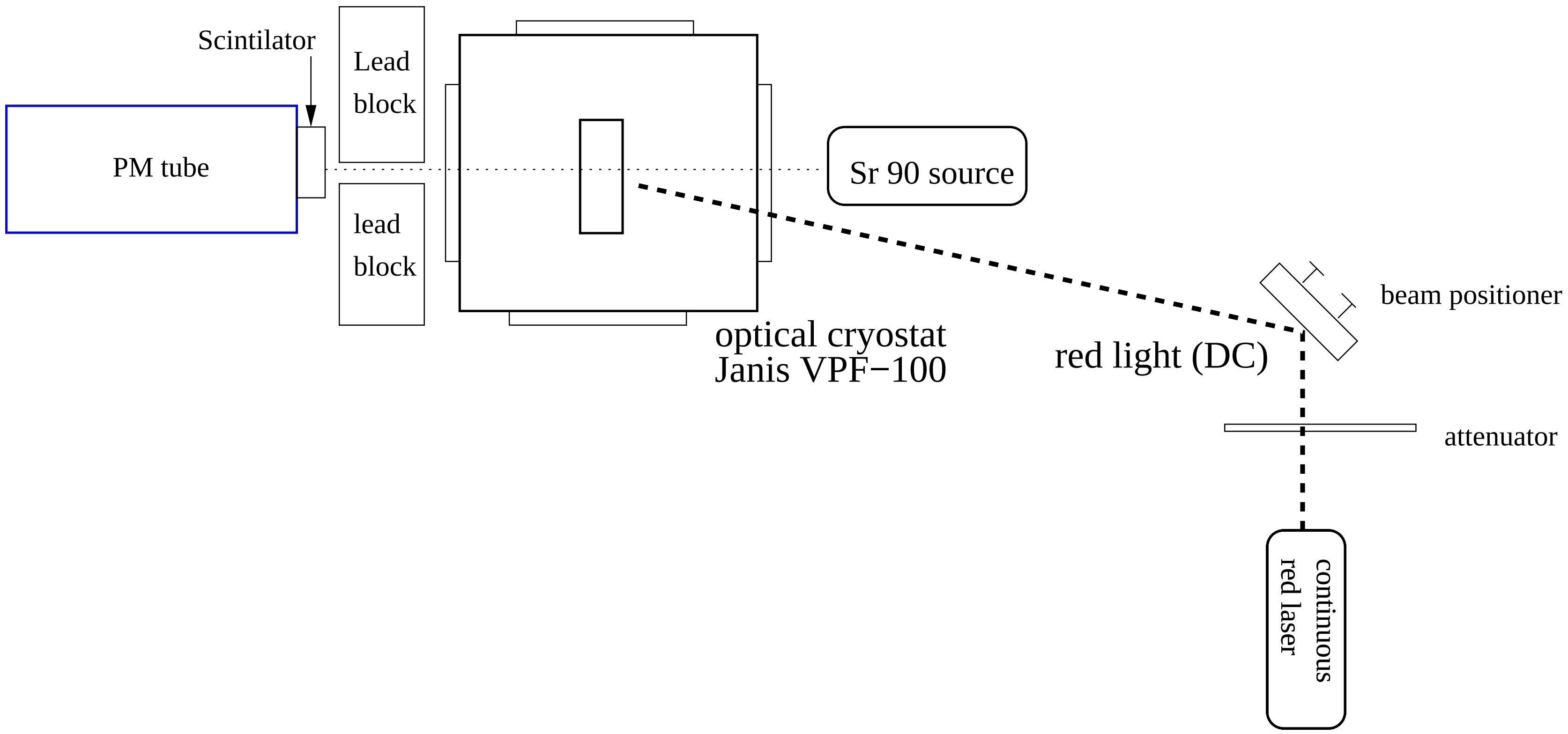
- 4 diodes: $S = 0.5 \times 0.5\ cm^2$, $D = 300\ \mu m$, $\rho = 15\ k\Omega cm$

- irradiated with neutrons in TRIGA reactor in Ljubljana.
  Equivalent fluences: 5×10^{14}, 1×10^{15}, 4×10^{15} and $8 \times 10^{15}\ n/cm^2$

- diodes were kept for 14 days at room temperature after irradiation.
  After that they were stored at T = -17°C

- CCE was measured on our TCT setup:
    - liquid nitrogen cryostat which allows illumination of diodes with laser
    - ^{90}Sr source with set of collimators
    - trigger provided by scintilator + PMT (rate ~ 5 events/s)
    - MITEQ AM-1309 wide band current amplifier
    - digital oscilloscope
    - pulses were stored in computer and integrated in 18 ns time window offline
    - spectra of integrated pulses were fitted with convolution of Landau and Gaussian distribution
    - collected charge measured with unirradiated diode used as normalization to calculate CCE

Setup:


Scintilator
Lead
block
PM tube
lead
block
Sr 90 source
optical cryostat
Janis VPF−100
beam positioner
red light (DC)
attenuator
continuous
red laser

Reverse bias, DC illumination of n side with red light (hole injection):

- injection of holes into irradiated detector influences the occupation probability of deep levels:
  - ➢ it reduces the concentration of negative space charge (trapping of holes)
    - ➔ lower full depletion voltage
    - ➔ effective space charge sign can be reinverted to positive

More in: G. Kramberger et al., Nucl. Instr. and Meth. A497 (2003) 440.

- Measurements of CCE with DC light illumination were done with high light intensity (in “saturated” mode)

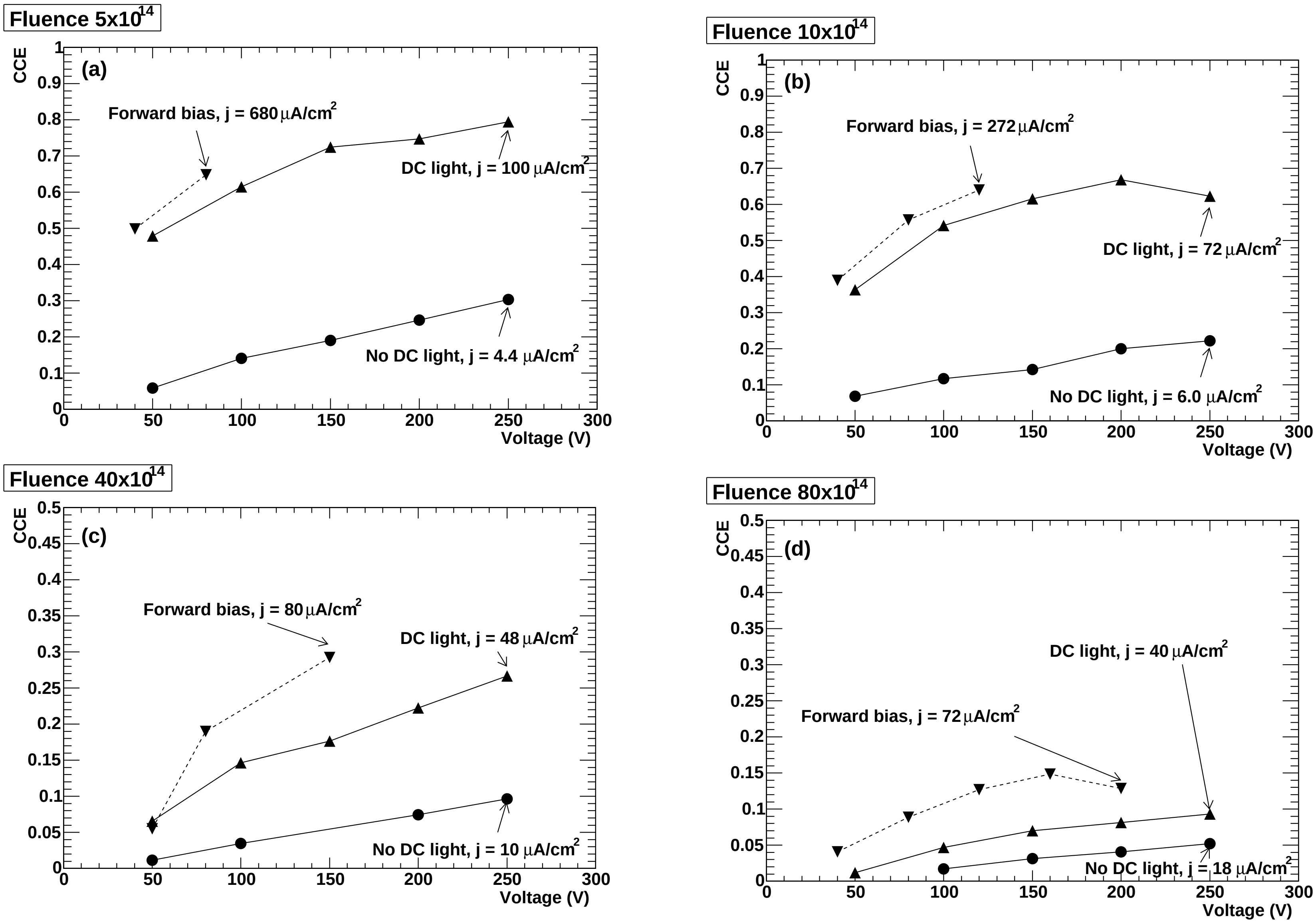
  - ➢ once the light intensity is high enough high field region moves from n-side to p-side (the space charge sign is re-inverted).

  - ➢ increasing the light intensity beyond this point doesn’t change the space charge much, because the e-h pairs created in the low field region recombine
    - ➔ Current vs. light intensity curve saturates

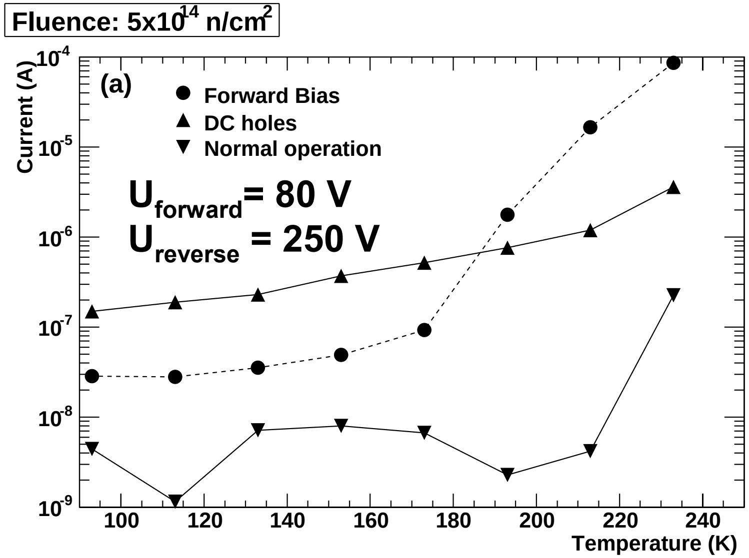
  ➔ CCE doesn’t depend much on light intensity once it is high enough

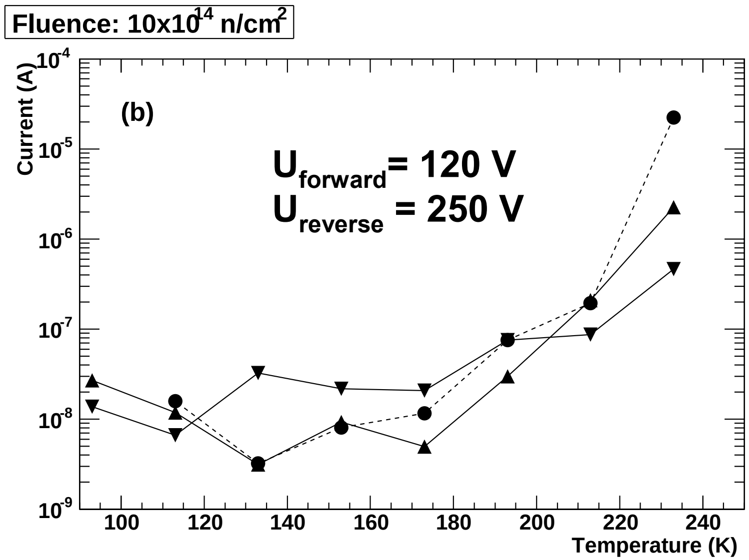
CCE vs. bias voltage for standard operation, DC light (hole injection) and forward bias

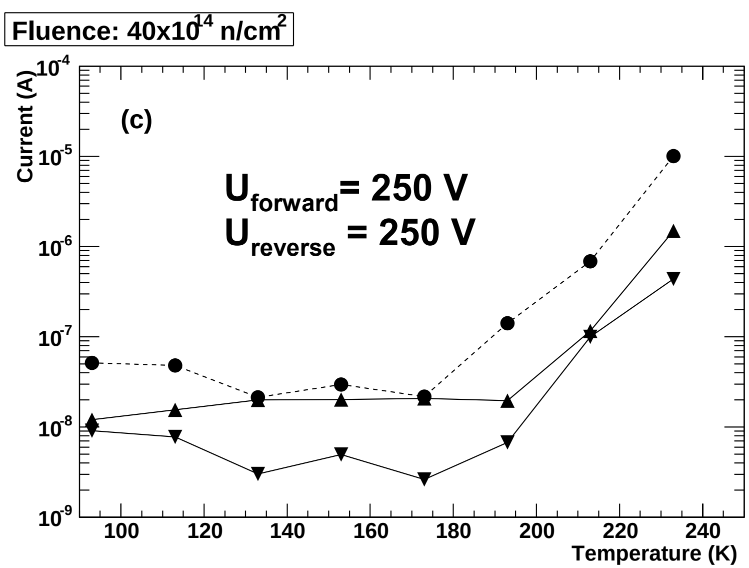
T=-30˚C Highest CCE at given voltage measured with forward bias!

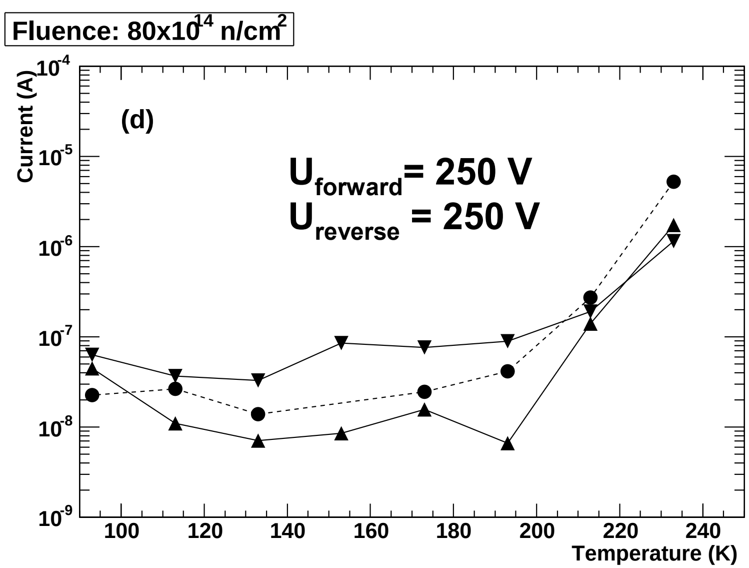


Current measurements at different temperatures and modes of operation

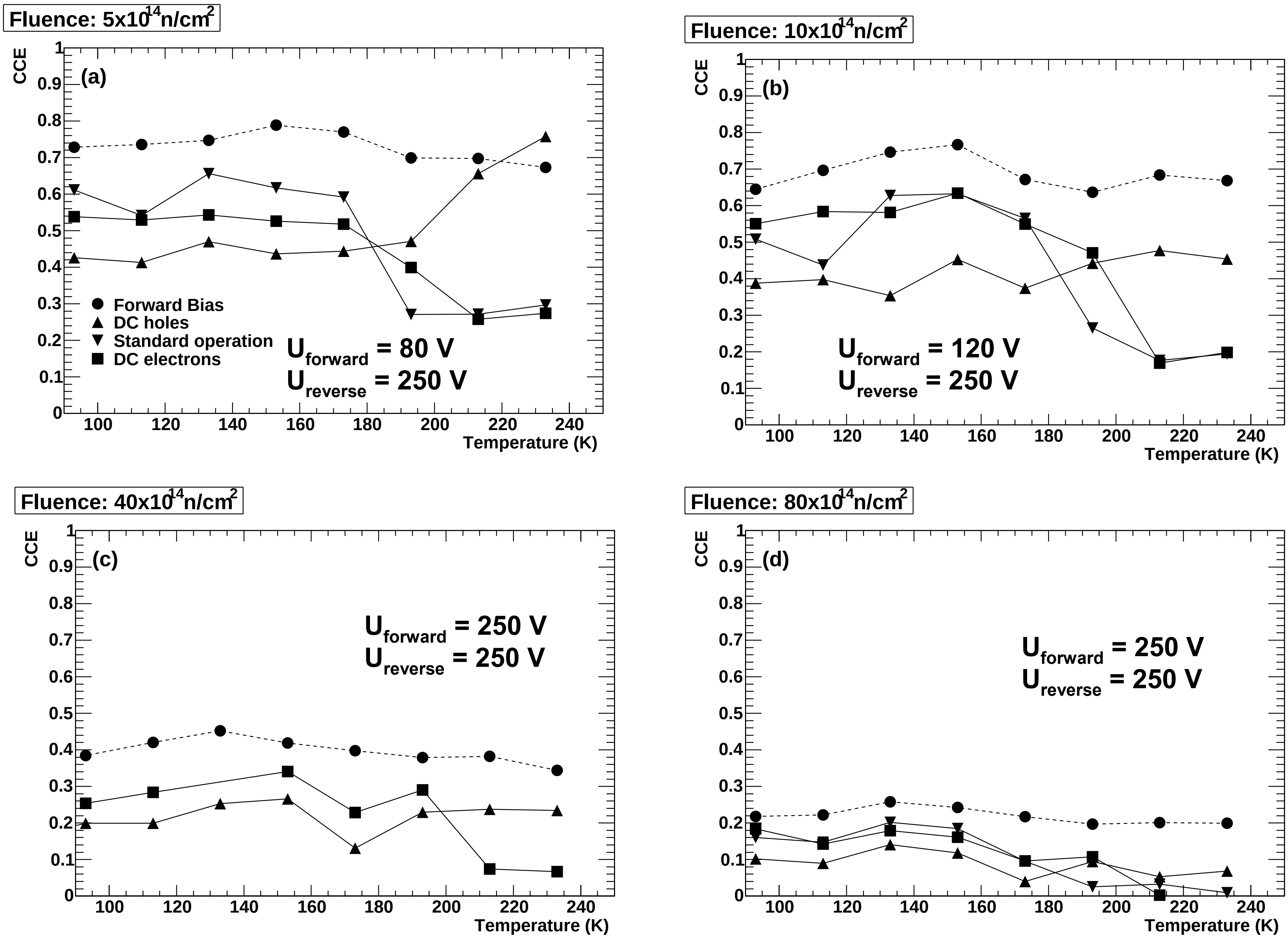








- CCE vs. temperature



- CCE under forward bias doesn't change much with temperature

- Hole injection:
  - transition from beneficial to harmful with falling T at low fluence
- Standard mode or electron injection:
  - improvement with falling T
  - ➔ both transitions occur between 180 and 220 K

These results agree with Space Charge Sign Inversion occurring in this temperature range.
Temperature of transition agrees with temperatures of SCSI and CCE transitions reported in the RD39 paper:
E. Verbitskaya et al., NIM A514 (2003) 47-61.

Attempt of CCE calculation

- two dominant deep traps:

	$E_t - E_v$ (eV)	g_t (cm^{-1})	σ_e (cm^2)	σ_h (cm^2)
acceptor	0.57	1	15×10^{-15}	2×10^{-15}
donor	0.52	0.07	1×10^{-15}	300×10^{-15}

- parameters of the traps chosen from parameter intervals of dominant electron and hole trap from the paper:

G. Kramberger et al., "Determination of the effective electron and hole trap in neutron-irradiated silicon detector" NIM A516 (2004) 109

- effective space charge and trapping times were calculated using equations for defects in general stationary state:

$$P_t = \left[\frac{c_p p + c_n n_i \chi_t}{c_n n + c_p n_i / \chi_t} + 1 \right]^{-1}, \chi_t = \exp(\frac{E_t - E_i}{k_b T})$$

- contribution of the trap to the space charge is given by:

$$Q_t = e_0 g_t \Phi_{eq} (k - P_t)$$ *k = 0,1* (donor, acceptor)

- effective trapping times for electrons and holes are obtained from:

$$1/\tau_e = v_{the} \sigma_e (1 - P_{te}) g_e \Phi_{eq}$$

$$1/\tau_h = v_{thh} \sigma_h P_{th} g_h \Phi_{eq}$$

- Free carrier concentration was estimated from current measurements. In the case of standard and forward bias operation it was assumed (simplification!) that electrons and holes contribute equally to the current. Therefore concentration of electrons and holes was estimated as:

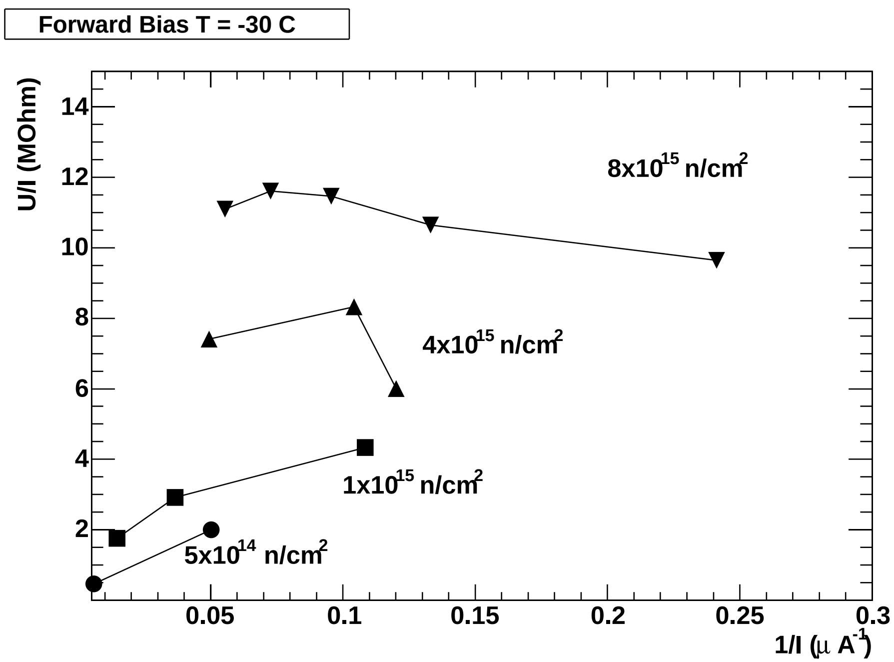
$$n = \frac{I}{2 \cdot S \cdot v_e} \qquad p = \frac{I}{2 \cdot S \cdot v_h}$$

- In the case of DC light illumination the additional carrier density was estimated from measurement of current increase, taking into account the surface of the illuminated area and the side of illumination.

Forward bias:

- electric field in forward bias approximated with $E = V_{bias}/D$ in the whole detector volume

- at high fluences forward bias I-V dependence is almost ohmic and one can calculate resistance of the material as $R = V_{bias}/I$



Resistance vs. 1/I in forward bias

Resistance at high fluence very high: 100 MΩcm at 8×10^{14} n/cm^2

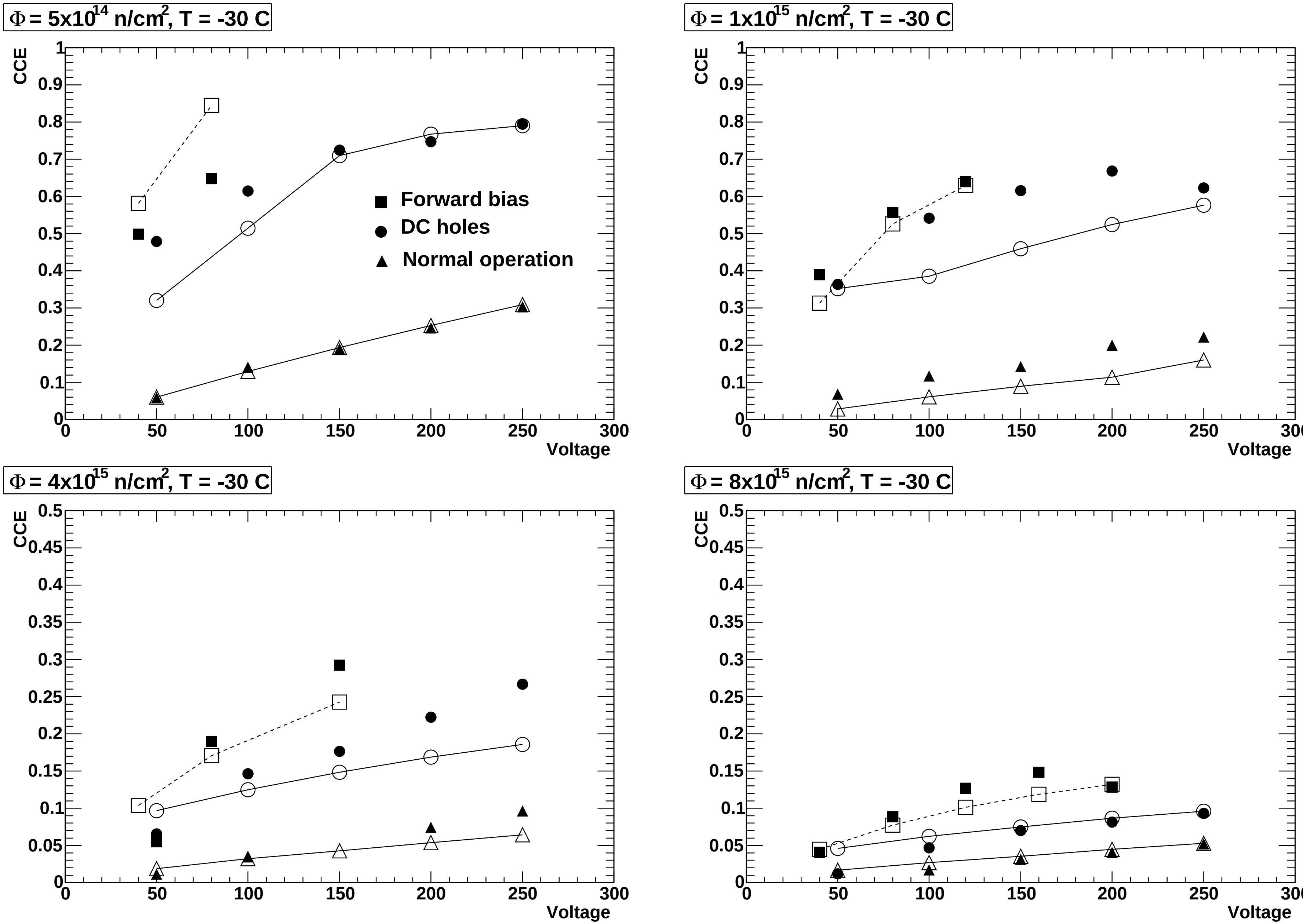
➔ also in reverse bias there should be significant voltage drop and therefore electric field in the undepleted region because of current flow: $E = \rho \cdot j$, (ρ = resistivity, j = current density)

➔ "undepleted" bulk should contribute to CCE

- in reverse bias: $U_{bias} = U_{junction} + I \cdot R$, ($R$ – resistance, I – current)
- in the junction $w=\sqrt{(2\varepsilon\varepsilon_0 U_{junction}/e_0 N_{eff})}$ el. field is $E_j \sim N_{eff} \cdot x$
- total field $E = E_j + j \cdot \rho$ inside the junction and $E = j \cdot \rho$ elsewhere

CCE vs bias voltage at T = -30C

Full markers: measurements, empty markers: calculation

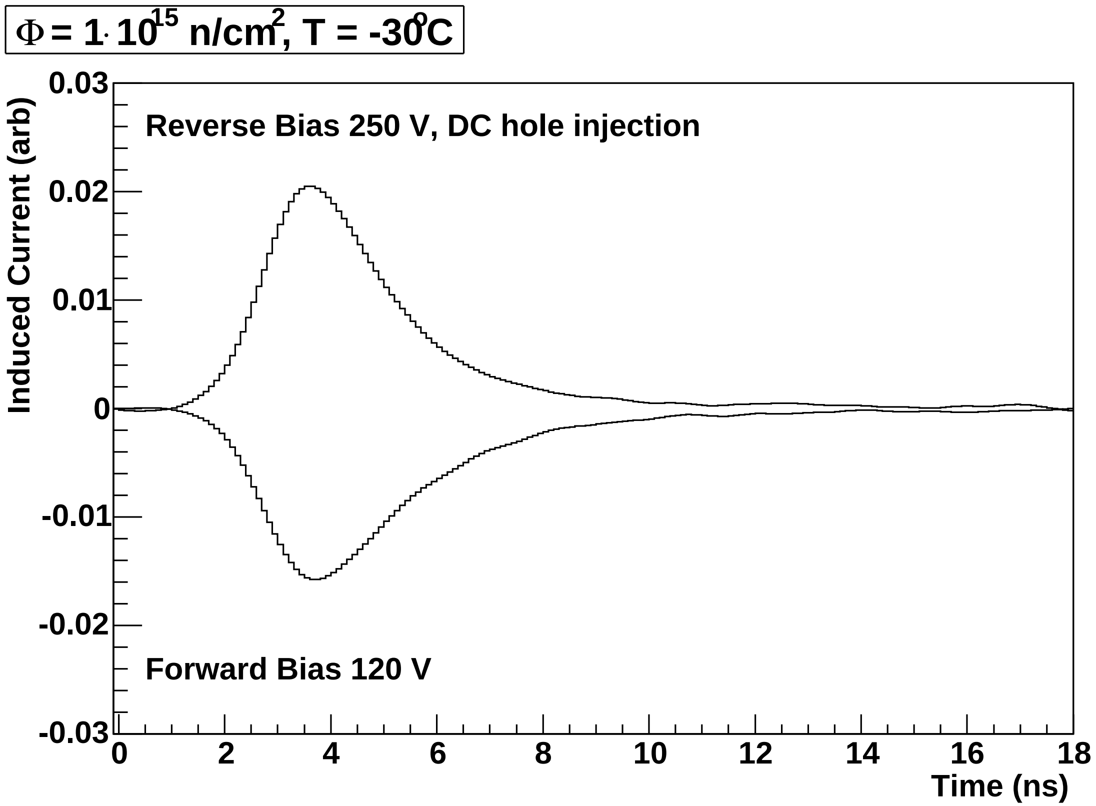


Conclusions:

- DC hole injection and forward bias operation greatly improve CCE at moderate voltages (up to 250 V) already at moderate cooling (-30°C)
- at given voltage, highest CCE achieved by operating under forward bias
- if operated at low temperature (below ~ 200 K) the problem of high current in forward bias is much smaller while CCE stays constant
- increase of CCE seems to be caused by increase of sensitive depth of the detector and to lesser extent by change of trapping times
- trapping is the main limitation for using standard Si detectors at high fluences $\Phi_{eq} > 10^{15}$ n/cm^2

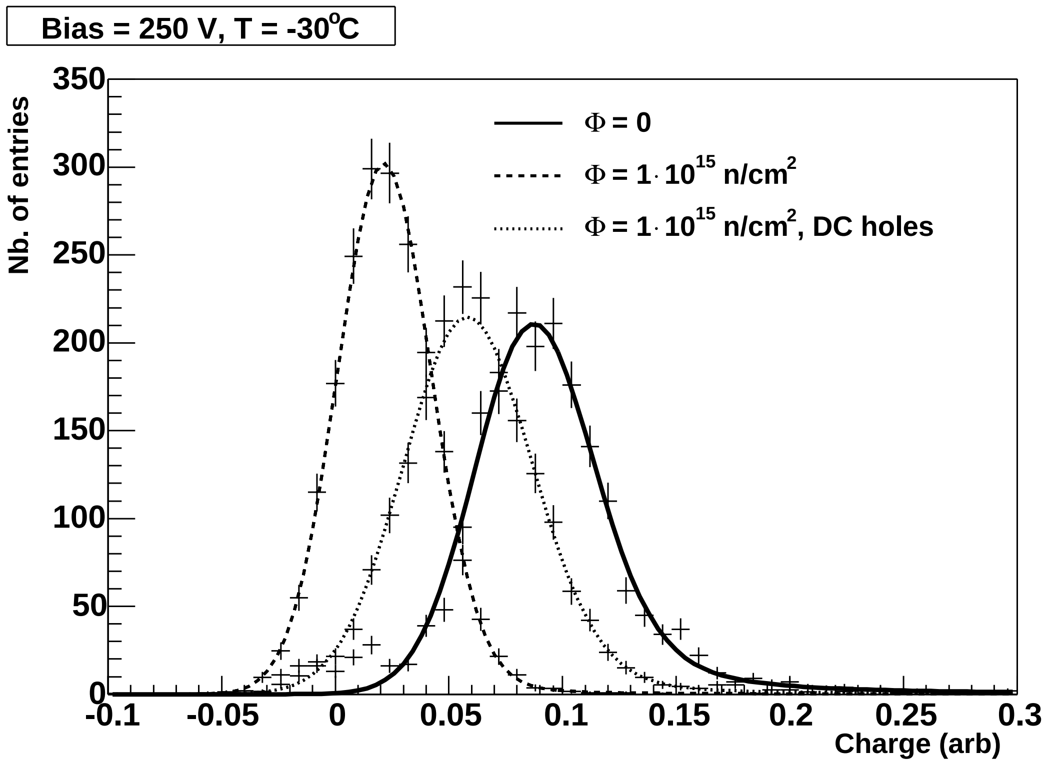
Examples of signals:

- averages of 5000 events:

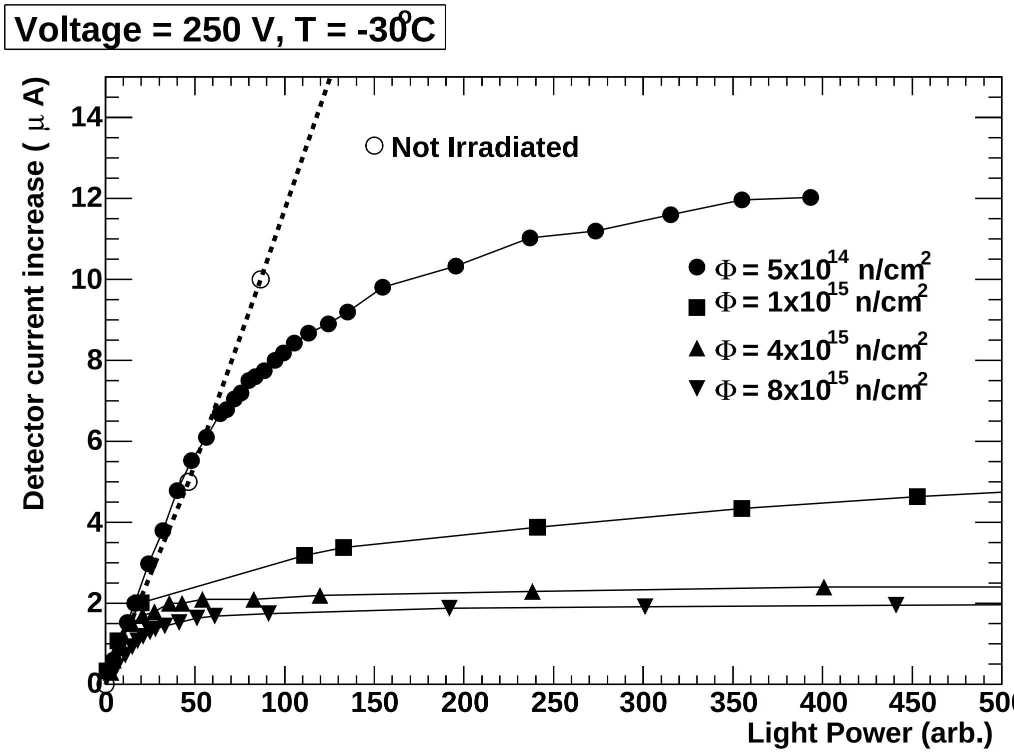


- spectra of integrated pulses were fitted with convolution of Landau and Gaussian distribution. The most probable value of the Landau distribution returned by the fit was taken as the measure of collected charge.
- collected charge measured with unirradiated diode was used as normalization to calculate CCE

Examples of fitted spectra:



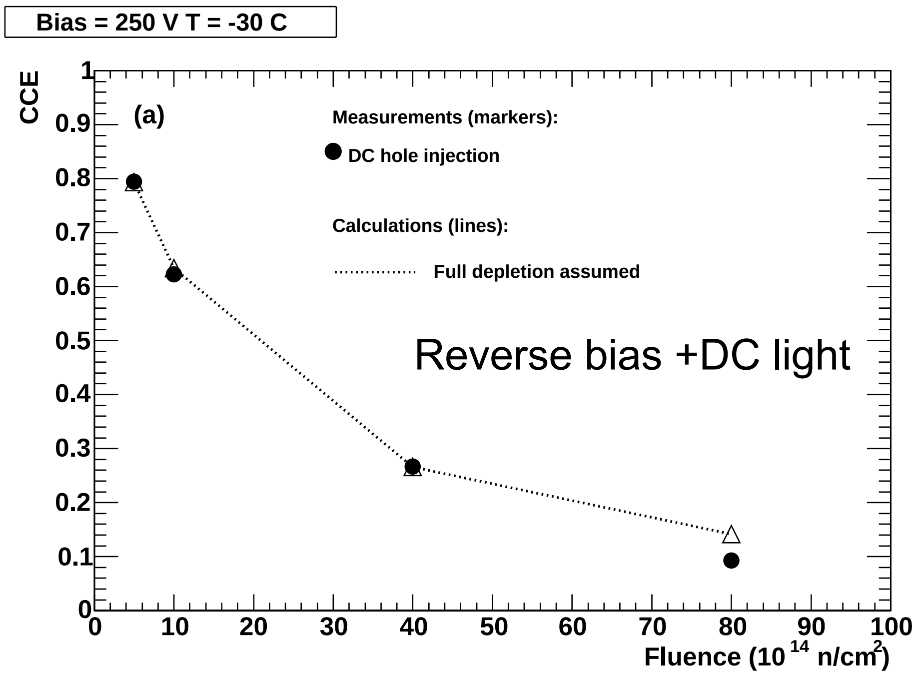
➔ CCE doesn't depend much on light intensity once it is high enough

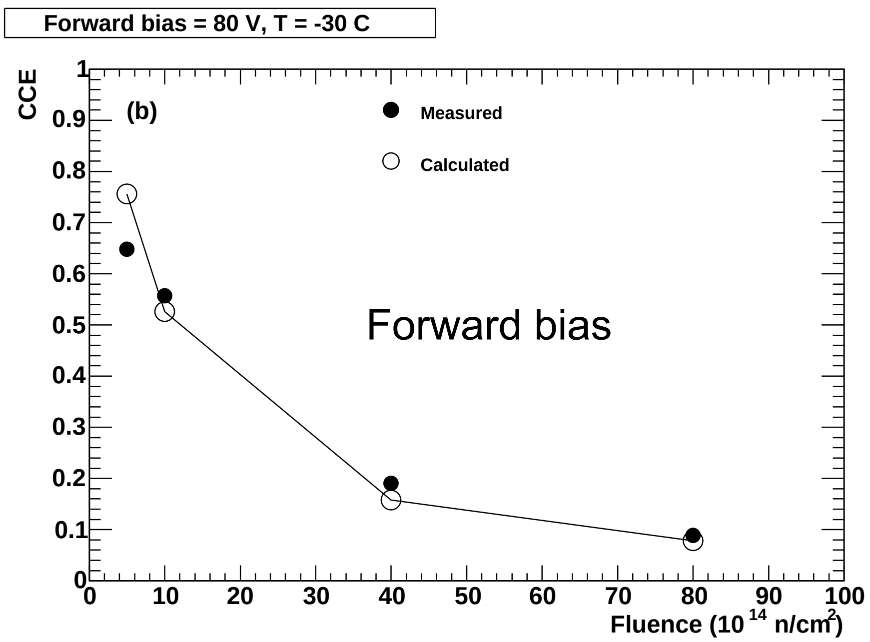


Measurements of CCE with DC light illumination were done with high light intensity (in "saturated" regime)

- calculate CCE vs. fluence at -30°C

  ➔ best agreement for DC light injection and forward bias if in both constant field *E* = *V/D* assumed in the whole detector at all fluences so that CCE is a function of trapping only

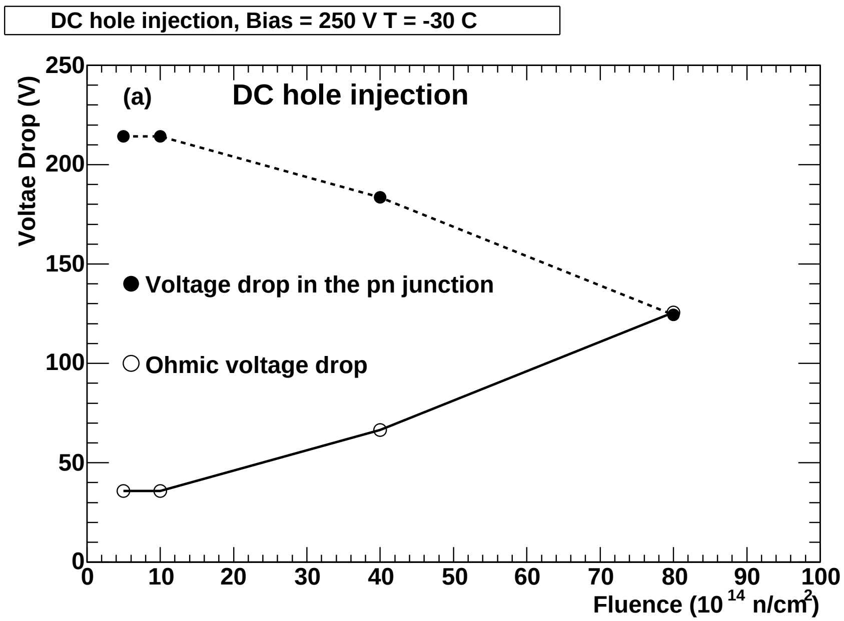




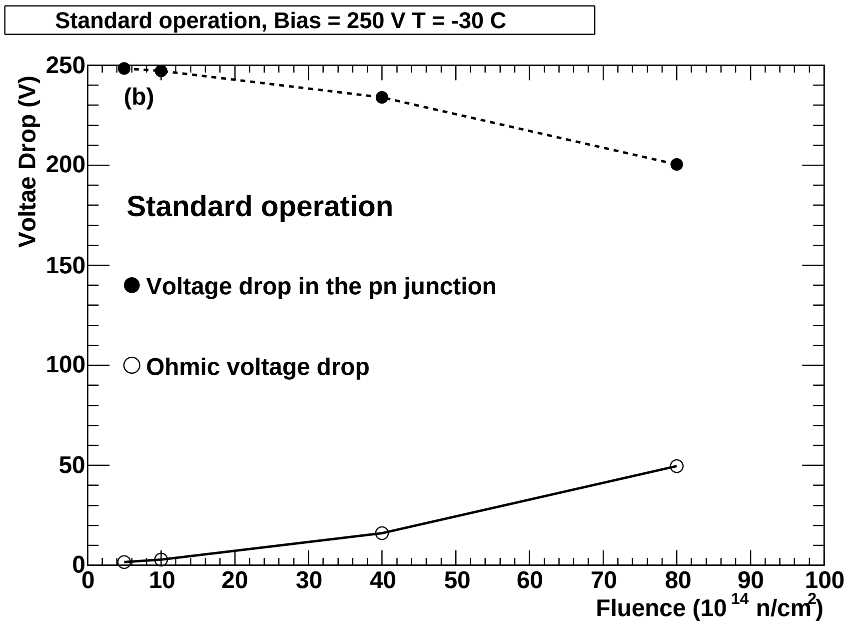
Measured and calculated CCE

Ohmic voltage drop ($I \cdot R$) and voltage drop in the junction ($V_j = V_{bias} - I \cdot R$)

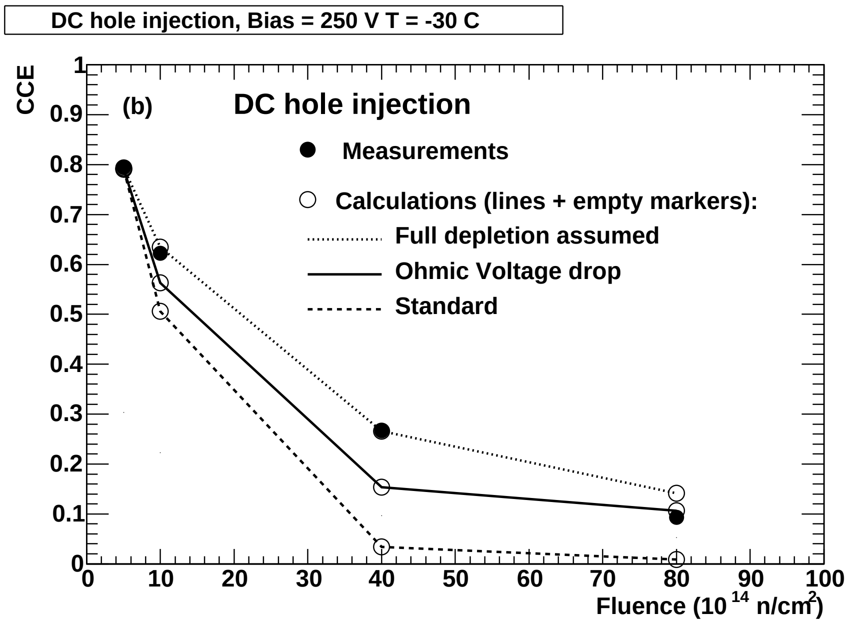
DC hole injection:

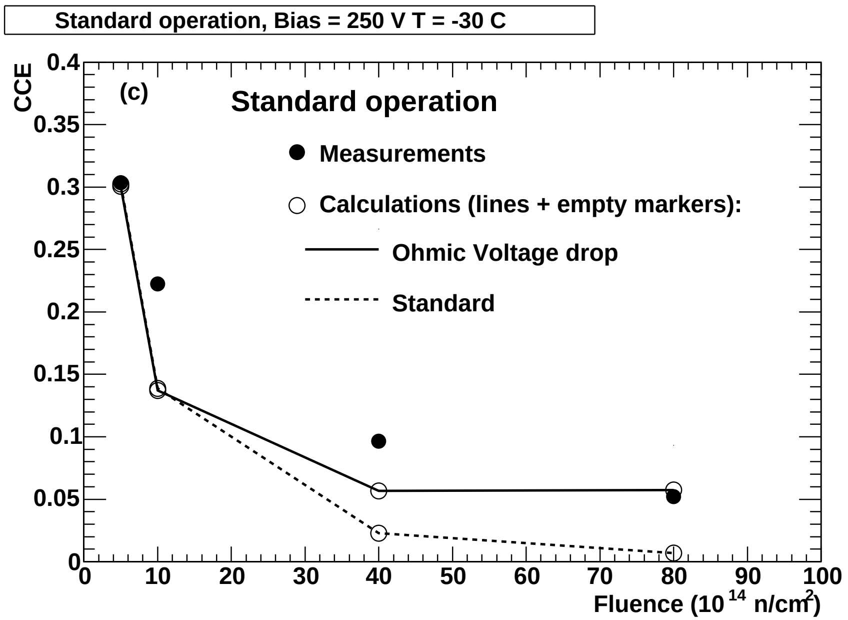


Standard operation:



Different calculations of CCE compared to measured CCE:





Disagreement smaller if *ohmic voltage drop* is taken into account.