Radiation damage models: comparison between Silvaco and Synopsys

J. Beyer[a)], M. Bomben [b)], A. Macchiolo[a)], R. Nisius[a)]

[a)]Max Planck Institut für Physik, München

[b)] LPNHE & Université Paris Diderot, Paris

20-22.11.2017

31st RD50 Workshop

Introduction & Outline

TCAD simulation became an essential tool when designing silicon pixel sensors and predicting their properties.

Two main tools are available: Silvaco and Synopsys TCAD tools.

Are they compatible with one another in default settings and simple questions?

Do common radiation damage models developed with one of them, also work for the other?

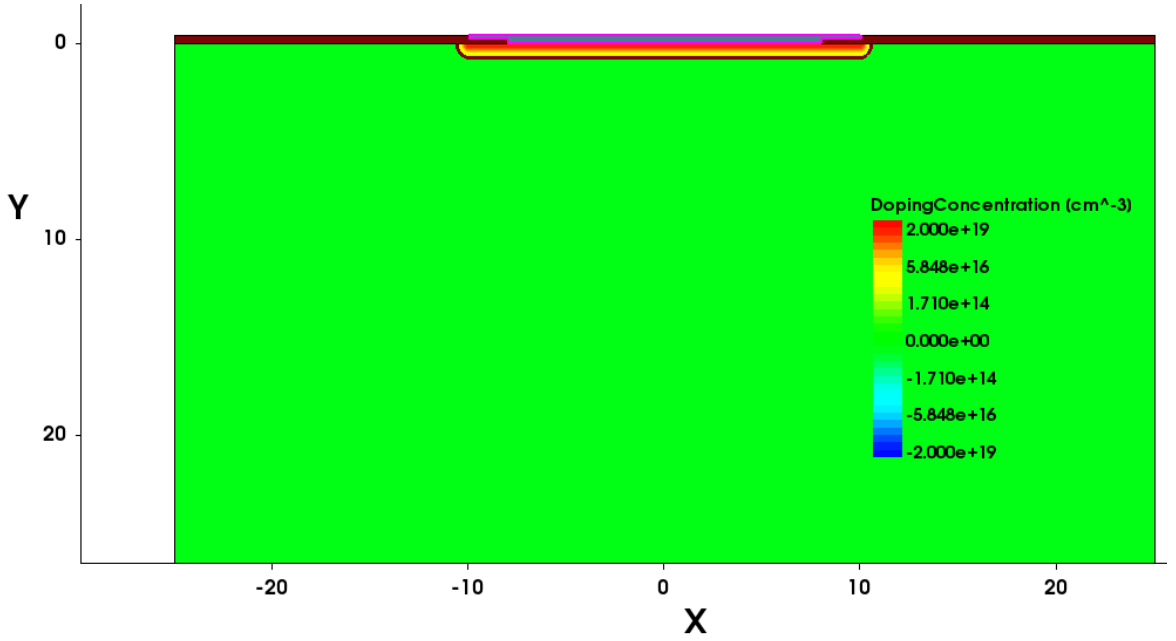
Setup for the comparison

Structure and perspectives

- use a simple 2D TCAD model to reduce any possible difference arising from different implementations of the structure

- aims:
  - compare CV and IV curves for not-irradiated case at various temperatures

  - compare CV, IV and CCE (MIP based) after irradiation
    - compare the models with one simulator
    - compare the simulators with one model



Setup for the comparison

Radiation damage models

- radiation damage in TCAD:
  - bulk damage:
    - traps characterised by energy level, e/h cross-section and introduction rate
    - use New Delhi[1] and Perugia 2017[2] irradiation model here
  - surface damage:
    - fixed oxide charge of $1\times10^{11}cm^{-2}$ for not-irradiated and $1\times10^{12}cm^{-2}$ for irradiated sensors
    - no interface traps
  - radiation level: 1×10^{15} $n_{eq}cm^{-2}$
  - temperature: -20°C, 0°C, 20°C

Perugia 2017

TABLE II
RADIATION DAMAGE MODEL FOR P-TYPE SUBSTRATES
(UP TO 7×10^{15} N/CM^2)

Type	Energy (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η (cm^{-1})
Acceptor	Ec-0.42	1×10^{-15}	1×10^{-14}	1.613
Acceptor	Ec-0.46	7×10^{-15}	7×10^{-14}	0.9
Donor	Ev+0.36	3.23×10^{-13}	3.23×10^{-14}	0.9

New Delhi

Trap Type	Energy Level (eV)	Introduction Rate (cm^{-1})	σ_e (cm^2)	σ_h (cm^2)
Acceptor	E_C - 0.51 eV	4	$2 . 10^{-14}$	$3.8 . 10^{-14}$
Donor	E_V + 0.48 eV	3	$2 . 10^{-15}$	$2 . 10^{-15}$

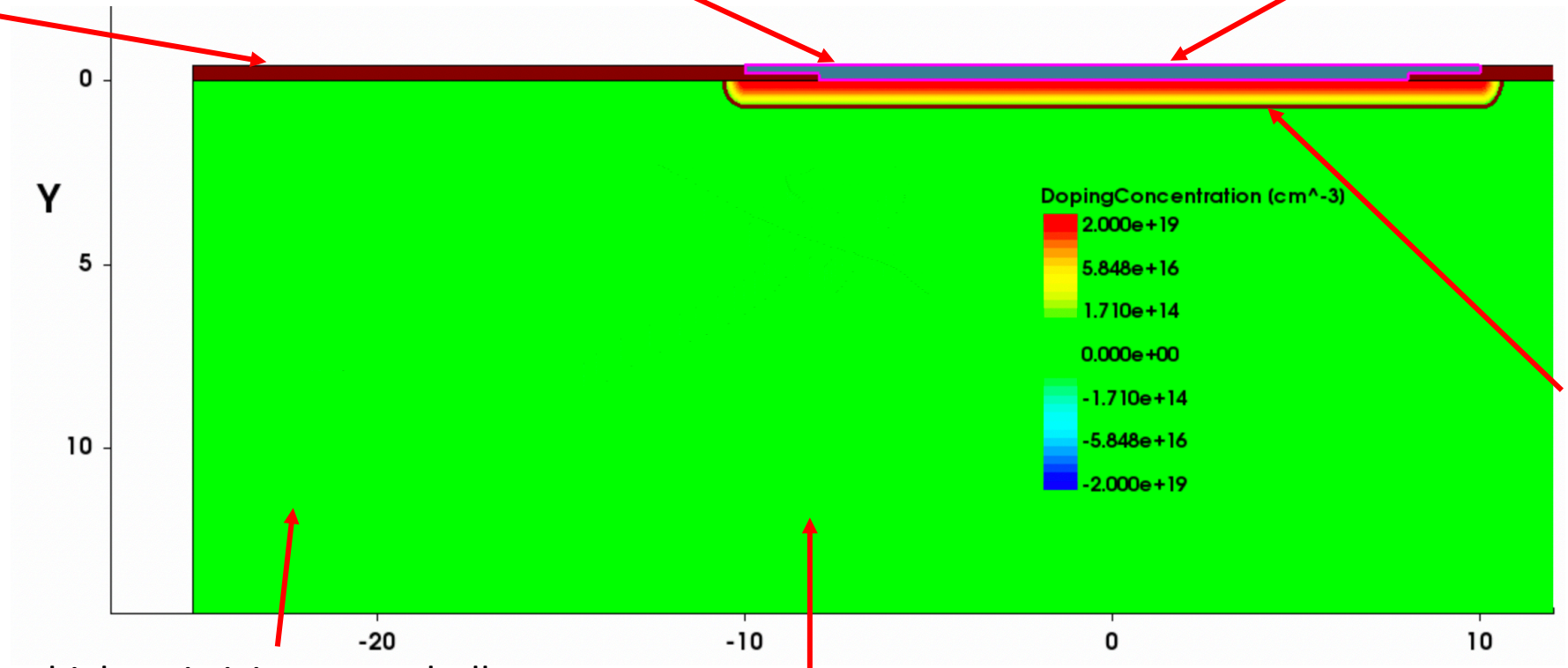
Energy levels based on work of Eremin / Verbitskaya / Li

1 R. Dalal et al., Simulation of Irradiated Si Detectors ,PoS Vertex2014 (2015).

2 F. Moscatelli et al., Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC, IEEE Trans. on Nucl. Science 2017

Setup for the comparison

Structure of interest



electrical contact on top of the aluminum

aluminum contact to implant

passivation: SiO_2

n^+ pixel implant

high resistivity p-type bulk material (3×10^{12} cm^{-3})

simulated thicknesses: 200µm

Setup for the comparison

Physics models - Synopsys

Mobility:

- doping dependent mobility according to Masetti model:

$$\mu_{dop} = \mu_{min1}\exp\left(-\frac{P_c}{N_{A,0}+N_{D,0}}\right) + \frac{\mu_{const}-\mu_{min2}}{1+((N_{A,0}+N_{D,0})/C_r)^{\alpha}} - \frac{\mu_1}{1+(C_s/(N_{A,0}+N_{D,0}))^{\beta}} \quad (245)$$

- high field saturation according to extended Canali model (Electrical field as driving force):

$$\mu(F) = \frac{(\alpha+1)\mu_{low}}{\alpha+\left[1+\left(\frac{(\alpha+1)\mu_{low}F_{hfs}}{v_{sat}}\right)^{\beta}\right]^{1/\beta}} \quad (338)$$

$$\beta = \beta_0\left(\frac{T}{300\,\mathrm{K}}\right)^{\beta_{exp}} \quad (339)$$

Recombination:

- Shokley-Read-Hall (with doping, temperature and electric field (Hurx lifetime) dependence)
- no avalanche

$$R_{net}^{SRH} = \frac{np - n_{i,eff}^2}{\tau_p(n+n_1)+\tau_n(p+p_1)}$$

$$\tau_{dop}(N_{A,0}+N_{D,0}) = \tau_{min} + \frac{\tau_{max}-\tau_{min}}{1+\left(\frac{N_{A,0}+N_{D,0}}{N_{ref}}\right)^{\gamma}} \quad (367)$$

Band-gap narrowing

- Old Slotboom

$$\chi(T) = \chi_0 + \frac{(\alpha+\alpha_2)T^2}{2(T+\beta+\beta_2)} + \mathtt{Bgn2Chi}\cdot E_{bgn} \quad (160)$$

Formulas from Synopsys sDevice manual

Setup for the comparison

Physics models - Silvaco

Mobility:

- Lookup table depending on concentration and simple power law temperature dependence.
- Field dependent mobility model: Caughey and Thomas for low field regime; Schwarz and Russe for high field

Recombination:

- Concentration dependent SRH recombination term (Roulston, Arora and Chamberlain - Law – Fossum, Lee and Lee)

Band-gap narrowing

- Klaassen model

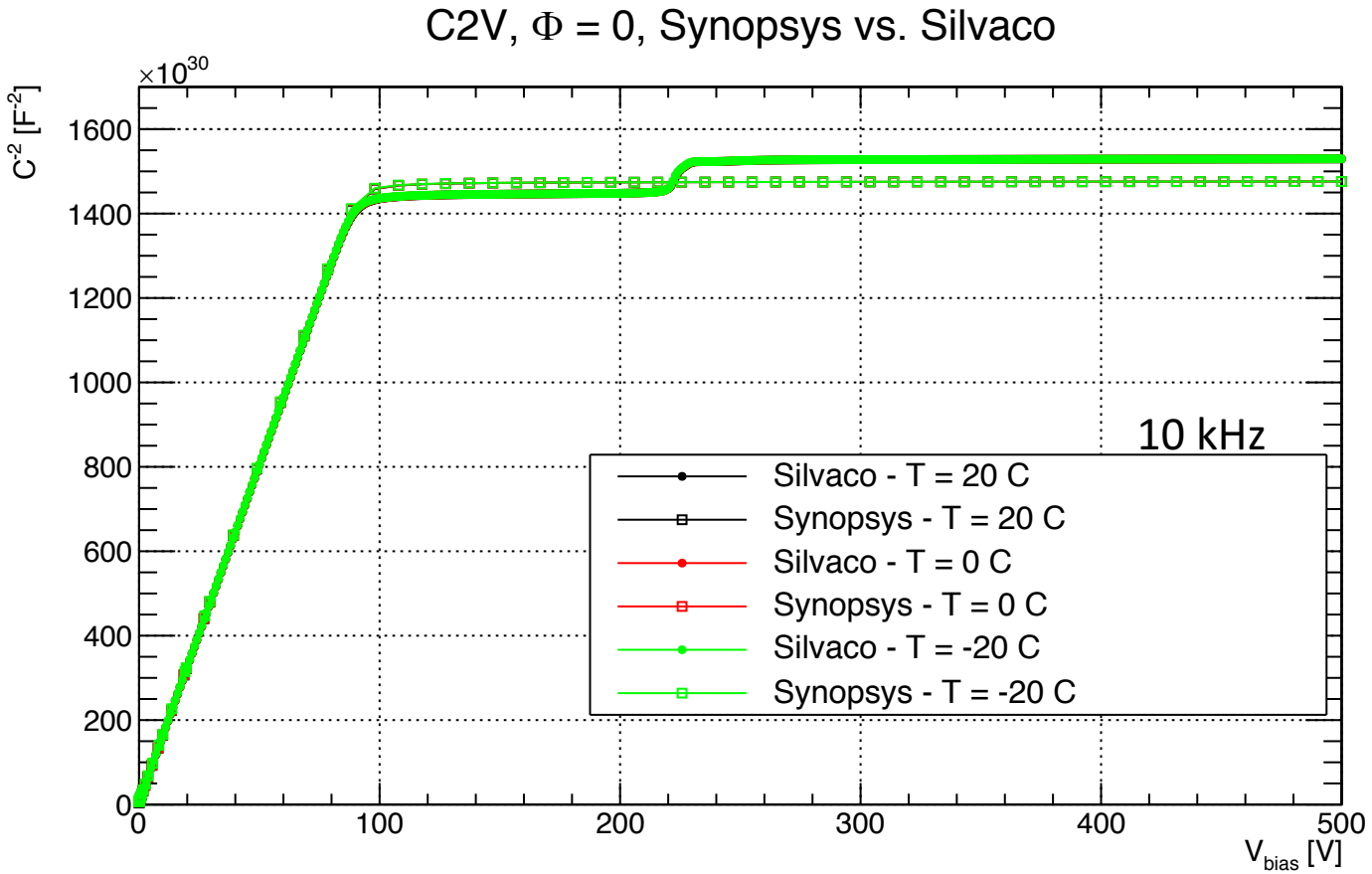
Want to cross-check physics models one by one across the two simulators in the future!

First tests

Not-irradiated structure – CV curves

- comparing CV curves at various temperatures
  - no temperature dependence between -20°C and 20°C

- Synopsys vs. Silvaco
  - rising etdge matches perfectly
  - step in plateau observed with Silvaco but not with Synopsys
    - but agreement in the important (pre)-depletion region is at % level

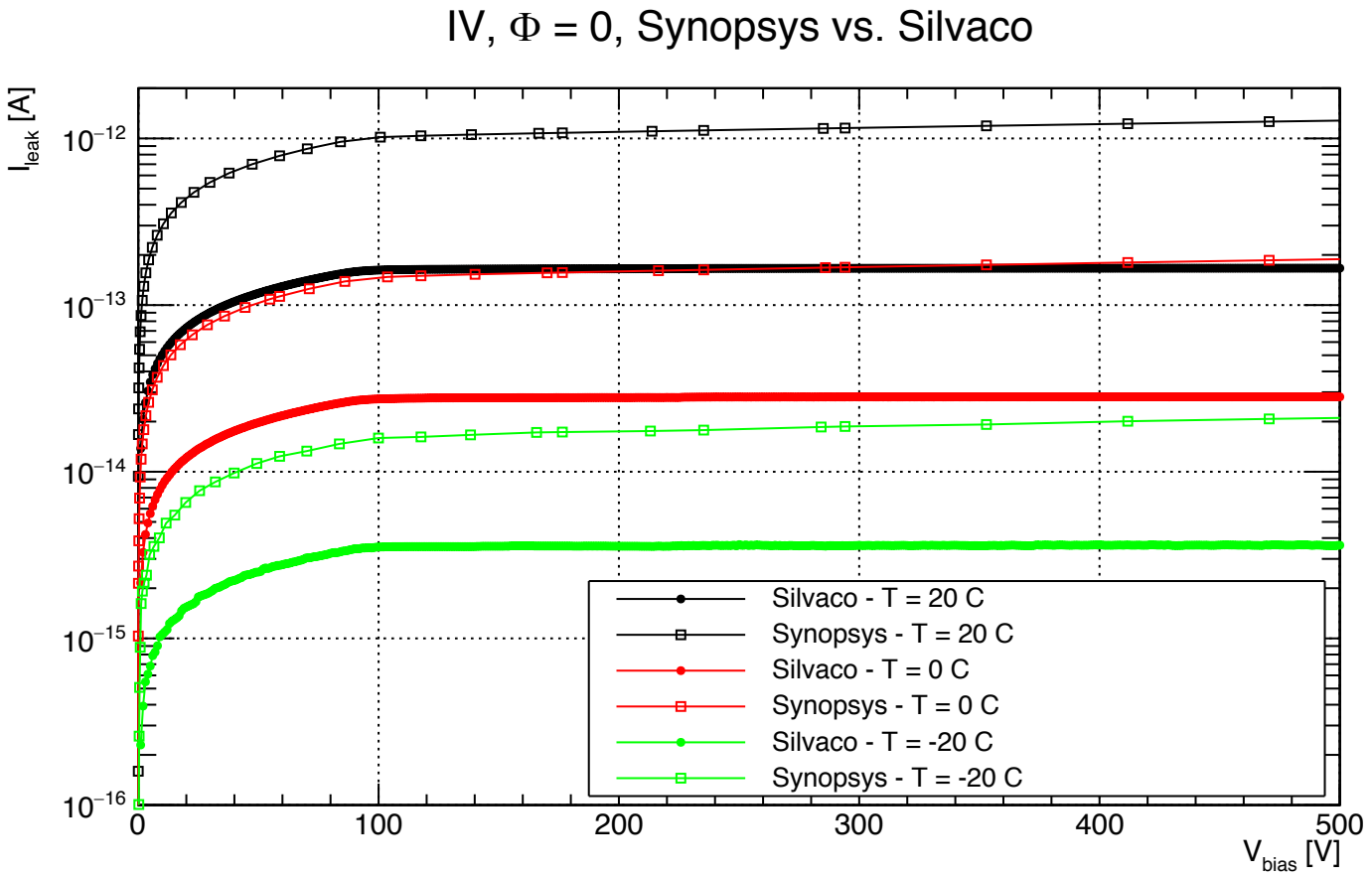


First tests

Not-irradiated structure – IV curves

- comparing IV curves at different temperatures

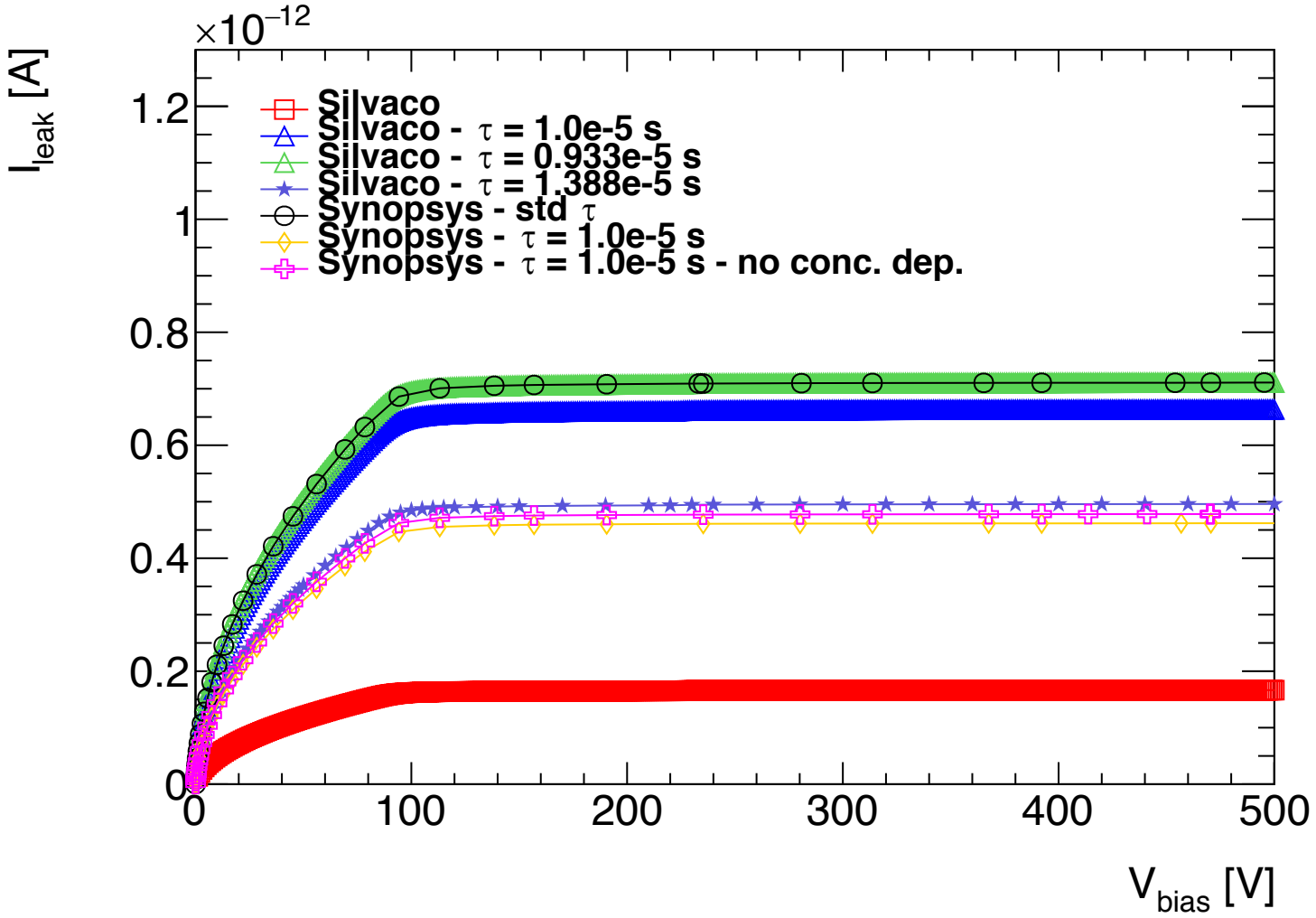
- Synopsys vs. Silvaco
  - Synopsys predicts slightly increasing plateau current
  - differences between Silvaco and Synopsys increase with increasing temperature
  - big difference in predicted plateau
    - what is the cause?



First tests

Not-irradiated structure – IV curves, closer look

- comparing IV curves at 20°C, vary the carrier lifetime τ
- can join the two simulators by artificially changing the carrier lifetime
- the differences in default τ between Silvaco and Synopsys shouldn't matter after irradiation



Irradiated Structure – $1\times10^{15}n_{eq}cm^{-2}$

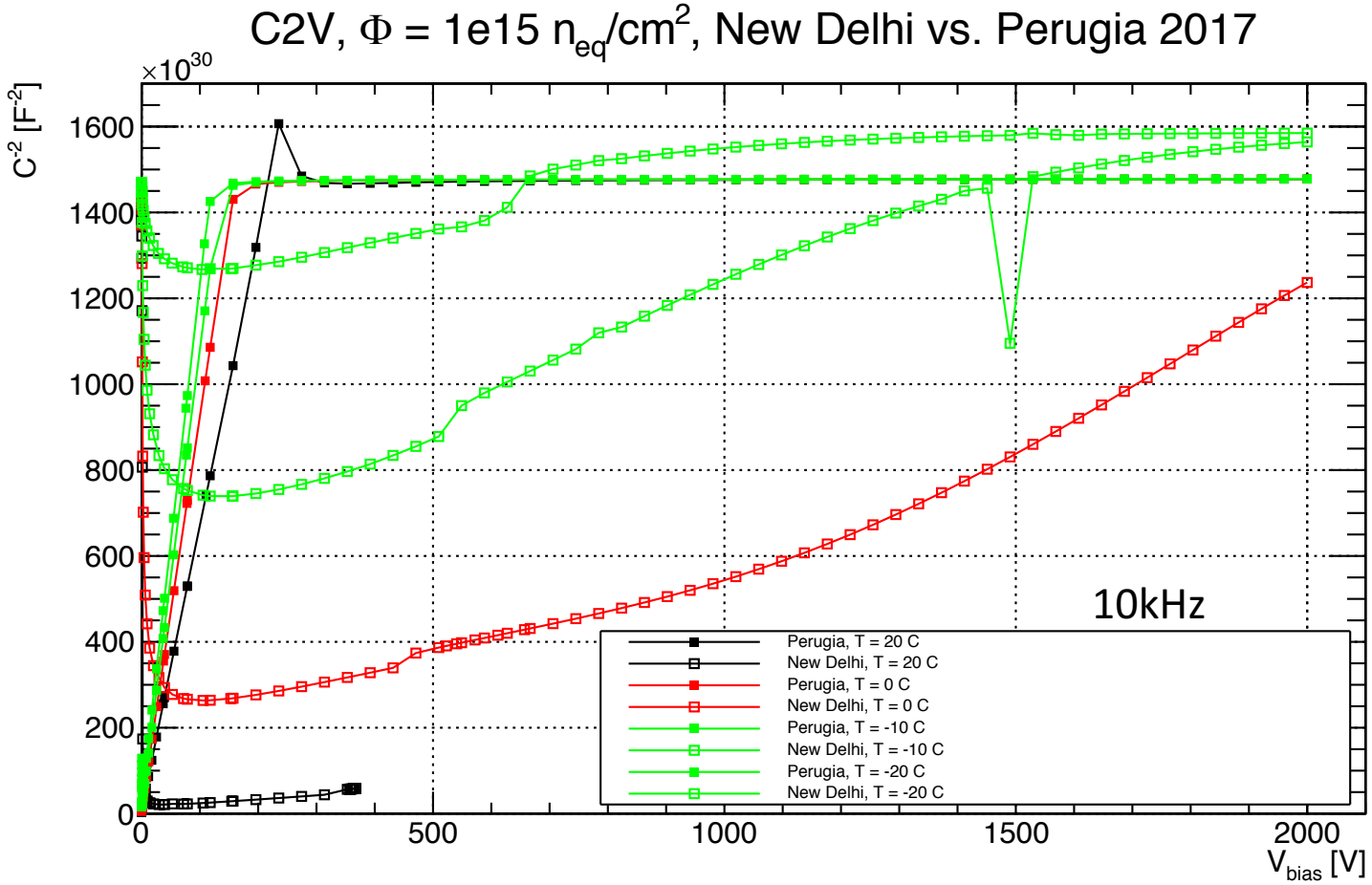
1.comparing Perugia and New Delhi models (Synopsys)

2.comparing Synopsys and Silvaco (Perugia model)

Comparison of models - Synopsys

Irradiated structure – CV curves

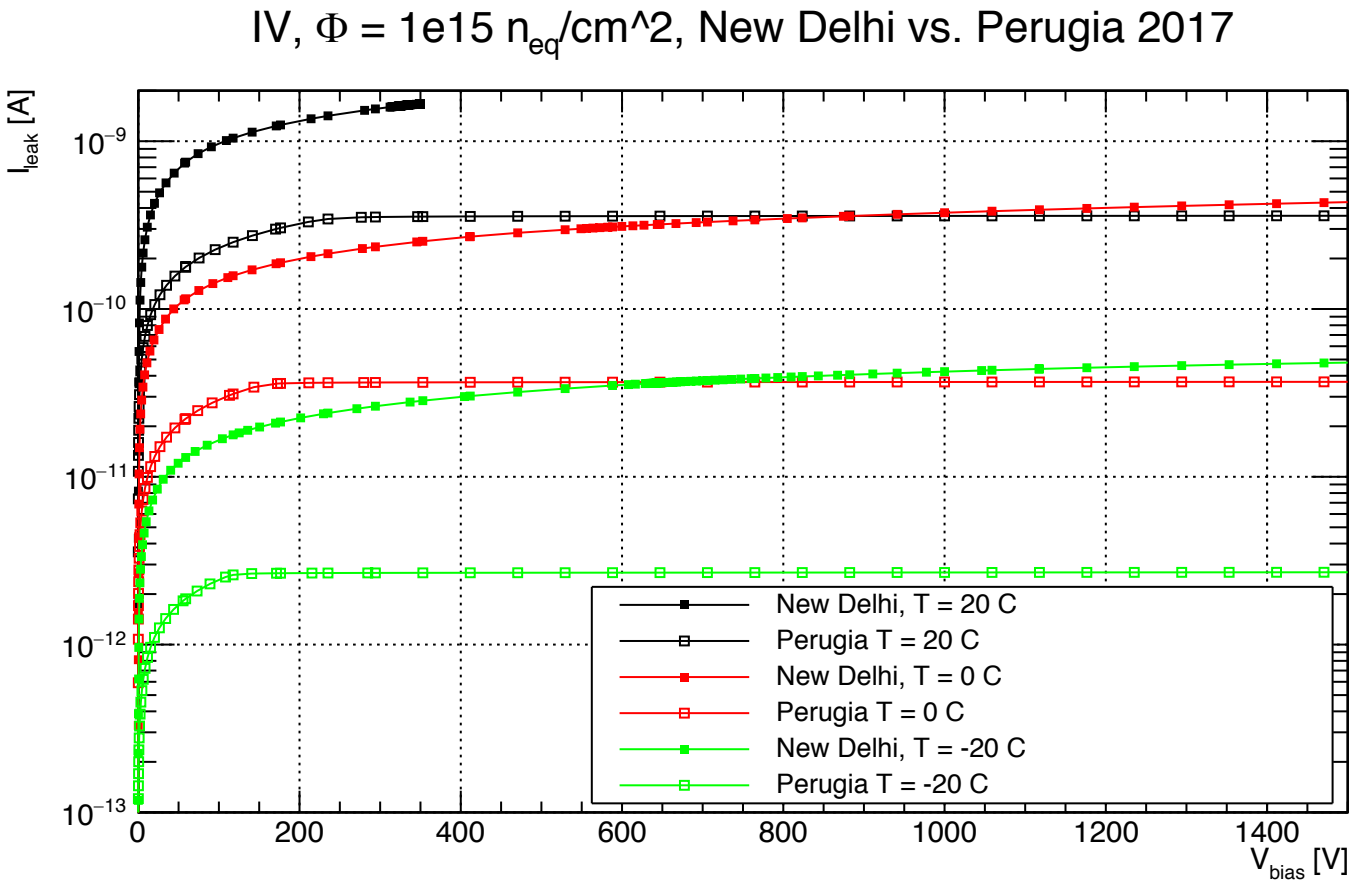
- comparing CV curves at various temperatures
  - depletion with Perugia 2017 in a reasonable range of 100-200V
  - small temperature dependence
  - depletion with New Delhi at 650 - >>2000V bias voltage
  - huge temperature dependence
    - expected given the energy levels are much closer to the intrinsic level than in Perugia model



Comparison of models - Synopsys

Irradiated structure – IV curves

- comparing IV curves at various temperatures
  - significantly higher current with New Delhi model
  - New Delhi predicts increasing plateau current, should be due to no depletion yet
  - differences between the models get smaller for increasing temperature

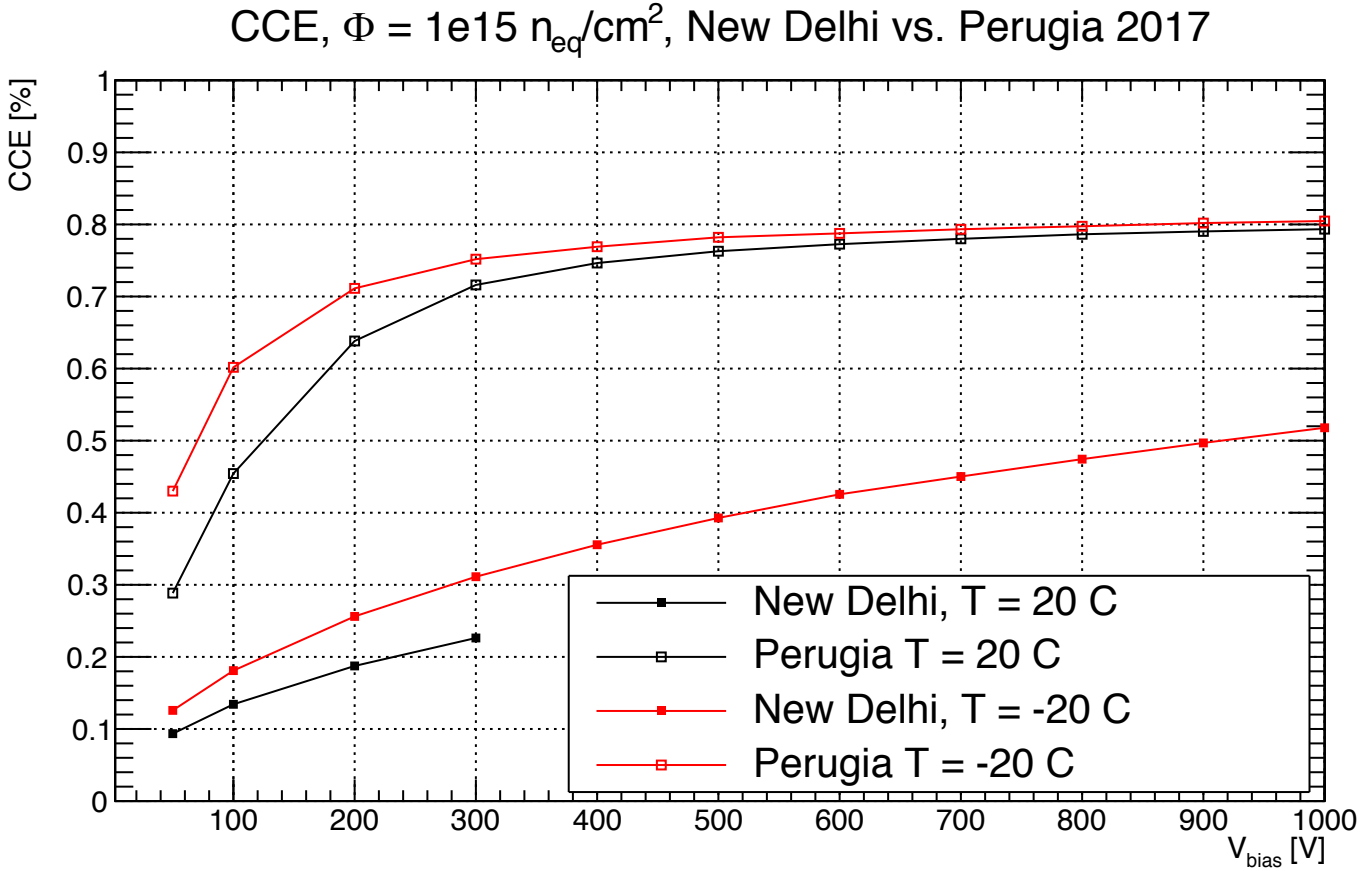


Comparison of models - Synopsys

Irradiated structure – charge collection efficiency

- comparing CCE at different temperatures
  - temperature dependence for Perugia model mainly in the rising edge in agreement with depletion voltage variation
  - New Delhi model seems to exhibit more difference for higher bias voltages

- comparing New Delhi and Perugia 2017 model
  - significantly less charge collected using New Delhi model
    - plateau is not yet reached at 1000V
    - reason: bulk not yet depleted ($C^{-2}V$)



Irradiated Structure – $1\times10^{15}n_{eq}cm^{-2}$

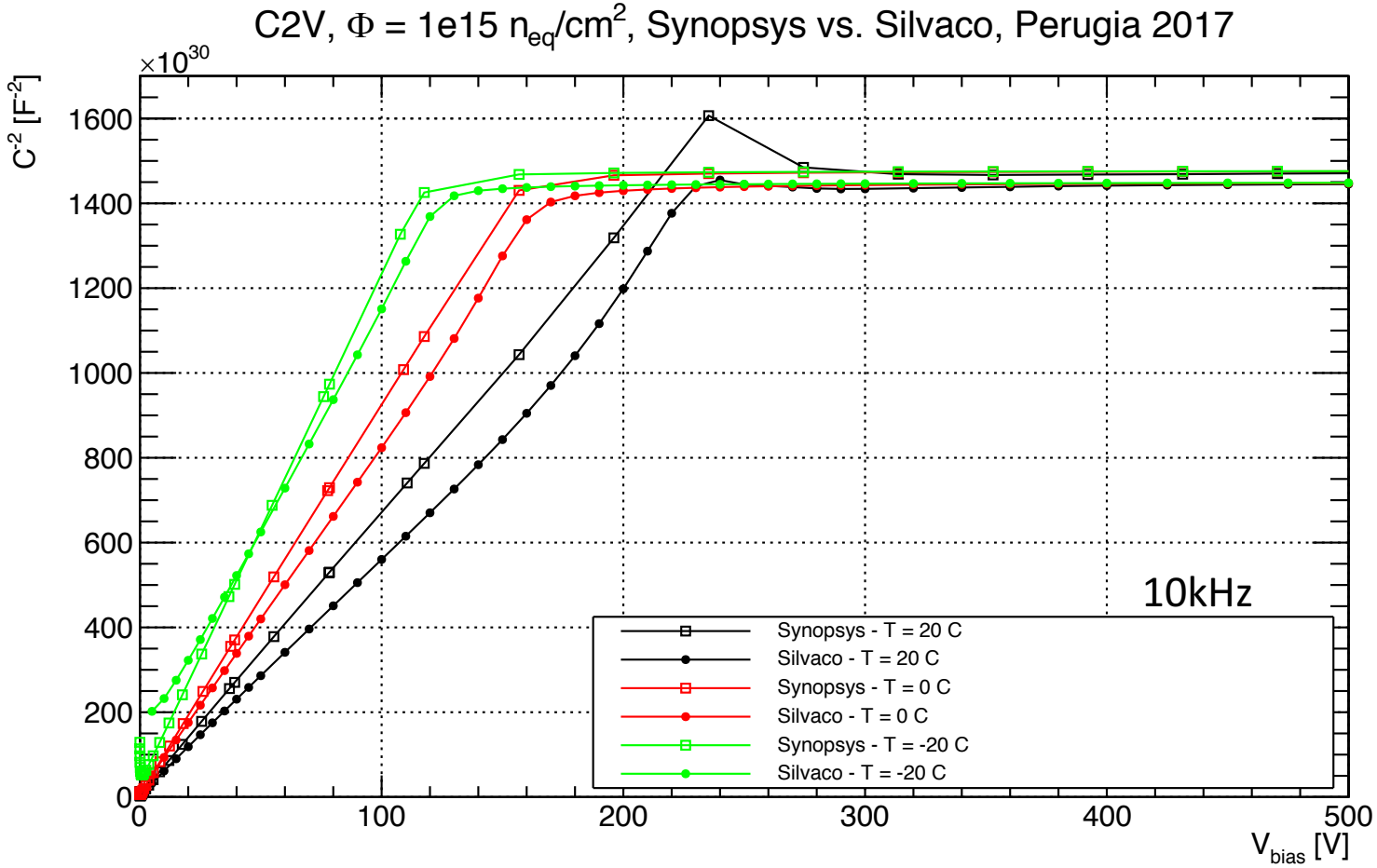
1.comparing Perugia and New Delhi models (Synopsys)

2.comparing Synopsys and Silvaco (Perugia model)

Comparison of Simulators - Perugia

Irradiated structure – CV curves

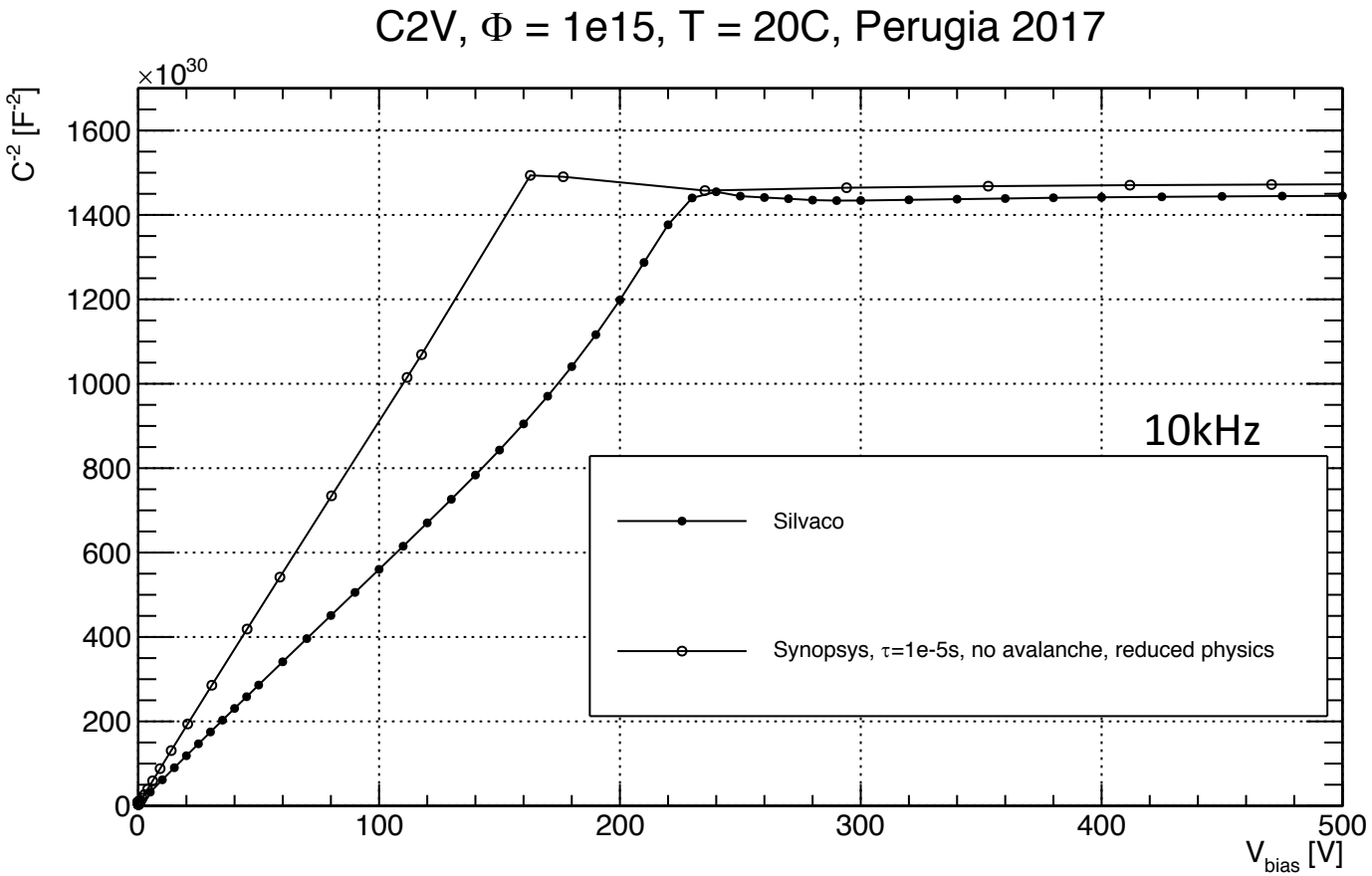
- compare CV curves from both simulators at different temperatures
  - overall good agreement between Synopsys and Silvaco
  - differences increasing with increasing temperature
  - difference is between 10V – 30V



Comparison of Simulators - Perugia

Irradiated structure – closer look: CV curves

- investigating the impact of physics models
  - start with Synopsys reduced physics and adapted carrier lifetime to match IV not-irr

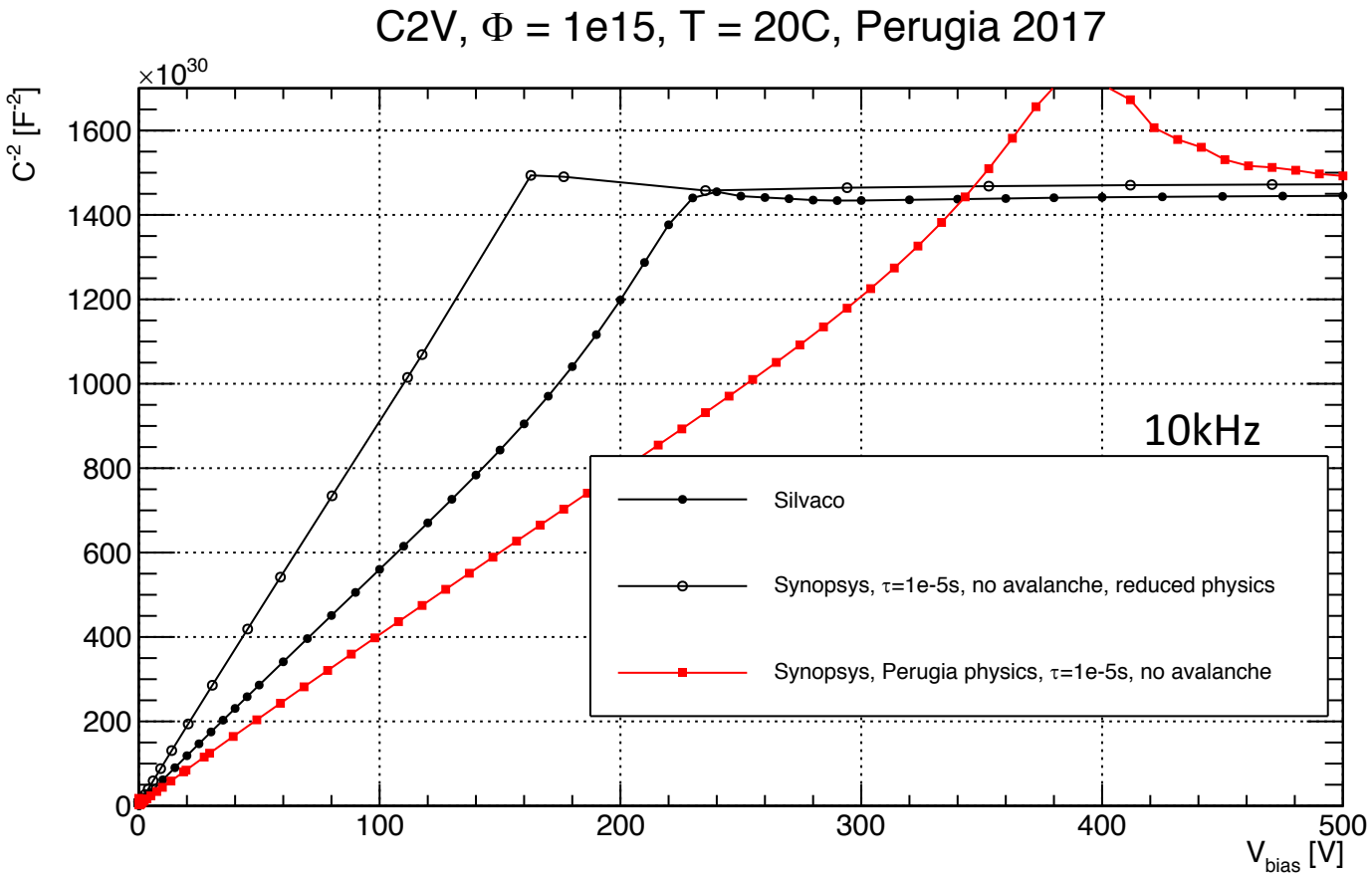


Tool	Silvaco	Synopsys
V_{depl} [V]	~ 240	~ 160

Comparison of Simulators - Perugia

Irradiated structure – closer look: CV curves

- investigating the impact of physics models
  - start with Synopsys reduced physics and adapted carrier lifetime to match IV not-irr
  - use advanced physics models as used by the Perugia group

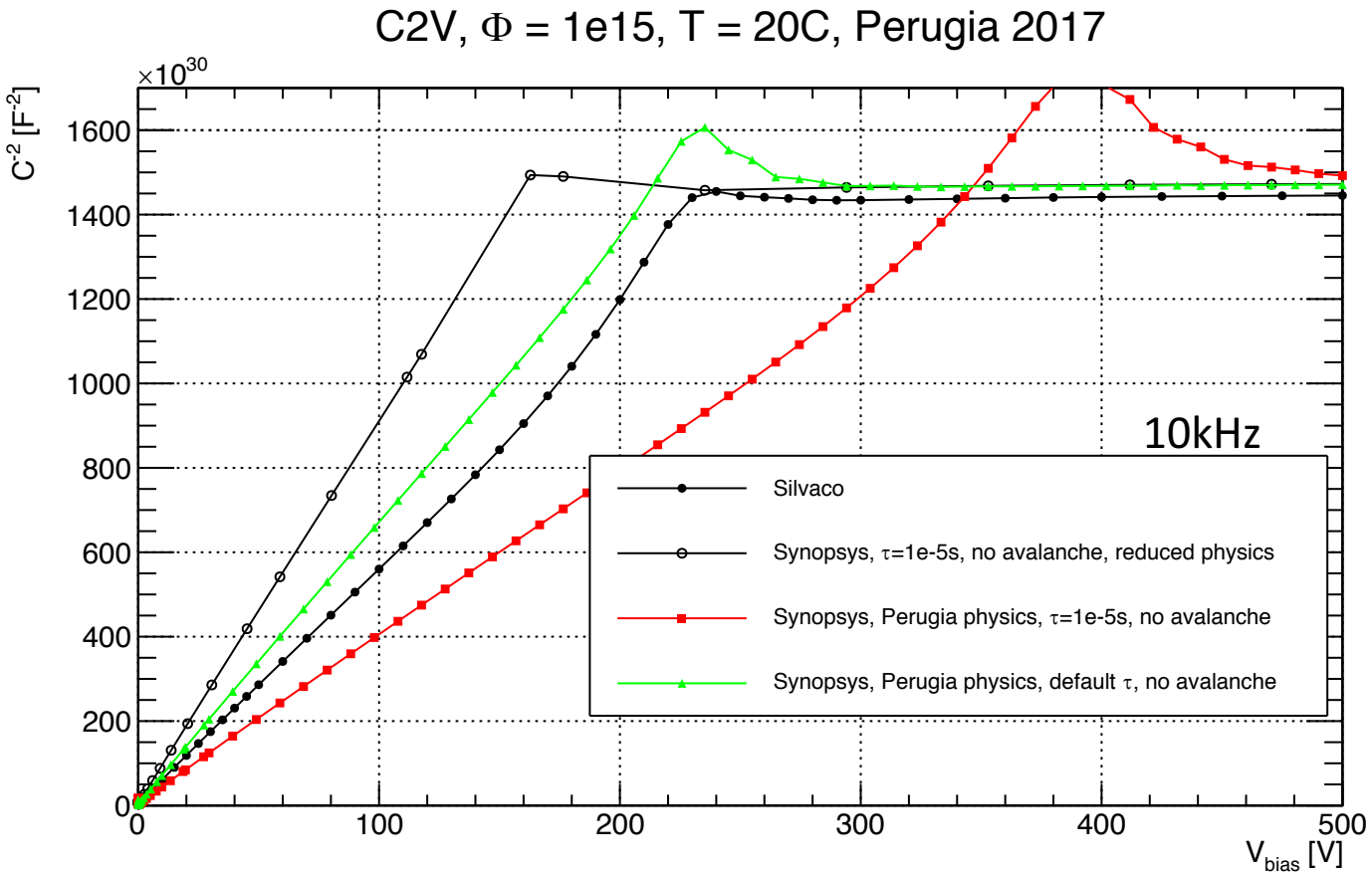


Tool	Silvaco	Synopsys	+physics
V_{depl} [V]	~ 240	~ 160	~400V

Comparison of Simulators - Perugia

Irradiated structure – closer look: CV curves

- investigating the impact of physics models
  - start with Synopsys reduced physics and adapted carrier lifetime to match IV not-irr
  - use advanced physics models as used by the Perugia group
  - use the default carrier lifetime again

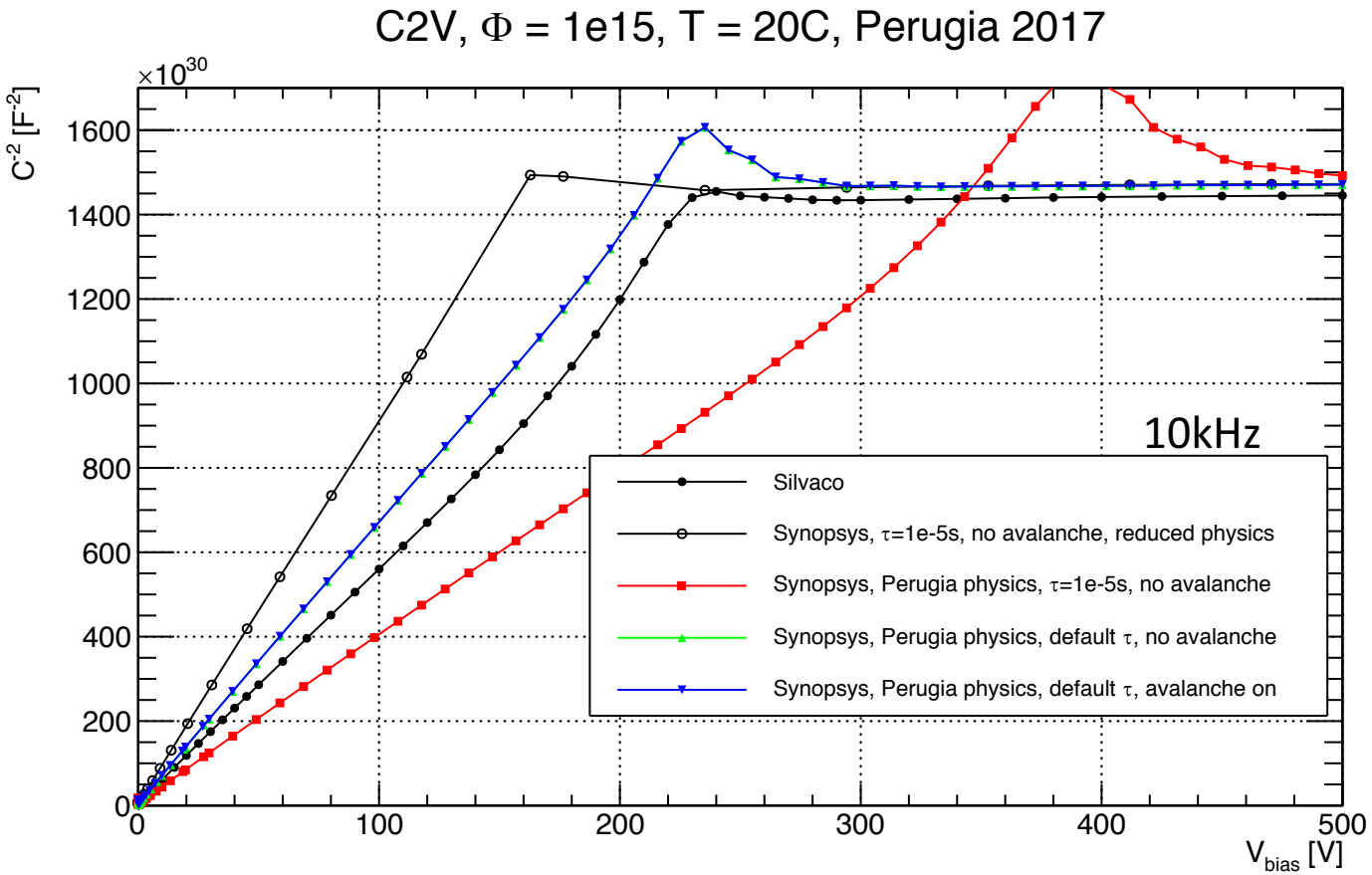


Tool	Silvaco	Synopsys	+physics	+default τ
V_{depl} [V]	~ 240	~ 160	~400V	~220

Comparison of Simulators - Perugia

Irradiated structure – closer look: CV curves

- investigating the impact of physics models
  - start with Synopsys reduced physics and adapted carrier lifetime to match IV not-irr
  - use advanced physics models as used by the Perugia group
  - use the default carrier lifetime again
  - add avalanche

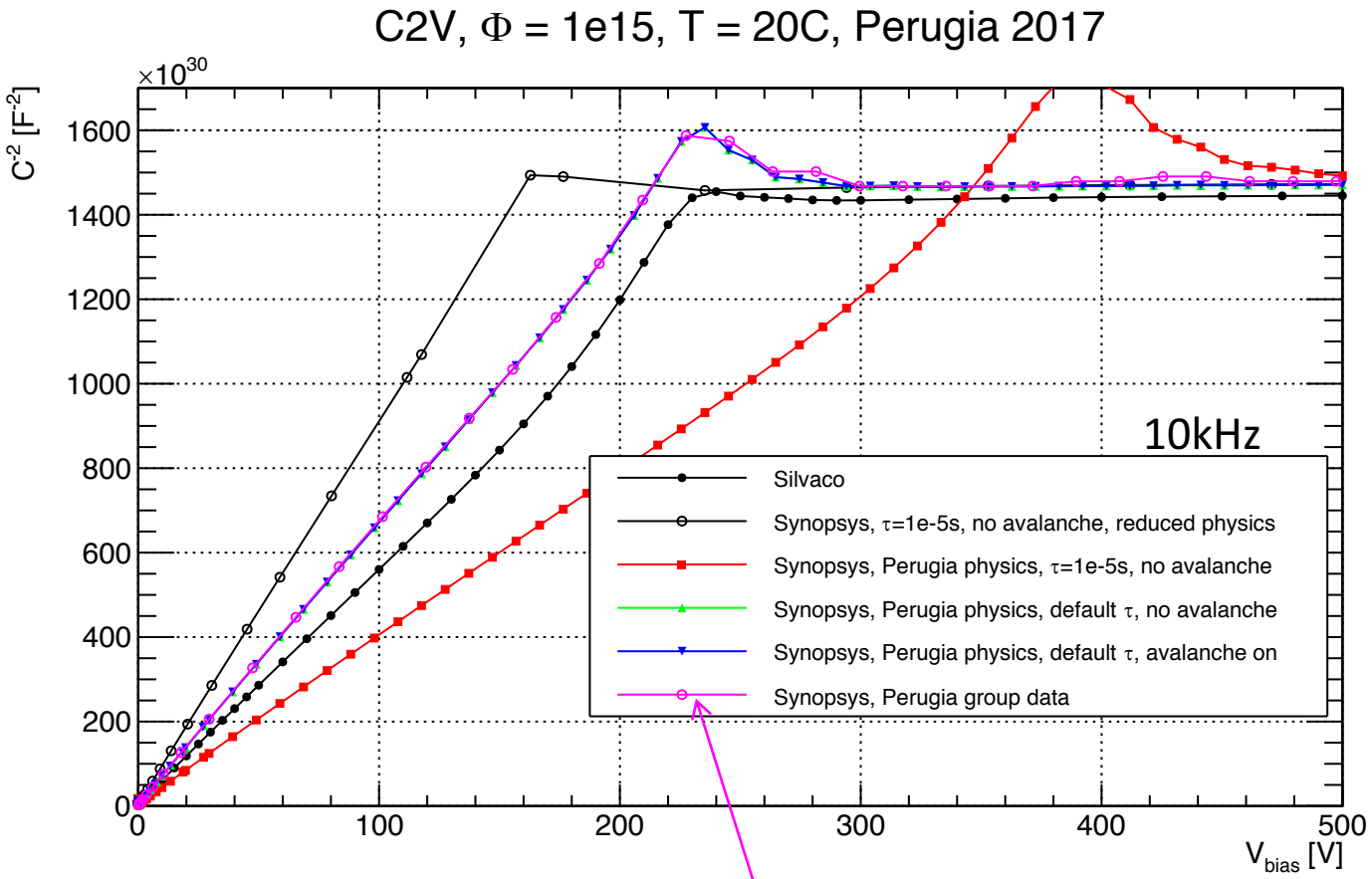


Tool	Silvaco	Synopsys	+physics	+default τ
V_{depl} [V]	~ 240	~ 160	~400V	~220

Comparison of Simulators - Perugia

Irradiated structure – closer look: CV curves

- investigating the impact of physics models
  - start with Synopsys reduced physics and adapted carrier lifetime to match IV not-irr
  - use advanced physics models as used by the Perugia group
  - use the default carrier lifetime again
  - add avalanche
  - compare to data simulated by the Perugia group



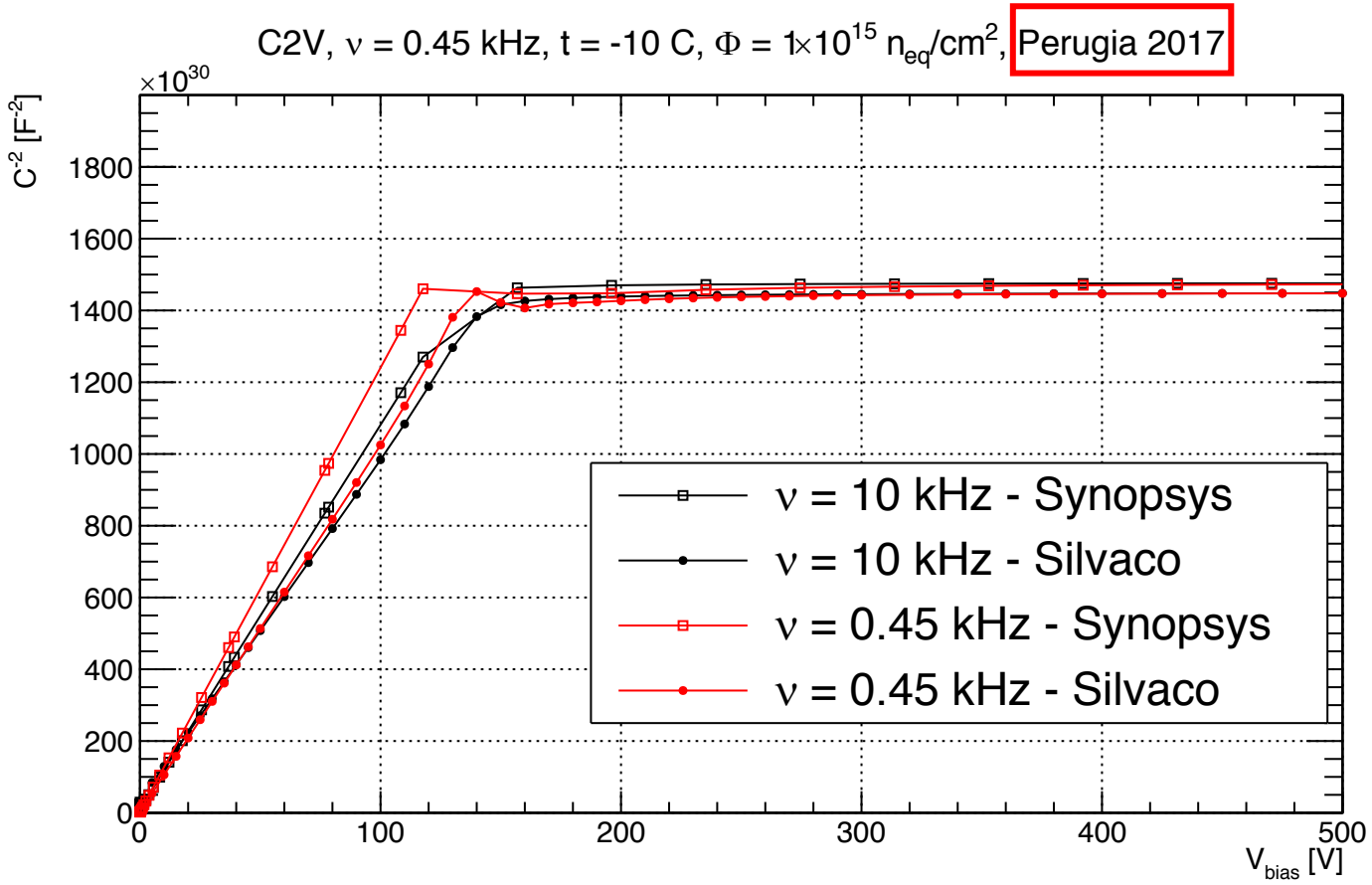
Tool	Silvaco	Synopsys	+physics	+default τ
V_{depl} [V]	~ 240	~ 160	~400V	~220

Cfr. Bomben, 28th RD50 WS, Torino, June 2016

Comparison of Simulators - Perugia

Irradiated structure – influence of frequency on CV

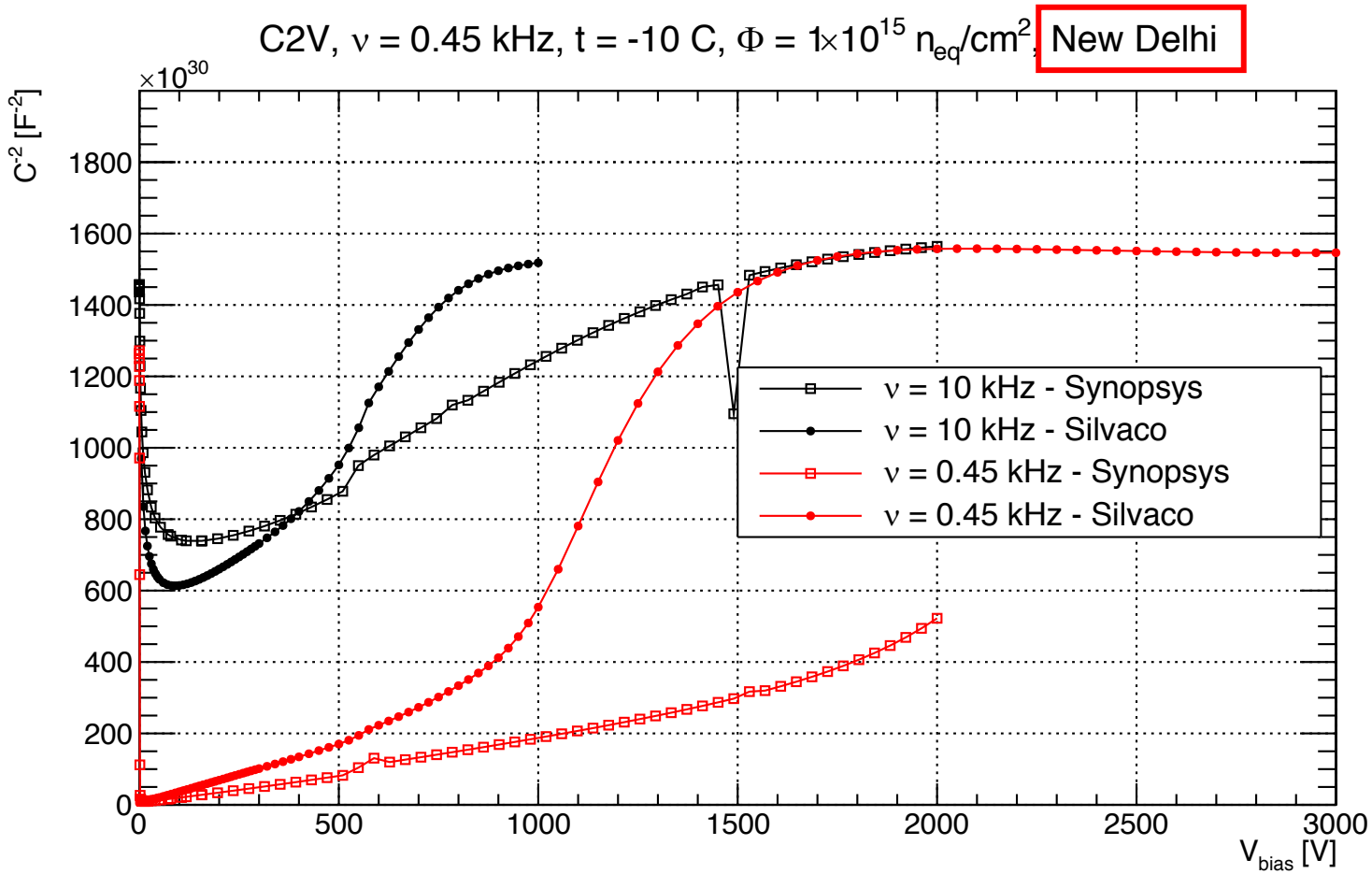
- compare $C^{-2}V$ with the default 10kHz and 0.45kHz at -10°C for both simulators
  - same trend of higher depletion voltage for higher frequency
  - smaller influence on Silvaco simulation
  - overall small influence only



Comparison of Simulators – Delhi

Irradiated structure – influence of frequency on CV

- compare $C^{-2}V$ with the default 10kHz and 0.45kHz at -10°C for both simulators
  - same trend of higher depletion voltage for lower frequency (opposite of Perugia)
  - smaller influence on Silvaco simulation
  - huge influence by frequency



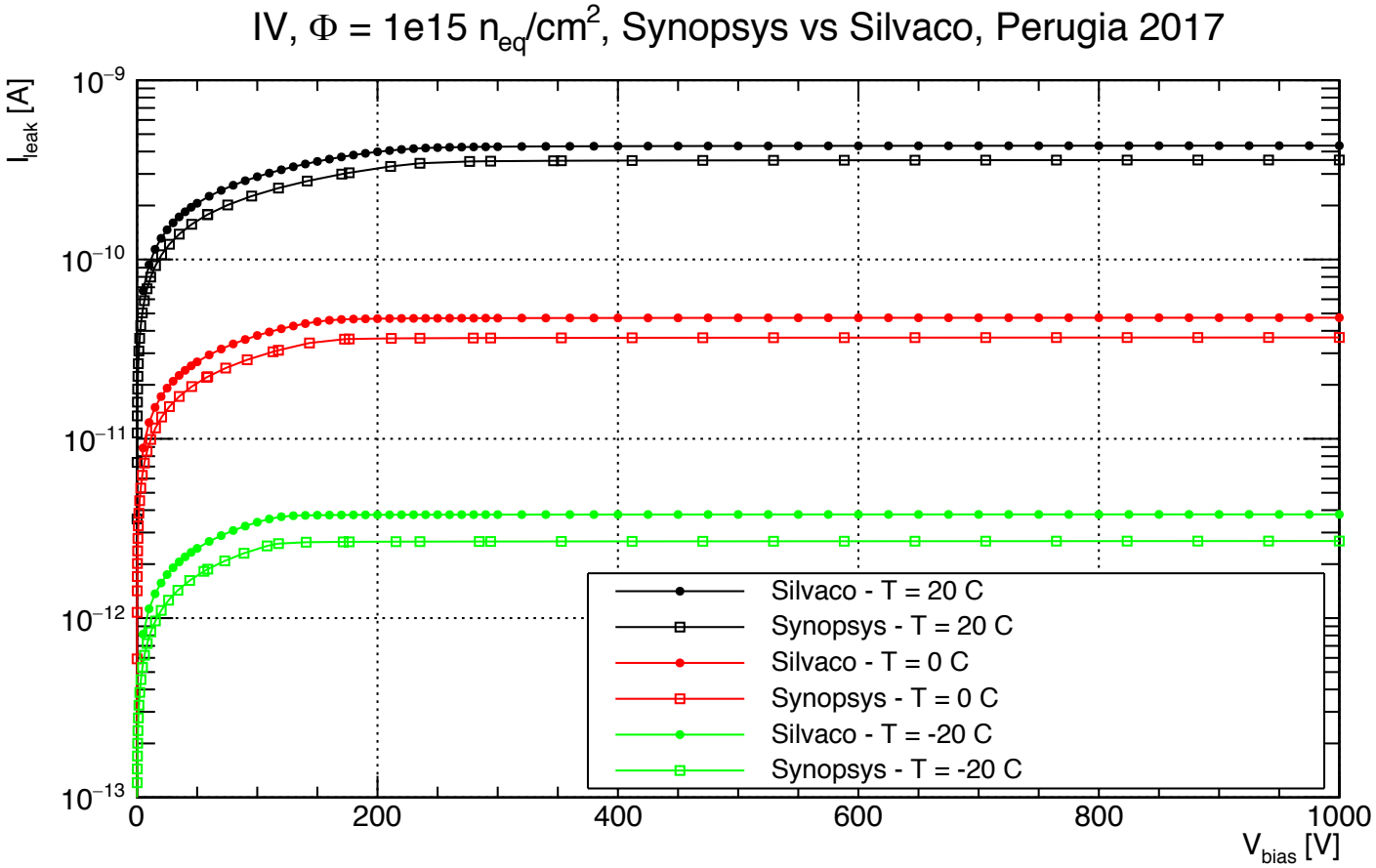
Comparison of Simulators - Perugia

Irradiated structure – IV curves

- compare IV curves from both simulators at different temperatures
  - small difference between the two
  - current lower in Synopsys
  - constant ratio – difference could be due to temperature scaling

Evaluation of the current related damage rate α at 20 C (no rescale for temperature needed) gives:

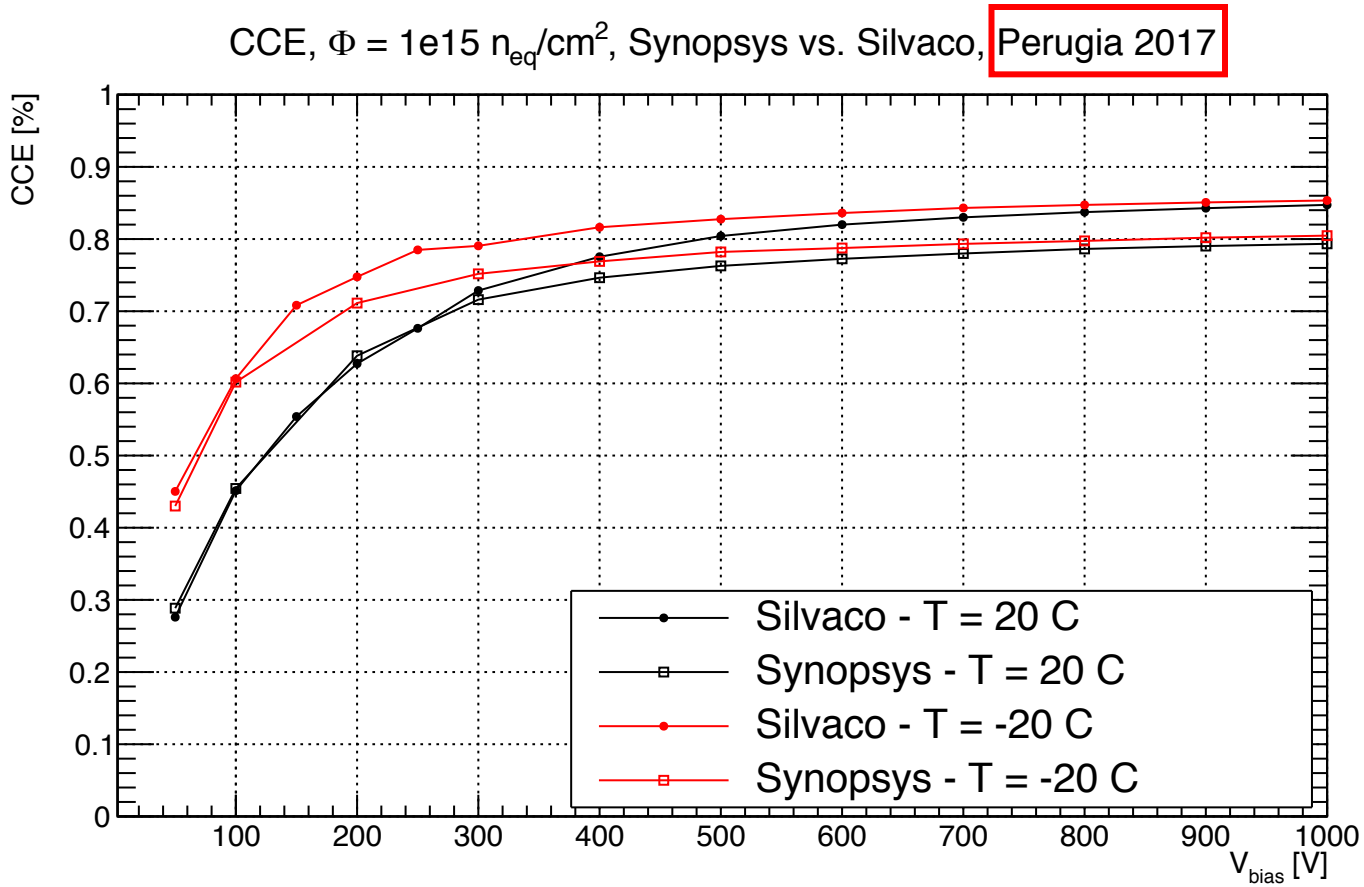
Tool	Silvaco	Synopsys
α [10^{-17} A/cm]	4.2±0.1	3.5±0.1



Comparison of Simulators - Perugia

Irradiated structure – charge collection efficiency

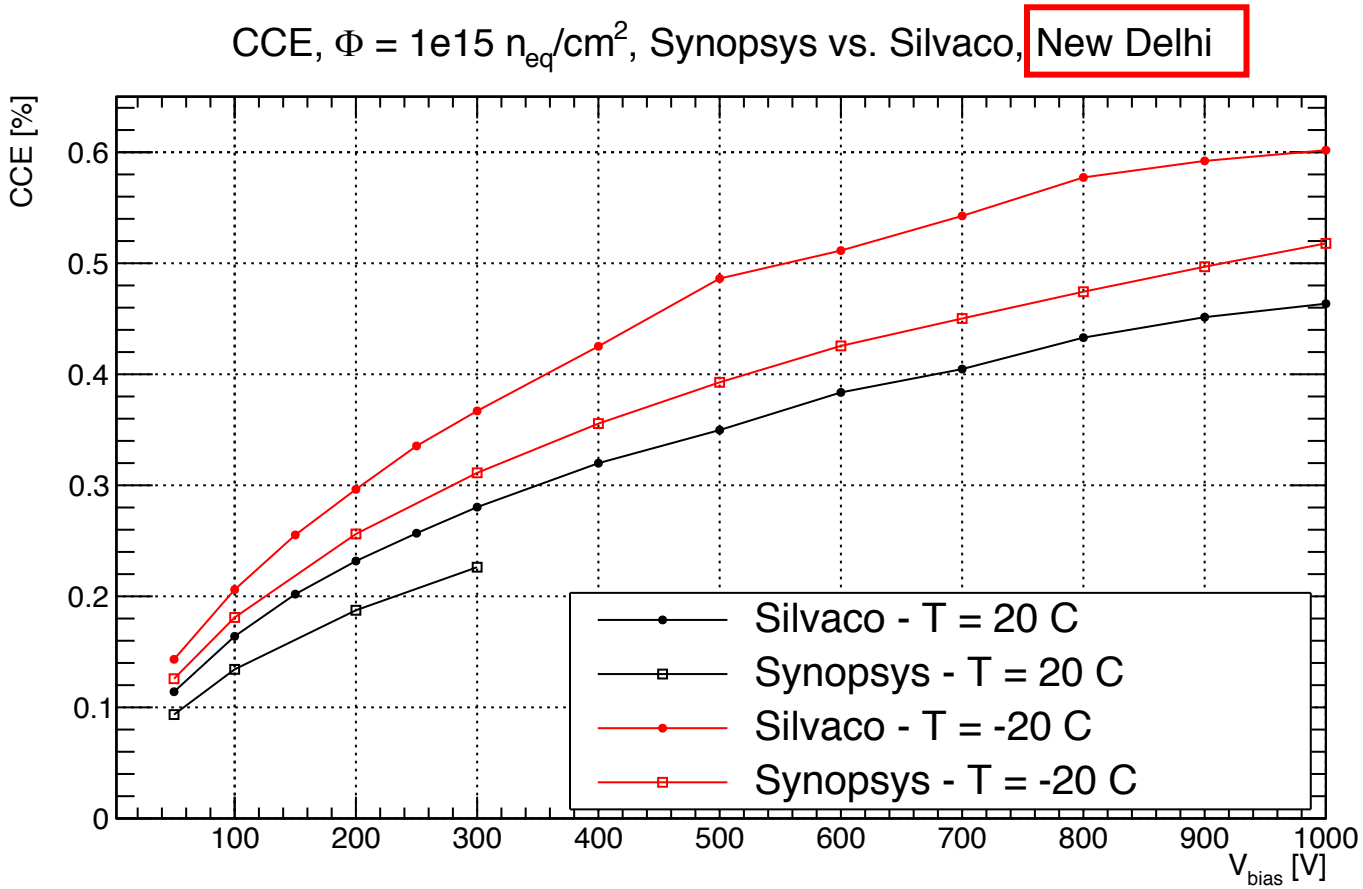
- compare charge collection efficiency for Perugia model at -20°C and 20°C
- normalised to collected charge at 200V-500V, before irradiation
    - exact same rising edge
    - same temperature dependence
    - plateau efficiency different by ~5%



Comparison of Simulators - Delhi

Irradiated structure – charge collection efficiency

- compare charge collection efficiency for New Delhi model at -20°C and 20°C
  - both do not reach a plateau
  - efficiency different by ~14% at 1000V



Summary

1. Comparing New Delhi and Perugia 2017 radiation damage models
   - depletion voltage much higher and much larger temperature dependence using New Delhi model
   - higher currents and no saturation of current up to 1500V given the high depletion voltage
   - CCE is ~80% for Perugia and ~50% for New Delhi @ 1000V and 1x15n_{eq}/cm^2

2. Comparing Synopsys and Silvaco TCAD tools
   - CV agrees down to the % level before irradiation, after irradiation small differences with Perugia model
   - IV different before irradiation due to different τ value, after irradiation close together, compatible with 2016 data
   - CCE in good agreement in the rising edge, plateau slightly different, difference is 5%-14%

3. Outlook:
   - project has just started, more cooperation planned
     - *DEFPIXELS* project, Embassy of France in Germany and DAAD Procope grant call
   - compare the physics models in more detail between the two simulators
   - more complex structures to spot higher order differences
   - compare avalanche models

Thank you for your attention!

Backup