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# ***Simulation of the Temperature Dependence of the Charge Transfer Inefficiency in a High-Speed CCD***

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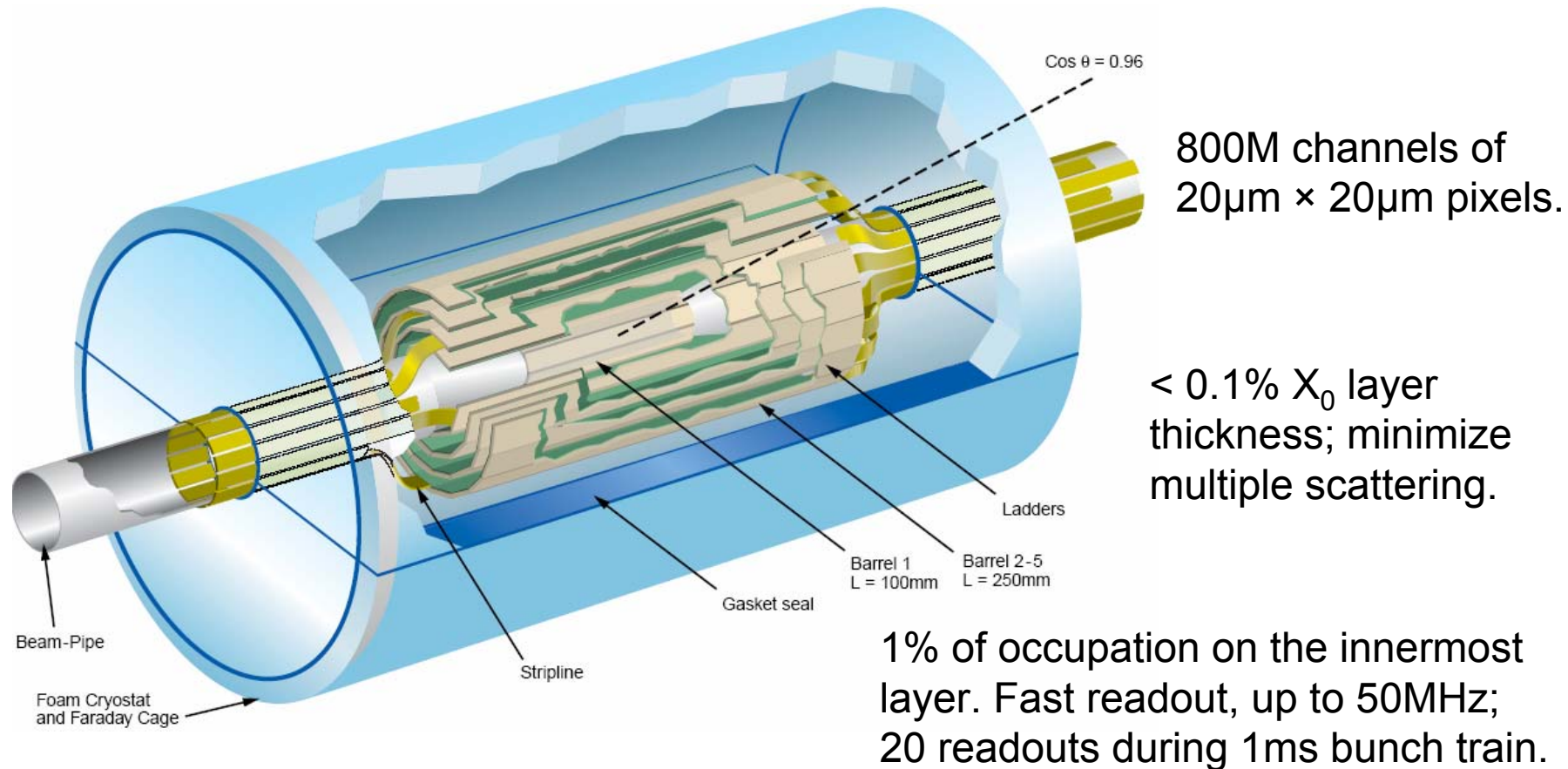
**Rutherford Appleton Laboratory:** C. Damerell, K. Stefanov, S. Worm

**Liverpool University:** T. Greenshaw, K. Hayrapetyan, T. Tikkanen, T. Woolliscroft

**Biskra University:** K. Bekhouche, L. Dehimi

# A Vertex Detector for the International Linear Collider

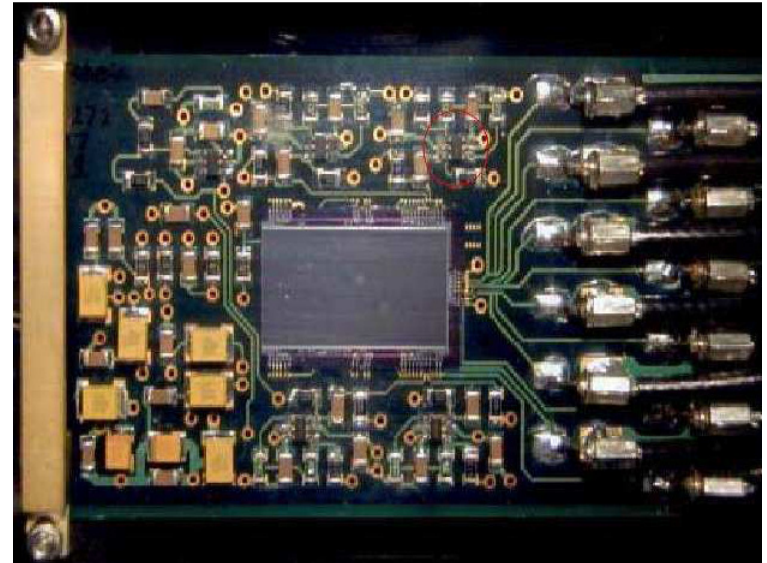
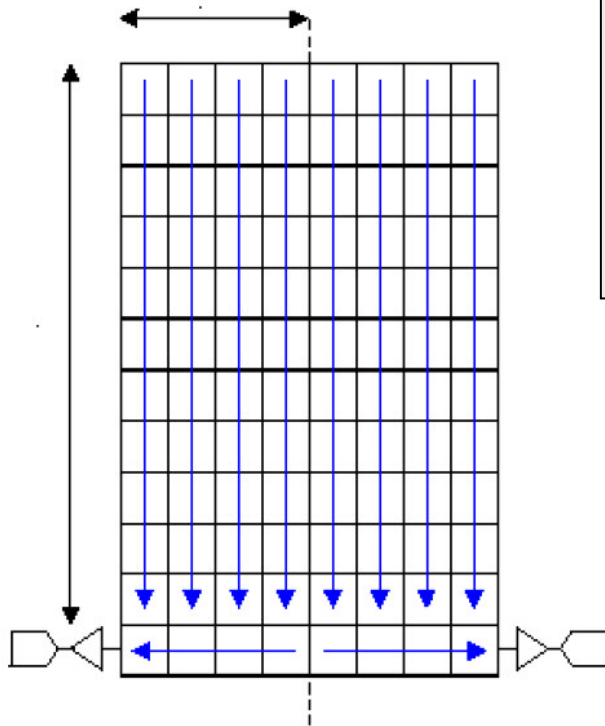
LCFI: Linear Collider Flavour Identification collaboration



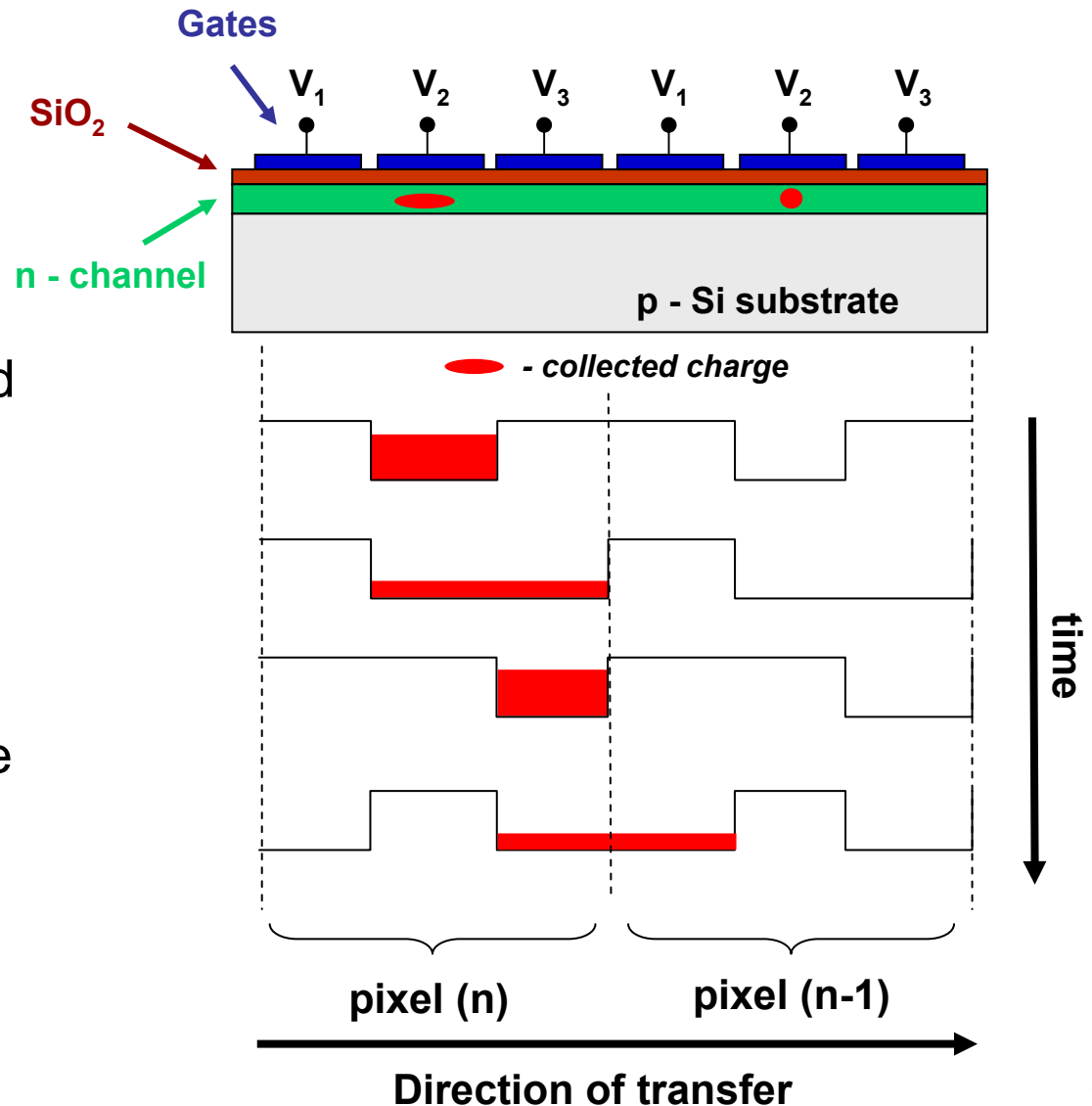
**Requires radiation hardness studies.**

# Serial CCD

- Serial readout
- Parallel shift register
- Three-phase device
- Two readout channels
- Up to 50MHz readout
- 2.1 Mpixels
- $12\mu\text{m} \times 12\mu\text{m}$  pixel size



# Charge Transfer for 3-phase CCD

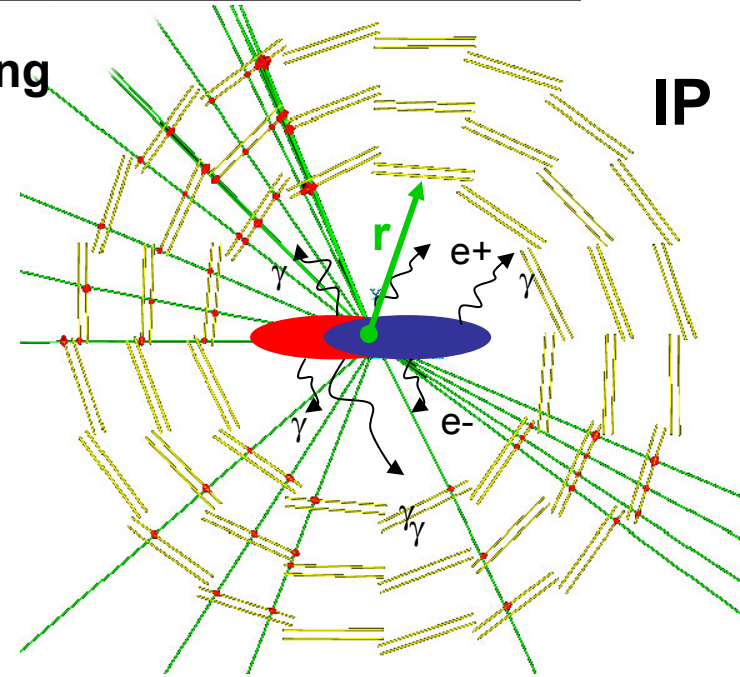
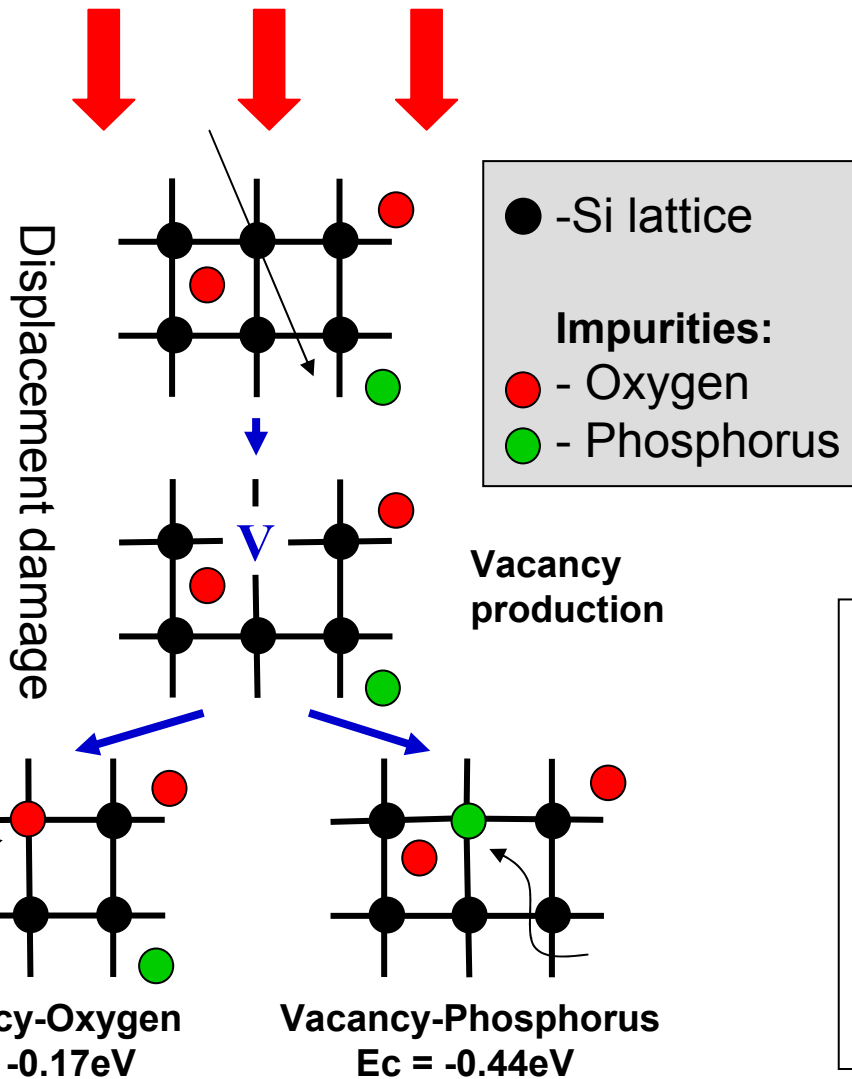


Electrons are collected from ionization of incident particle.

Charge is transferred inside n-channel to the output by applying voltage changes to gates.

# Background and its Implication for the CCD

## Background production during bunch crossing



Radiation damage produces energy levels (**traps**) within the band gap.

**Traps** capture electrons from the conduction band which are later released.

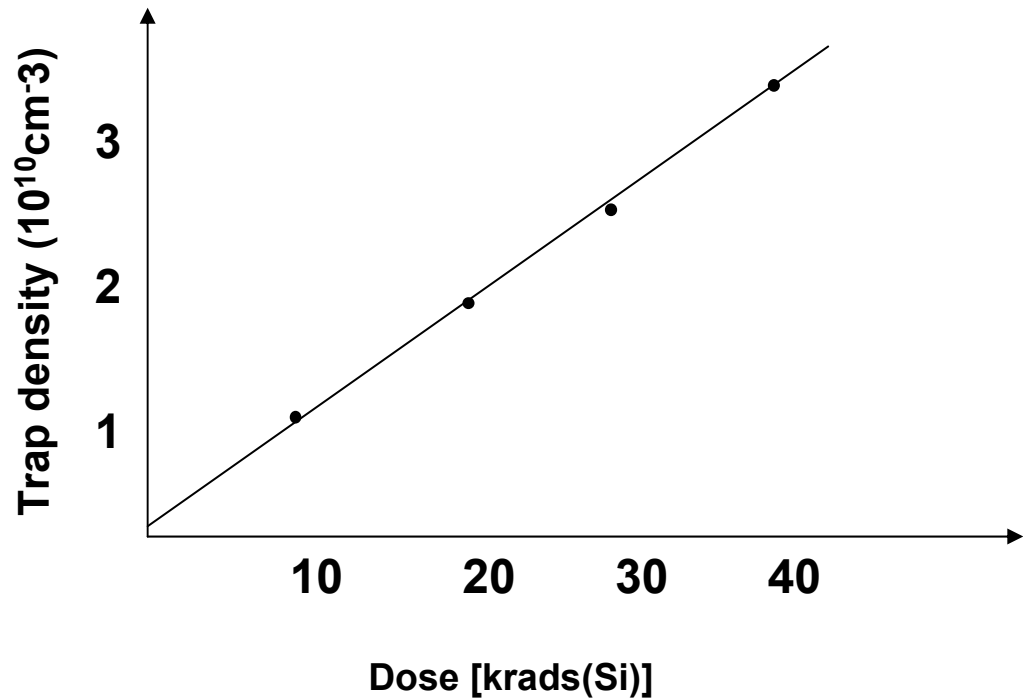
# Estimation of Background Rates

Simulator	SiD	LDC	GLD
<b>CAIN/Jupiter</b> hits/cm <sup>2</sup> /bx	<b>2.9</b> (nominal)	<b>3.5</b> (TESLA)	<b>0.5</b> (24mm radius, nominal)
<b>GuineaPig</b> hits/cm <sup>2</sup> /bx	<b>2.3</b> (nominal)	<b>3.0</b> (TESLA)	<b>2.0</b> (20mm radius, nominal)

Results from simulations (T.Maruyama, C.Rimbault)

- 2820 bx/train
- 5 trains per second
- 10<sup>7</sup> seconds in the 'Snowmass year'

**1.41·10<sup>11</sup> bunches/year**



# Background and Trap Density

Expected background rates for 14 mm radius from IP.

Parameter	electrons	neutrons
average energy	~ 10 MeV	~ 1 MeV
no. particles / bx / cm <sup>2</sup>	3.5	0.01
fluence	$0.5 \cdot 10^{12}$	$1.6 \cdot 10^9$ Vogel $1 \cdot 10^9$ Maruyama

Estimated trap densities.

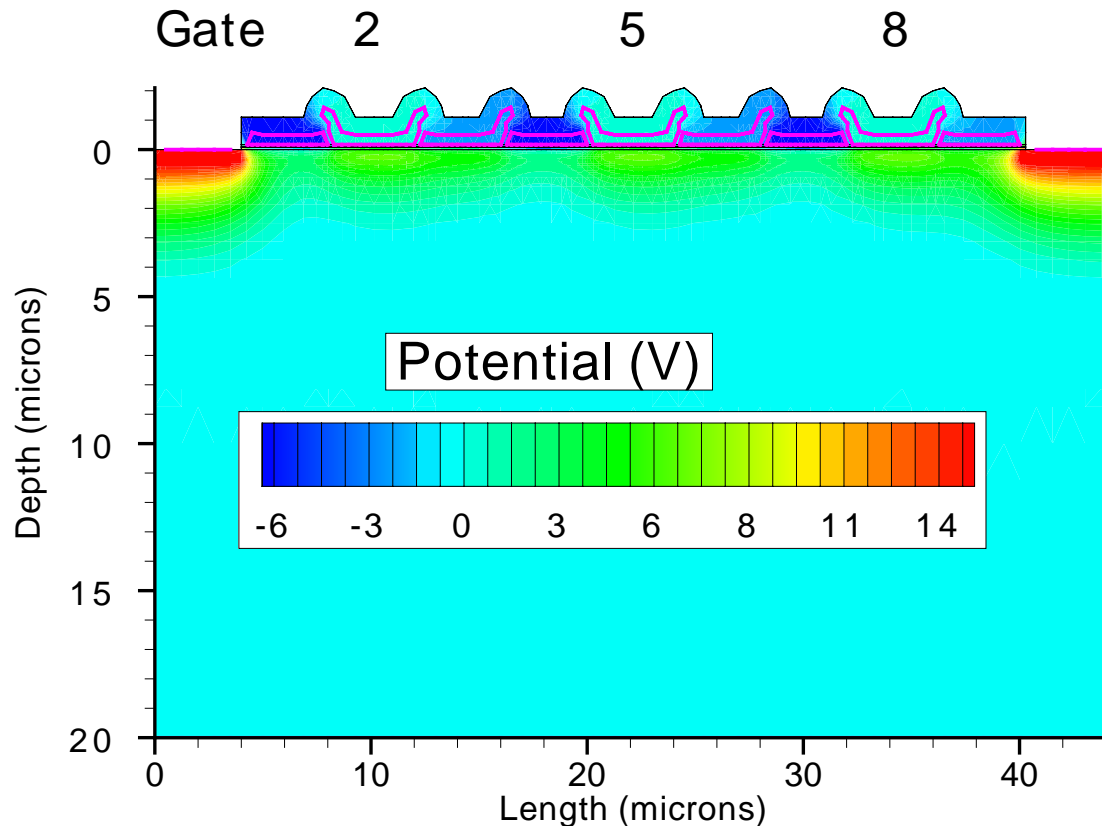
Source	0.17 eV trap	0.44 eV trap
Electrons	$\sim 3 \cdot 10^{11} \text{ cm}^{-3}$	$\sim 3 \cdot 10^{10} \text{ cm}^{-3}$
Neutrons	$\sim 7.1 \cdot 10^8 \text{ cm}^{-3}$ $\sim 4.5 \cdot 10^8 \text{ cm}^{-3}$	$\sim 1.1 \cdot 10^{10} \text{ cm}^{-3}$ $\sim 7.0 \cdot 10^9 \text{ cm}^{-3}$
total	$\sim 3 \cdot 10^{11} \text{ cm}^{-3}$	$\sim 4.1 \cdot 10^{10} \text{ cm}^{-3}$ $\sim 3.7 \cdot 10^{10} \text{ cm}^{-3}$

Used in simulations.

Traps	Trap density	Electron capture $\sigma$
0.17 eV	$1 \cdot 10^{11} \text{ cm}^{-3}$	$1 \cdot 10^{-14} \text{ cm}^2$
0.44 eV	$1 \cdot 10^{11} \text{ cm}^{-3}$	$3 \cdot 10^{-15} \text{ cm}^2$

**CTI : Charge Transfer Inefficiency** = 
$$\frac{\text{Charge transfered from pixel (n) to (n+1)}}{\text{Charge entered the pixel (n)}}$$

- CTI vs. Temperature for different traps
- CTI vs. Clock frequency
- CTI vs. Voltage applied to gates

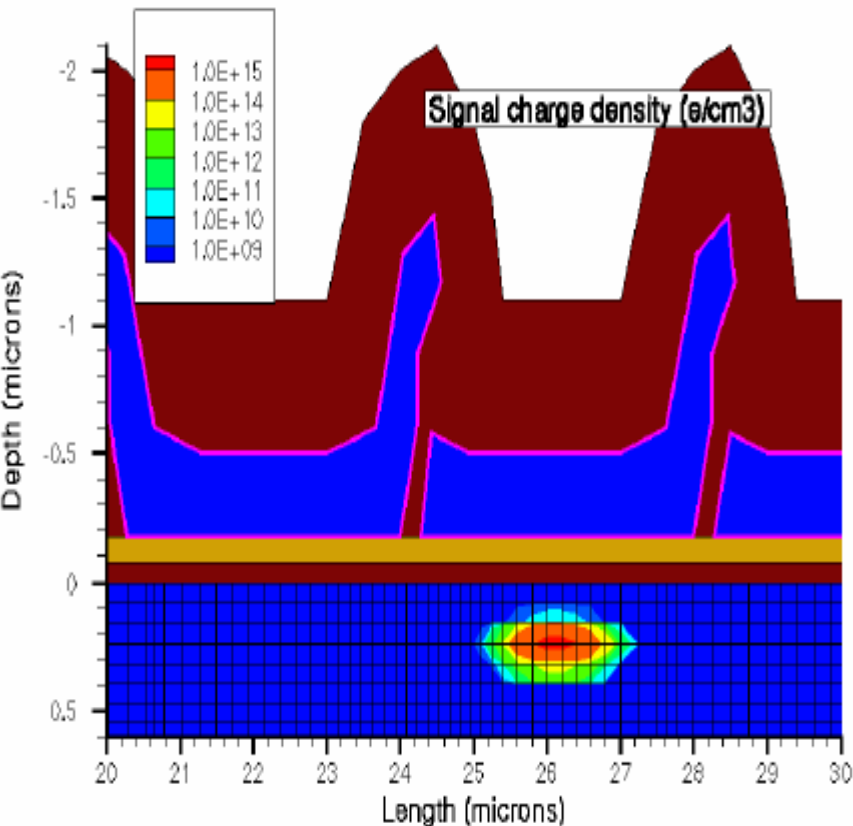


Detector structure and potential at gates after initialization. The signal charge is injected under gate 2.

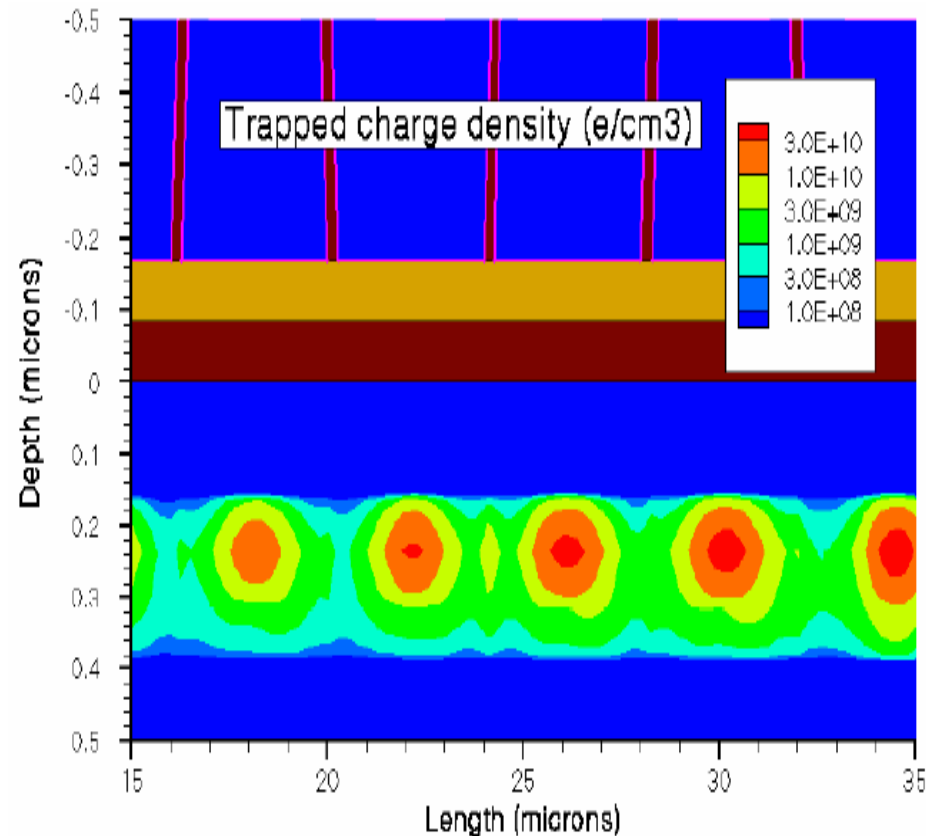


# CCD simulation

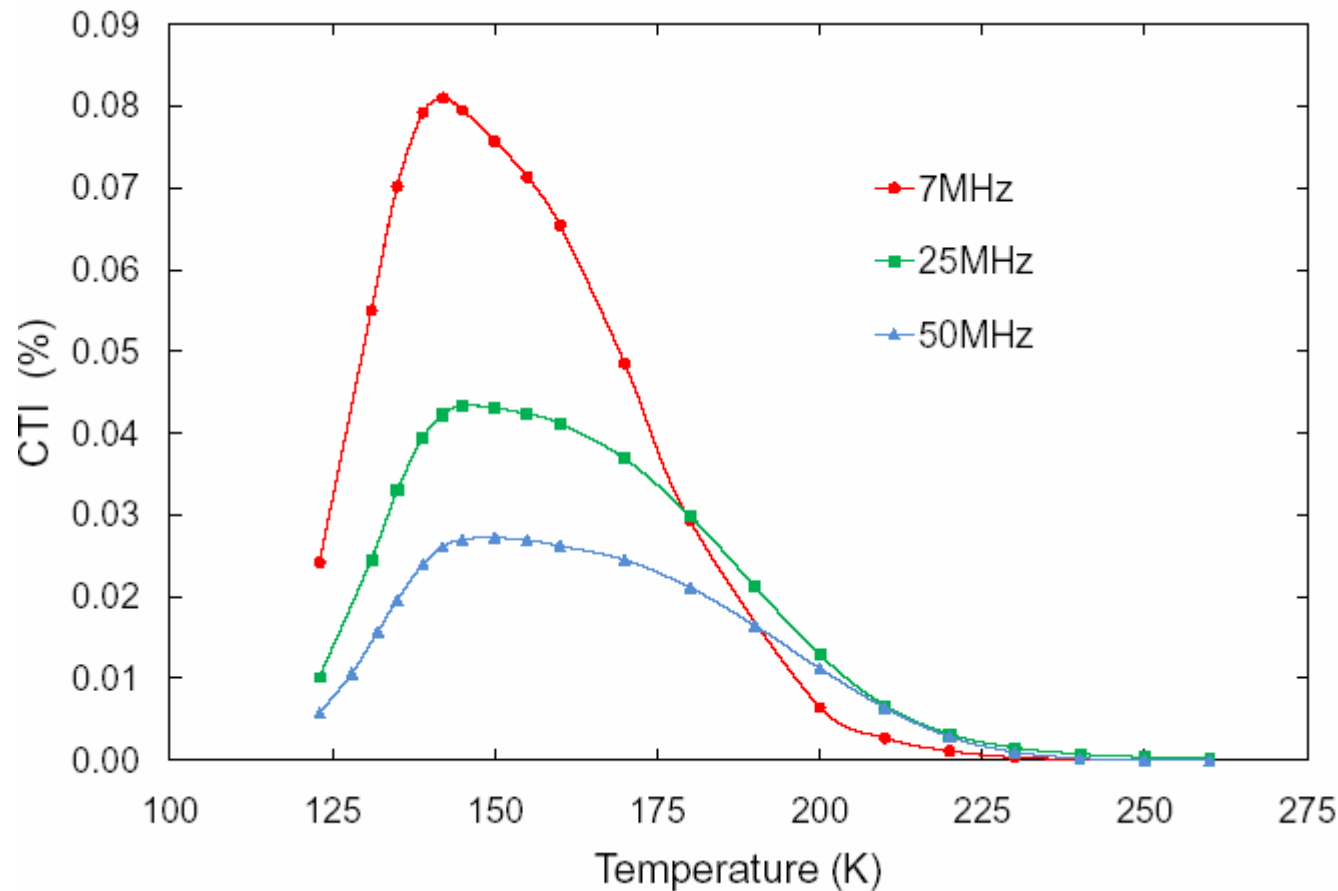
Signal charge density  
entering pixel (n)



Signal charge passed all gates and  
trapped charge decreases from right  
to left due to emission.



# CTI vs. Temp. and Freq. 0.17 eV Traps

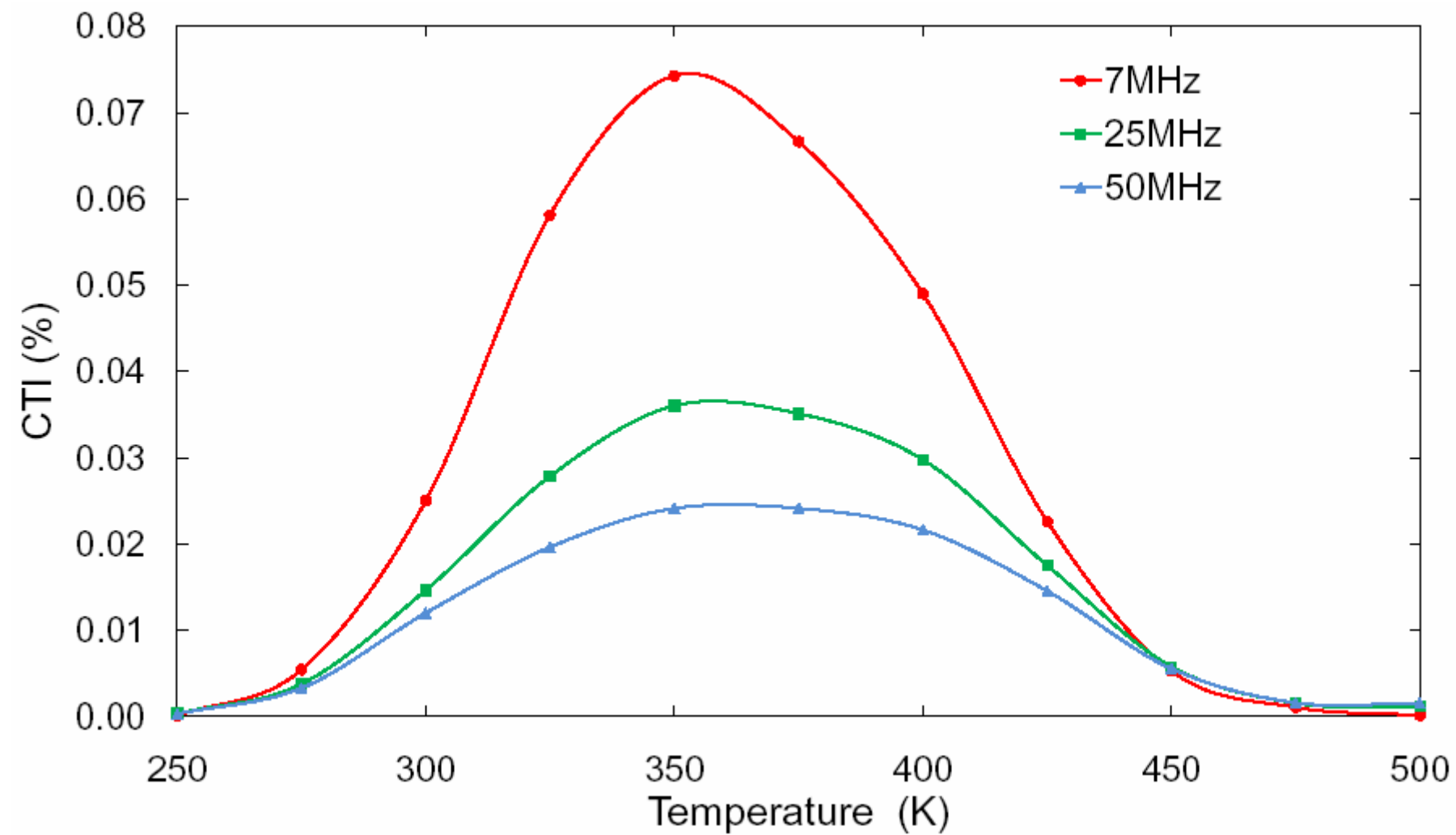


**Frequency Dependence:**  
in peak region high freq. (faster transfer) and less time for traps to capture charge. Thus, increasing freq. results in decreases CTI.

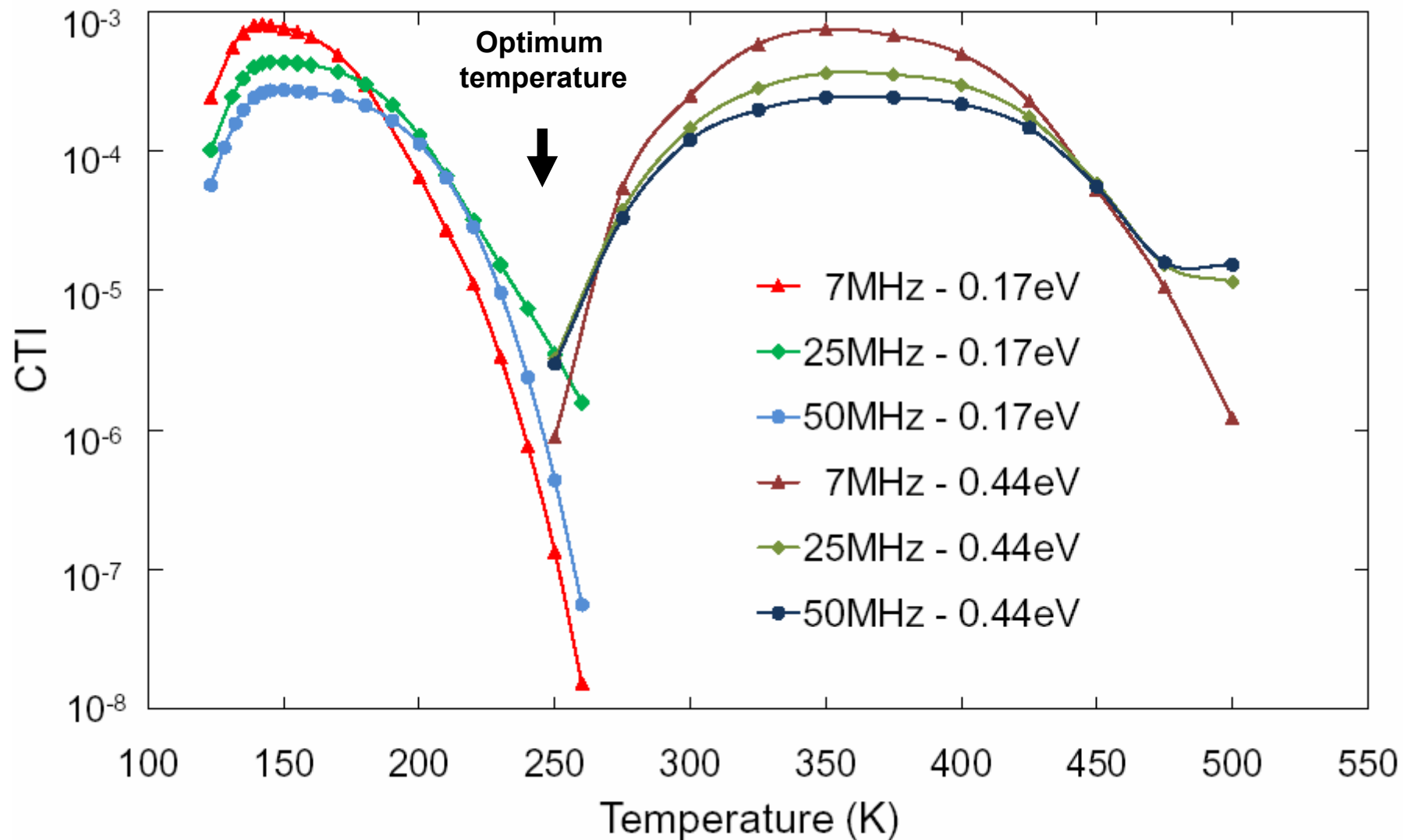
**High temperatures:** emission time is very short, charge can be captured and released during the same transfer. Low CTI.

**Low temperatures:** emission time is very long, charge can be captured but not released during the same transfer. Low CTI if traps were filled before.

# CTI vs. Temp. and Freq. 0.44 eV Traps

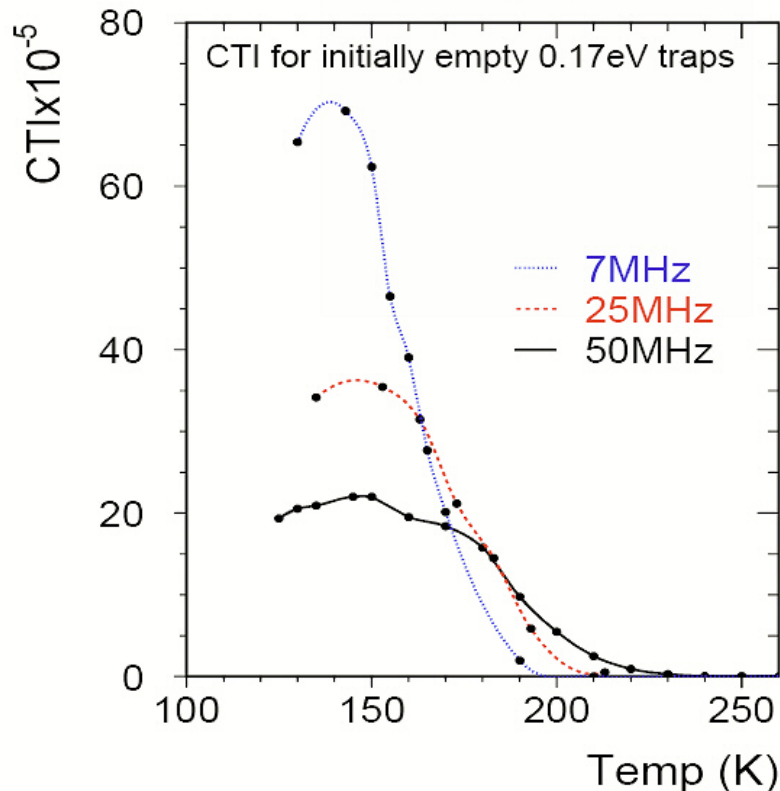


# Optimum Operation Temperature

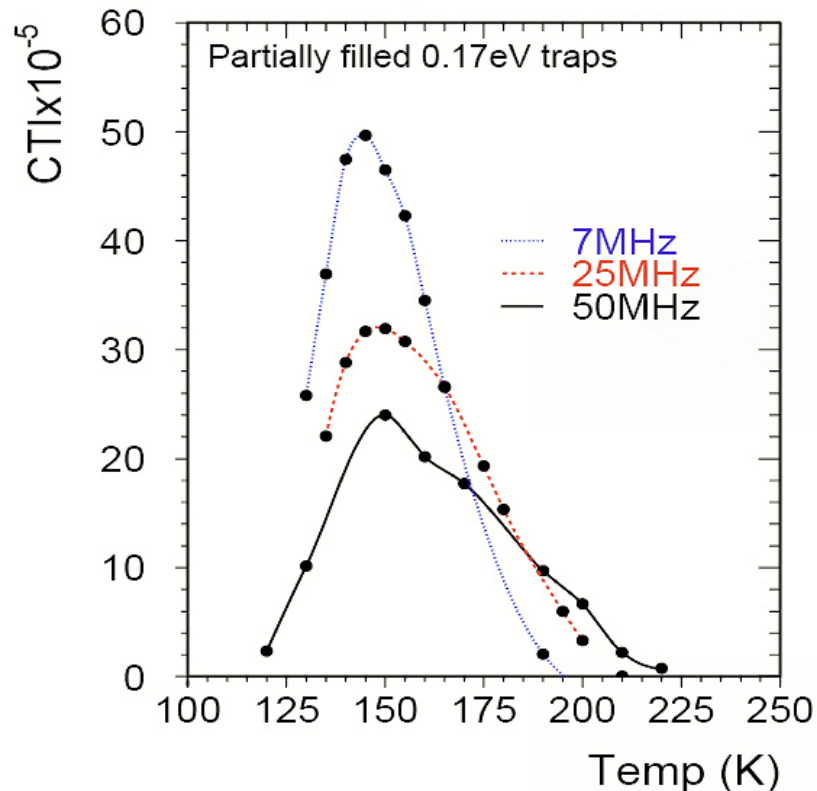


# Occupancy Effects

## Initially empty



## Partially filled



Fill ratio is determined by the decay time between  $t=0$ s (when the traps are filled) and the charged injection. CTI is reduced as expected for partially filled traps.

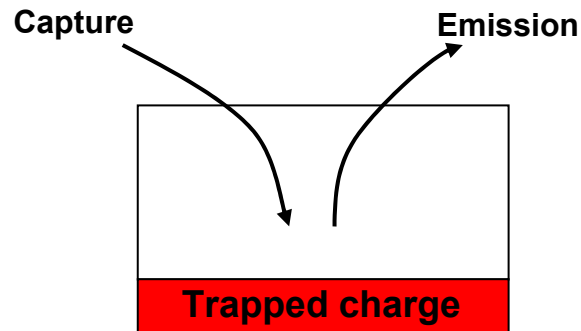
# CTI Modelling

**ISE-TCAD simulations:**

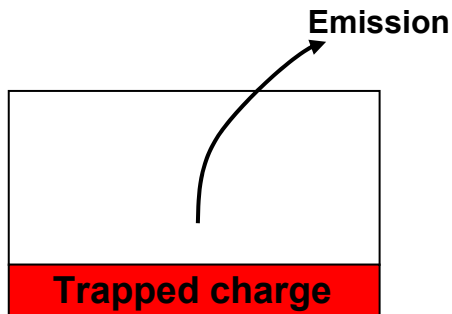
- takes detailed effects of charge transfer into account
- large CPU time

**Analytical CTI modelling:**

- very faster compared to ISE TCAD simulations
- provides insight into factors affecting CTI
- Traps undergo two basic processes:
  - Traps capture electrons from the signal charge.
  - Electrons are emitted from filled traps.
- Processes occur at different rates. Governed by capture  $\tau_c$  and emission  $\tau_e$  time constants.



During transfer

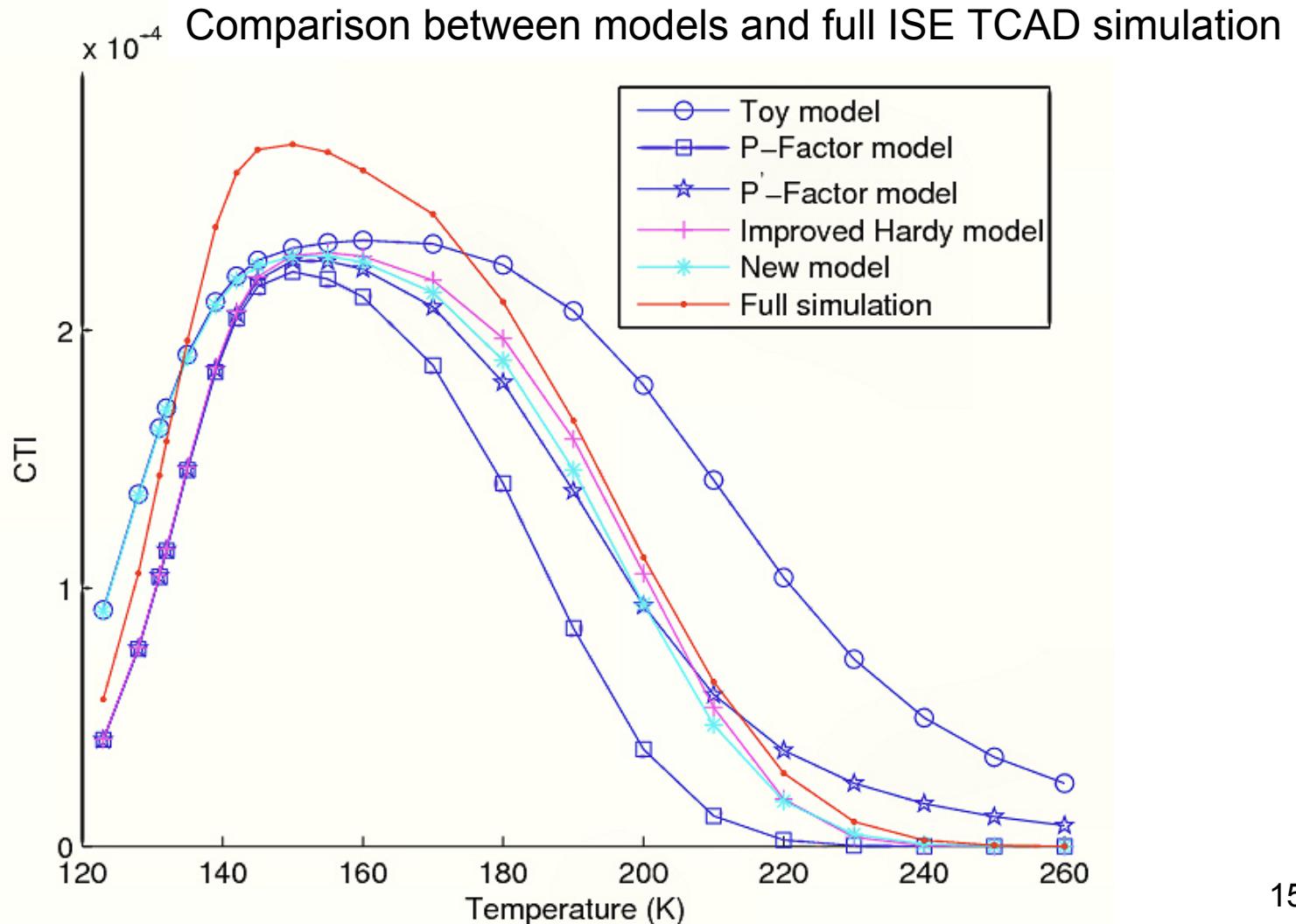


$$\tau_c = \frac{1}{\sigma_n v_{th} n_s}$$

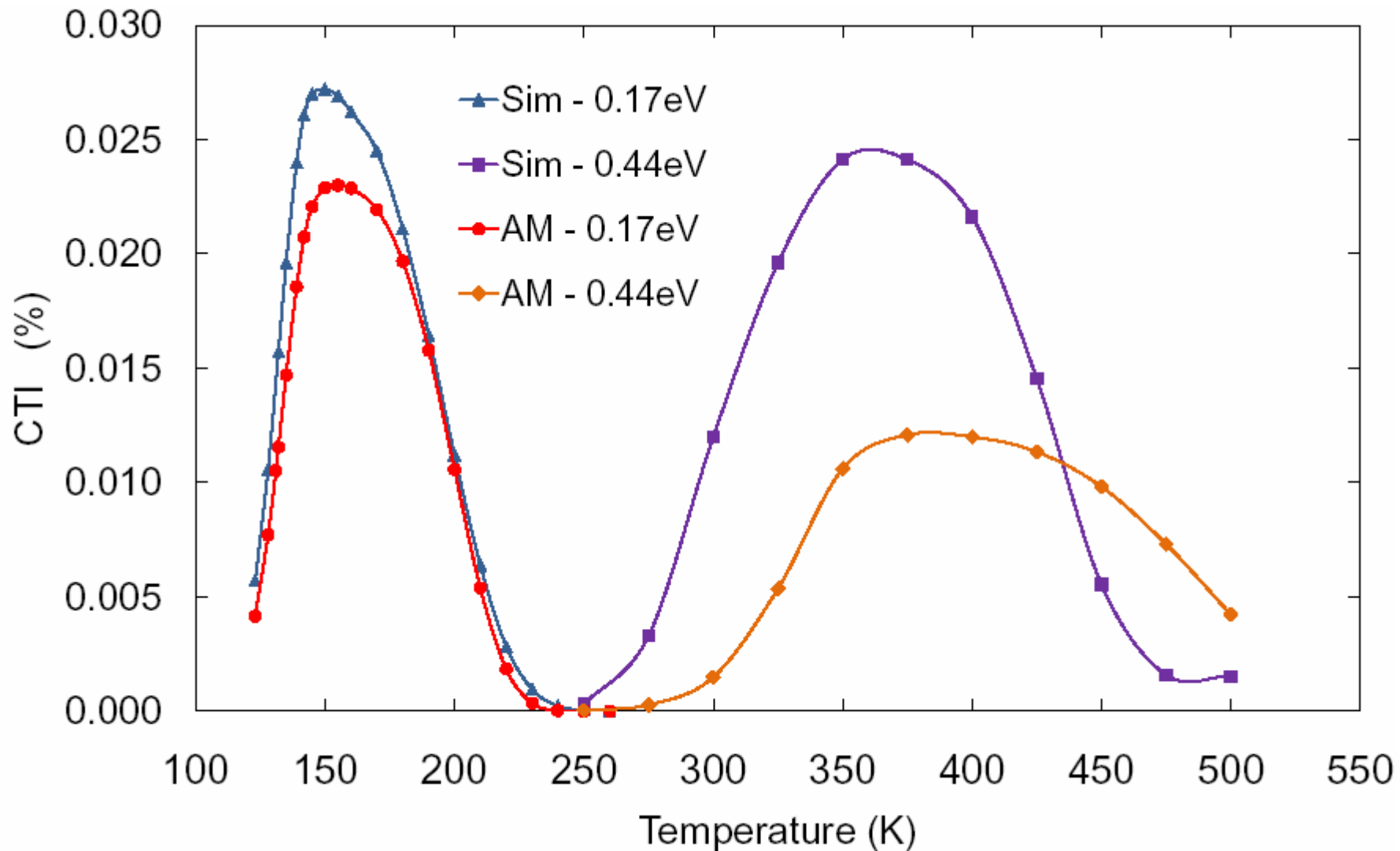
$$\tau_e = \frac{1}{\sigma_n X_n v_{th} N_c} \exp\left(\frac{E_c - E_t}{kT}\right)$$

After transfer

# Comparison Between Models and Simulations for 0.17eV Traps



# Analytic Model vs. ISE TCAD Simulations for 0.17eV and 0.44 eV Traps

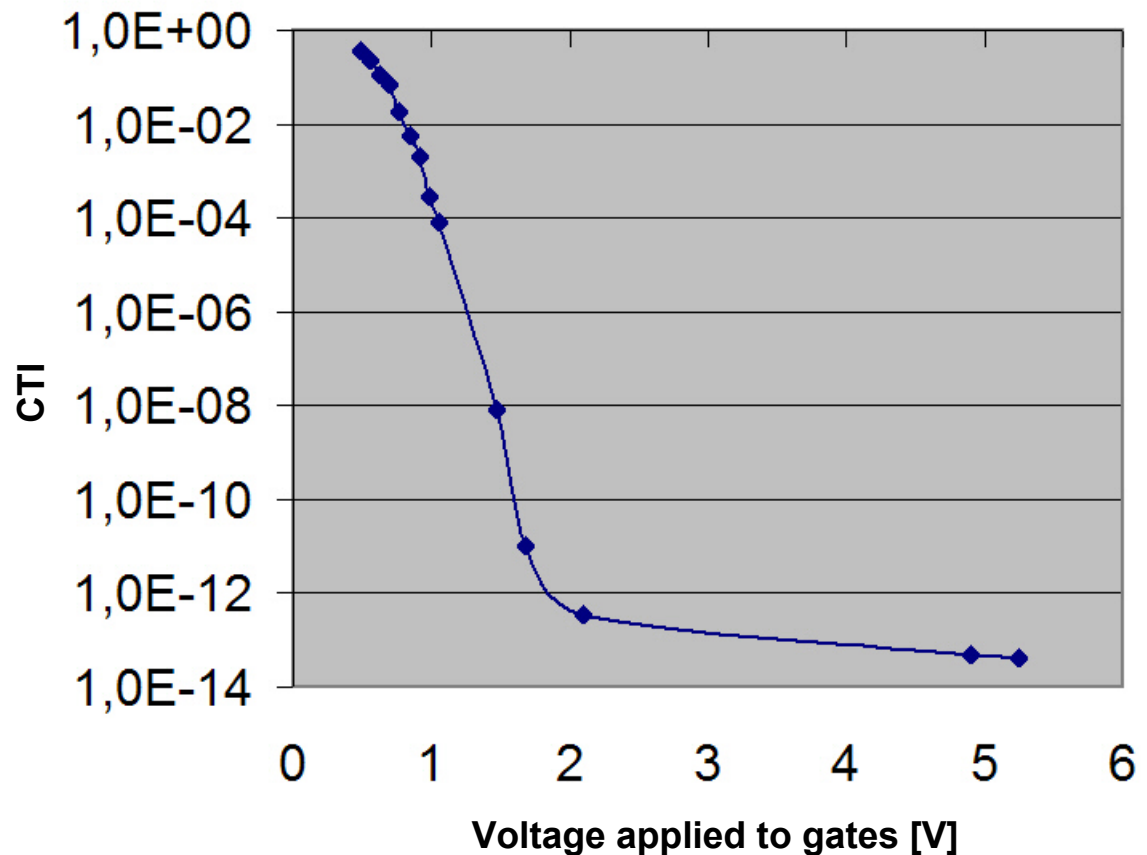




# Simulations of Clock Voltage Induced CTI

CTI vs. applied voltage behaves as expected.

Simulated threshold around 1.8 V.

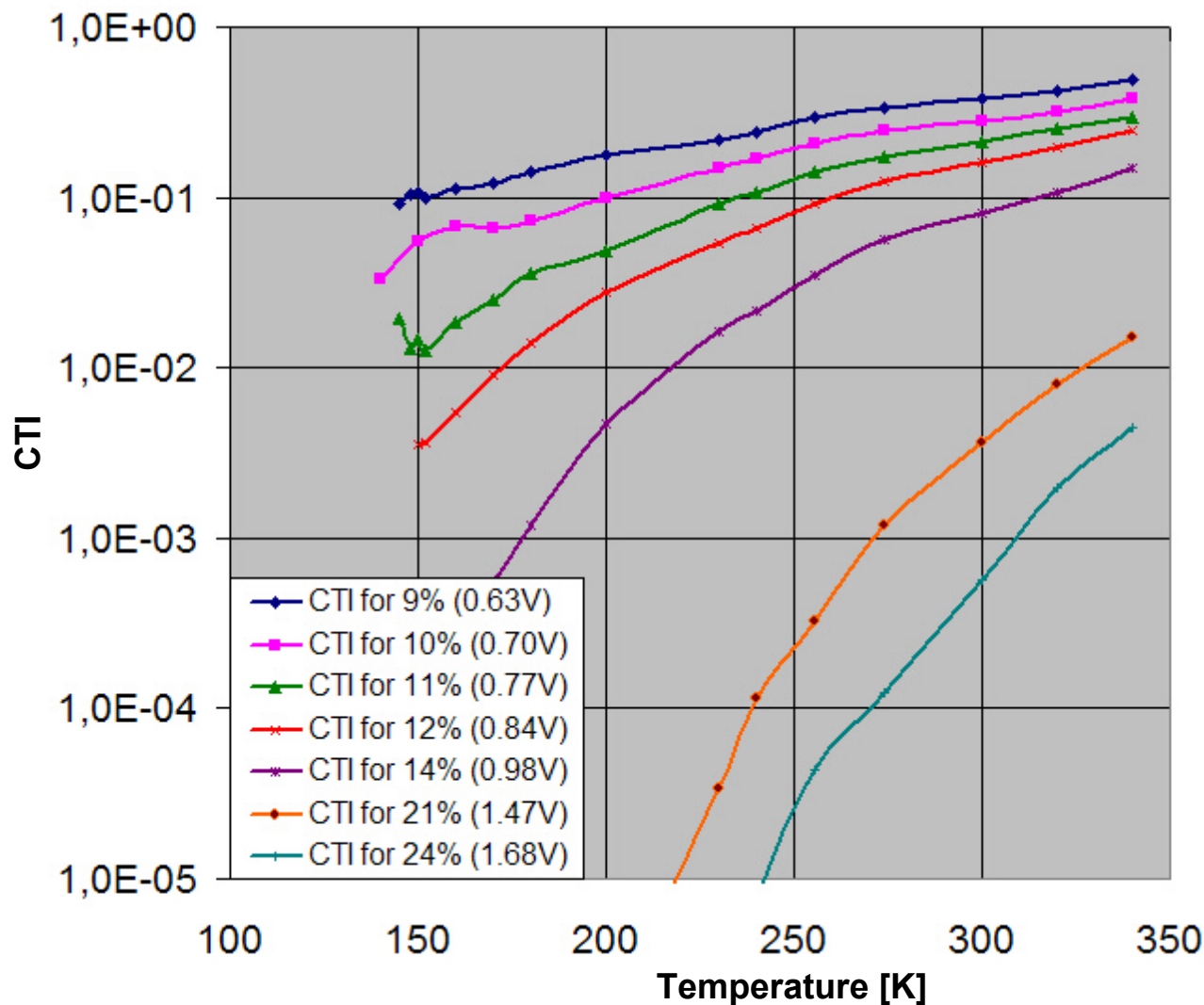


Expected  
simulation  
uncertainty  
around  $10^{-7}$

# Simulations of Voltage Induced CTI Temperature Dependence

For the same voltage on gates changes of CTI can be observed depending on temperature.

Decrease of electron mobility with rising temperature.



# Summary

- ISE TCAD simulations and analytical modelling have been applied in order to predict the Charge Transfer Inefficiency (CTI) for a three-phase CCD detector.
- Expected radiation hardness is well understood as a function of temperature and frequency.
- The optimal operation temperature has been determined where the CTI expectation has a minimum.
- Results obtained from ISE TCAD simulation and analytical modelling are compared. Good agreement has been found for the 0.17 eV traps, but not for the 0.44 eV traps.
- The experience gained with the CCD58 simulation served already much for the simulation of a CP-CCD with Column-Parallel readout. A comparison with direct measurements of the CP-CCD is in preparation.
- **Radiation hardness studies are an important aspect in the development of a vertex detector for the ILC and new simulation for a CP-CCD are in progress.**