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Progress report for CRP on *Utilization of ion accelerators for studying and modelling of radiation induced defects in semiconductors and insulators*

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Outline

- The goal of the CRP
- Characterization of whole are irradiated Helsinki diodes
- Characterization of neutron irradiated diodes
- Search for better devices
- Improvement of damage calculations with Marlowe
- TCAD (Silvaco ATLAS 2D) modeling of the Helsinki diodes
- Conclusion (future?)

The goal of the CRP and SNL's role in it

The goal of this CRP is to study the effect of radiation (ion, electron, and gamma) on the charge induction in semiconductor devices through irradiation/IBIC experiments and modeling.

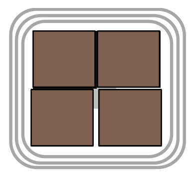
SNL was tasked with:

- Electrical characterization of the selected devices
- Selection of irradiation conditions
- Damage and ionization profile calculations for the selected irradiation conditions
- Ion beam irradiation using the SNL nuclear microprobe
- IBIC characterization
- Modeling

Whole are irradiated Helsinki and Hamamatsu diodes

8 MeV He rastered whole area irradiation was performed at ANSTO on an n-type Helsinki diode and two S5821 Hamamatsu PINs

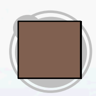
N-FZ Helsinki diode ("S1")
irradiation pattern



a=1.1mm

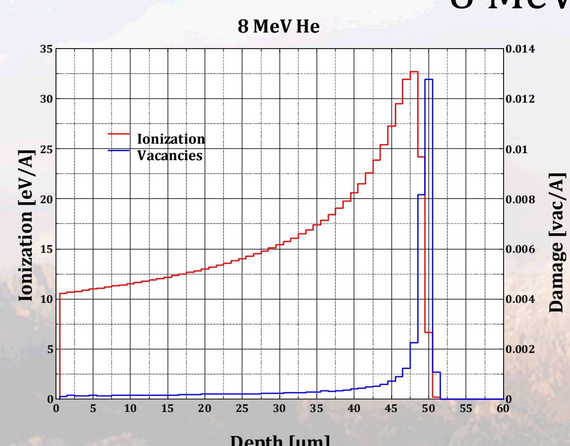
Device	Area [mm²]	Fluence
N_FZ Helsinki	2.5x2.5	1E+10
S5821 #16171	1.1	1E+10
S5821 #1814	1.1	1E+09

Hamamatsu S5821 ("16171" & "1814")
irradiation pattern



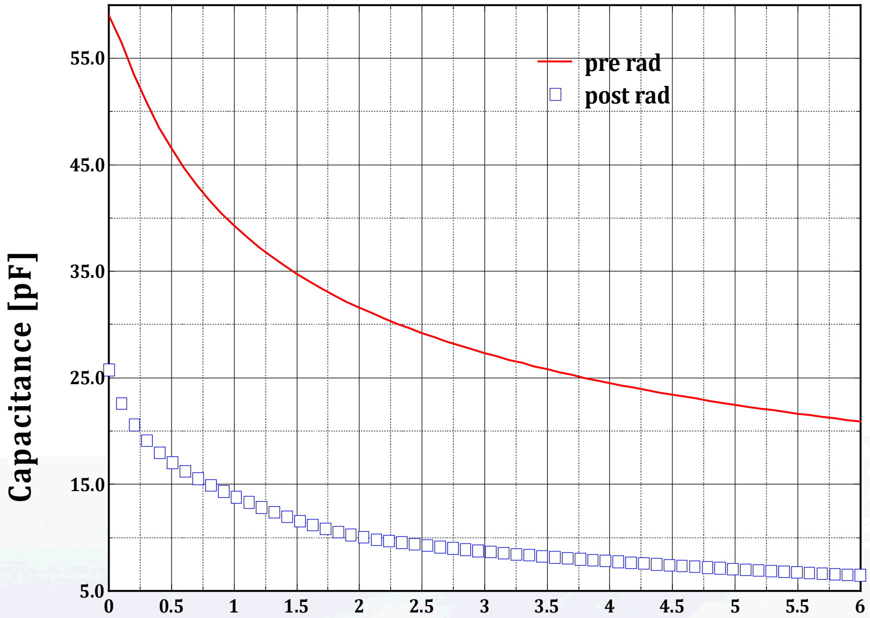
S5821

- Doping from C-V ~ 10^{13} 1/cm^3
- Depletion depth @ 50 V 45 μm
- 8 MeV EOR ~ 50 μm



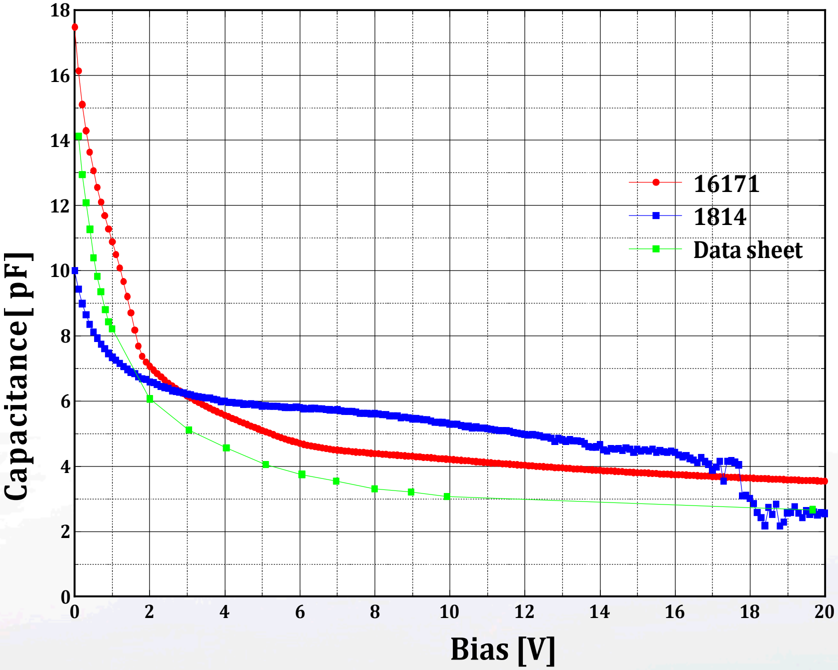
C-V measurements

Helsinki diode



(a)

S5821



(b)

Expected behavior, decreased capacitance after irradiations. Slight difference from SNL's previous pulsed irradiation.

Low fluence is kind of OK, but the high fluence does not make sense. Capacitance increased after irradiation! EOR damage peak is far behind the region probed!

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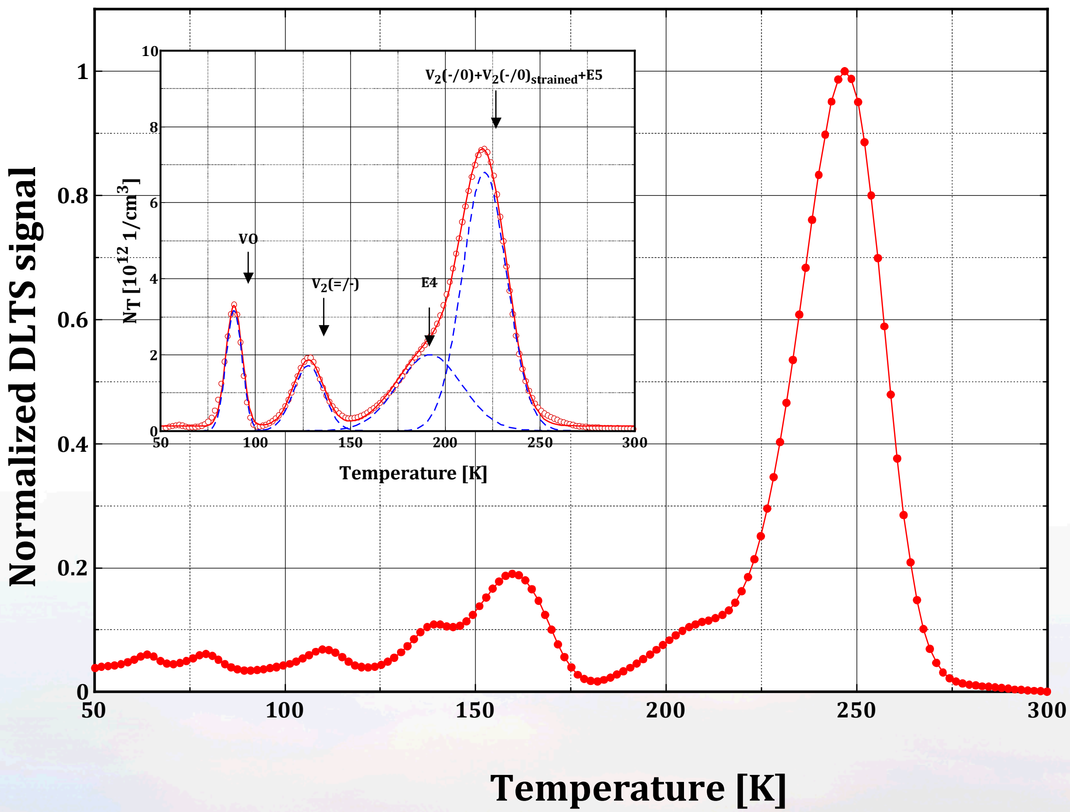
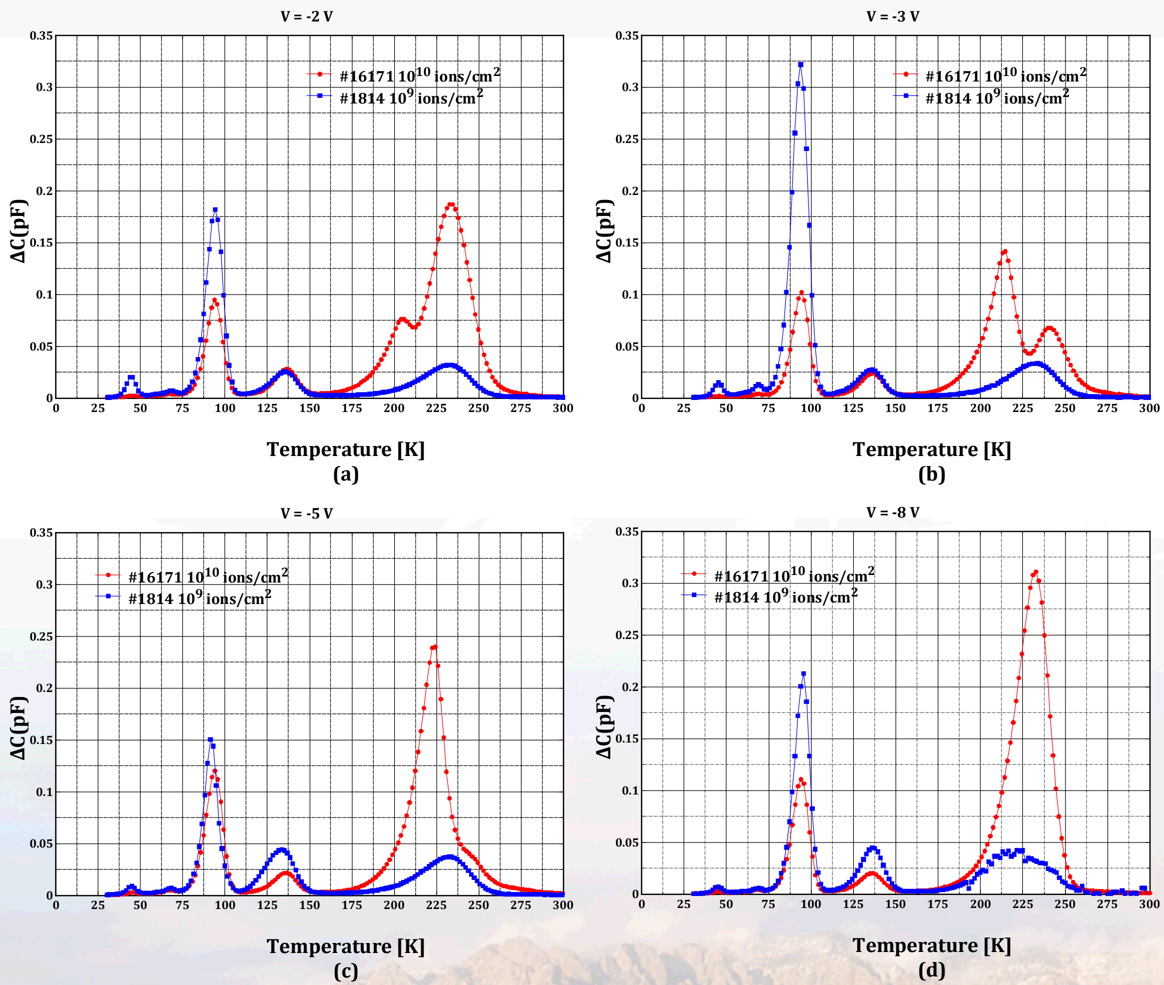
DLTS Helsinki diode



Typical heavy ion (or EOR) spectrum, although the VO peak is missing probably due to defect compensation.
The device is already almost depleted to 50 µm (EOR) at 0 V; therefore, the DLTS probes the EOR, high damage region.
8 MeV He EOR damage is neutron like (clustered)!

DLTS scan on S5821



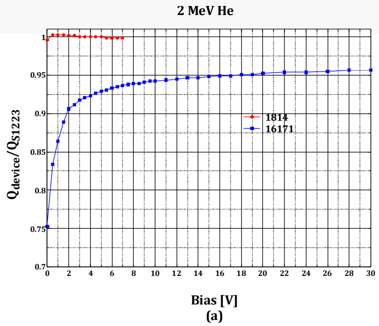
DLTS sees only up to 20-30 µm where the damage is light and uniform. We expect electron like damage (equal height di-vacancy peaks) and no change in the structure of the spectrum. The peaks should grow with the applied voltage as more and more defects are included in the probed region.

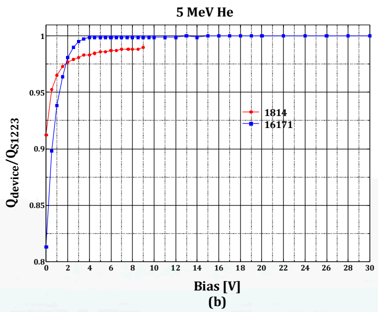
Low fluence: OK

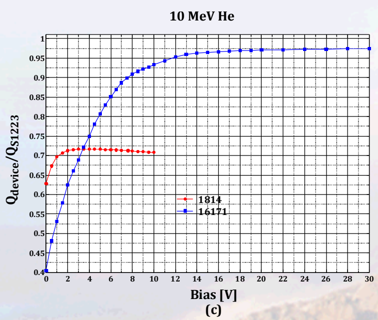
High fluence: ?

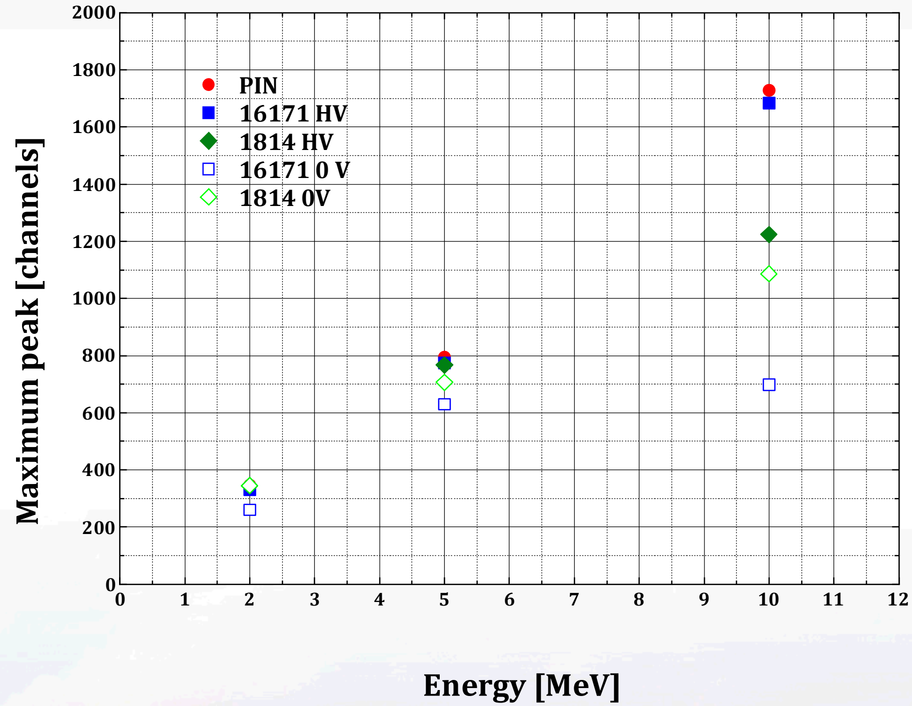
Charge trapped in field oxide or passivation layer?

IBIC measurements









- Large leakage current prohibits applying larger bias
- 2 MeV: all charge is created in the depletion layer even at 0 V
- 5 MeV: charge is deposited up to 20 µm, some diffusion effect can be seen.
- 10 MeV: Carriers have to diffuse through the the highly damaged region
- #16171: Not clear what the actual bias is!

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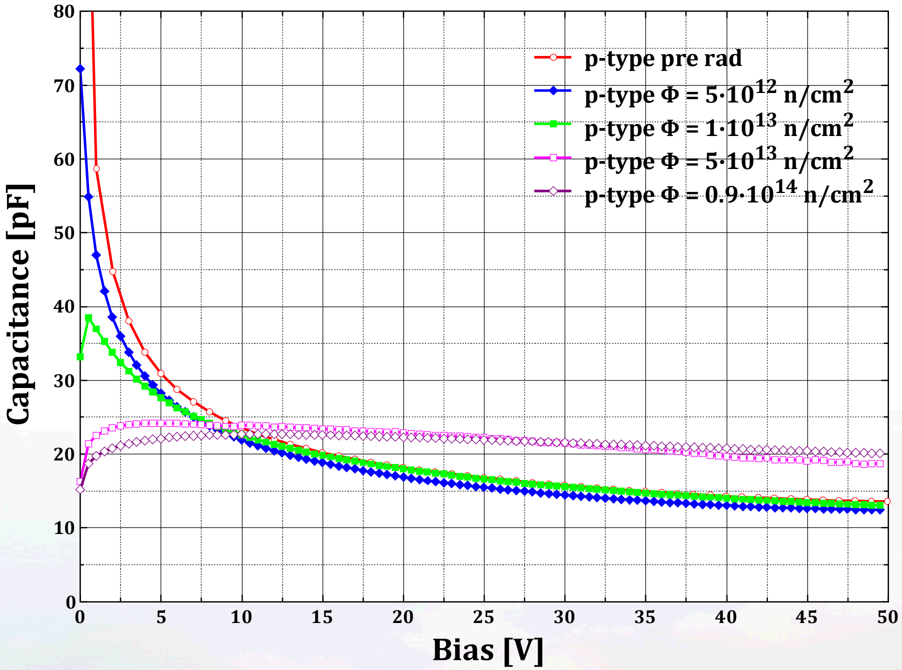
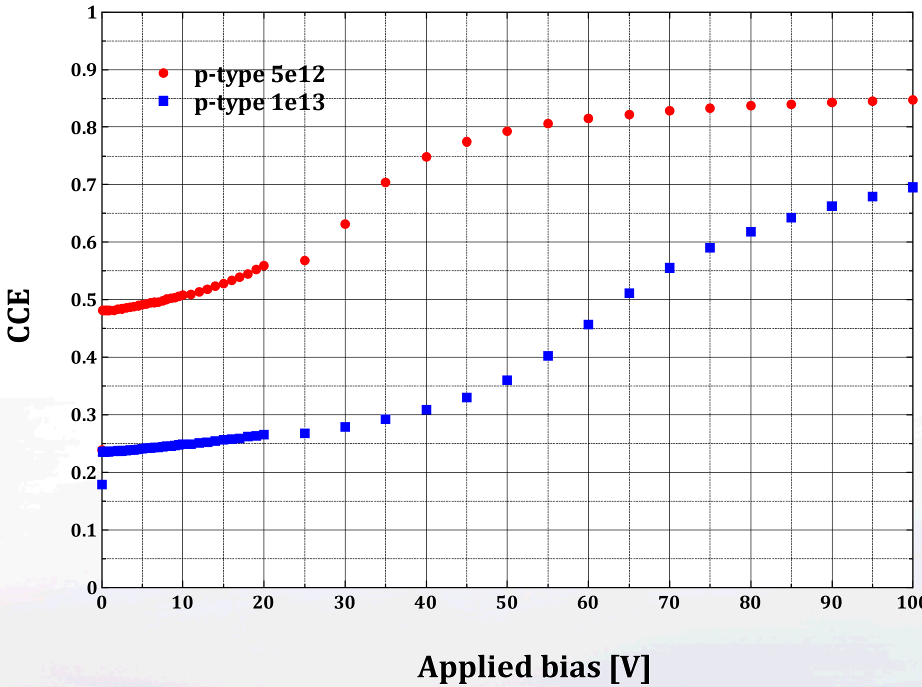
Neutron irradiation of Helsinki diodes

SNL's Annual Core Research reactor, $5 \cdot 10^{12}$ to $9 \cdot 10^{13}$ $1/cm^2$ 1 MeV n equivalent fluences

ACCR irradiated Helsinki diodes





Neutron irradiation should be perfect for modeling: uniform damage throughout the entire device independent of contacts, passivation layers, etc.
The large amount of damage causes large increase in the leakage current, changes electrostatics of device due to charge trapped in defects. This is a large problem for diodes with very low doping as the Helsinki ones.

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Searching for new devices

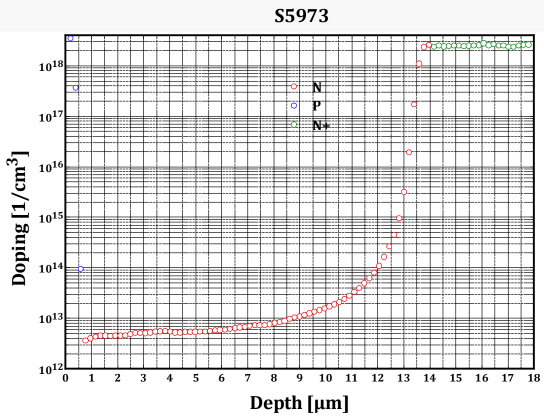
Why do we need new devices?

- **The problems**
  - The Helsinki diodes are too large, it is very difficult to do full area irradiations for C-V and DLTS.
  - Even light uniform damage throughout the device increases leakage current and leads to biasing problem.
  - The defects trap enough charge to alter the electrostatics of the device which the current model cannot account for.

New devices:

- Hamamatsu PIN (S5821 and S5973) and PN (S2386) diodes
- S5973 and S2386 are characterized at SNL (structure and spreading resistance
- Commercial cheap devices
- The have small areas (~ 1 mm^2) for full are irradiation but large enough for C-V and DLTS
- ACRR neutron irradiation up to $9 \cdot 10^{13}$ $1/cm^2$ 1 MeV n equivalent fluences (worst case scenario)
- C-V, IBIC measurements

Device characteristics



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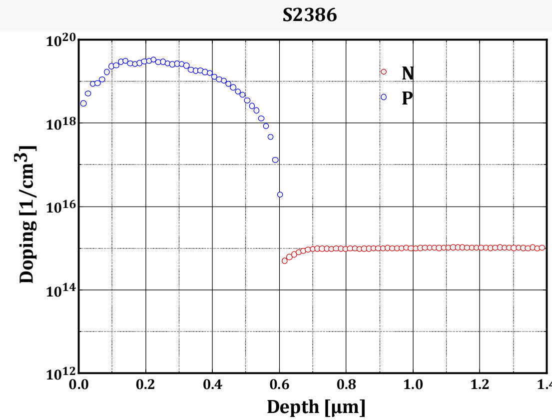

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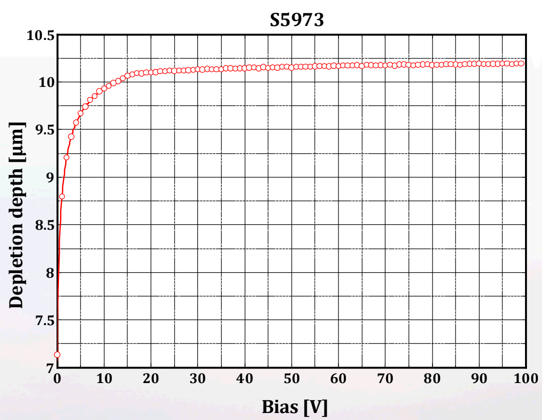

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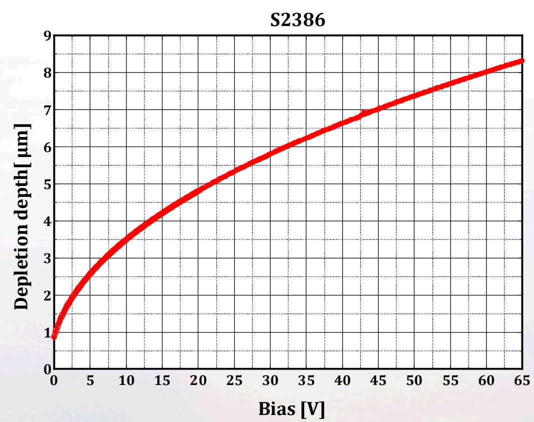
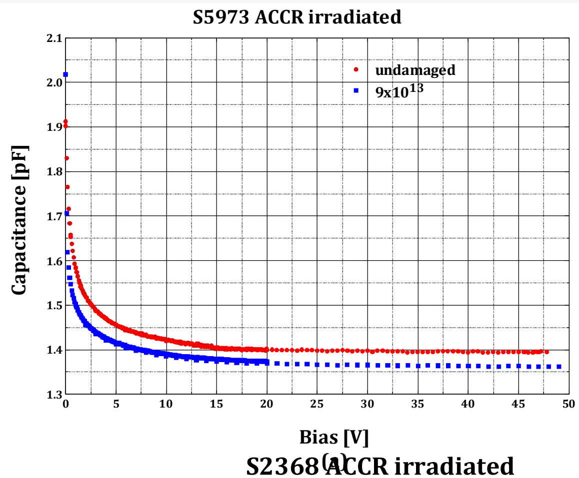
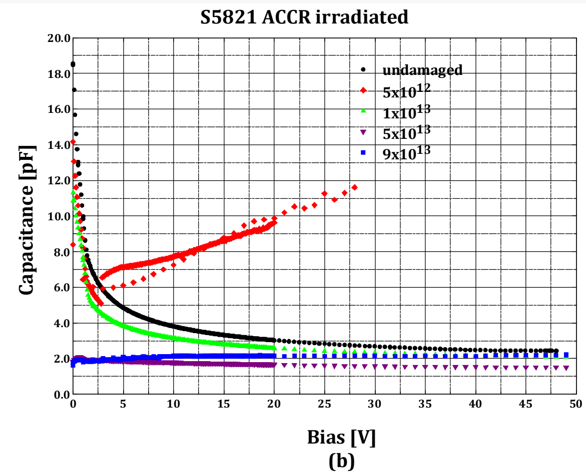
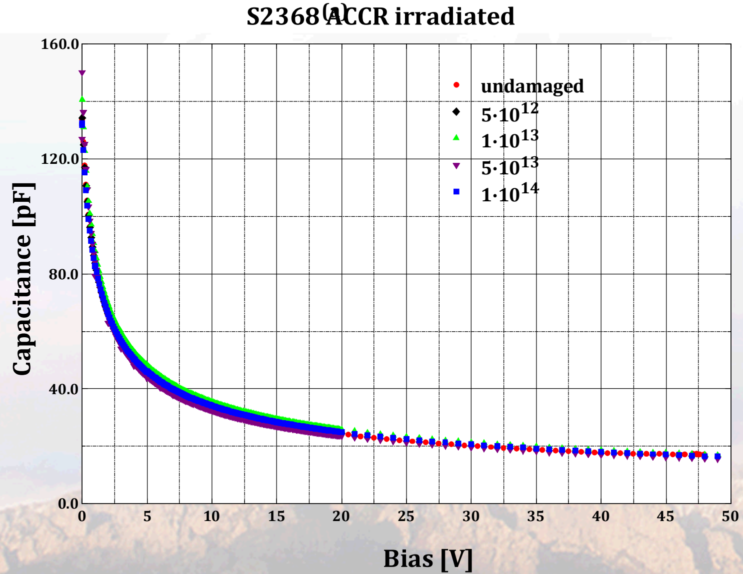


(d)

C-V







The PIN diodes exhibit similar problems as the Helsinki diodes.

Hardly any change in C-V or I-V for even the highest fluence in the PN diode!

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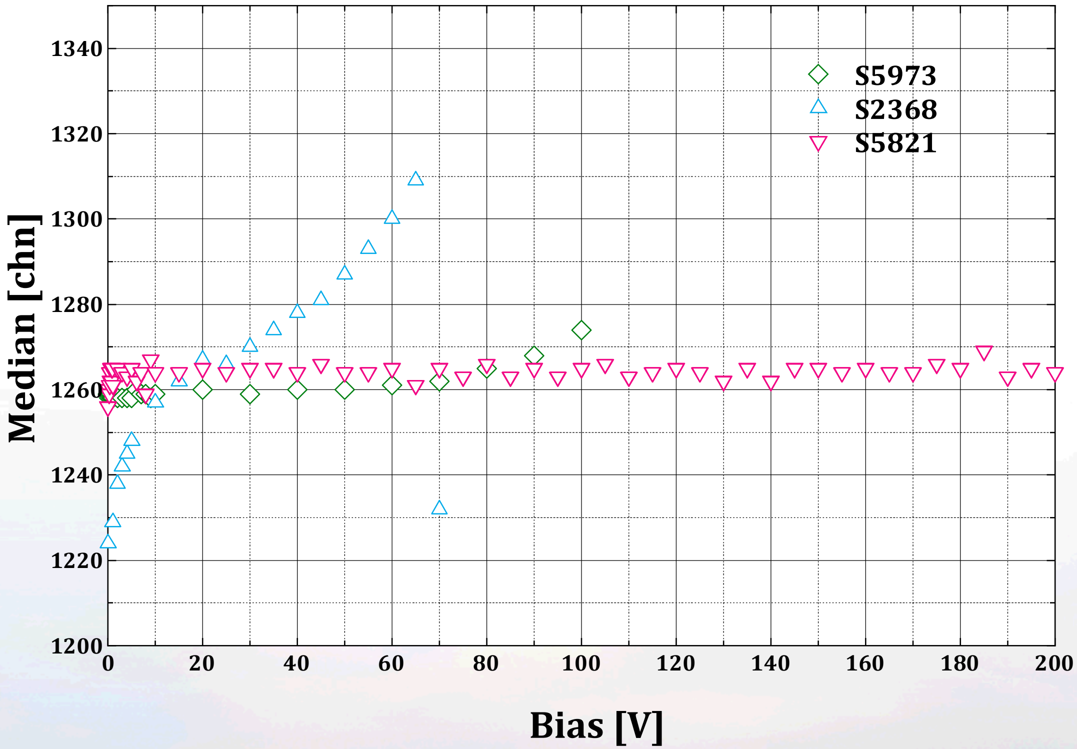
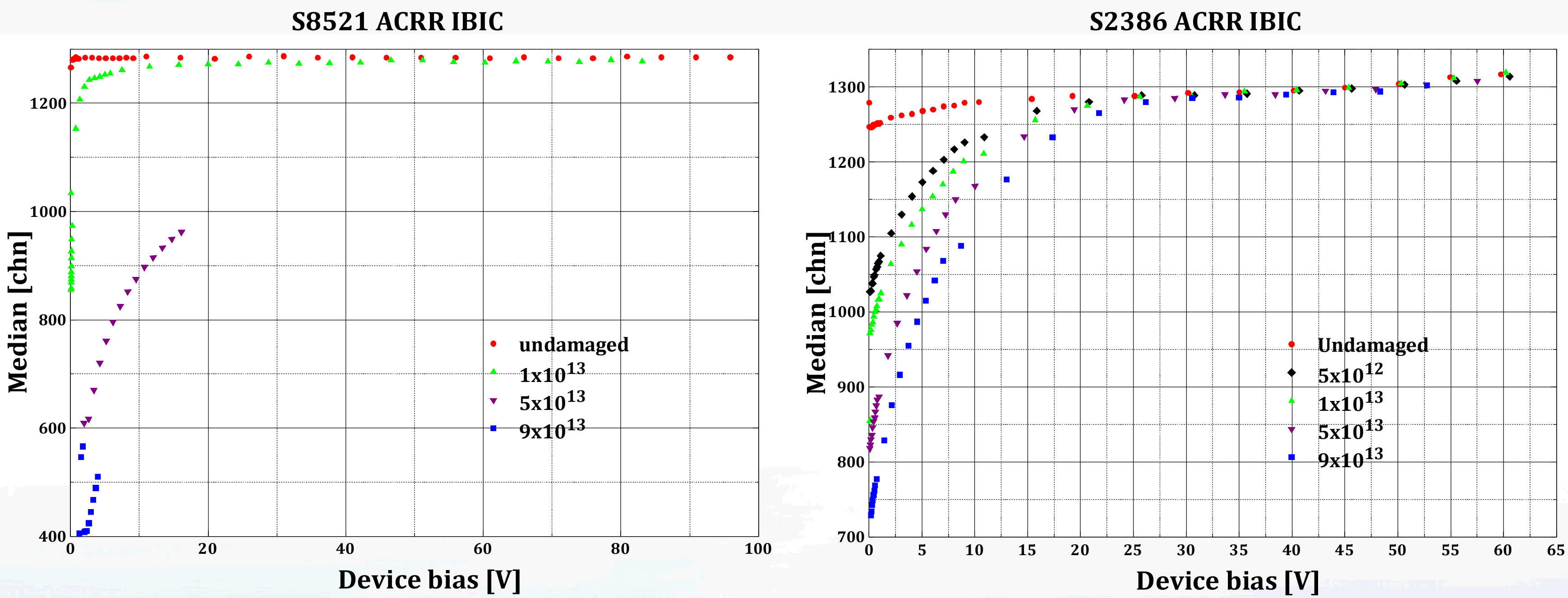
IBIC before irradiation 2 MeV He



- PINs have practically no bias dependence (fully depleted to 2 MeV He range at 0 V)
- PN shows depletion dependence of the CEE but then avalanche seems to develop @ ~ 20 V

IBIC after irradiation



(a) (b)

- PINs have leakage current problems (unable to bias) even at moderate damage
- PN has no problems, nice gradual decrease of CCE at all bias voltages, it would be ideal for modeling

The Marlowe problem

- Marlowe does not use the displacement energy concept, it uses binding energy (cohesion energy)

- The displacement energy is not a very good concept for BCA codes
  - “In the case of Frenkel pairs production, an energy threshold was found experimentally below which no Frenkel pair is produced. This suggests an energy threshold value for BCA computations. Unfortunately, this threshold value was found to be dependent on the direction in which momentum is given, which was also predicted by MD. Thus, depending on direction, the mechanisms involved in producing Frenkel pairs is different, and, therefore, **its quantitative estimate for BCA calculations is ambiguous.”** Marc Hou, NIM B 187 (2002) 20-35

- SRIM like codes do not care do not care about recoils stopping in the close vicinity of a vacancy. Although, this Frenkel-pair recombines SRIM considers it a permanent defect.

Prompt recombination

- **Interstitials distort the lattice**
- **If there is a vacancy nearby recombination puts the lattice into an energetically more preferable state (the lattice "pushes" the recoil into the vacancy).**
- **Question: What is "nearby" (the recombination radius) ?**
- **Marlowe method:**
  - In close pairs, the site nearest the atom is vacant.
  - In near pairs, that site is occupied or already paired, but a neighboring site defined by the crystal description, is vacant and unpaired. If more than one such site is available, the nearest is chosen.
  - All other configurations constitute distant pairs.
- **According to Marlowe the permanent Frenkel-pairs are all the distant pairs. Are they?**

The EBND parameter

- **This is the energy needed to remove an atom from its lattice site, usually the cohesion energy. This energy is subtracted from the energy transferred to the recoils.**
- **A further complication: There are 3 EBND parameters**
  - EBND(1) – this is the normal binding energy
  - EBND(2) – this is the binding energy for an interstitial or impurity atom. It is not really important since the probability of a recoil colliding with another, stopped recoil is very, very low.
  - EBND(3) – this is the binding energy in a replacement collision.
- **Argument**
  - In a replacement collision the state of the lattice does not change; therefore, no energy needs to be removed from the energy of the moving atom.
  - Initially, 0 eV was used but they found that it overestimates the displacements (compared to MD). Now it is said that it is a small amount, less than EBND(1). Changing EBND(3) from 0 to EBND(1) can change the number of total displacements by a factor of 2!

WARNING! Turning off pairing in Marlowe (LORG=0) will cause EBND(3)=EBND(1) in the calculations!

What we need to do?

- **Determining EBND(3)**
  - Calculate the total number of displacements as the function of EBND(3) for various energies and compare it to MD.
- **Determine the recombination radius**
  - Using this EBND(3) parameter run calculations with the same energies with better statistics.
  - Calculate the separation distribution for close, near, and distant pairs.
  - Calculate $N(x) = \int_{x}^{\infty} f(x')dx'$
  - Match *N(x)* to the number of Frenkel-pairs calculated by MD.
  - Hope that this number is the same for every energy.
- **The comparison of Marlowe and MD found EBND(3) to be 1.68 eV**

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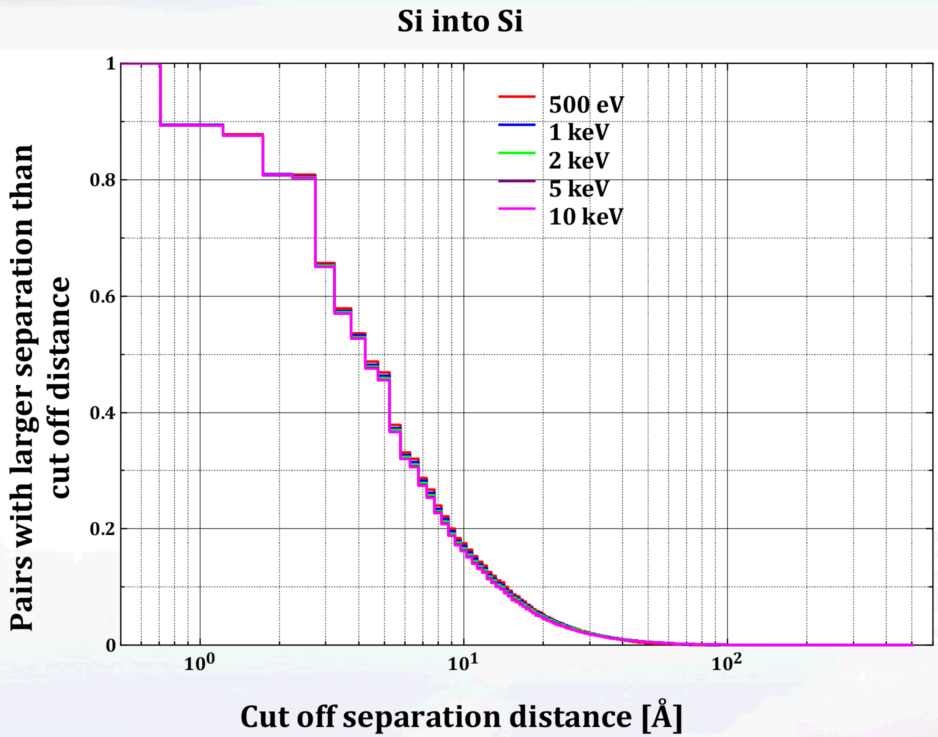
Determining of the recombination radius



Energy	Cut-off distance
500	7.44
1000	7.42
2000	7.25
5000	7.41
10000	7.47
Average	7.398
Stdev	0.086
Percentage	1.16%

The separation distributions are almost identical for the energies used.
Most of the vacancies are created by the low energy recoils.

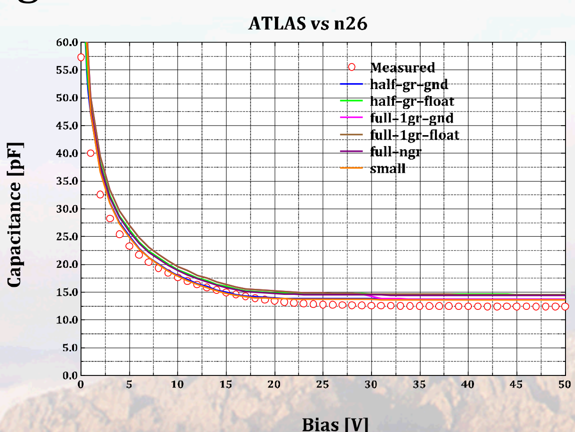
Which pairs are eliminated?

	500 eV						
	Correlated close	Uncorrelated close	Correlated near	Uncorrelated near	Correlated distant	Uncorrelated distant	Total
Recombined	3.97	1.31	3.97	6.19	4.17	6.22	25.83
Survived	0.00	0.00	0.00	0.00	0.22	9.88	10.10
Survival ratio	0.00%	0.00%	0.00%	0.00%	4.99%	61.39%	28.11%
	10 keV						
	Correlated close	Uncorrelated close	Correlated near	Uncorrelated near	Correlated distant	Uncorrelated distant	Total
Recombined	65.84	25.19	65.84	115.90	64.96	109.64	447.38
Survived	0.00	0.00	0.00	0.00	2.96	157.38	160.35
Survival ratio	0.00%	0.00%	0.00%	0.00%	4.36%	58.94%	26.38%

Similar calculations with ZBL local electronic energy loss:
EBND(3) = 1.03±0.17, Recombination radius: 7.08±0.16

TCAD simulation of the Helsinki diode Electrostatics

- 2D model, full and half diode adapted from U. New Delhi
- Different configurations were tested whether we need to model a small piece of the devices, full devices and guard rings
- Size (when scaling capacitance and current properly did not seem to affect the calculations
- Full device with all guard rings cannot be simulated due to node number limitations
- Floating/grounding or entirely omitting guard rings does not change C-V and I-V significantly
- Doping of the intrinsic layer at 3.07x10^{11} 1/cm3 and lifetimes of 380 μs give very good agreement with the measurements



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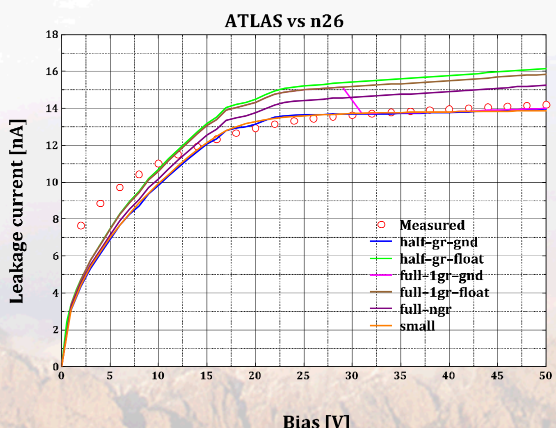
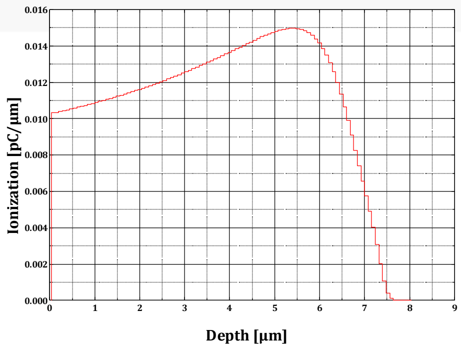


(b)

IBIC: 2 MeV He



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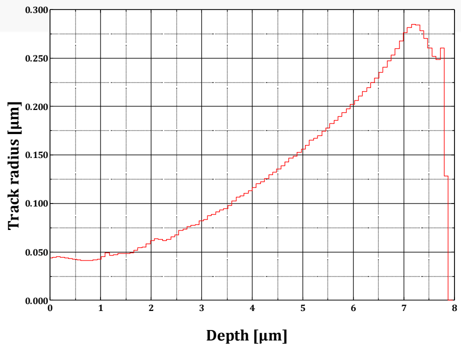

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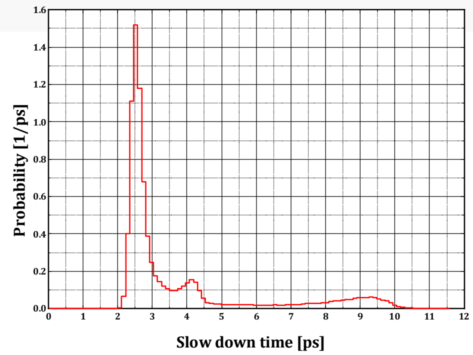
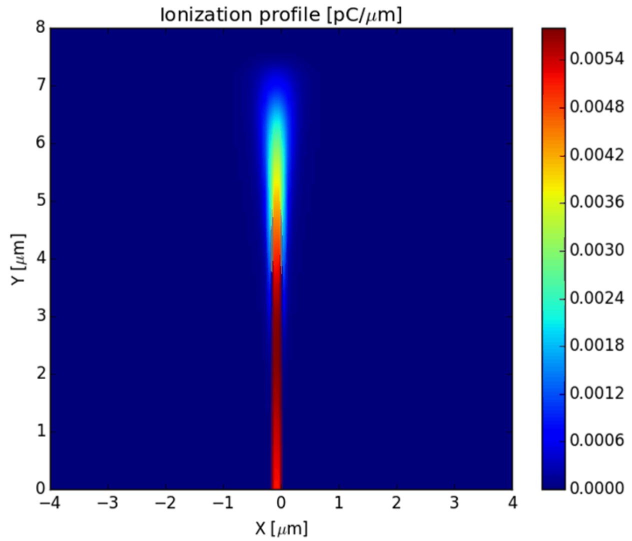
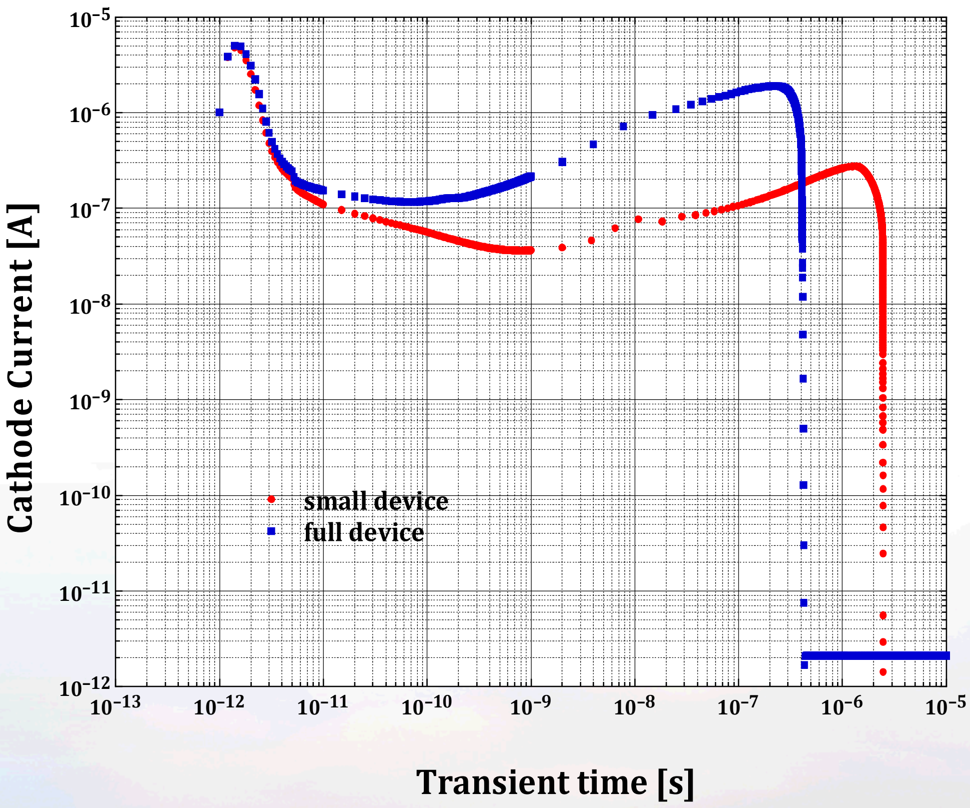




Ion track

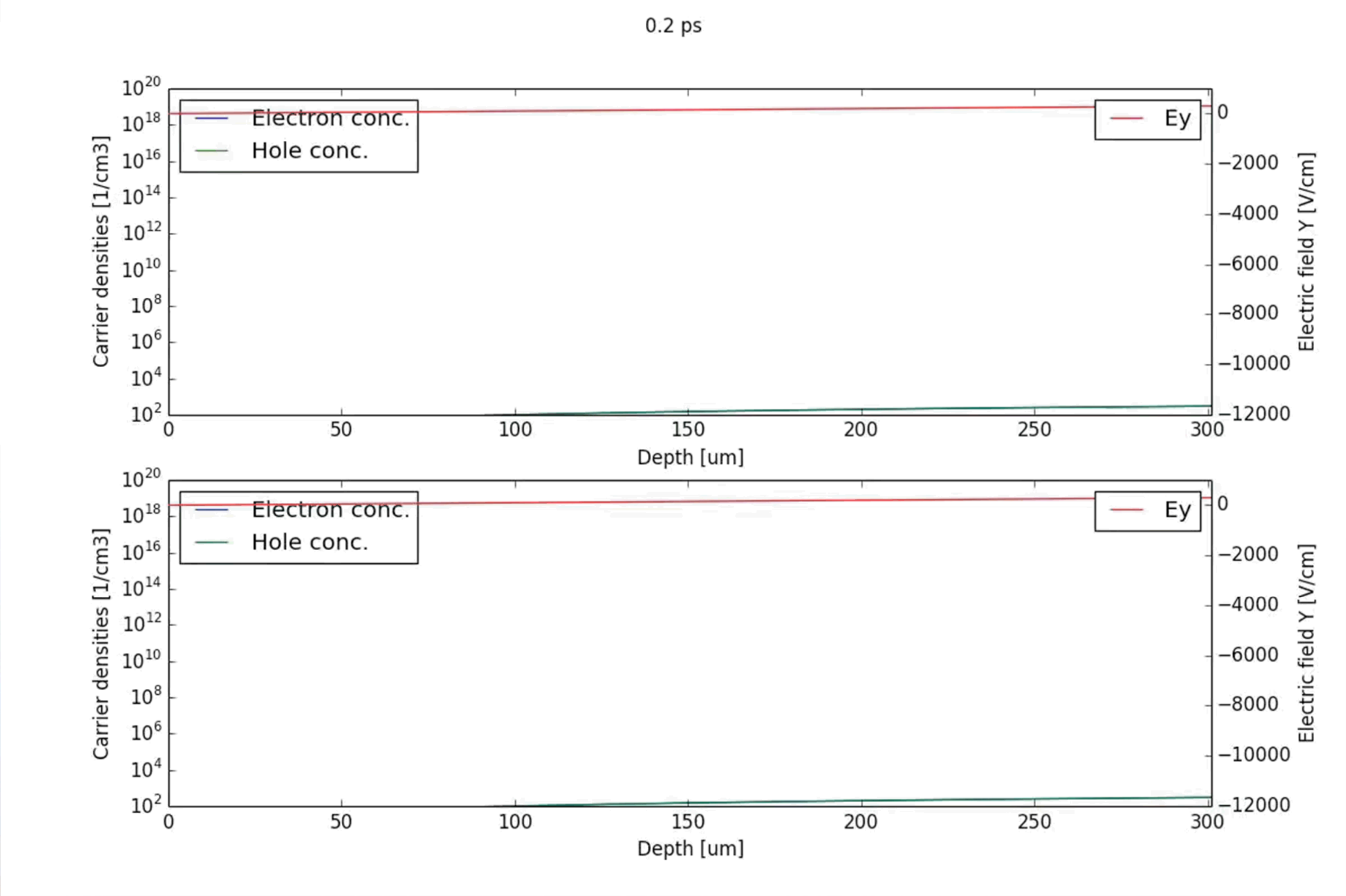
- 2D distribution from SRIM, column with Gaussian cross section with depth dependent width.
- Time dependence from Marlowe, 3 ps pulse length.

The induced current according to ATLAS



- Very short initial current
- Current lasting very long time and increasing toward the end of the IBIC pulse
- Obvious size effect in the simulation (full device need to be modeled)

What is happening?



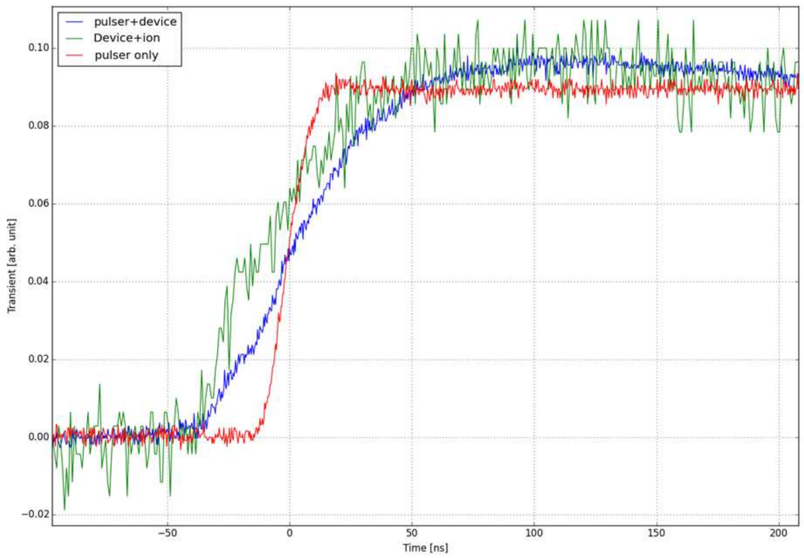
What is happening (in words)?

- Ion hits and creates a plasma column with charge density much higher than the doping level.
- At the edges of the plasma electrons and holes are quickly separated creating huge negative and positive charge densities. The result is that the electric field is pushed out from the plasma and concentrated at the edges.
- Some of the electrons will drift toward the cathode but most of them will be in the region with zero electric field. They will diffuse together with the holes.
- As the plasma is moving toward the cathode it pushes the electric field ahead of it like a snow plow.
- When the carrier density drops low enough the plasma collapses and the electric field is restored. The remaining carriers drift through the device quickly.

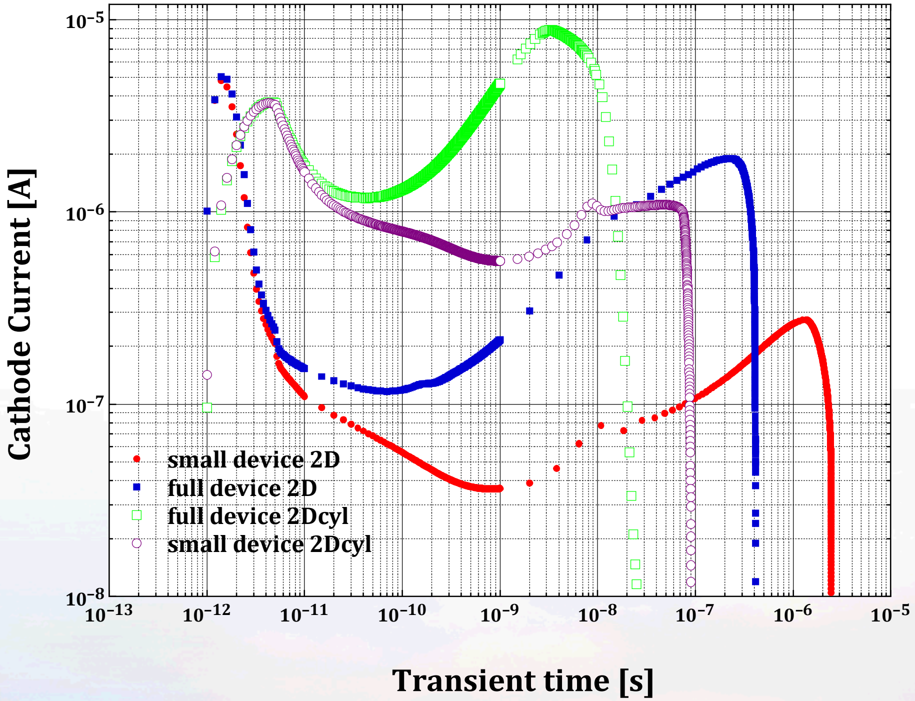
2D movies

Is the model correct?

- If the model is correct and the charge induction last hundreds of ns then the preamp waveform should show it.
- Measurement did not show this very long IBIC signal.
- The model is not correct because this phenomenon is a 3D effect. 2D simulation assumes the structure extending the same way in the third dimension (1 µm in case of ATLAS)



Solution: 2D cylindrical simulation



- The effect is real but much smaller the IBIC signal is tens of ns not hundreds of ns
- The size of the simulation has a very big effect.
- The change of the electric field during the IBIC pulse is still a concern for the 1D simple modeling.

Moving along the center line

2D movies

Conclusion

- **We might not have selected the best device for the project**
  - Large area and very low doping leads to high leakage currents for full area irradiation.
  - Charge trapped in defects can change the electrostatics of the device.
  - Even very low LET IBIC measurement can cause plasma effects that change the electric field that seriously limits the use of the Gunn theorem.
- **Future to do**
  - TCAD simulations of damaged diodes
  - Using new devices that allow the use of the Vittone model (?)
- **SNL participation**
  - The support completely dried up for this project.
  - Might be able to complete some TCAD simulation for damaged devices.