TCAD analysis of leakage current and breakdown voltage in small pitch 3D pixel sensors

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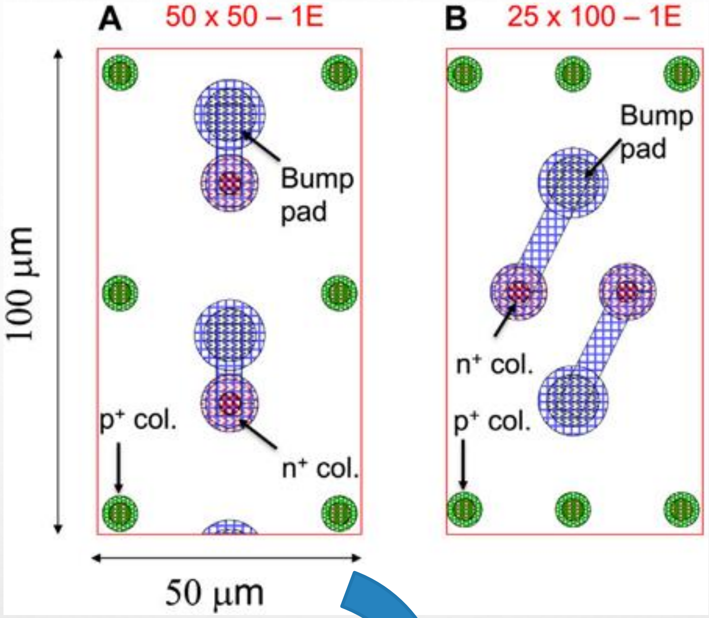
Content

1. Introduction

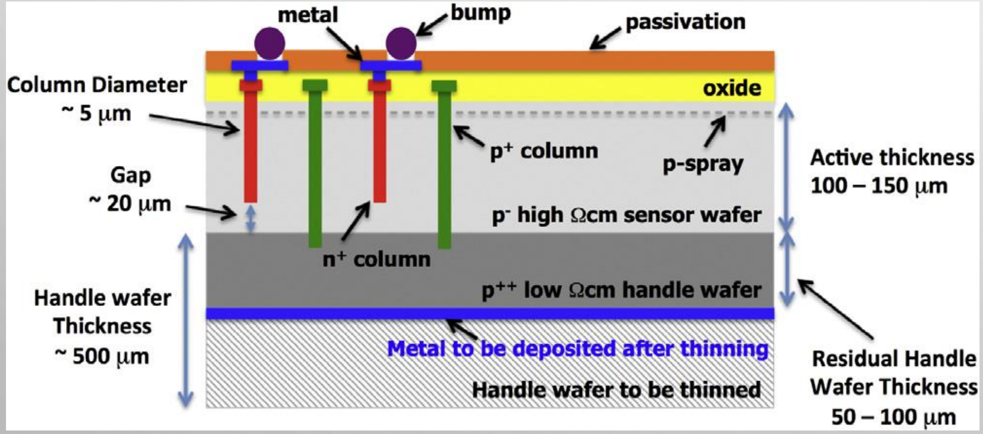
ATLAS ITk specifications:

- *Radiation tolerance up to* $2*10^{16} n_{eq}/cm^2$;
- *Operation voltage* $V_{op} < 250$ *V;*
- *Power dissipation* < 10 mW/cm^2;
- *Hit efficiency > 97%.*



Smaller inter-electrode distance translates into:

- *lower event pile up;*
- *stronger radiation hardness.*



Geometrical parameters of small-pitch 3D detectors:

- *active thickness 150* μm;
- *nominal radius ~2.5* μm;
- *effective gap ~20* μm.

1. Introduction

Beam Test Results:

- *At 10^{16} n_{eq}/cm^2 a hit efficiency of 96% reached below 100V with perpendicular beam incidence;*
- *Larger voltages (~150 V) required at $1.8x10^{16}$ n_{eq}/cm^2.*

Problem:

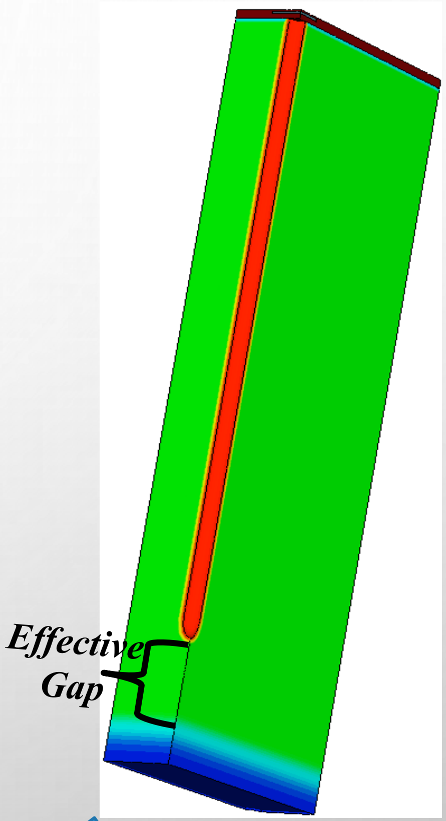
- *Breakdown voltage not large enough compared with the required voltage for the worst cases;*
- *Power dissipation.*

Objective:

- *Locate the origin of the breakdown;*
- *Improve the breakdown voltage from geometry point of view.*

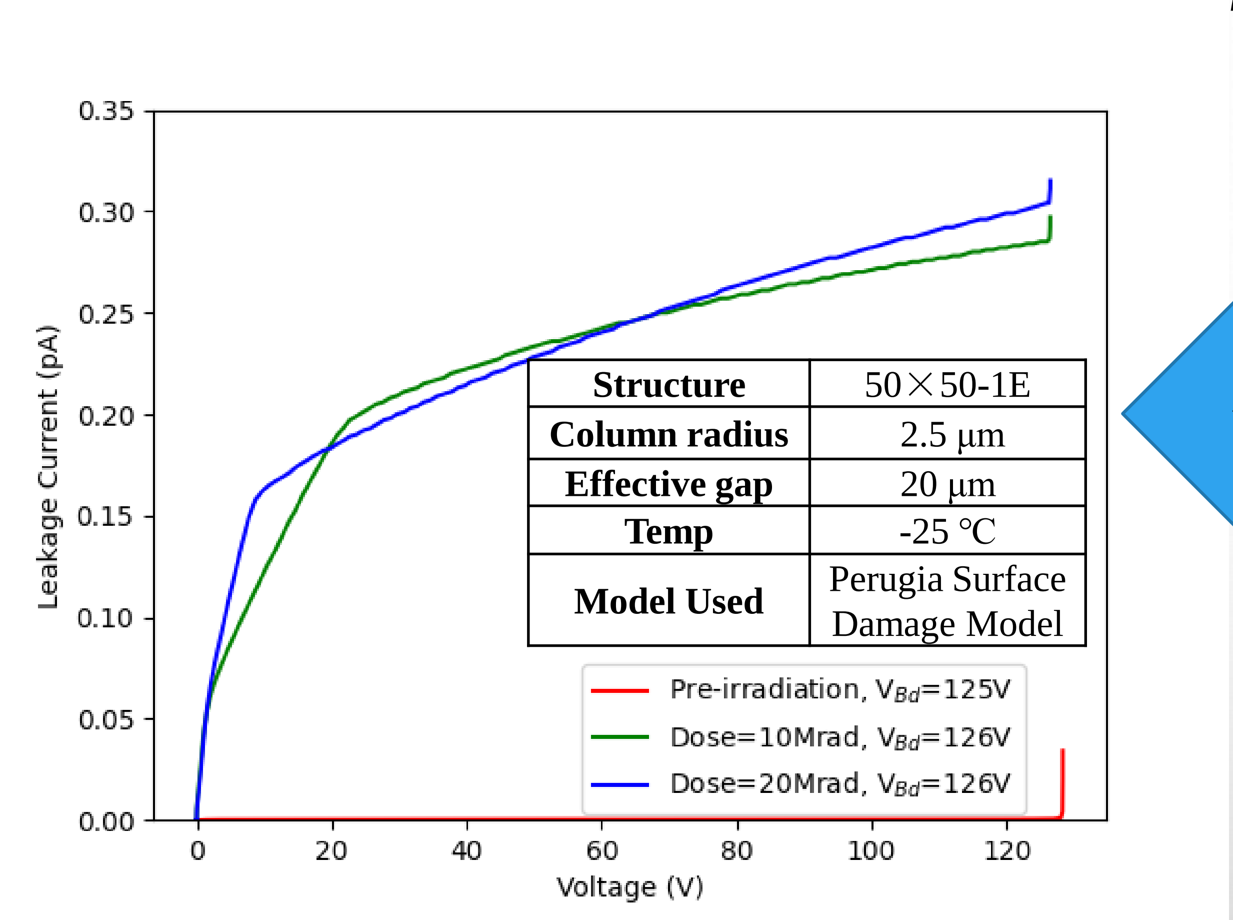
Model Used	Temp
Perugia Surface Damage Model	-25 ℃
Perugia Bulk Damage Model	-25 ℃
CERN Bulk Damage Model	-38 ℃

TCAD Simulation



Simulation domain
25×100-1E

2. Simulation of Existing Detectors

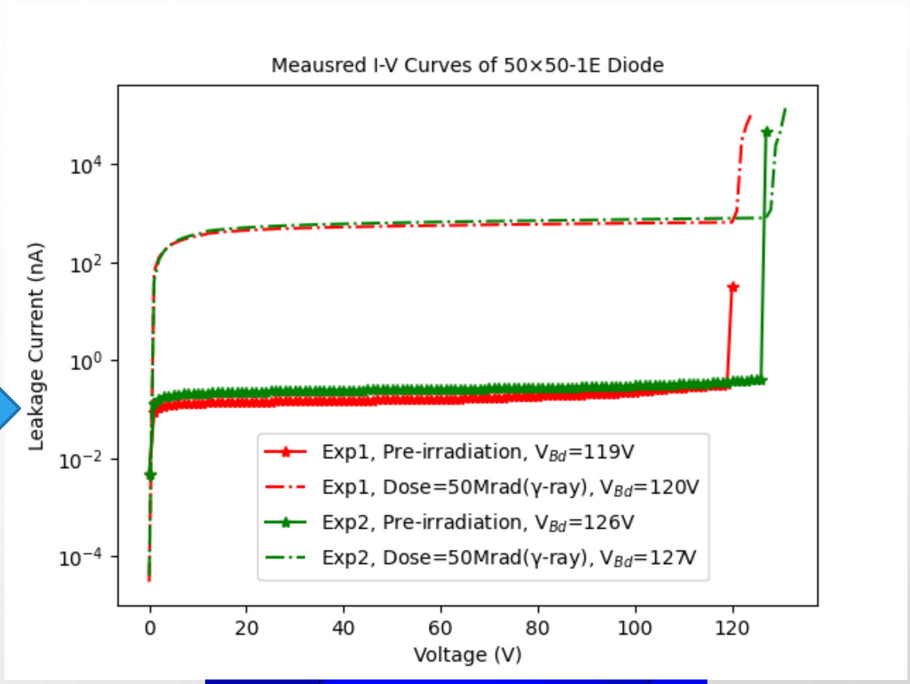


Structure	50×50-1E
Column radius	2.5 μm
Effective gap	20 μm
Temp	-25 °C
Model Used	Perugia Surface Damage Model

I-V simulation based on Perugia Surface Model

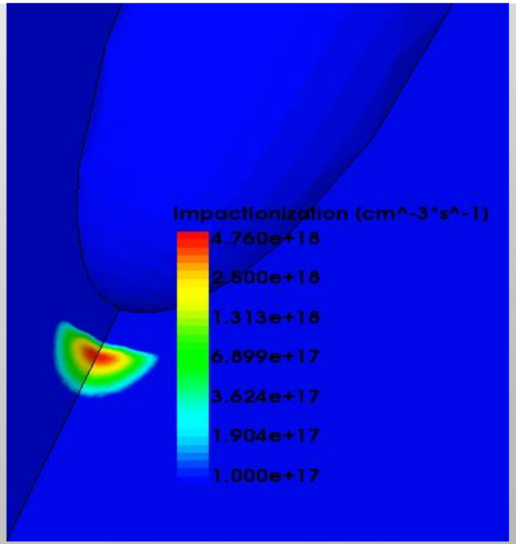
$$k(I,V) = \frac{\Delta I}{\Delta V} \cdot \frac{V}{I},\ k_{bd} \geq 4$$

Same breakdown voltage with/without surface damage.



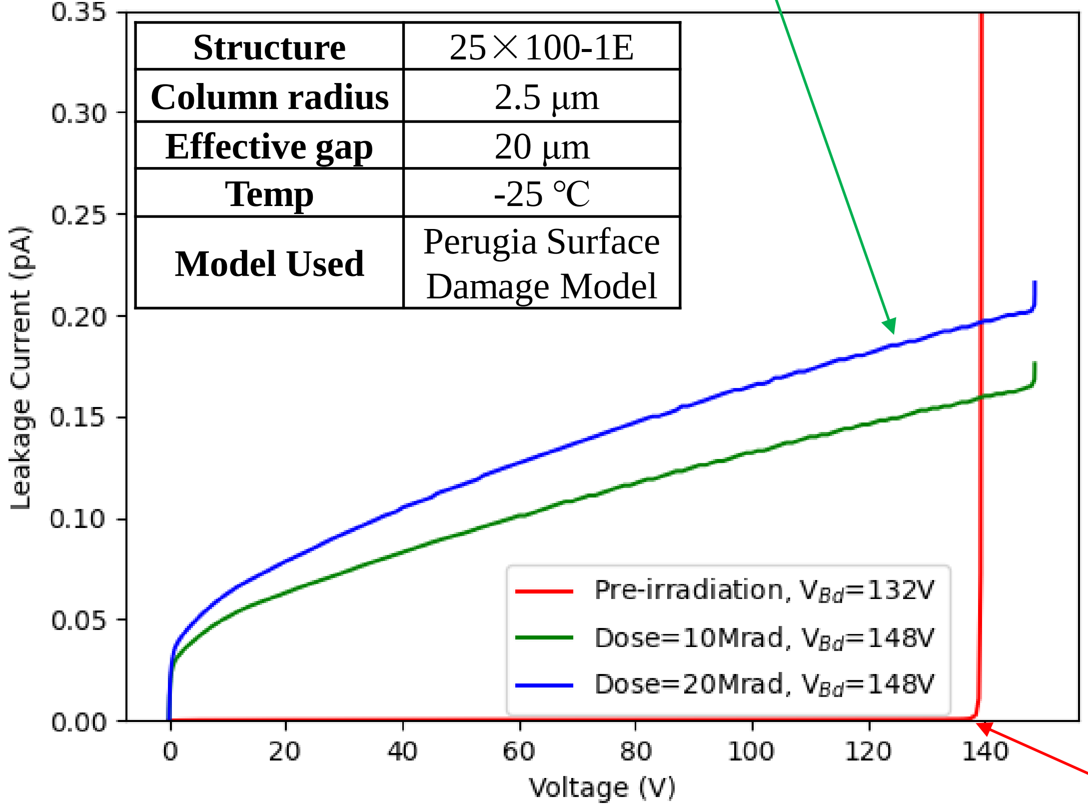
Simulation in agreement with experiment before and after surface damage.

Breaks down at the Tip with/without surface damage.



2. Simulation of Existing Detectors

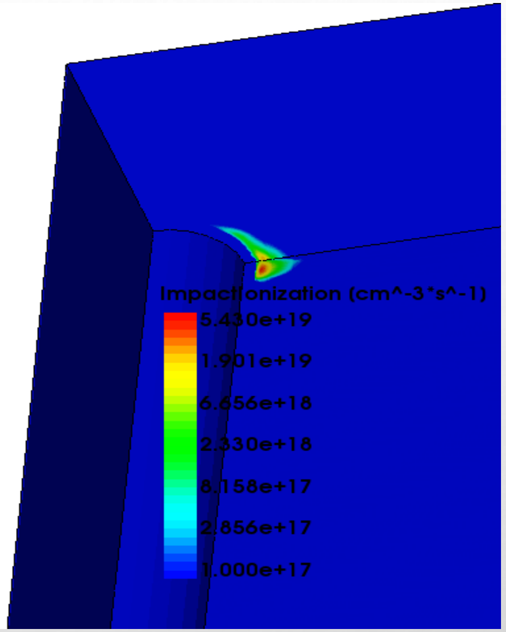
Deviation from experiment probably due to column depths uncertainty of the fabrication.



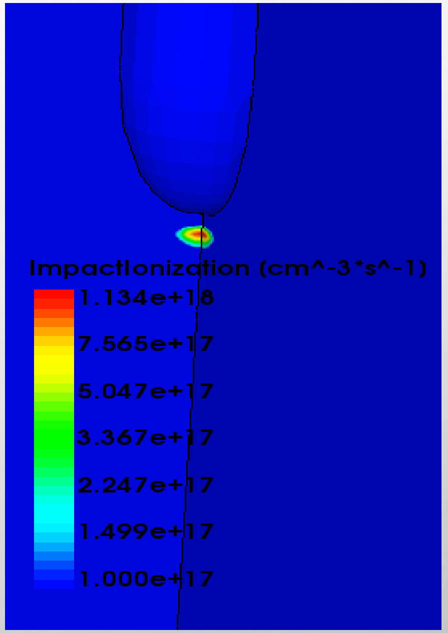
Structure	25×100-1E
Column radius	2.5 μm
Effective gap	20 μm
Temp	-25 ℃
Model Used	Perugia Surface Damage Model

I-V simulation based on Perugia Surface Model

Breakdown shifts from the surface to the Tip after surface damage



Before surface damage: Max impact ionization on the surface



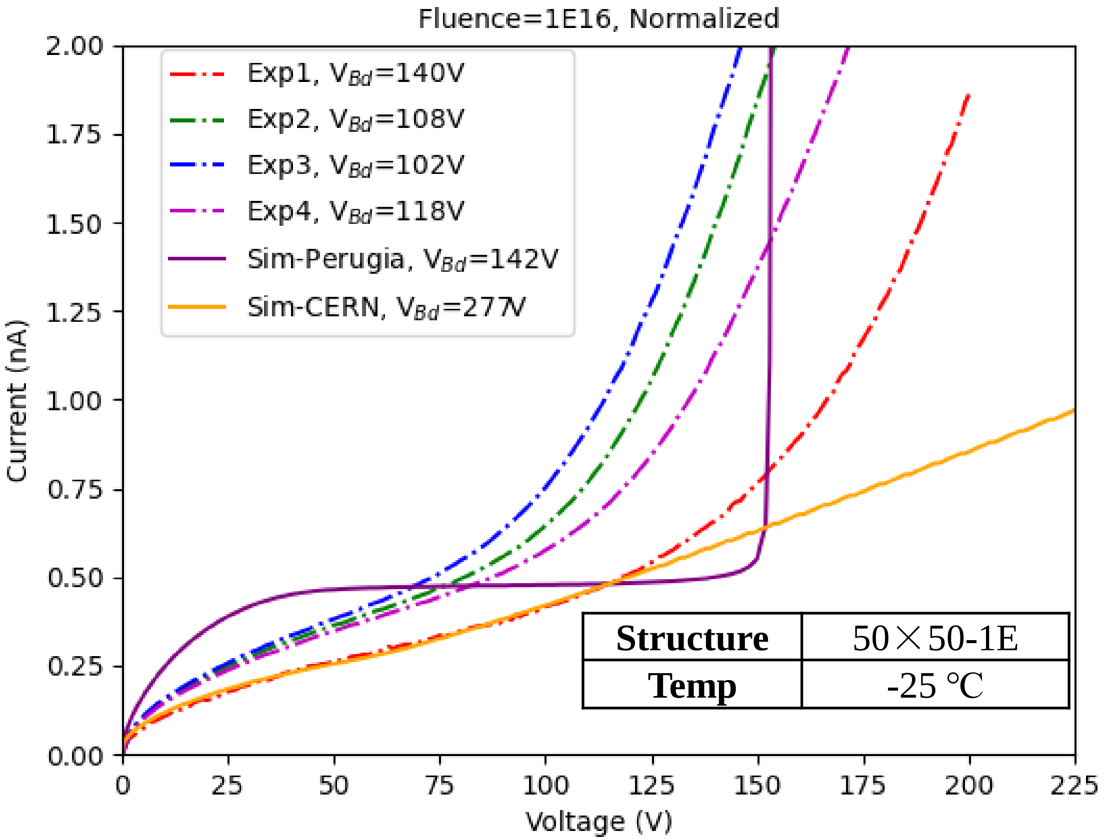
After surface damage: Max impact ionization on the tip

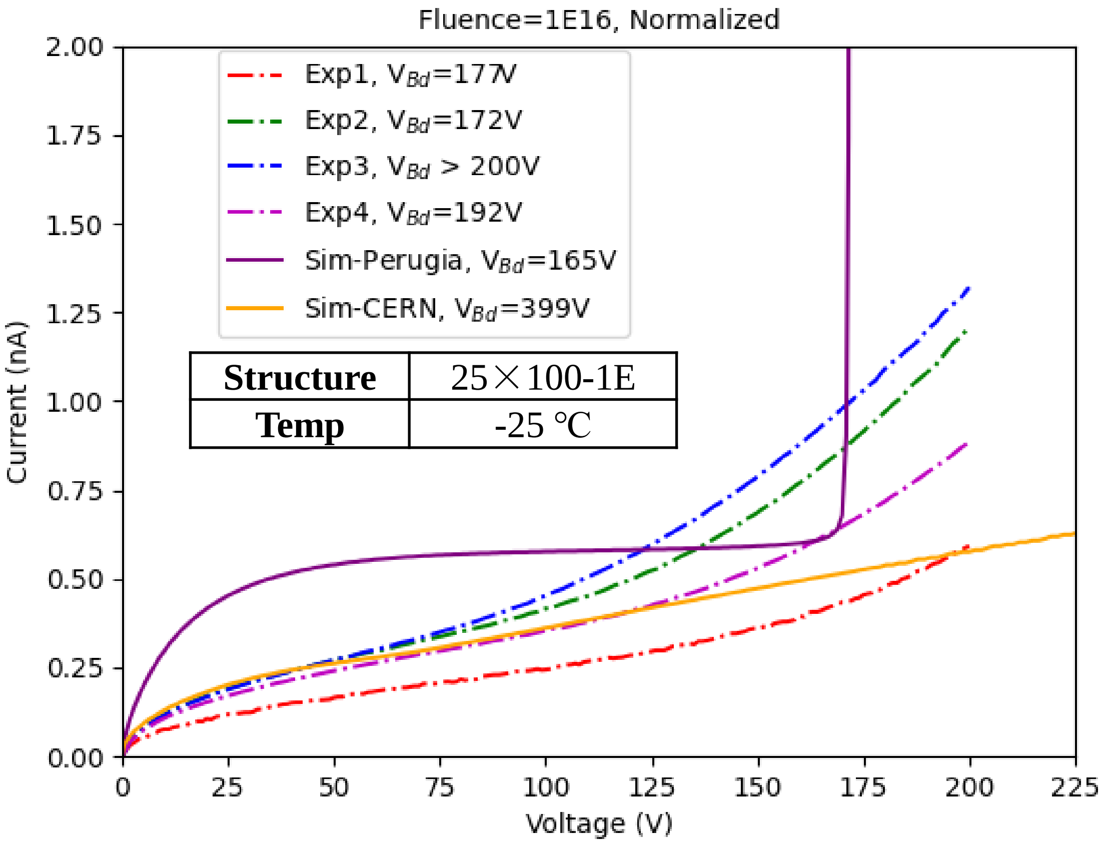
Simulation in agreement with experiment (breakdown voltage ~130V).

Always breaks down at the Tip regardless of the bulk damage model used or the structure.

2. Simulation of Existing Detectors

Simulation based on the CERN Bulk Damage Model used Temp=-38 ℃, the leakage current was then scaled to -25 ℃ using the SRH model.





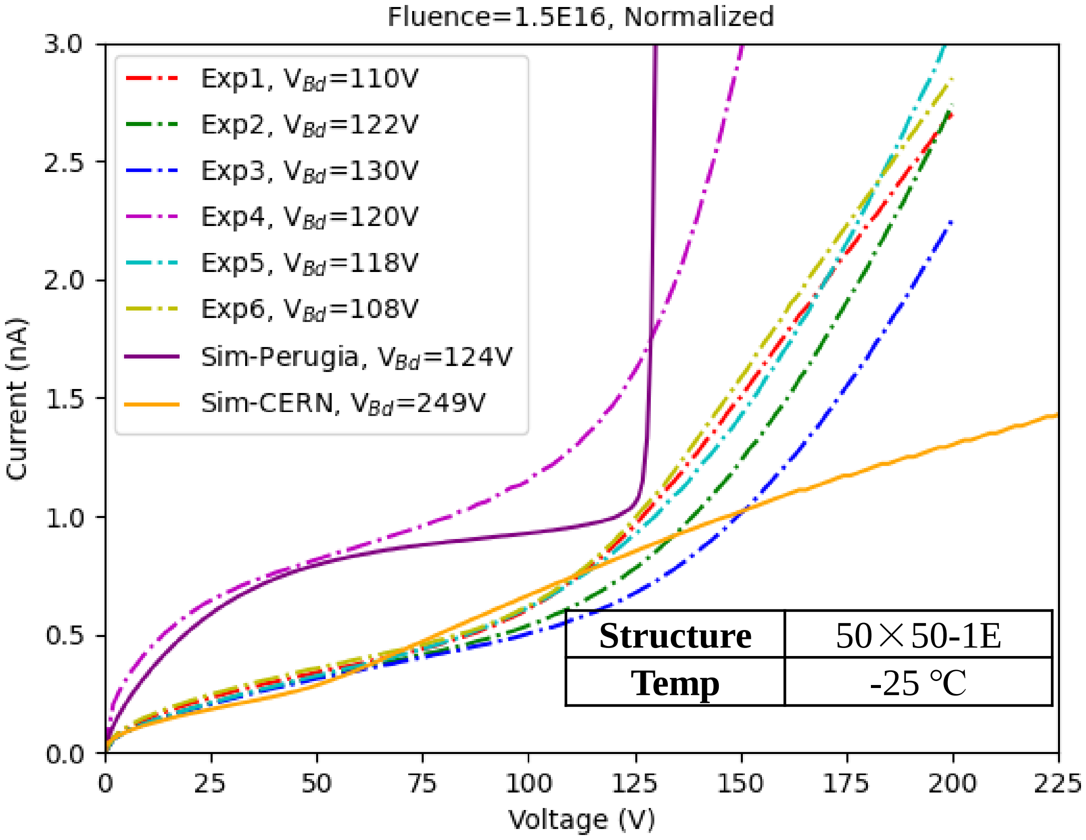
Comparison between simulation & experiments

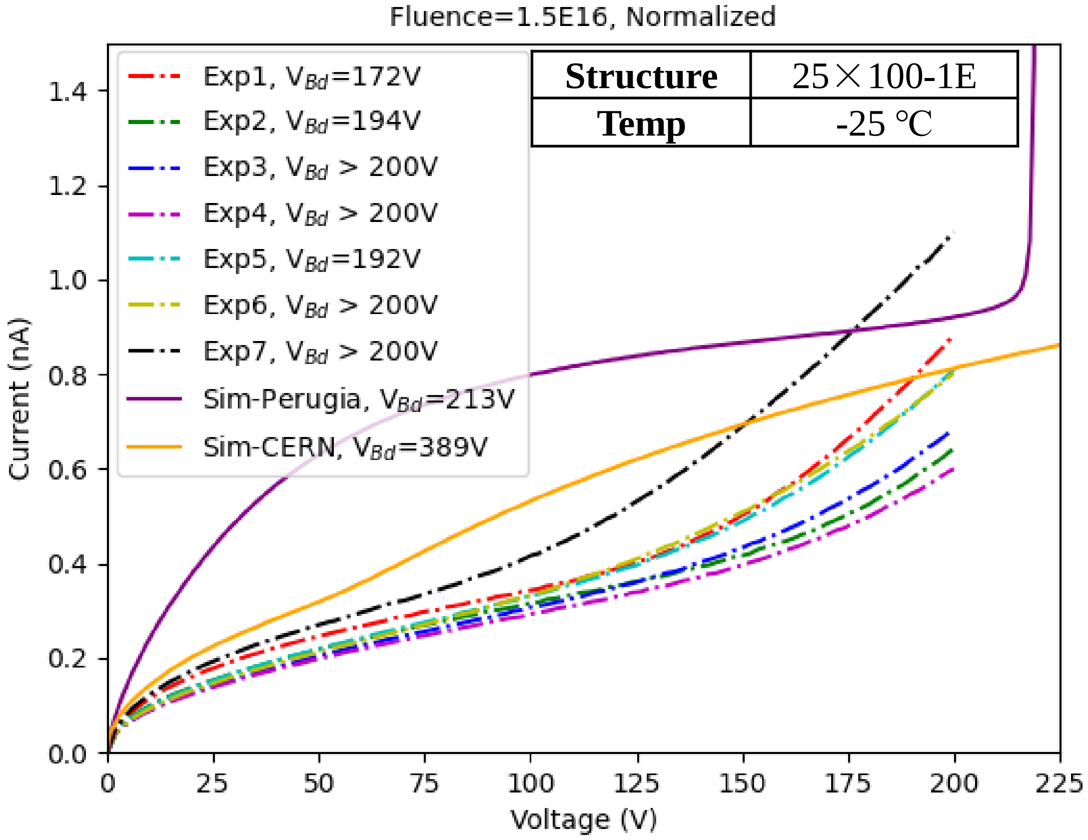
Calculated Damage Rate at V_b=100V, T=20℃

Irradiation	Fluence (n_{eq}/cm^2)	Structure	α^* Experiment (10^{-17}A/cm)	α^* Perugia Model (10^{-17}A/cm)	α^* CERN Model (10^{-17}A/cm)
Neutron	1.0×10^{16}	50×50-1E	6.92±1.14	5.54	4.87
		25×100-1E	4.25±0.91	6.69	4.22

Always breaks down at the Tip regardless of the bulk damage model used or the structure.

2. Simulation of Existing Detectors





Comparison between simulation & experiments

Calculated Damage Rate at V_b=100V, T=20℃

Irradiation	**Fluence (n_{eq}/cm^2)**	**Structure**	**α^* Experiment (10^{-17}A/cm)**	**α^* Perugia Model (10^{-17}A/cm)**	**α^* CERN Model (10^{-17}A/cm)**
Neutron	1.5×10^{16}	50×50-1E	7.79± 2.53	10.74	7.65
		25×100-1E	3.87±0.43	9.25	6.13

2. Simulation of Existing Detectors

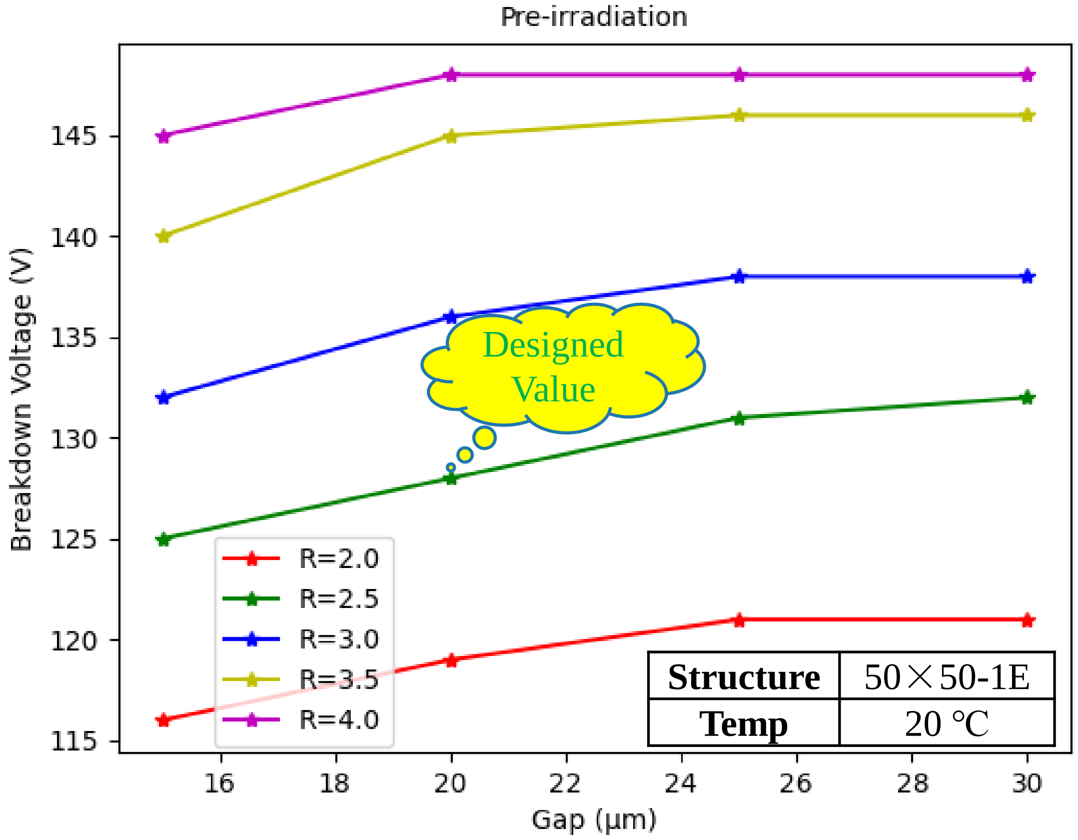
Perugia Model:

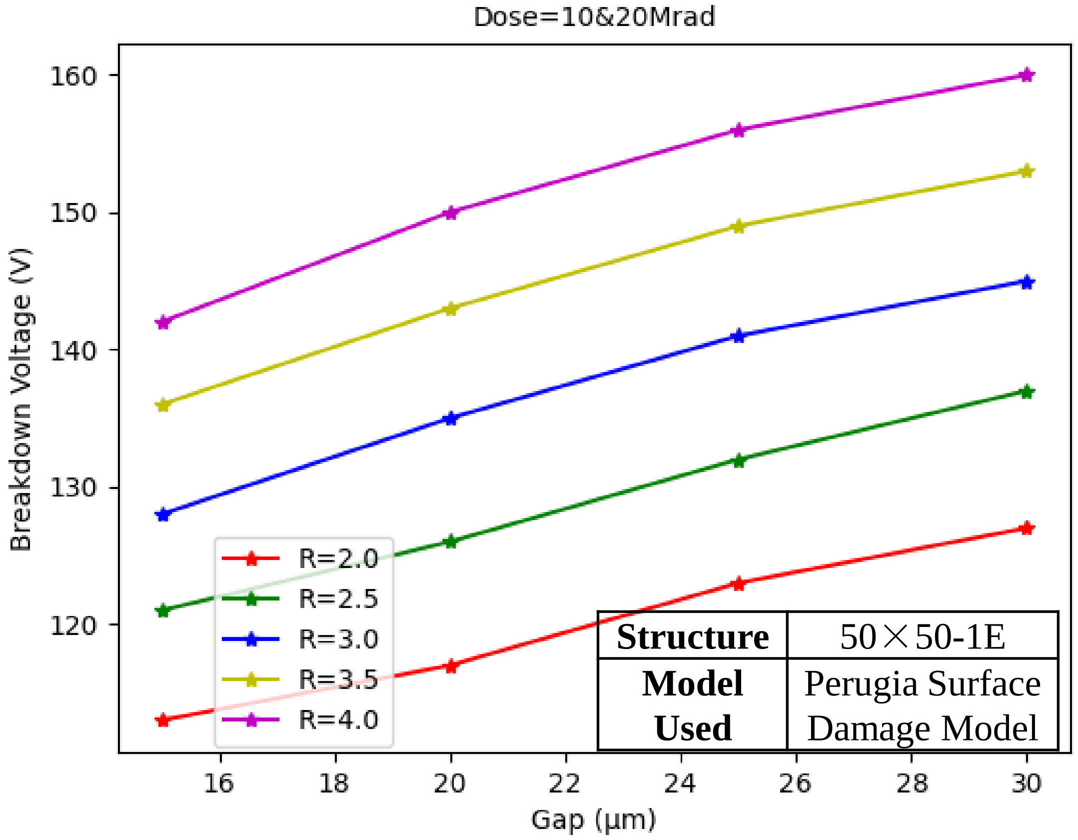
- ***predicted breakdown voltage of both layouts before and after surface damage;***
- ***the prediction of breakdown voltage is still in good agreement with experiment after bulk damage;***
- ***the shape of the leakage current is different from the measured I-V curve.***

CERN Model:

- ***leakage current well predicted at low reverse bias when the fluence is low;***
- ***leakage current starts to deviate from measured results at high fluence;***
- ***over-estimates the breakdown voltage for all simulated scenarios, including different layouts and fluences.***

3. Influence of Geometrical Parameters





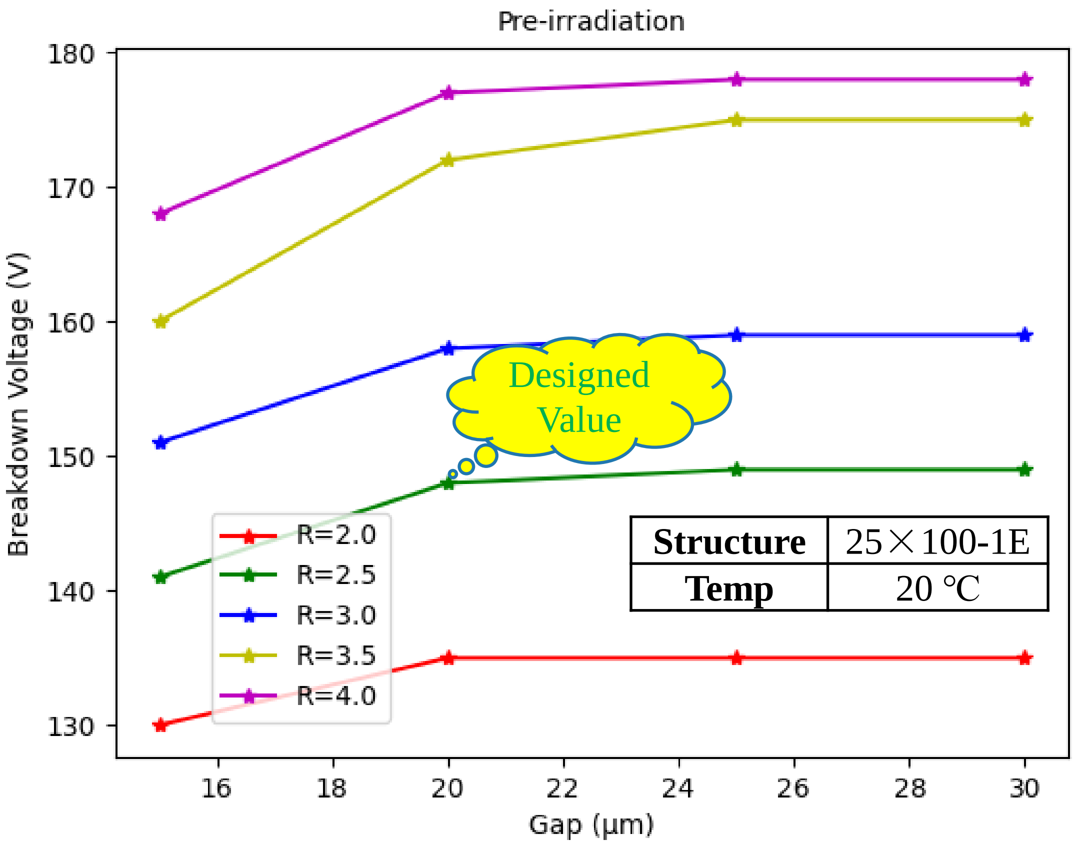
Conclusion:

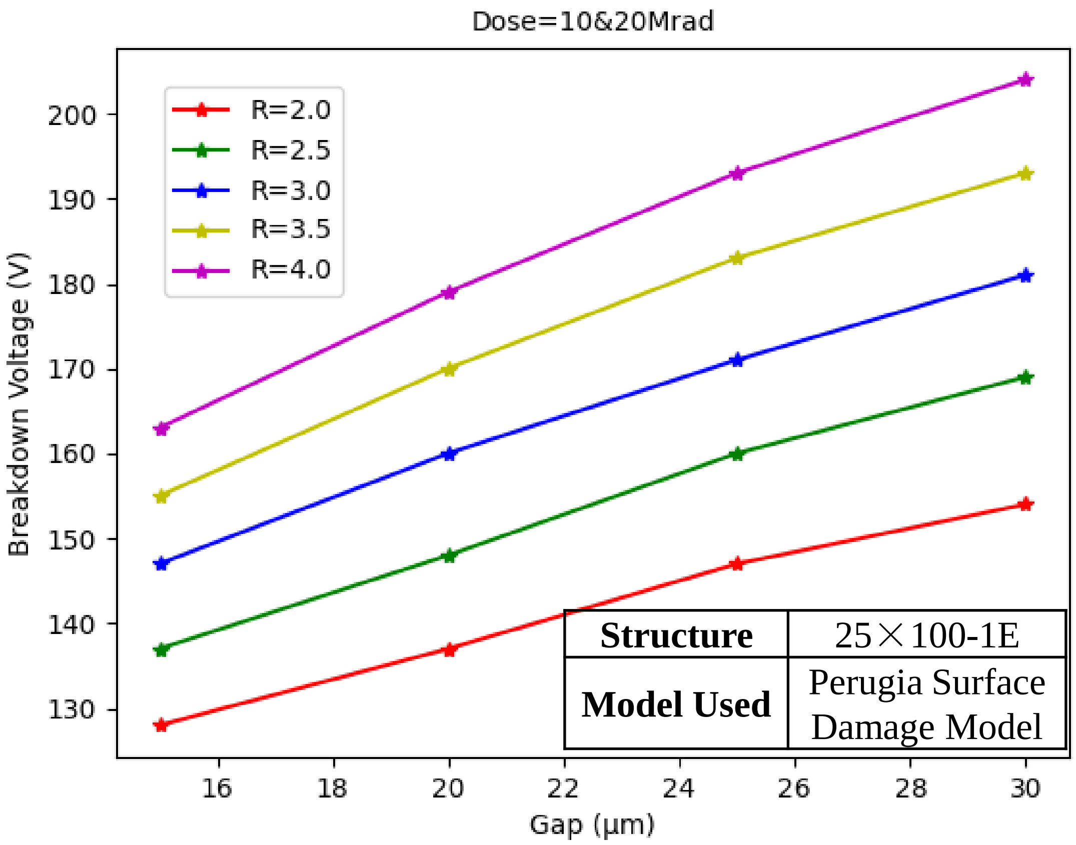
- *Breakdown voltage increases with the Radius and the Gap;*
- *Always breaks down at the Tip, contribution from the surface gets more and more important;*
- *The Radius & the Gap effect saturates.*

Conclusion:

- *Always breaks down at the Tip;*
- *Same breakdown voltage for both Doses due to long distance of the Tip from the surface;*
- *Breakdown voltage increases with the Radius & the Gap.*

3. Influence of Geometrical Parameters

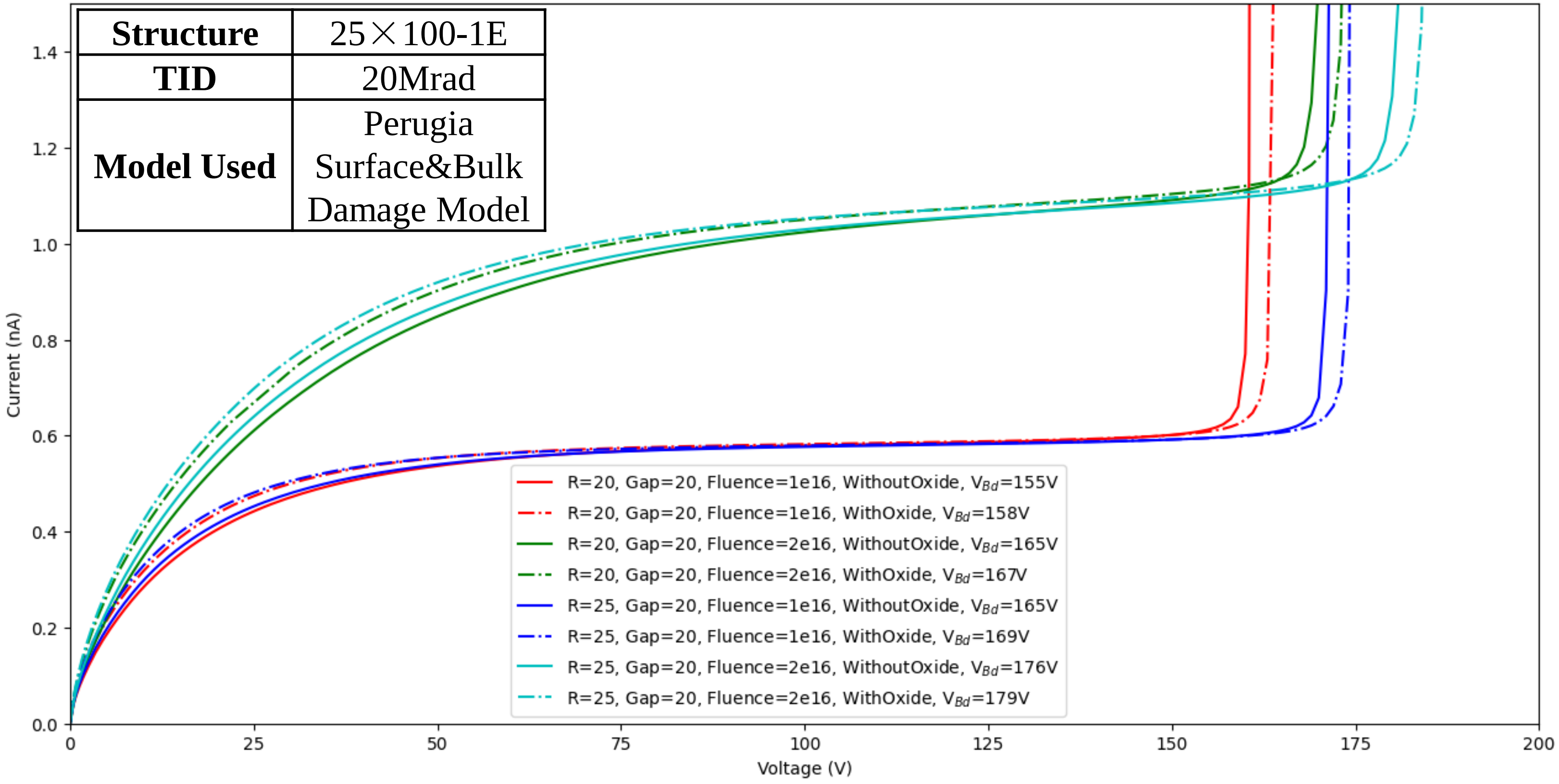




Conclusion:
1): Breakdown voltage increases with the Radius;
2): The Radius & the Gap effect saturates.

Conclusion:
1): Breakdowns at the Tip after surface damage, thus same breakdown voltage for both Doses;
2): Breakdown voltage increases with the Radius & the Gap.

3. Influence of Geometrical Parameters



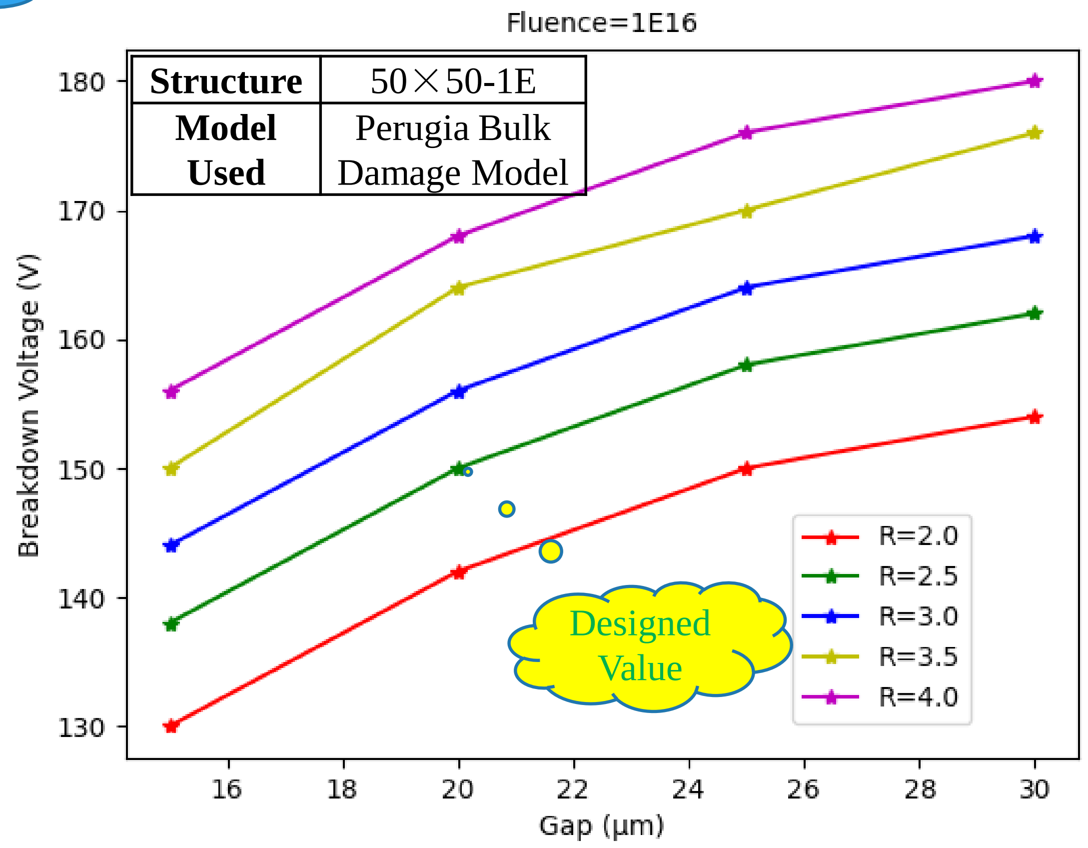
Breakdown simulation With/Without Oxide

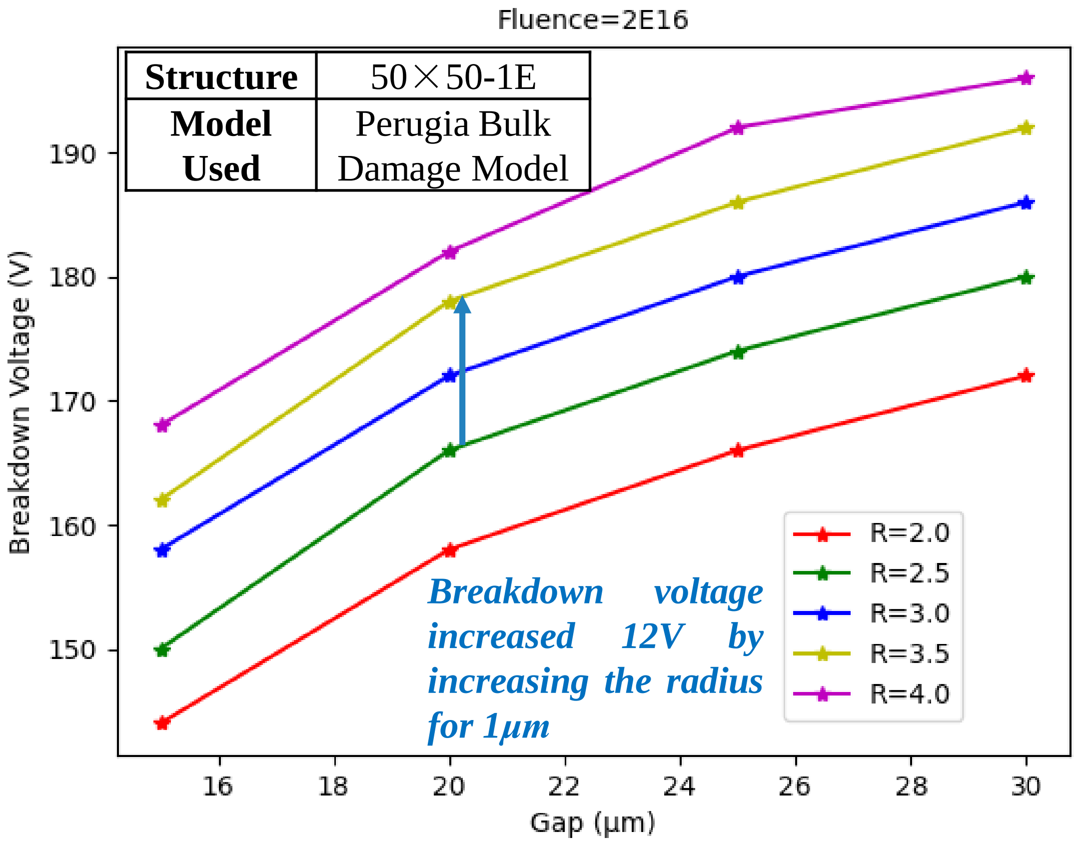
Difference in the breakdown voltage with/without Oxide is negligible;
The trend applies for the CERN Model as well.

Safe to use only the bulk for breakdown prediction after radiation damage to boost the simulation.

Only the Bulk

3. Influence of Geometrical Parameters





Conclusion:

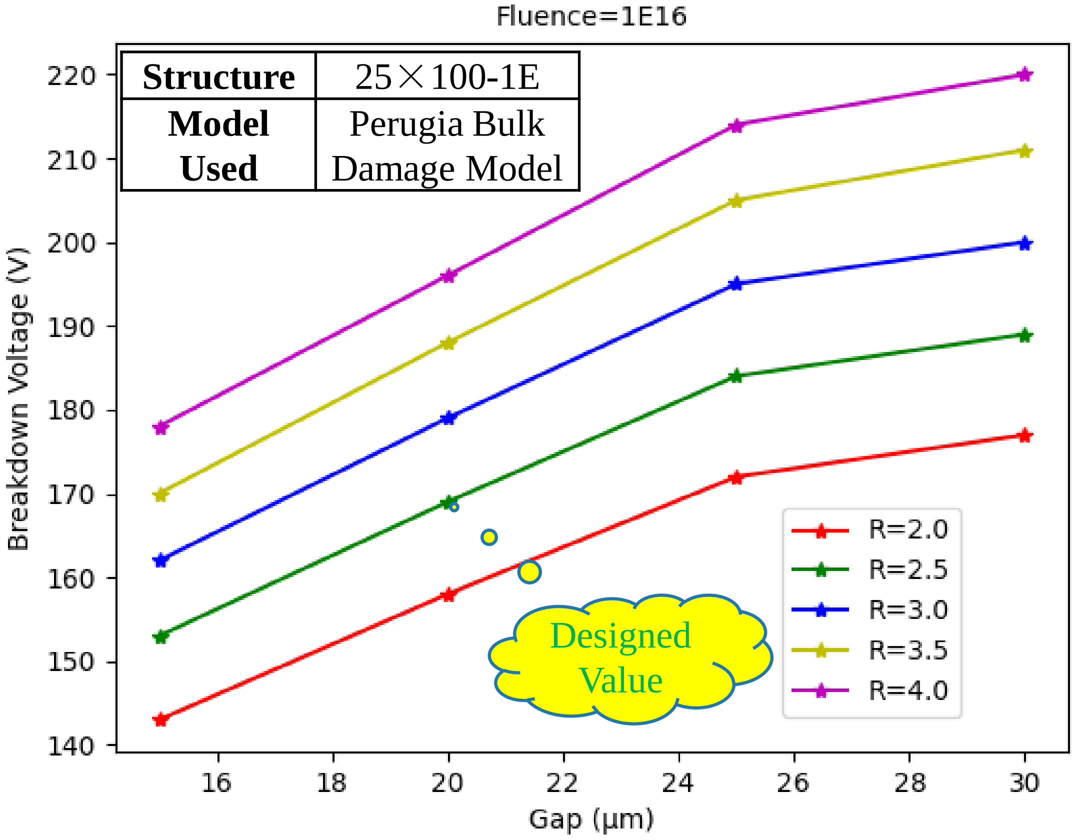
1): Higher Fluence leads to higher breakdown voltage;

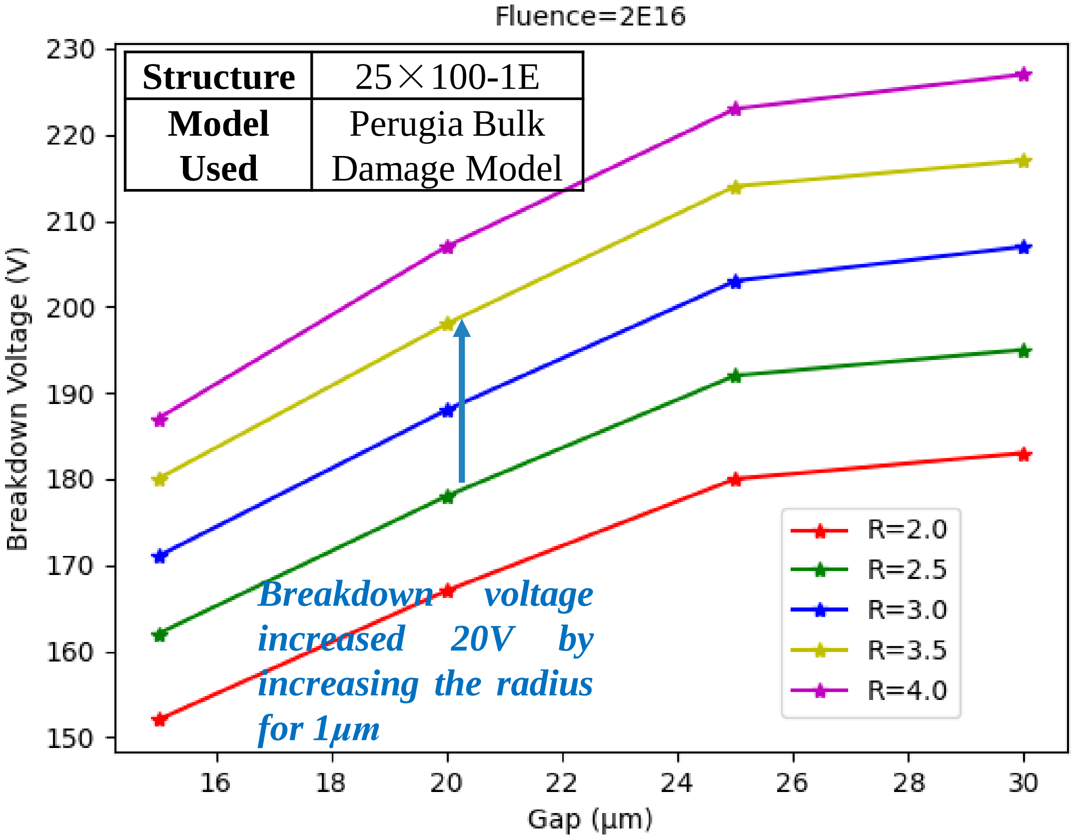
2): Breakdown voltage increases with the Radius & the Gap;

3): The Radius & the Gap effect saturates.

3. Influence of Geometrical Parameters

Only the Bulk





Conclusion:

1): Higher Fluence leads to higher breakdown voltage;

2): Breakdown voltage increases with the Radius & the Gap;

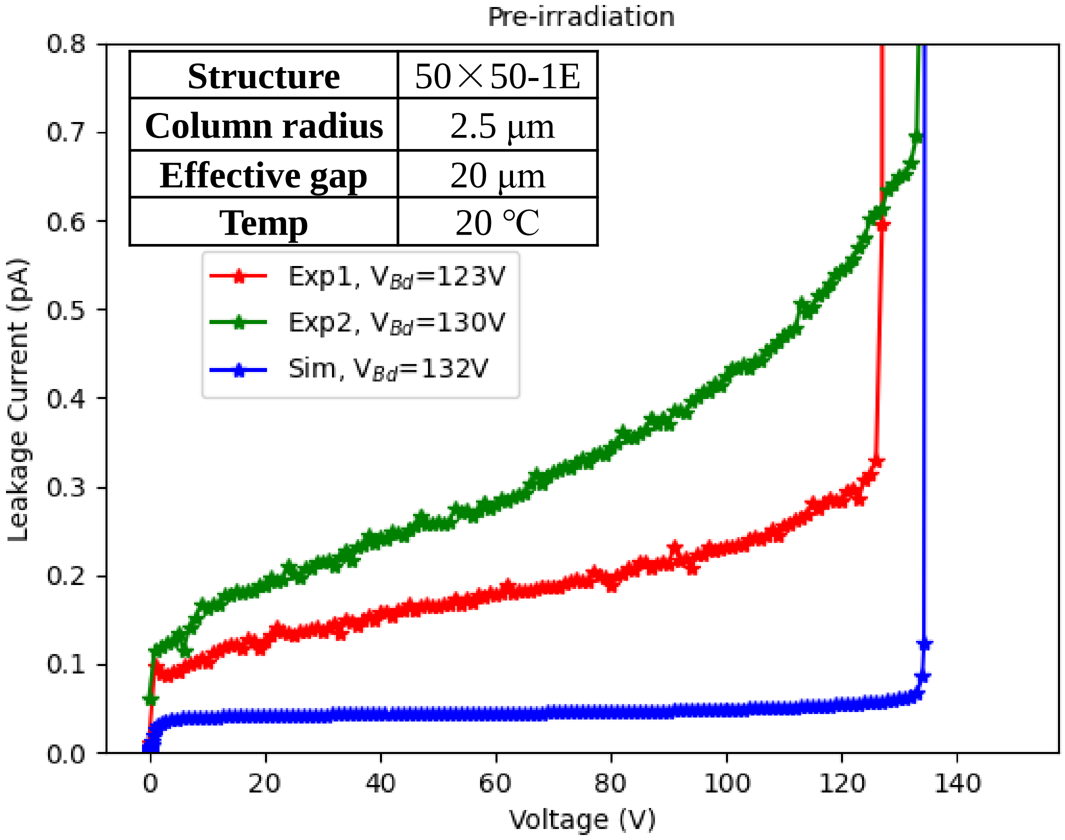
3): The Radius & the Gap effect saturates.

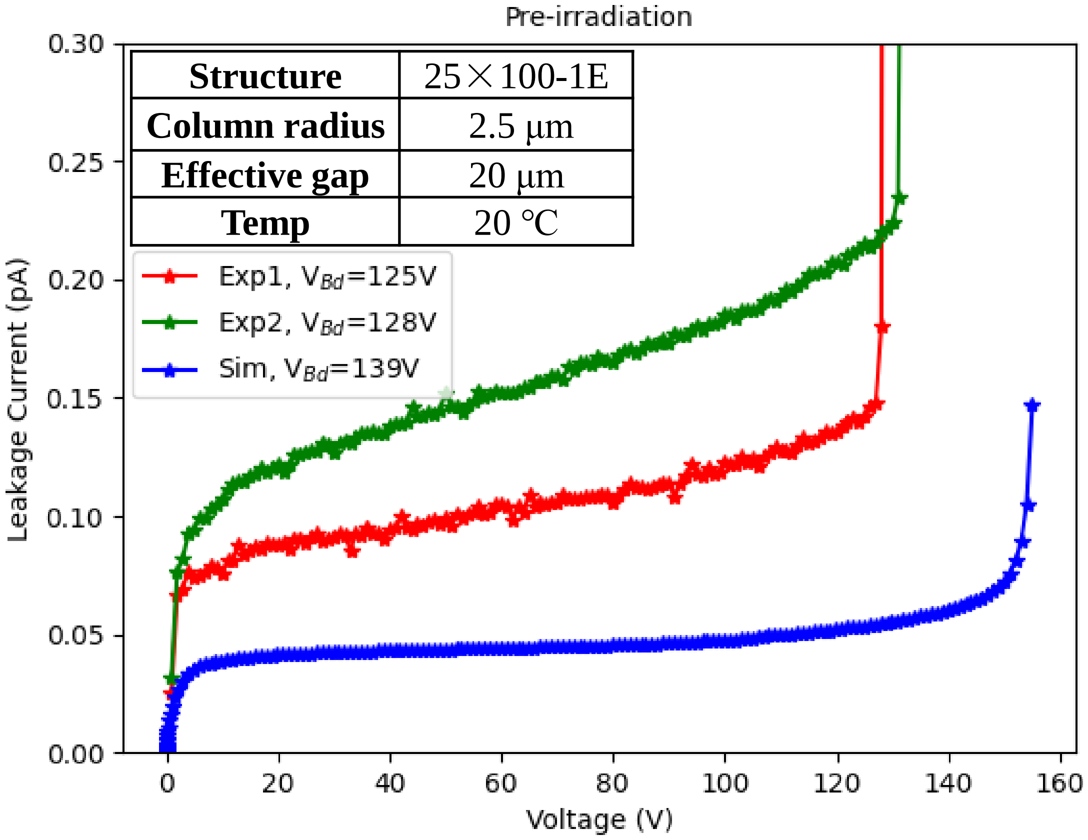
4. Summary

- ***The Tip limits the breakdown voltage, especially after radiation damage;***
- ***25×100-1E has higher breakdown voltage due to larger inter-electrode distance;***
- ***Perugia Bulk Damage Model can predict the breakdown quite accurately, CERN Bulk Damage Model is better at predicting the leakage current;***
- ***It is possible to increase the breakdown voltage of both designs by increasing the Radius/Gap, but the Radius & the Gap effect saturates.***

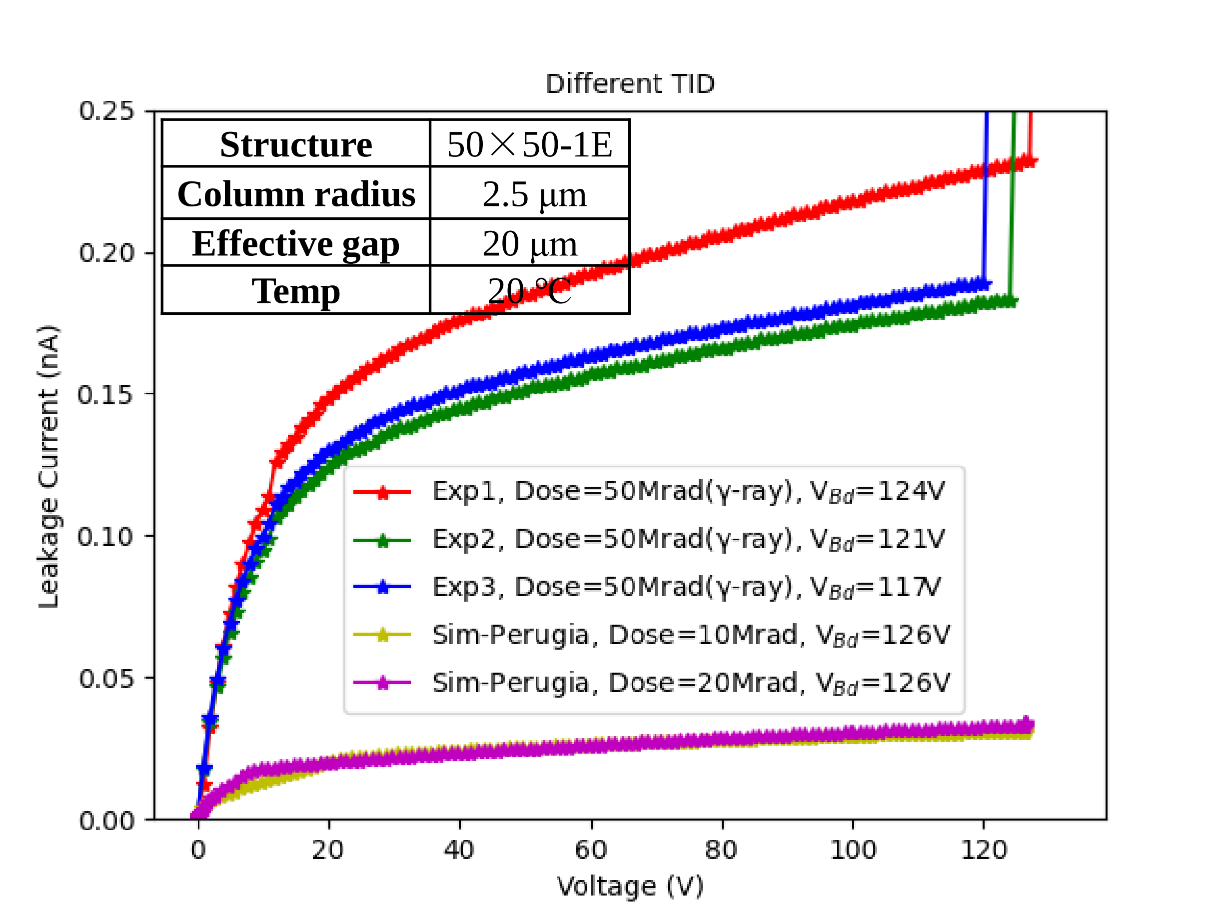
Thank you for your time!

Backup – Pre-irradiation





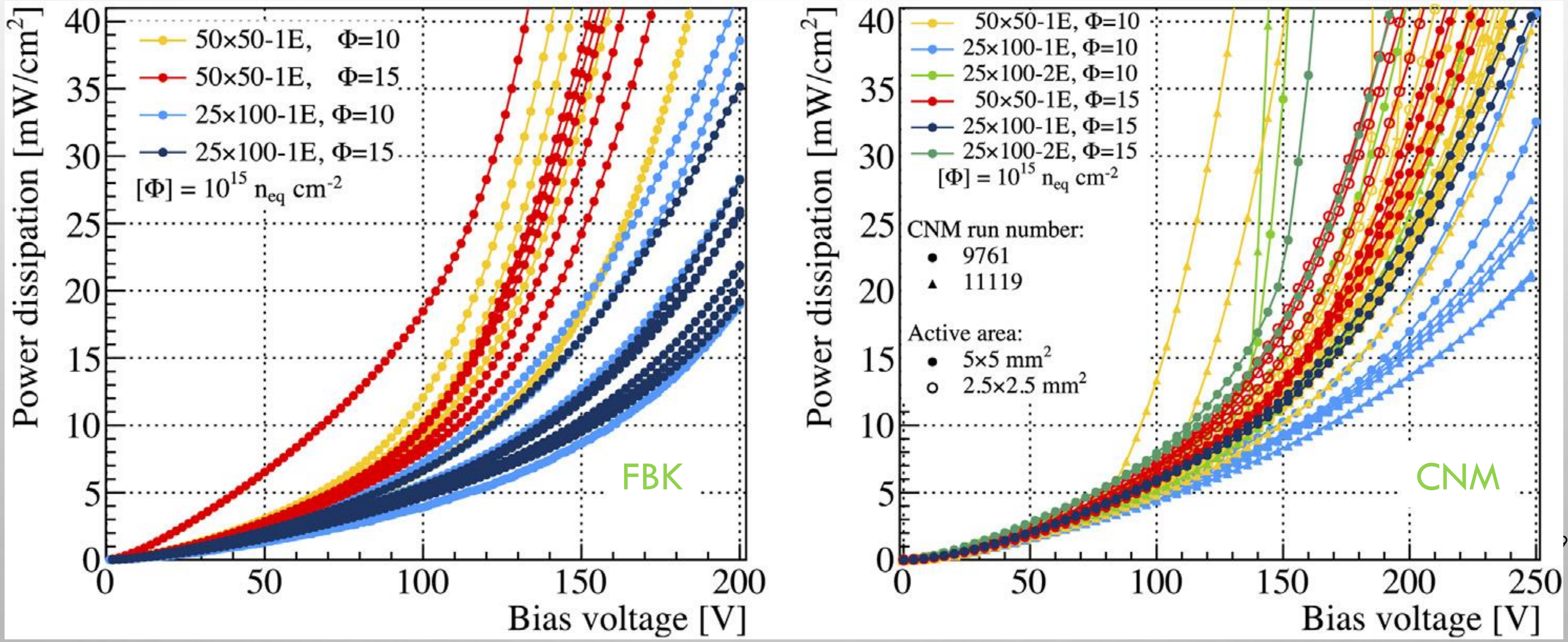
Back – Surface Damage



Backup - Power dissipation

- *At the voltages of interest for a high hit efficiency, the power dissipation is still low*

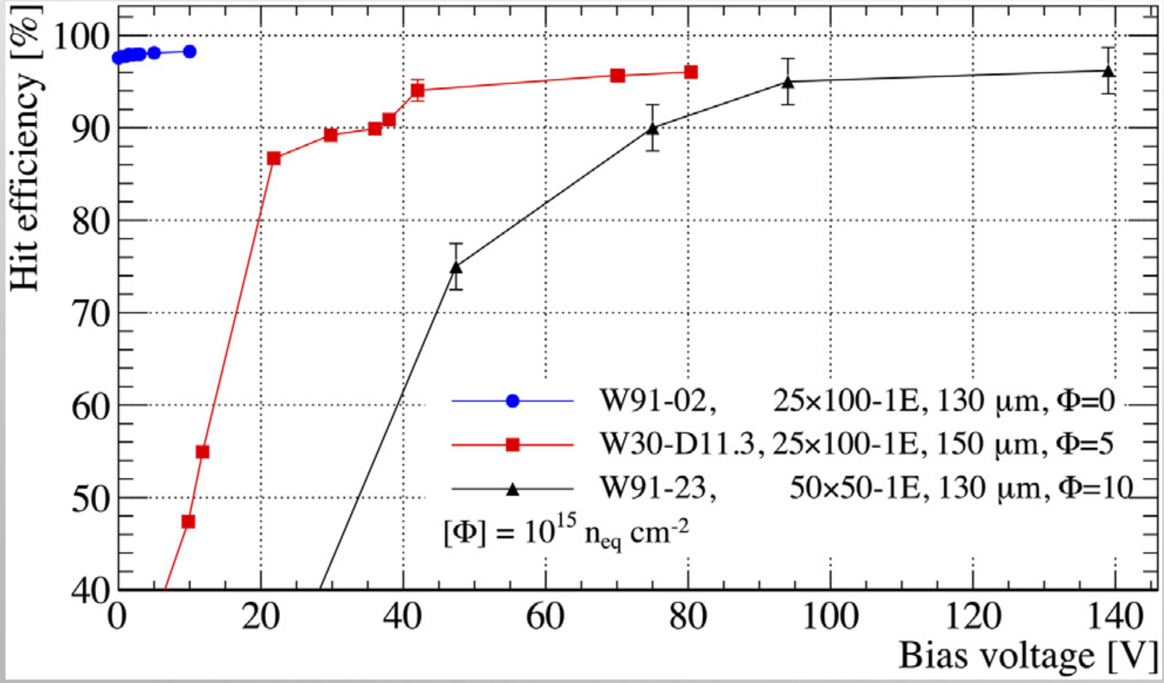
S. Terzo et al., Frontiers in Physics 9:624668



Back – Efficiency of irradiated modules at beam test

- *RD53A assemblies with different 3D sensor geometries*
- *At 10^{16} n_{eq}/cm^2 a hit efficiency of 96% at normal beam incidence reached below 100 V*
- *Larger voltages (~150 V) required at $1.8x10^{16}$ n_{eq}/cm^2*

S. Terzo et al., Frontiers in Physics 9:624668



G. Bardelli et al., IWORID 2022