Effects of carbon co-implantation on radiation hardness of IHEP_IMEv2 LGAD

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Outline

- Overview on LGAD designs of IHEP_IME productions and plans
- Un-irradiated LGAD performance
  - Carbon induced issues
  - Boron distribution effects
- Acceptor removal parameterization

Roadmap of IHEP sensors

IHEP_IMEv1
2020

IHEP_IMEv2
2021

IHEP_IMEv3
2021-2022

IHEP_IMEv2 LGAD deigns

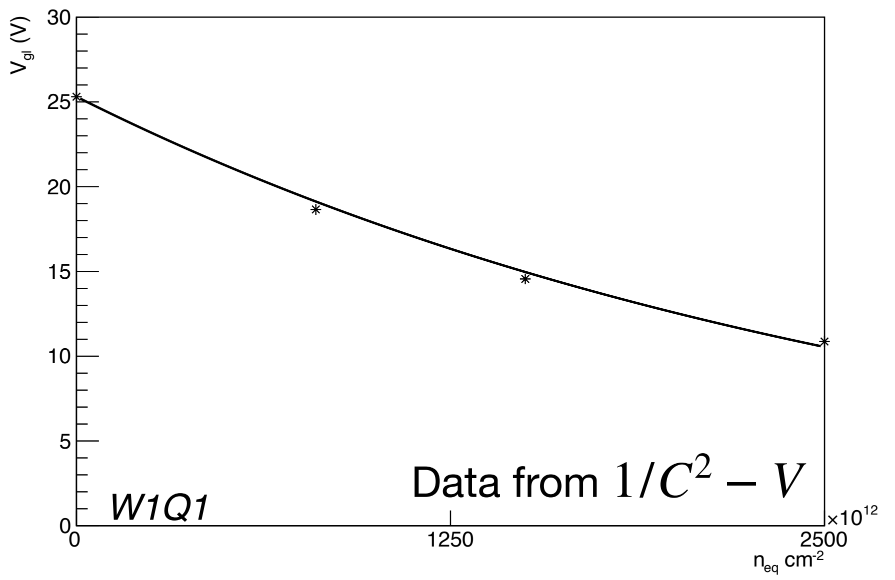
Sensor		Diffuse*	C dose(a.u.)	C factor (x10^16 cm2)
W1Q1		BL	-	3.50
W3Q4		BH	-	6.31
W4	Q1	CLBL	0.2	2.57
	Q2	CLBL	1	1.77
	Q3	CLBL	5	1.60
	Q4	CLBL	10	1.50
W7	Q1	CHBL	0.2	1.62
	Q2	CHBL	0.5	1.14
	Q3	CHBL	1	1.18
	Q4	CHBL	3	1.34
W8	Q1	CHBL	6	1.30
	Q2	CHBL	8	1.32
	Q3	CHBL	10	1.23
	Q4	CHBL	20	1.29

Non carbonated

B:Boron implant
C: Carbon implant
L:low thermal load
H:High thermal load

Effective boron dose decrease exponentially.

$$V_{gl}(\Phi) \propto N_B(\Phi) = N_B(0)e^{-c\Phi}$$



- All carbonated sensors have better radiation hardness than the non-carbonated.
- Carbon high thermal load leads to better radiation hardness.
- Implantation depth of Carbon (Boron) is same among all sensors.Boron dose are same among all carbonated sensors.

*:The notation of diffusion is learn from https://indico.cern.ch/event/983068/contributions/4223173/attachments/2191413/3703863/17022021_MarcoFerrero.pdf

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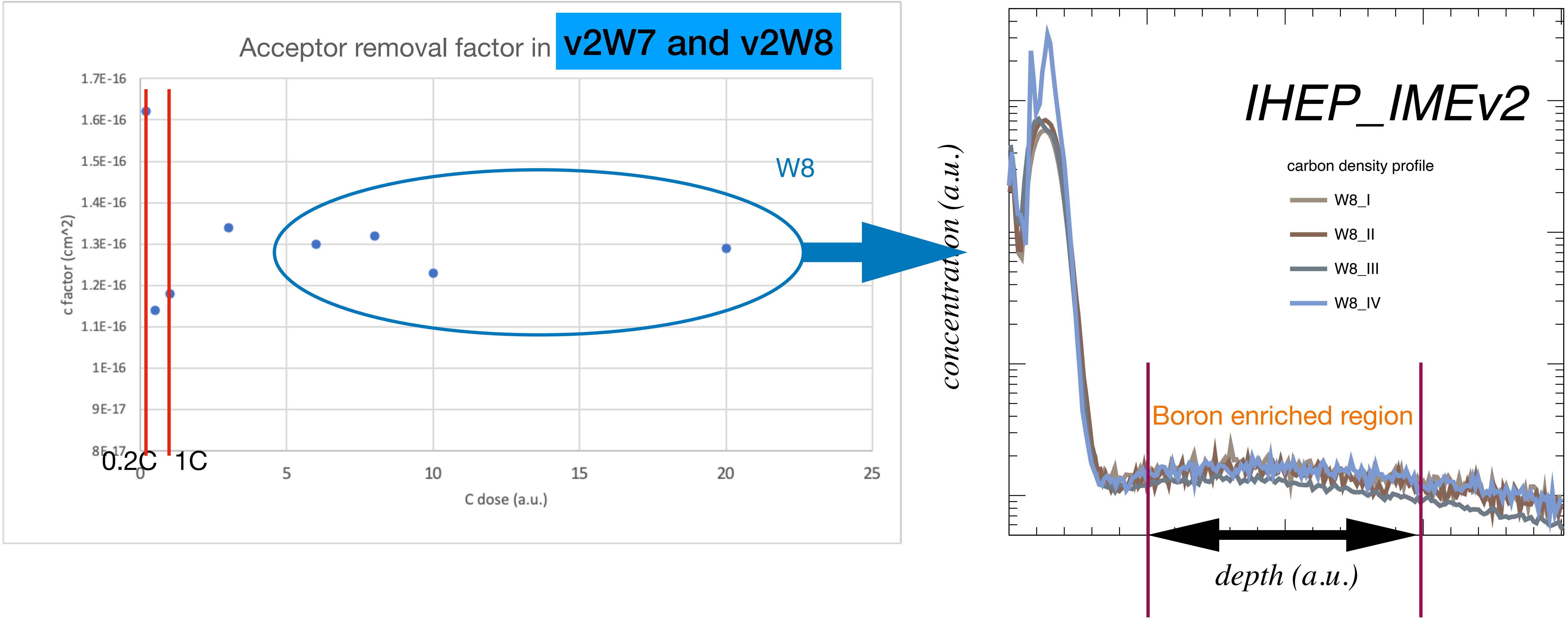
IHEP_IMEv3 LGAD NEW deigns

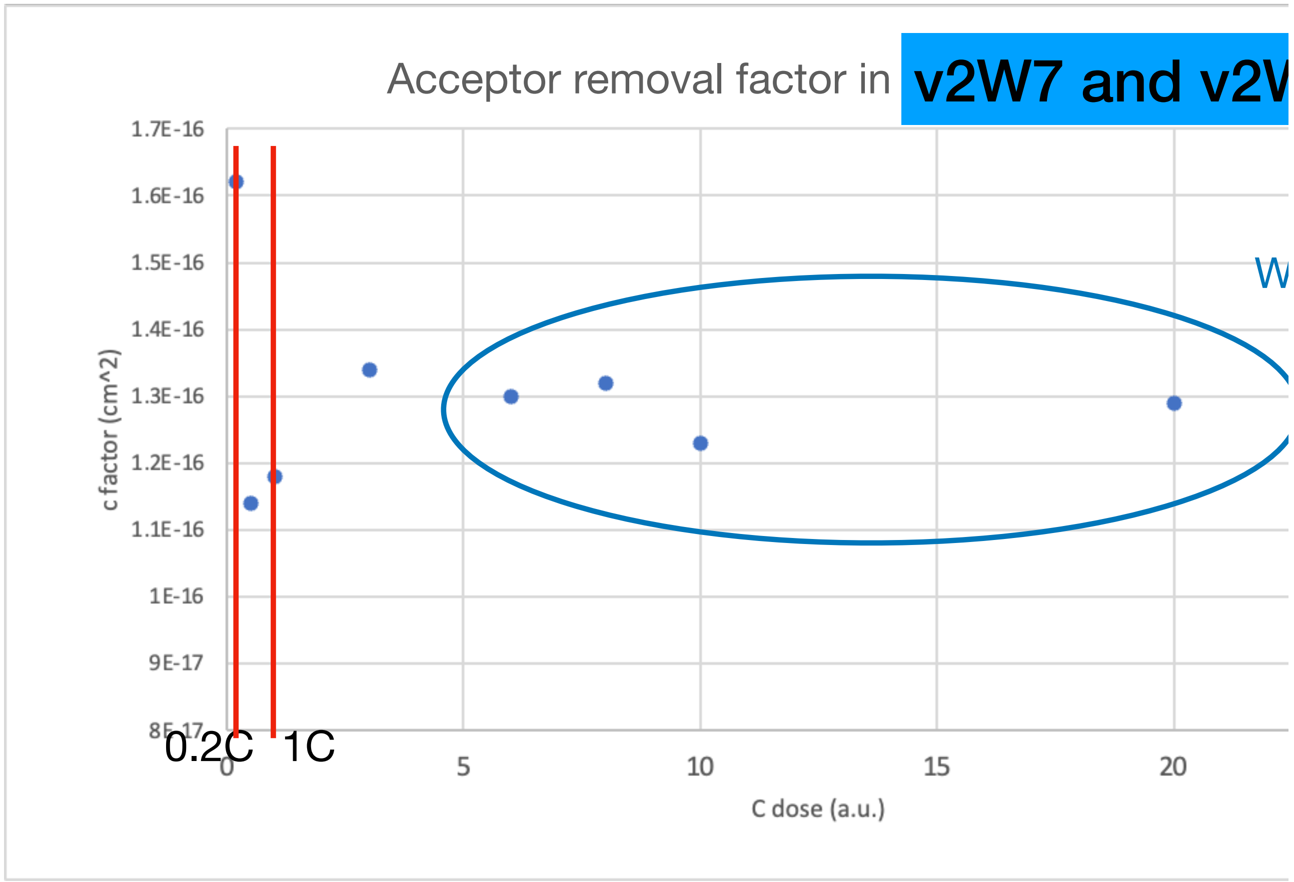
Sensor		**Diffuse**	**C dose(a.u.)**	
W15		CLBL	0.5	Different B dose
W16 **W17**	**W16Q1**	CHBL	0.2	Interpolate v2w7 to minimize the C factor.
	W16Q2		0.3	
	W16Q3		0.4	
	W16Q4		0.5	
	W17Q1		0.6	
	W17Q2		0.7	
	W17Q3		0.8	
	W17Q4		1	
W18		CMBL	0.5	Change c thermal load
W20 w21 w22		CLBL	0.2	Different C Depth
		CLBL	0.5	
		CLBL	1	

Minimization of C with CHBL design



- The minima will probably show up between 0.2 c to 1 c.
- For large dose (in W8), the c factor converges, the carbon distribution in these devices become similar.

Minimization of C with CHBL design



IHEP_IMEv3 LGAD NEW deigns

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	W17Q1		0.6	
	W17Q2		0.7	
	W17Q3		0.8	
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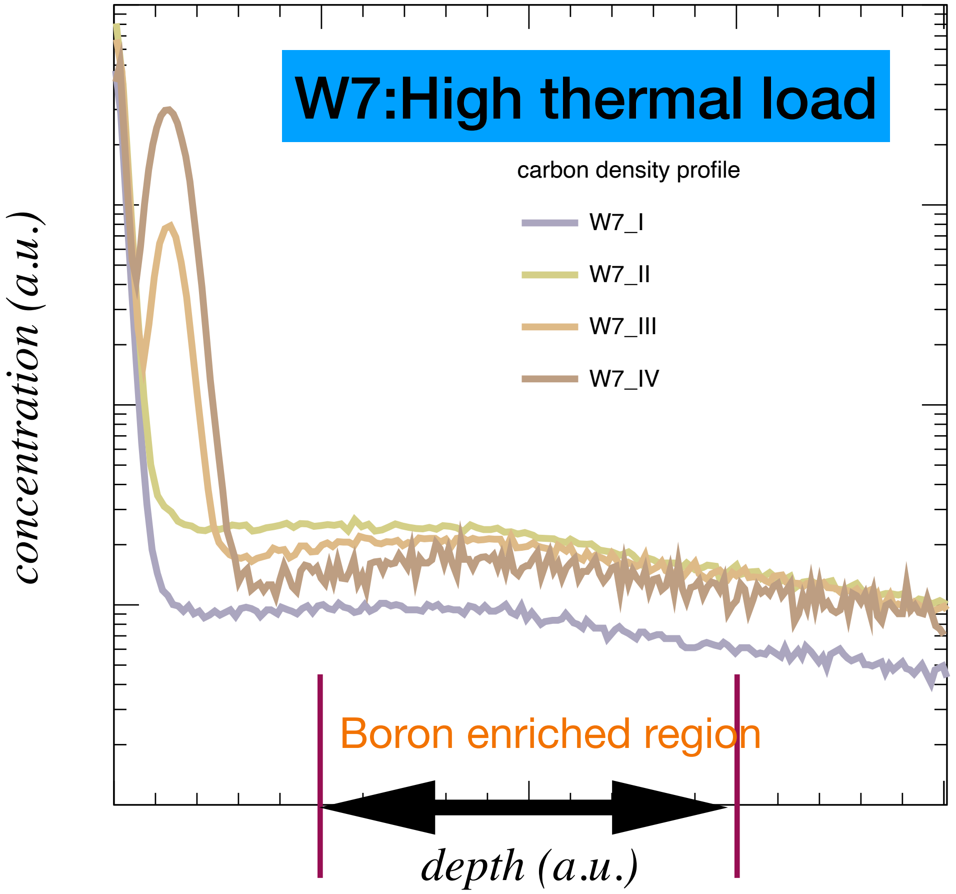
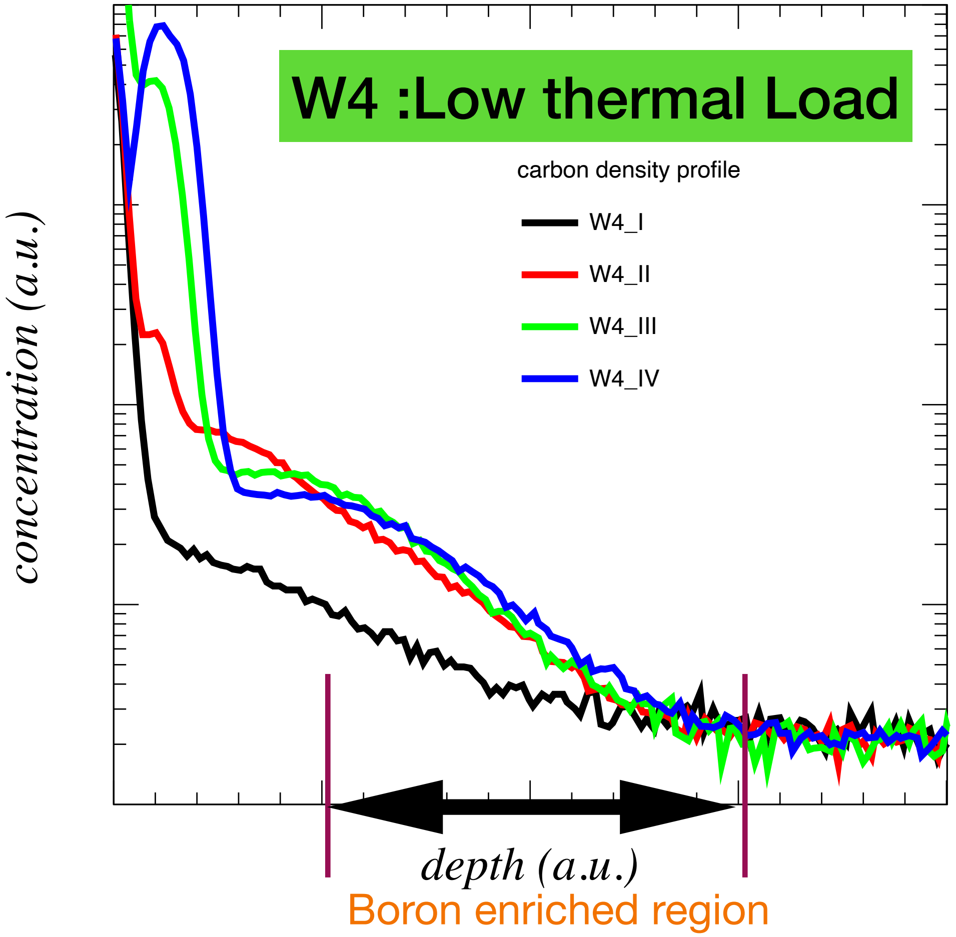
Issues of Carbon Implantation and Diffusion



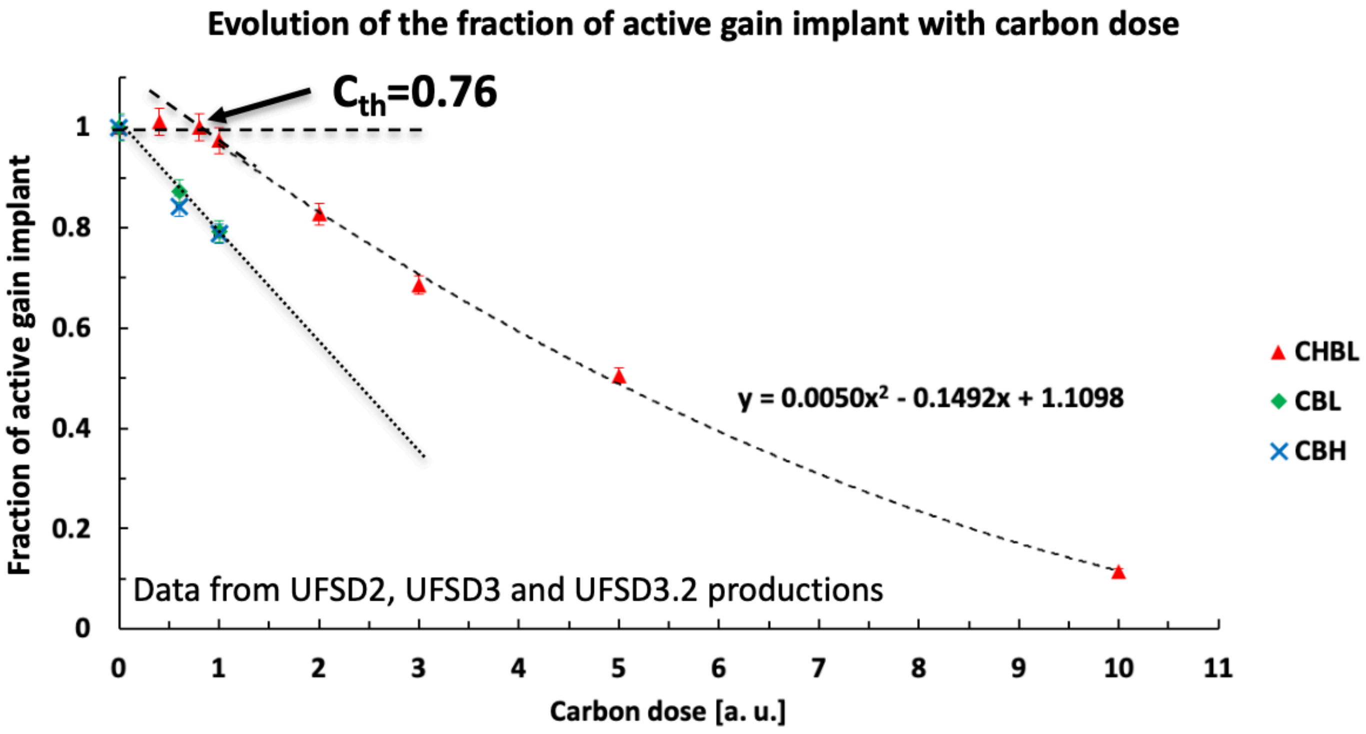


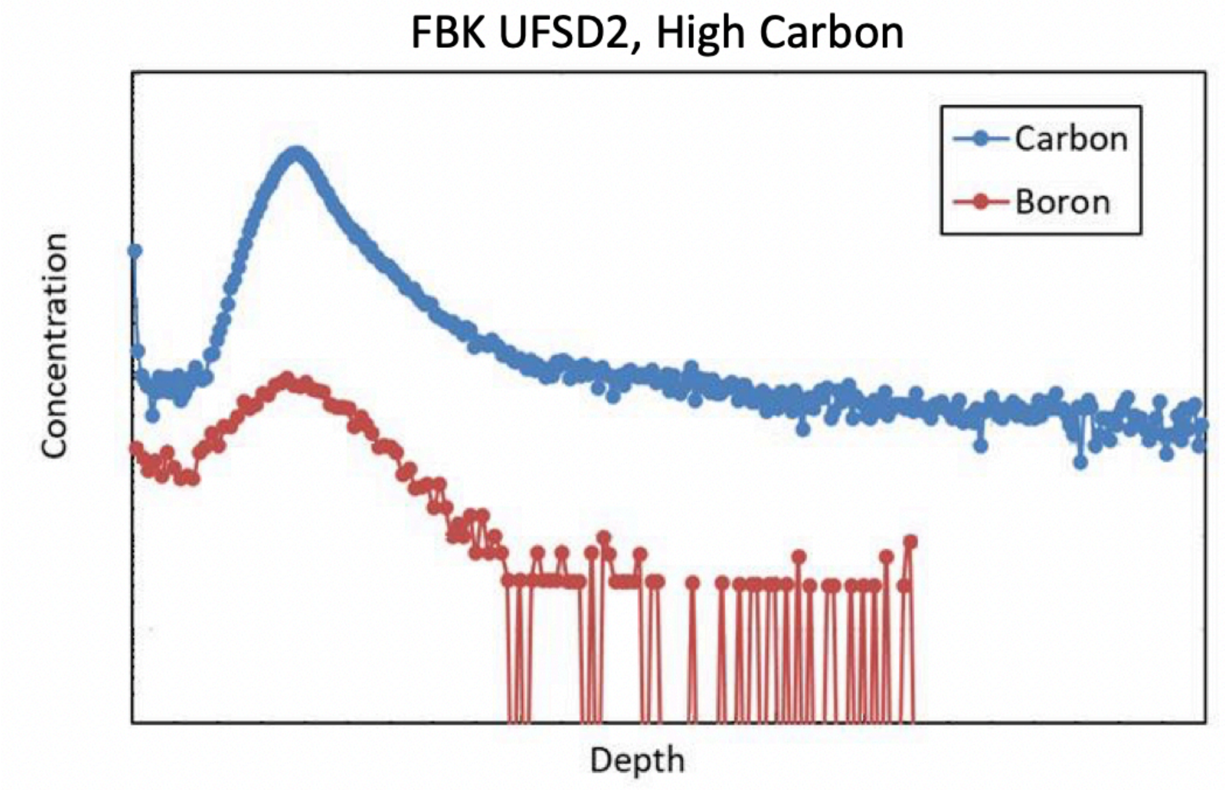
- Shape of Carbon profile:1 narrow peak (ion-implantation)+ 1 wild distribution (diffusion).
- For shallow penetration depth and high carbon thermal load, the carbon dose that diffused into the gain layer region (deeper) is not proportional to the implant dose but increase at first then decrease and eventually become stable.
- After thermal load, the carbon atoms that diffuse are substitute impurities, while the carbon remains in the penetration peak form clusters with silicon atoms(C_nI_m). 10.1063/1.1489715

CBI observed in FBK-UFSD sensors

Carbon Boron Inactivation

$$\text{Fraction of active } N_B = \frac{N_B(GL\ carbonted)}{N_B(GL\ not\ carbonated)} = \frac{V_{GL}(GL\ carbonated)}{V_{GL}(GL\ not\ carbonated)}$$

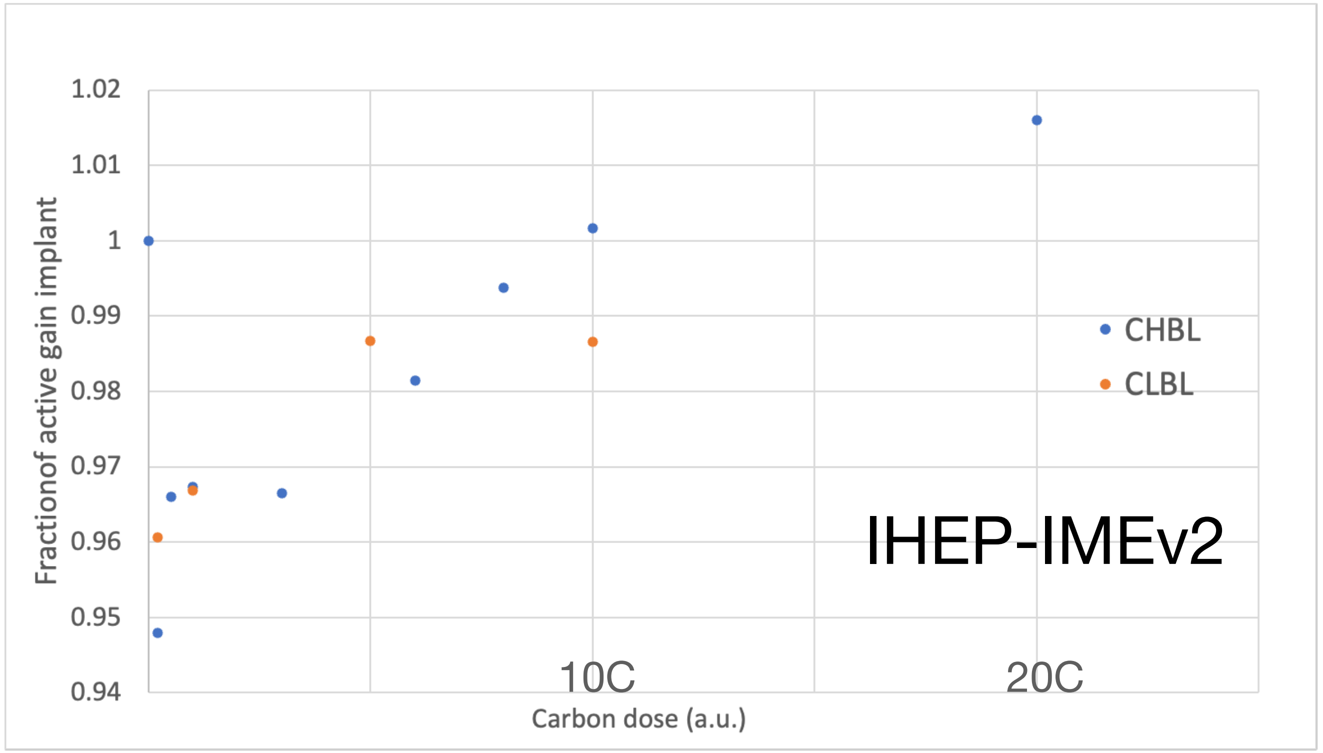




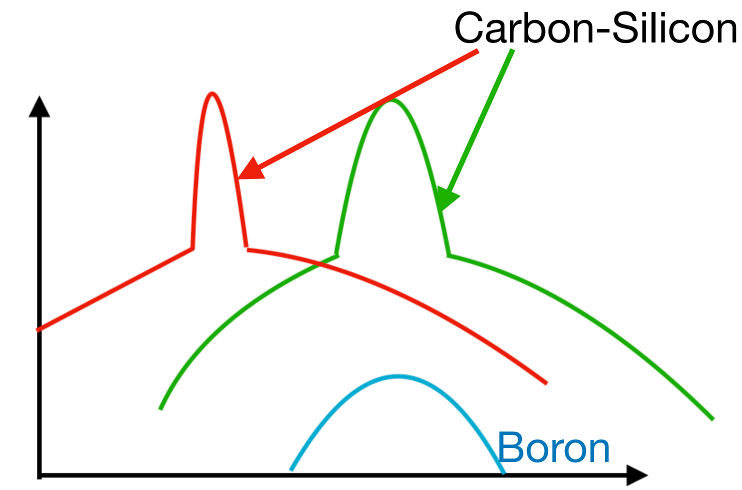
- Active fraction different in co-annealing and annealing separately result from different density of Si_I (more in CBL/CBH).

https://indico.cern.ch/event/983068/contributions/4223173/attachments/2191413/3703863/17022021_MarcoFerrero.pdf
https://indico.cern.ch/event/1096847/contributions/4742738/attachments/2400375/4106595/Gkougkousis_Tento_LGADs.pdf

Carbon related impacts on boron inactivation



If the boron are in same depth with the immobile carbon peak, it will be more complicated than separating them.
(supersaturation of Si_i lead to BCI)



- $\frac{N_{B+C}}{N_B} = 1^{+0.02}_{-0.05}$ **No BCI**
- The Carbon dose varies from $0.2C\ to\ 20C$.
- BCI seems to be induced by immobile carbons rather C_s formed by diffusion.

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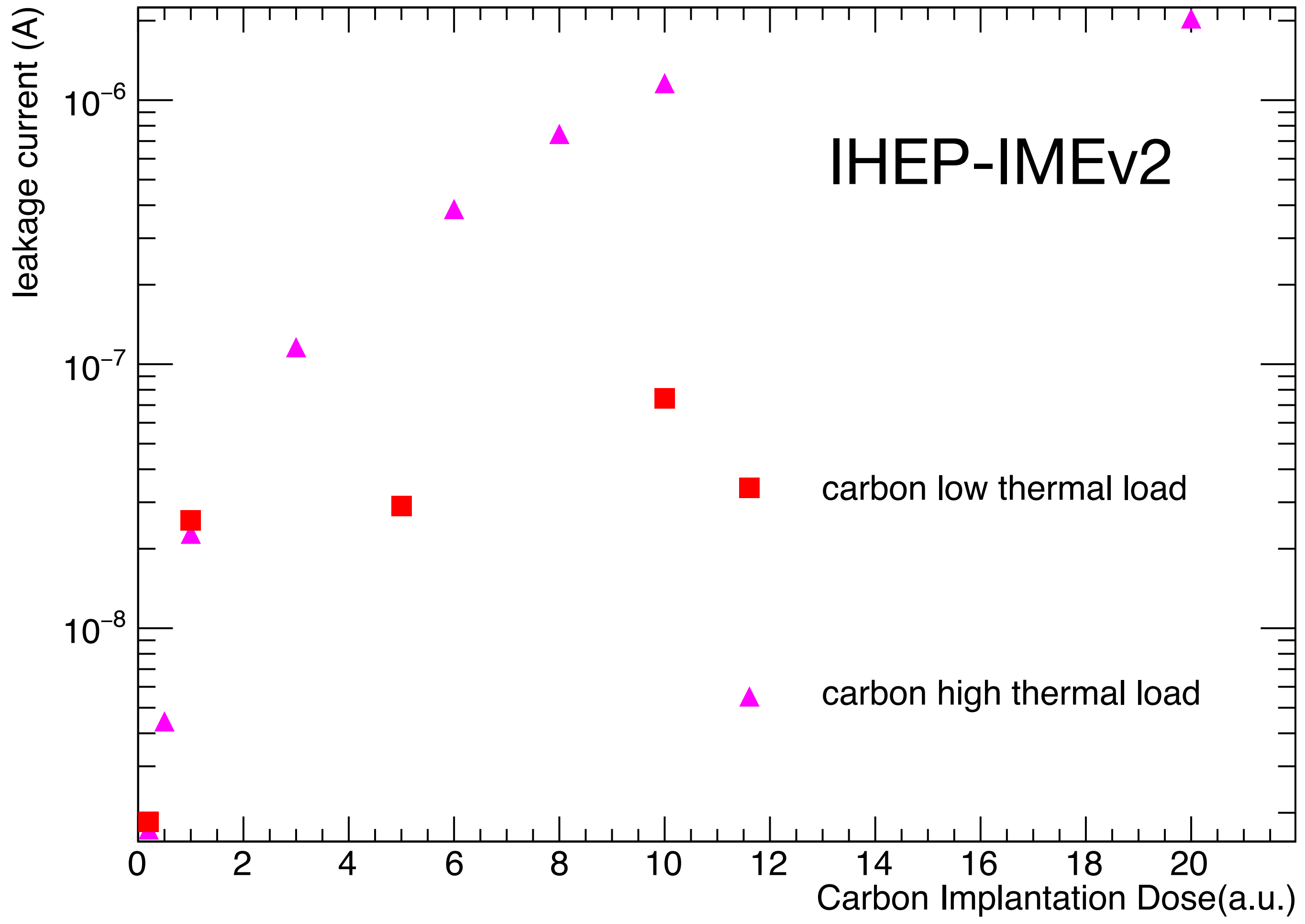
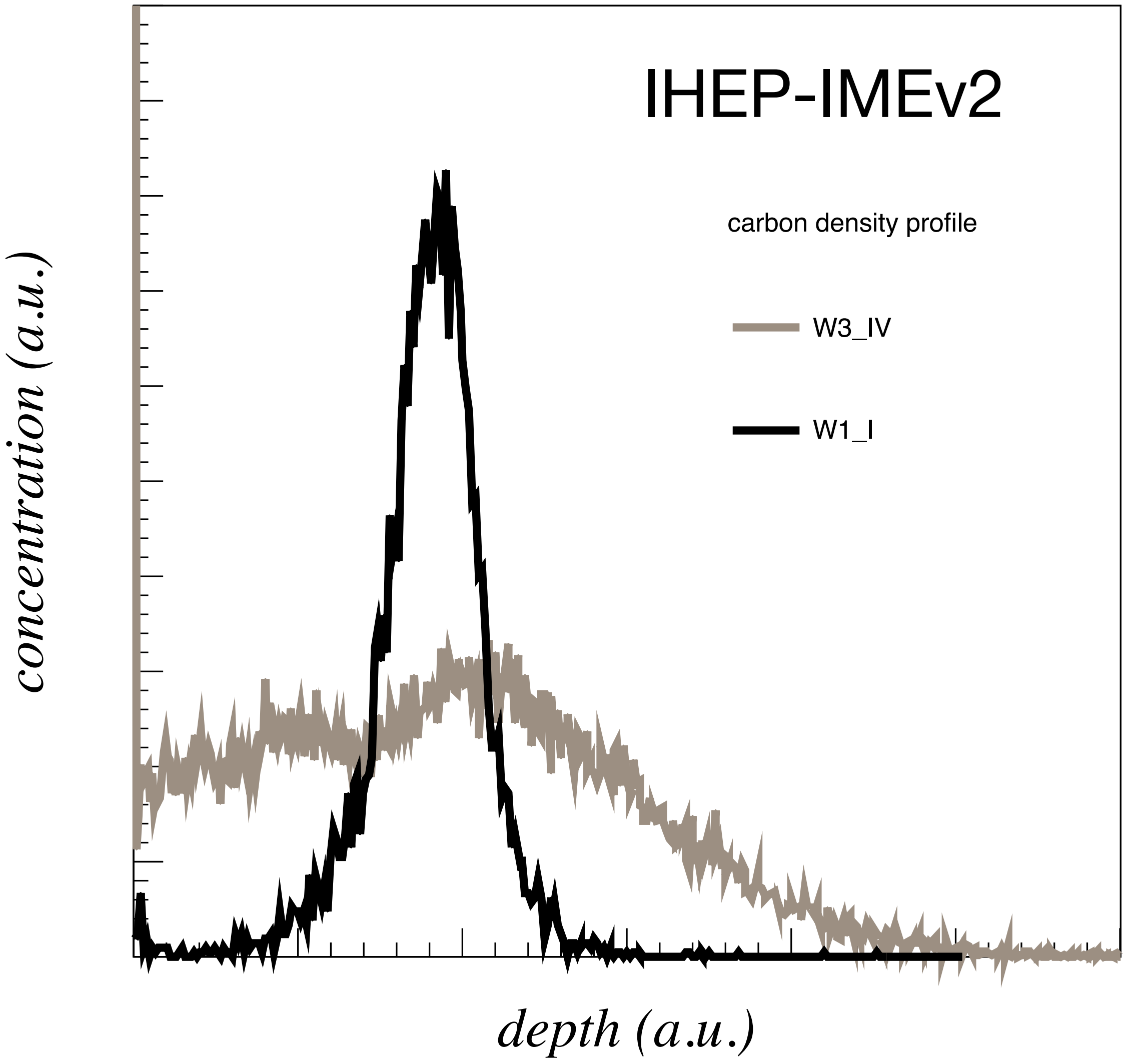
Leakage current in un-irradiated LGADs



- The leakage current increases with carbon dose.
- For carbon low thermal load, the increase is slower than high thermal load.

Why?

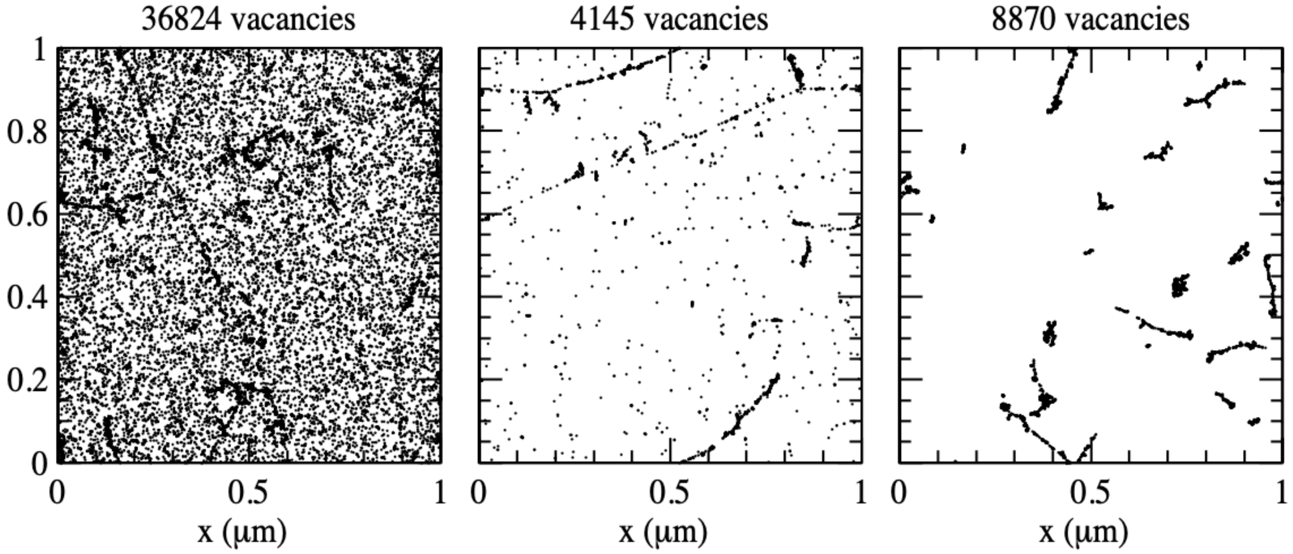
Boron diffusion impacts



Sensor	Thermal load	C factor (x10^16 cm2)
W1_1	Low	3.50
W3_4	High	6.31

- Same implantation dose and energy but different thermal load end up in different distribution.
- Low thermal load->High concentration+ low spread-> better radiation hardness.

Acceptor removal parameterization



https://doi.org/10.1016/S0168-9002(02)01227-5

$$Si \rightarrow I + V$$

Neutron induce Frenkel pairs

$$I + V \rightarrow Si$$

$$I + B_s \rightarrow B_i$$

$$I + C_s \rightarrow C_i$$

Competitors for I

Before irradiation, in the gain layer region, the initial density of boron B(0), carbon C(0) :determined from SIMS.

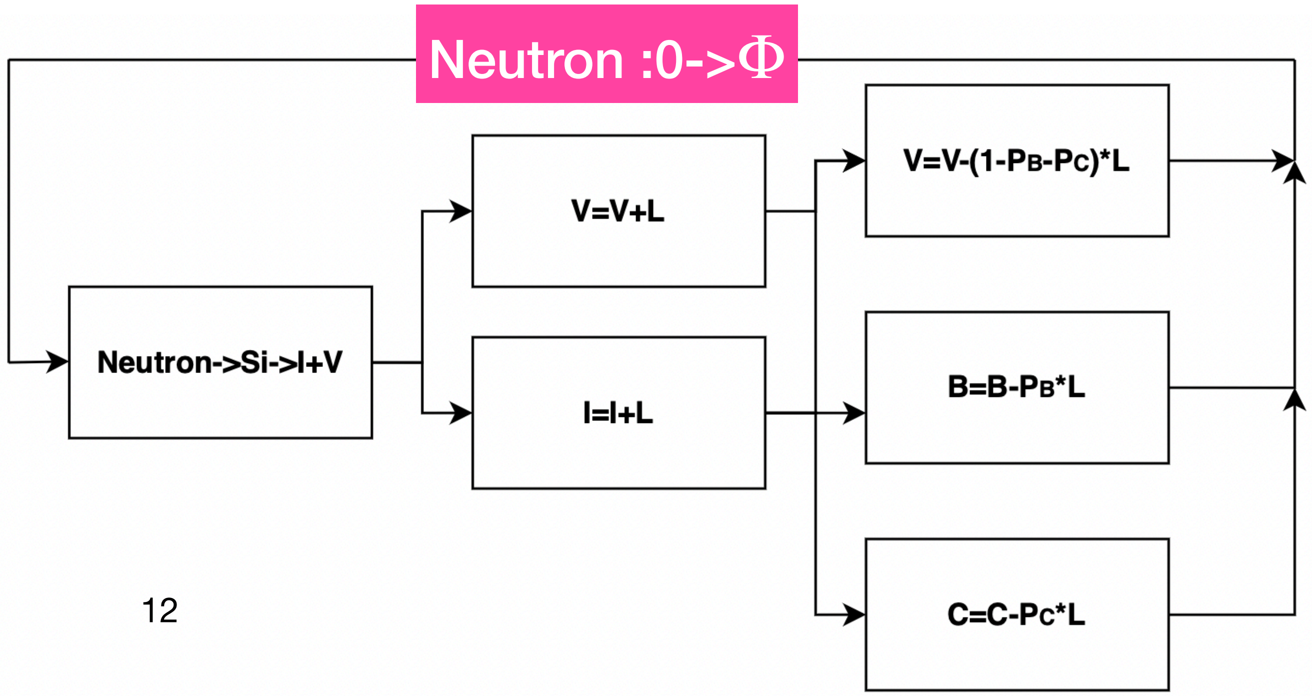
vacancy:V(0)=0 , fluence =ϕ.

Parameters:

1. L: I-V pair generated by neutron/cm
2. K: possibility fraction of C+I to B+I
3. M: possibility fraction of V+I to B+I

$$P_B = \frac{[B(\Phi-1)]}{[B(\Phi-1)]+[C(\Phi-1)]\times K+[V(\Phi)]\times M}$$

$$P_C = \frac{[C(\Phi-1)]\times K}{[C(\Phi-1)]\times K+[V(\Phi)]\times M}$$



Neutron :0->Φ

Neutron->Si->I+V

V=V+L

I=I+L

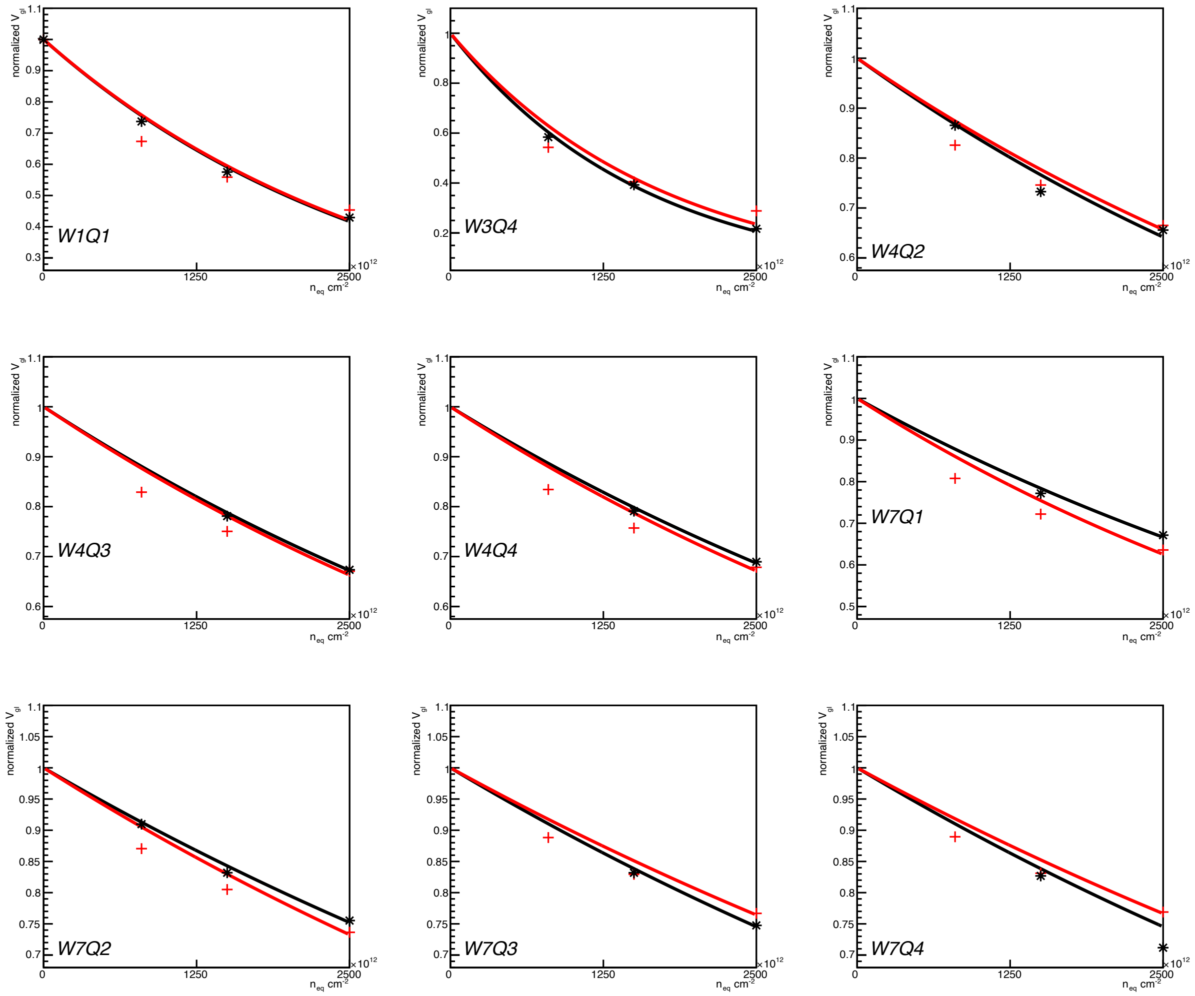
V=V-(1-P_B-P_C)*L

B=B-P_B*L

C=C-P_C*L

Acceptor removal parameterization

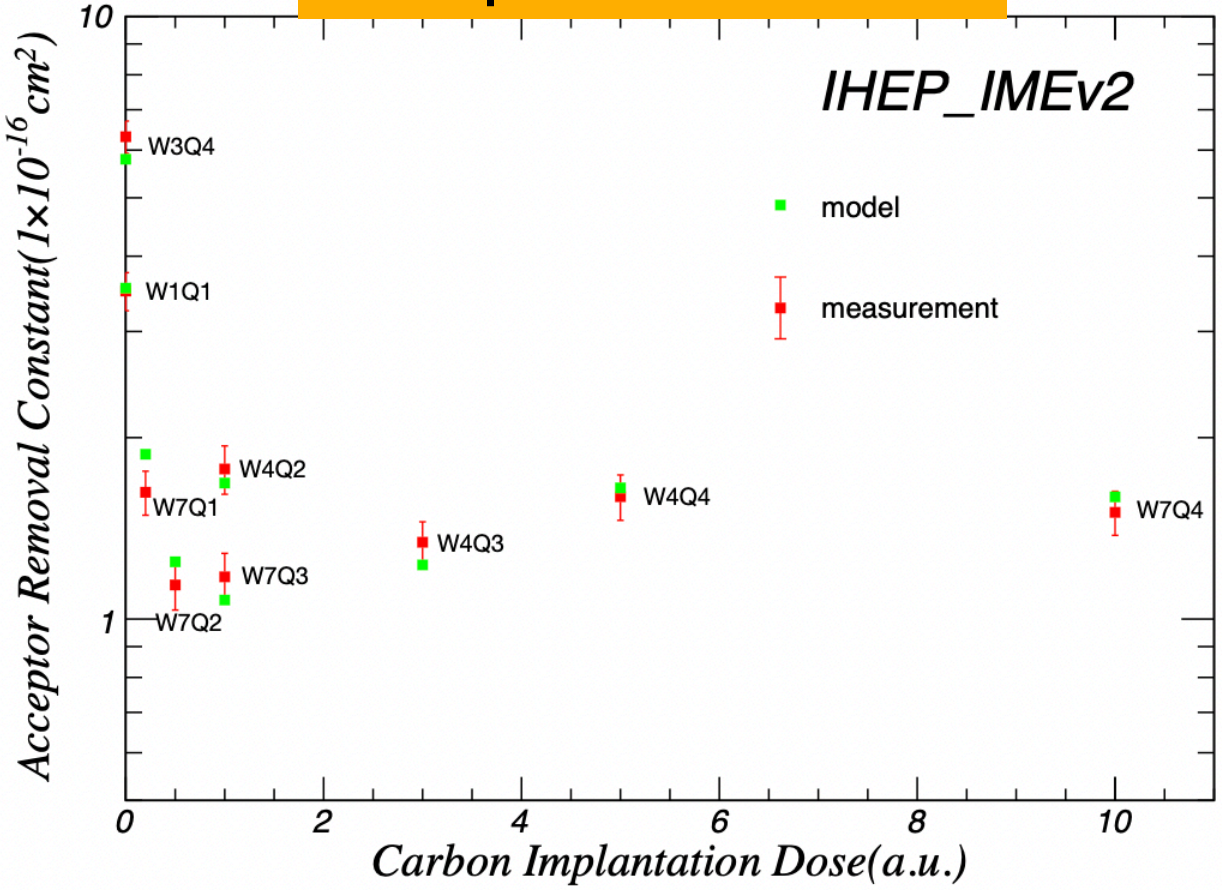
A comparison of shape



IHEP-IMEv2

Comparison of normalized Vgl by measurement and active Boron dose by modeling

A comparison of c values



- The modeled c factors have a good agreement with measurement.

Parameters under determination

1. L: I-V pair generated by neutron/cm
2. K: possibility fraction of C+I to B+I
3. M: possibility fraction of V+I to B+I

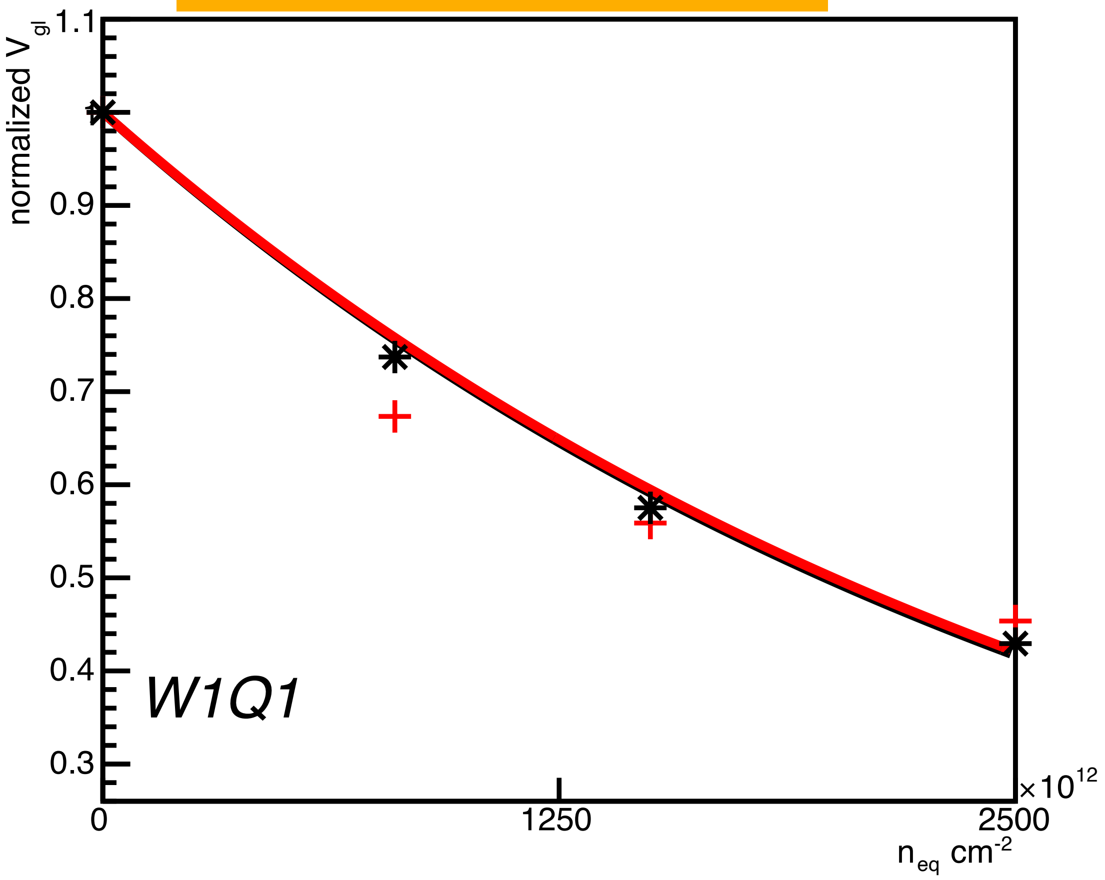
L≈ 50/cm

K ≈ 0.65

M≈ 10

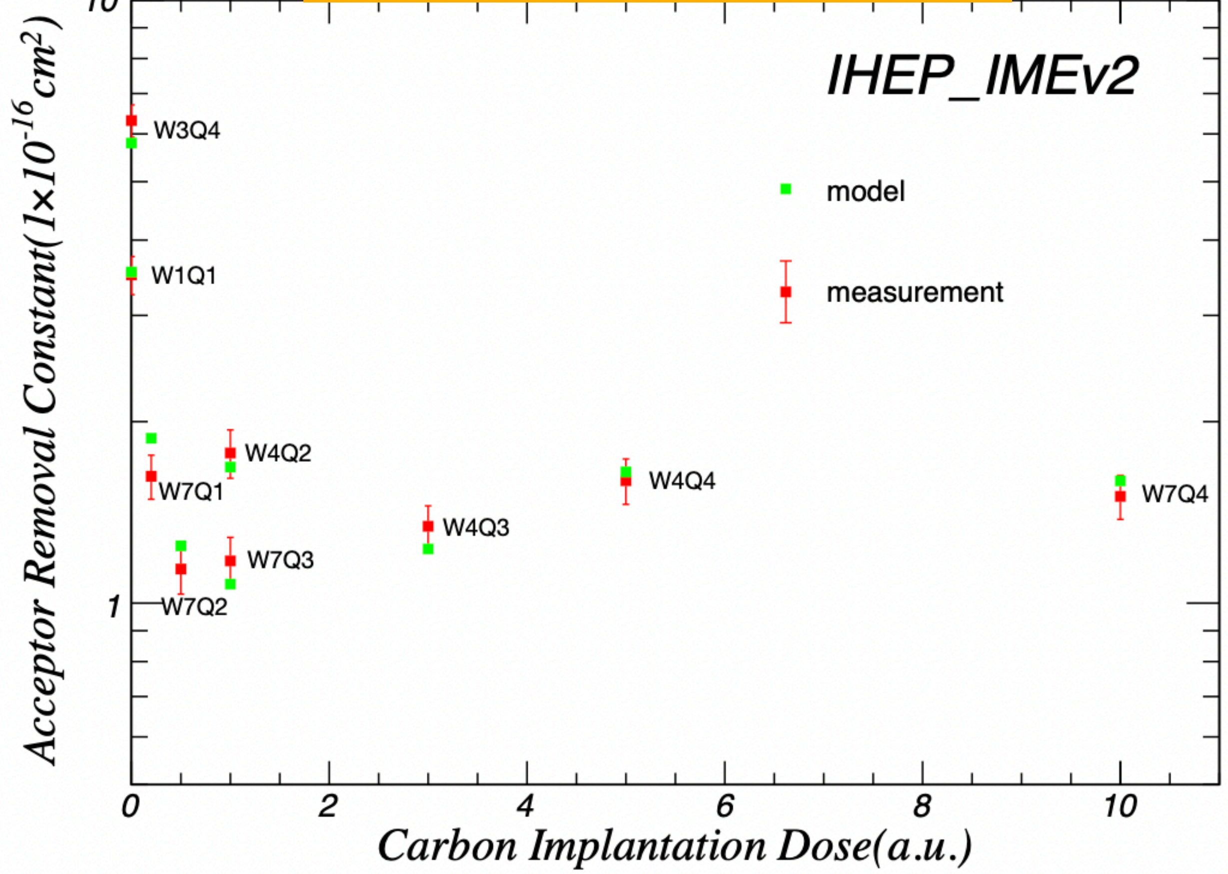
Acceptor removal parameterization

A comparison of shape



- While the simulation fit curve is similar with measurement fit, the modeled data point (+)seems to deviate more from exponential than test.

A comparison of c values



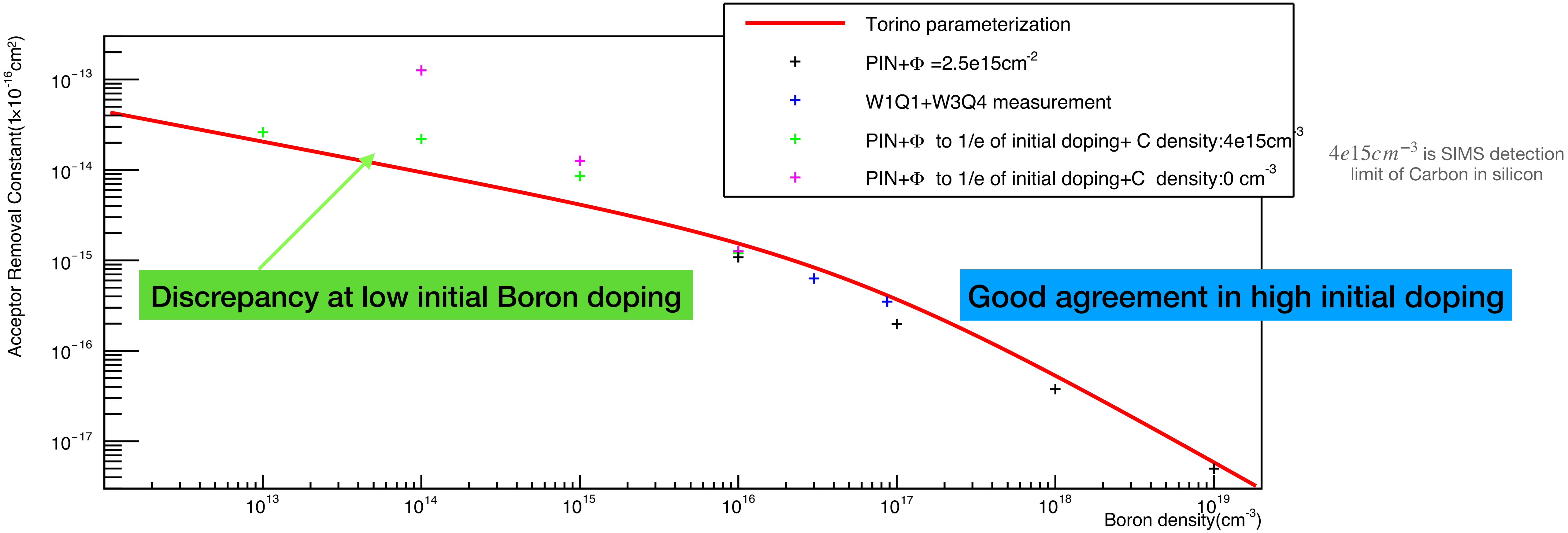
- The modeled c factors have a good agreement with measurement.

Parameters under determination

1. L: I-V pair generated by neutron/cm
2. K: possibility between B+I and C+I (including radios and probability)
3. M: possibility between B+I and V+I (including radios and probability)

L≈ 50/cm
K ≈ 0.65
M≈ 10

Comparison and Extrapolation



$4e15cm^{-3}$ is SIMS detection limit of Carbon in silicon

Discrepancy at low initial Boron doping

Good agreement in high initial doping

A comparison of Torino parameterization with model prediction and measurement:

- black crosses are simulated bulks (uniform Boron doping) irradiated to $2.5 \times 10^{15} n_{eq} cm^{-2}$
- blue crosses are LGAD data （X values are peak concentrations of Boron)
- green (crosses at low initial Boron density are bulks simulated to be irradiated to $\frac{1}{e}$ its initial doping.

This method could not describe the c coefficient at low initial boron density.

https://doi.org/10.1016/j.nima.2018.11.121

Summary

- To get a best radiation hardness performance, in IHEP_IMEv2 LGADs, applied specific doping strategy:

  1.Shallow Carbon implantation depth (separate with Boron and avoid BCI)

  2.High Carbon thermal load (diffuse more into Boron enriched region)

  3.Low Boron thermal load (high density)

- In the next version, more design in Carbon implantation dose will be utilized to minimize the c value.

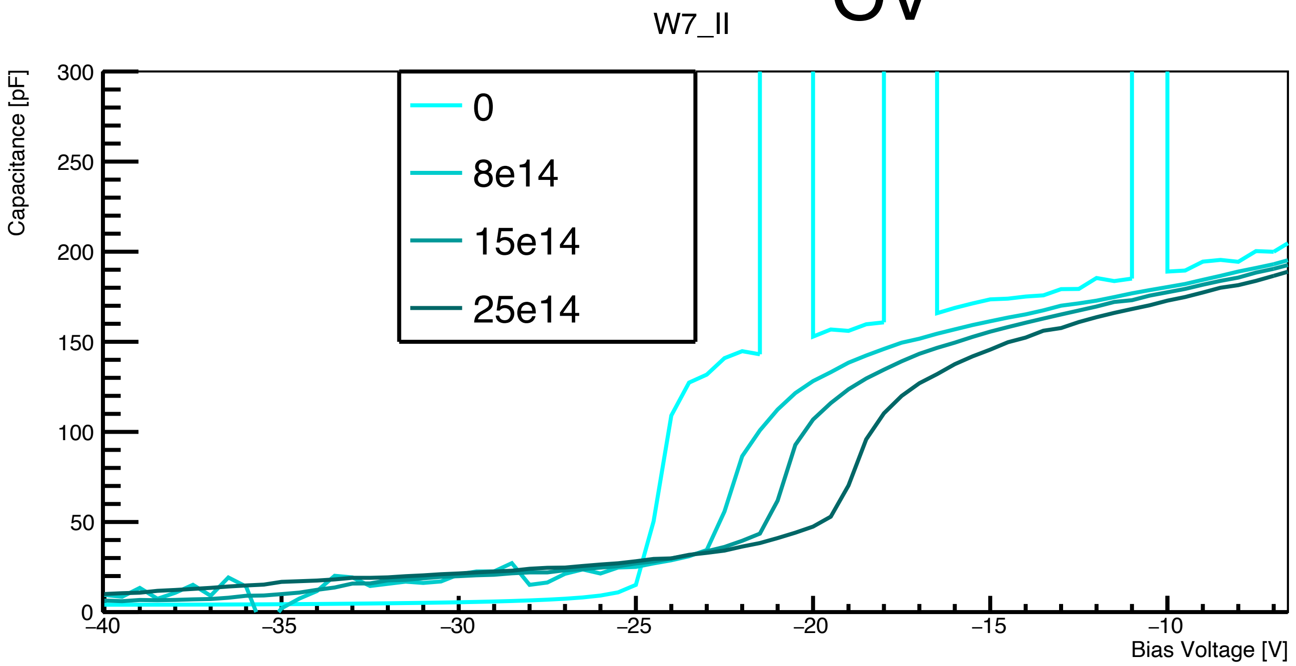
- Based on SIMS data of v2 devices, a parameterization of C factors is conducted.
  The modeling is in good agreement both with IHEP_IMEv2 devices and with Torino parameterization in high density region.

The drawback of the model is: unable to describe the c factor with low initial boron density. (Only 4 reaction are included in the sampling)

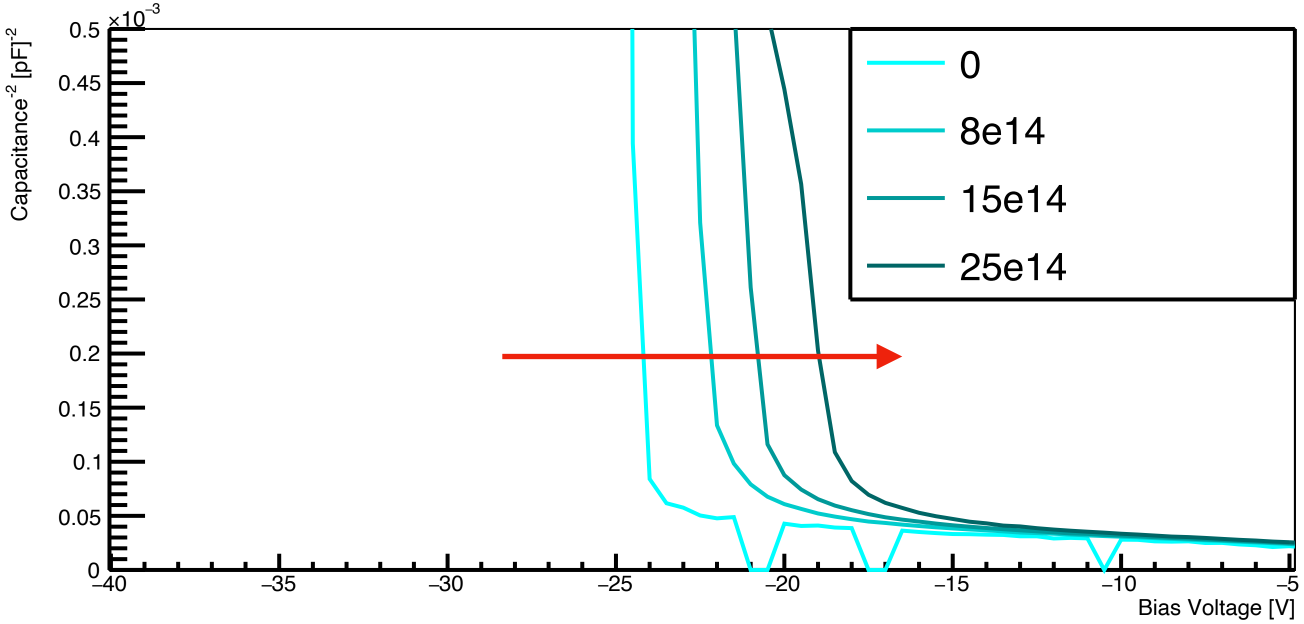
Thank you!

CV on LGADs

CV



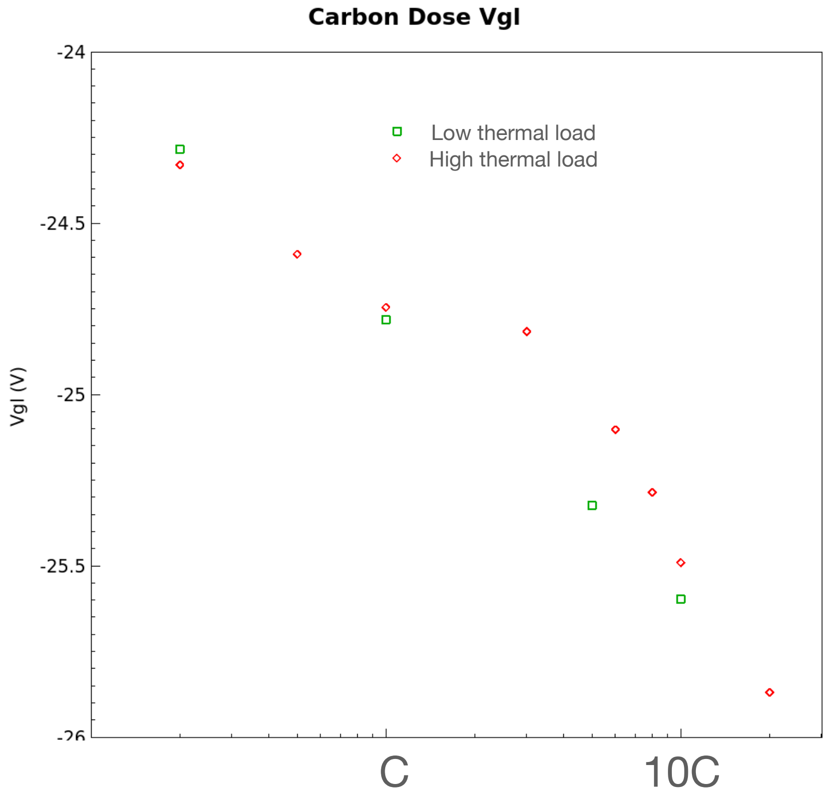
$C^{-2} - V$



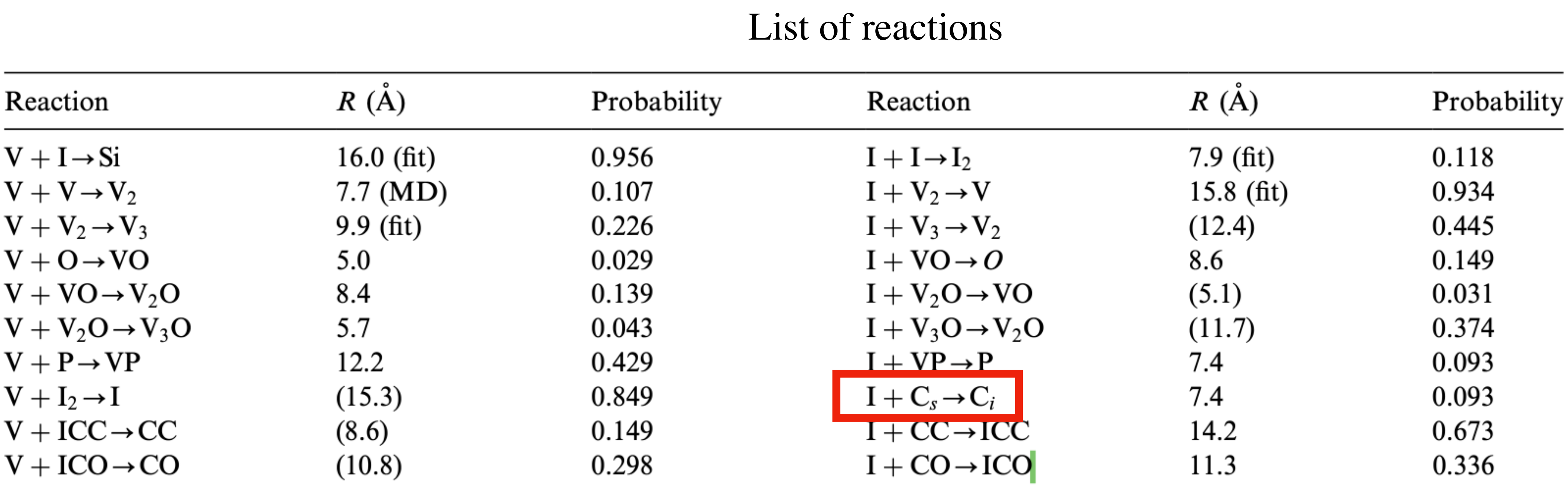
V_{gl} decreases with increasing Φ.

- Frequency: 1kHz,
- AC Amplitude:0.1V,
- DC step:0.5V
- RT:20$^{\circ}C$
- Each irradiated sensor has been annealed 80 min at 60°C before the test

Before irradiation



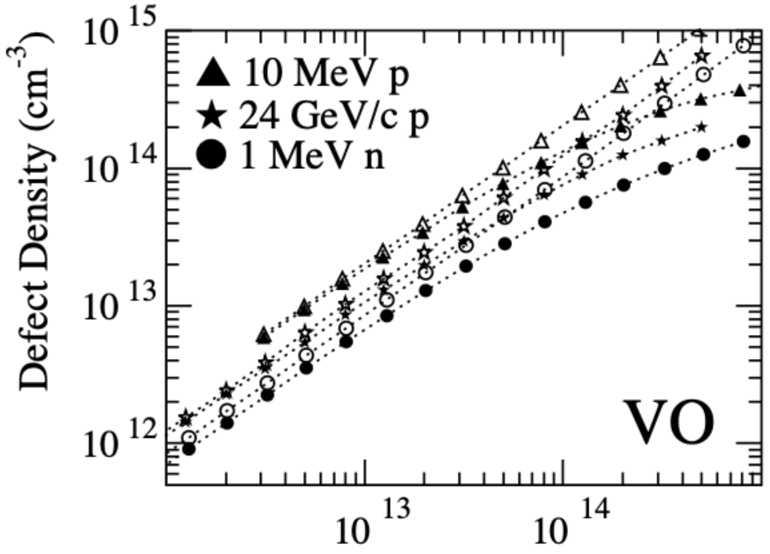
Other reactions unconsidered in low doping

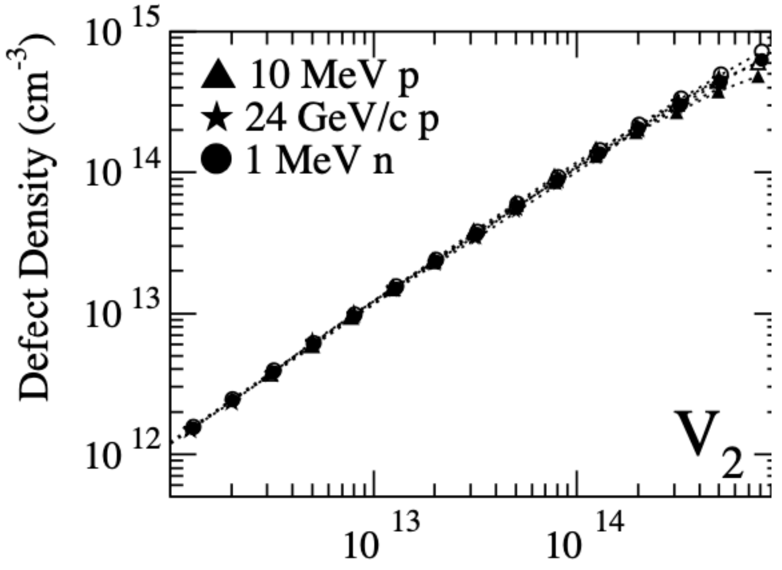


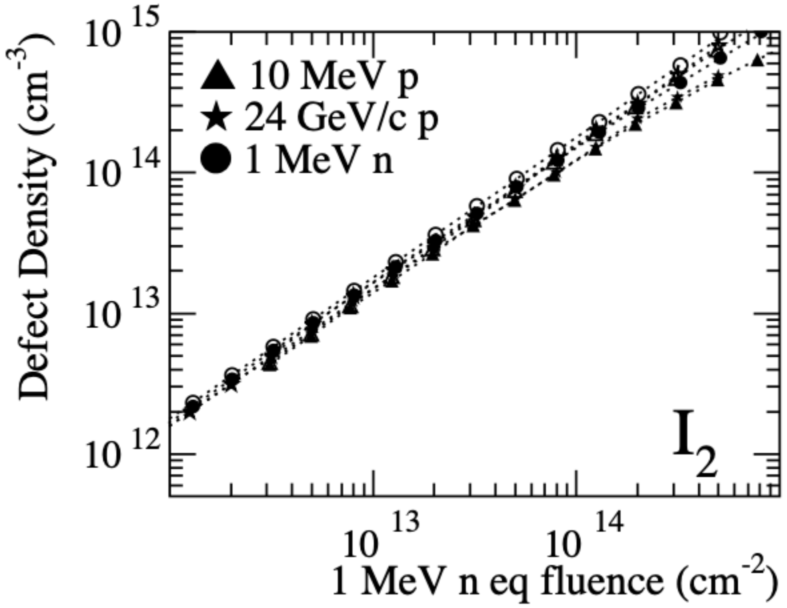
List of reactions

Reaction	R (Å)	Probability	Reaction	R (Å)	Probability
$V + I \rightarrow Si$	16.0 (fit)	0.956	$I + I \rightarrow I_2$	7.9 (fit)	0.118
$V + V \rightarrow V_2$	7.7 (MD)	0.107	$I + V_2 \rightarrow V$	15.8 (fit)	0.934
$V + V_2 \rightarrow V_3$	9.9 (fit)	0.226	$I + V_3 \rightarrow V_2$	(12.4)	0.445
$V + O \rightarrow VO$	5.0	0.029	$I + VO \rightarrow \mathit{O}$	8.6	0.149
$V + VO \rightarrow V_2O$	8.4	0.139	$I + V_2O \rightarrow VO$	(5.1)	0.031
$V + V_2O \rightarrow V_3O$	5.7	0.043	$I + V_3O \rightarrow V_2O$	(11.7)	0.374
$V + P \rightarrow VP$	12.2	0.429	$I + VP \rightarrow P$	7.4	0.093
$V + I_2 \rightarrow I$	(15.3)	0.849	$I + C_s \rightarrow C_i$	7.4	0.093
$V + ICC \rightarrow CC$	(8.6)	0.149	$I + CC \rightarrow ICC$	14.2	0.673
$V + ICO \rightarrow CO$	(10.8)	0.298	$I + CO \rightarrow ICO$	11.3	0.336

I+Bs->Bi







Oxygen density ≈ 1e17/cm3

Introducing rate of $VO, V_2, I_2 < 1/(cm \times N_{eq})$,while the removal rate is larger than 10

https://doi.org/10.1016/S0168-9002(02)01227-5