CEPC ToF Detector R&D Using LGAD

IAS Program on High Energy Physics (HEP)

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Outline

I. Motivation

II. AC-LGAD in IHEP

III. LGAD in IHEP

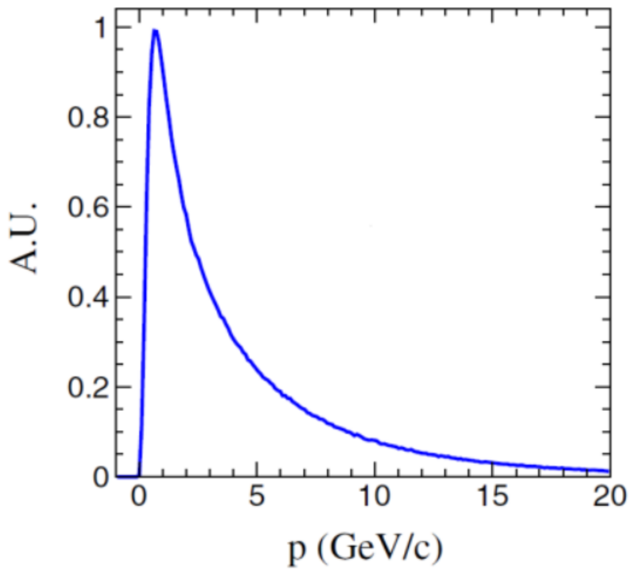
Motivation

Particle separation problems for CEPC flavor physics: k/pi、k/p

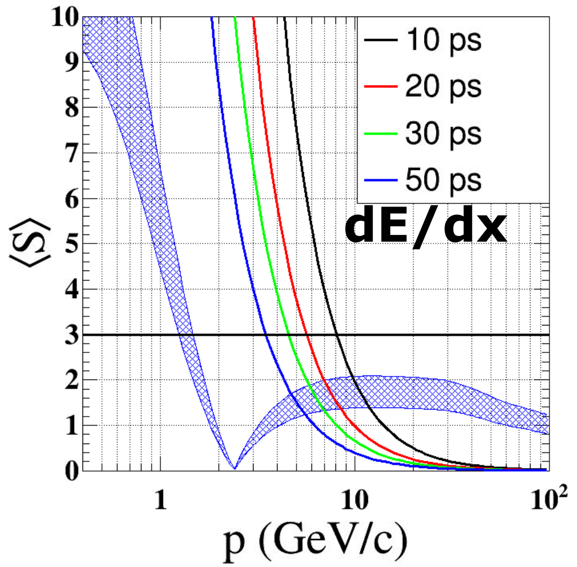
- dE/dx or dN/dx detector : **bad performance around 2GeV**
- **ToF improves the separation ability in the low-energy range**

Application of time flight detector : 50 ps-> 30ps-> 20 ps-> 10 ps,
extend the capabilities of particle separation of particles below 5 GeV

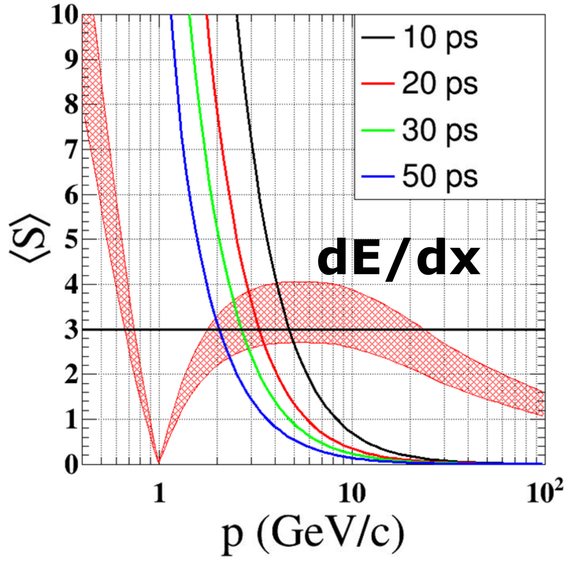
Distribution of CEPC particles



k/p Separation



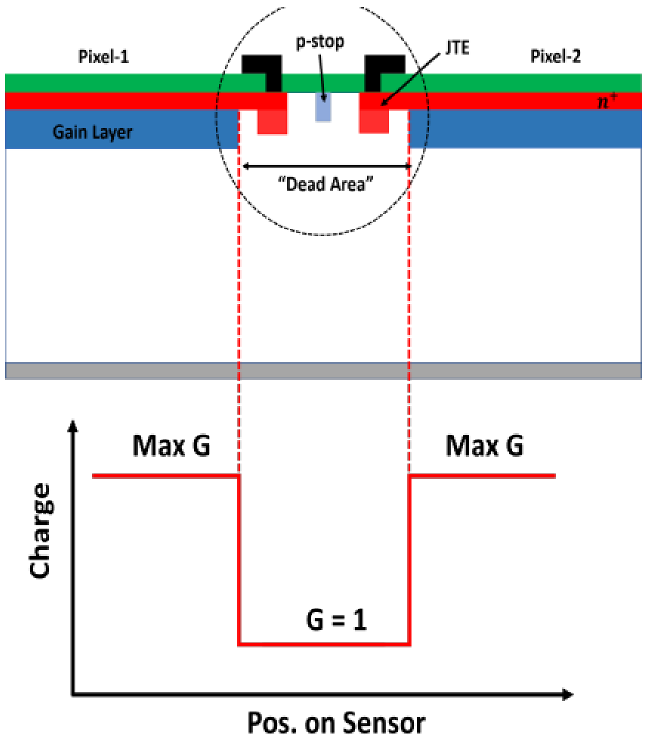
k/pi Separation

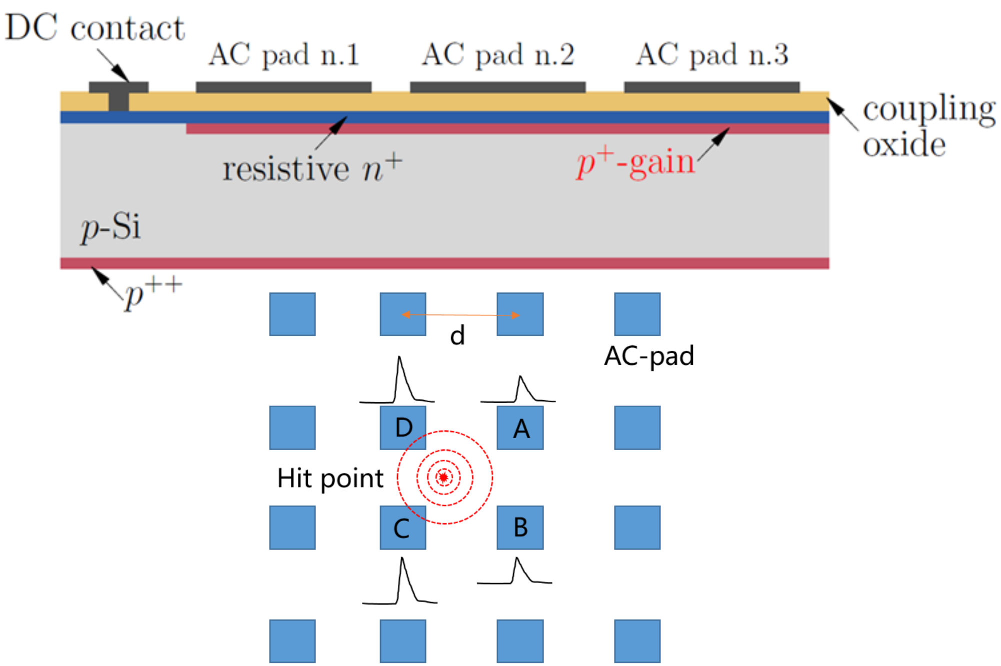


Candidate of ToF for CEPC

Candidate of ToF for CEPC

- **LGAD：** high timing resolution （30 ps） , low gain, high S/N
- **AC-LGAD：** 4 dimension detection (spatial and 30-40 ps time resolution)、no dead region





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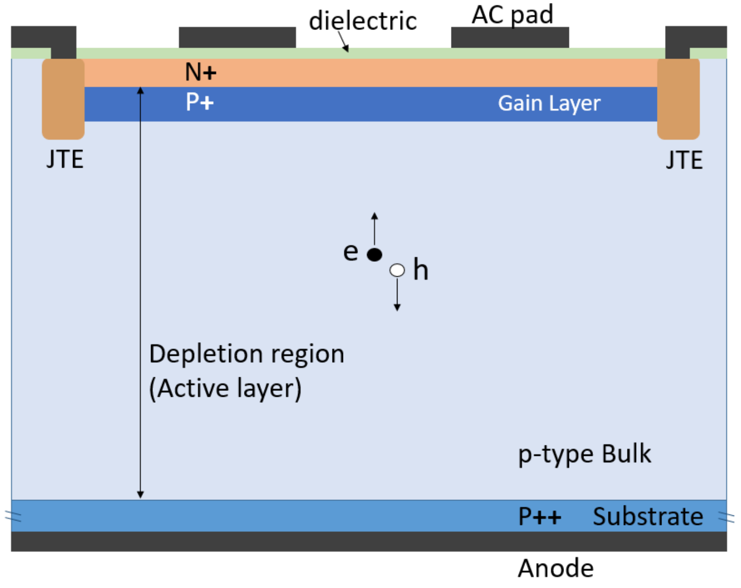
Design of AC-LGAD

Different designs of AC-LGAD in IHEP



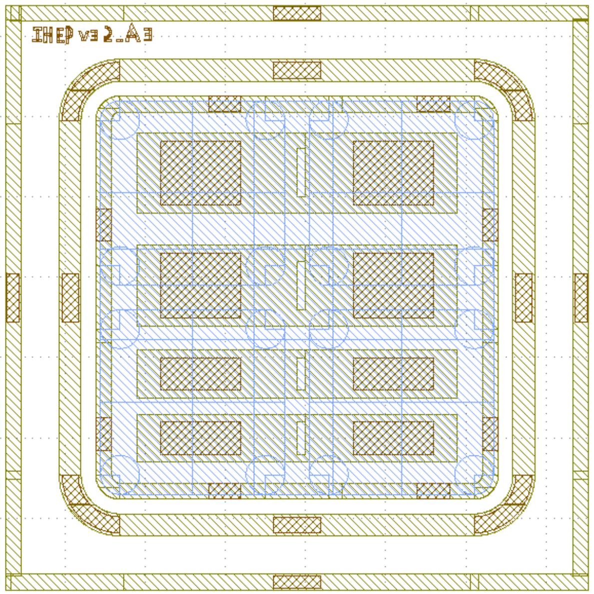
Geometric shape:

- ✓ Different arrange of pads: different signal path
- ✓ Pixels AC-LGAD
- ✓ Strip AC-LGAD

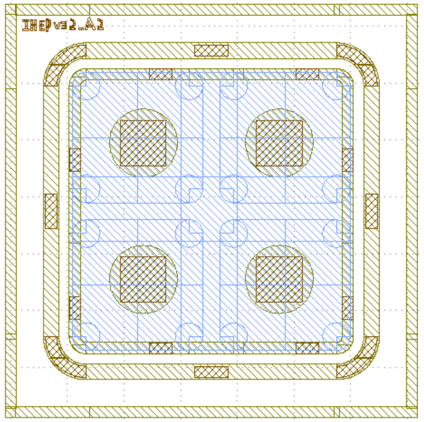
Different doping:

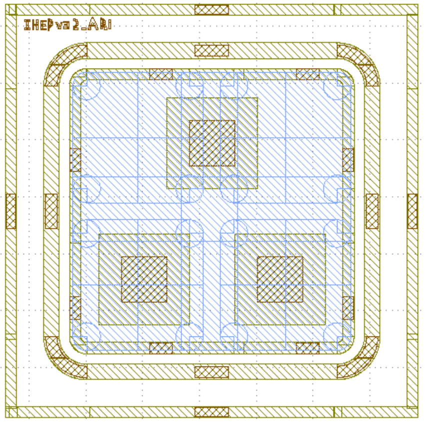
- ✓ N+dose: attenuation effect

Different widths of the pads



Different arrange of the pads



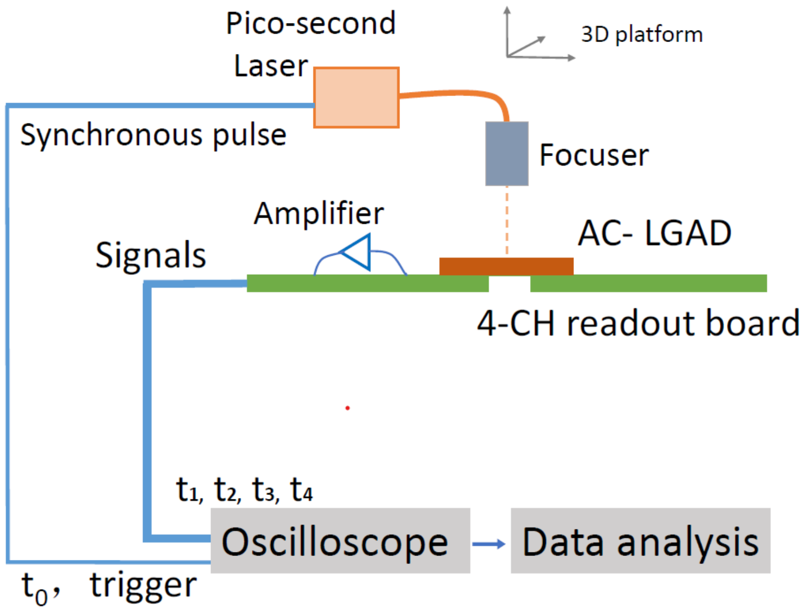


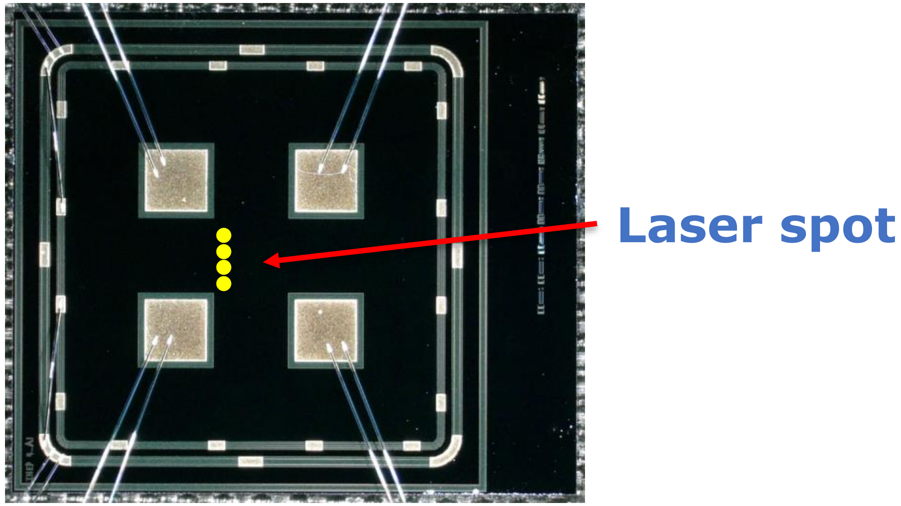
Different N+ dose

Sensors	N+ dose	AC-pad size [μm]	Pitch size [μm]
W7Q1	10.0 P	1000	2000
W5Q1	5.0 P	1000	2000
W5Q2	1.0 P	1000	2000
W5Q3	0.5 P	1000	2000
W5Q4	0.2 P	1000	2000

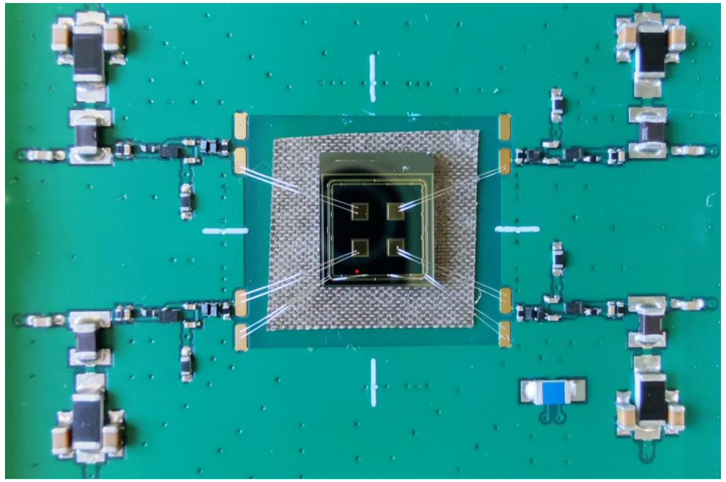
Performance Test Setup of AC-LGAD

- **Timing and spatial resolution test of AC-LGAD**
- **Transient current technique (TCT)**
- Picosecond Laser: 1065 nm， spot size10 μm (3σ)
- **4 channels readout board designed by IHEP**
  - 470 Ω Broadband inverting trans-impedance amplifie
  - Reference of 1 channel board designed by UCSC





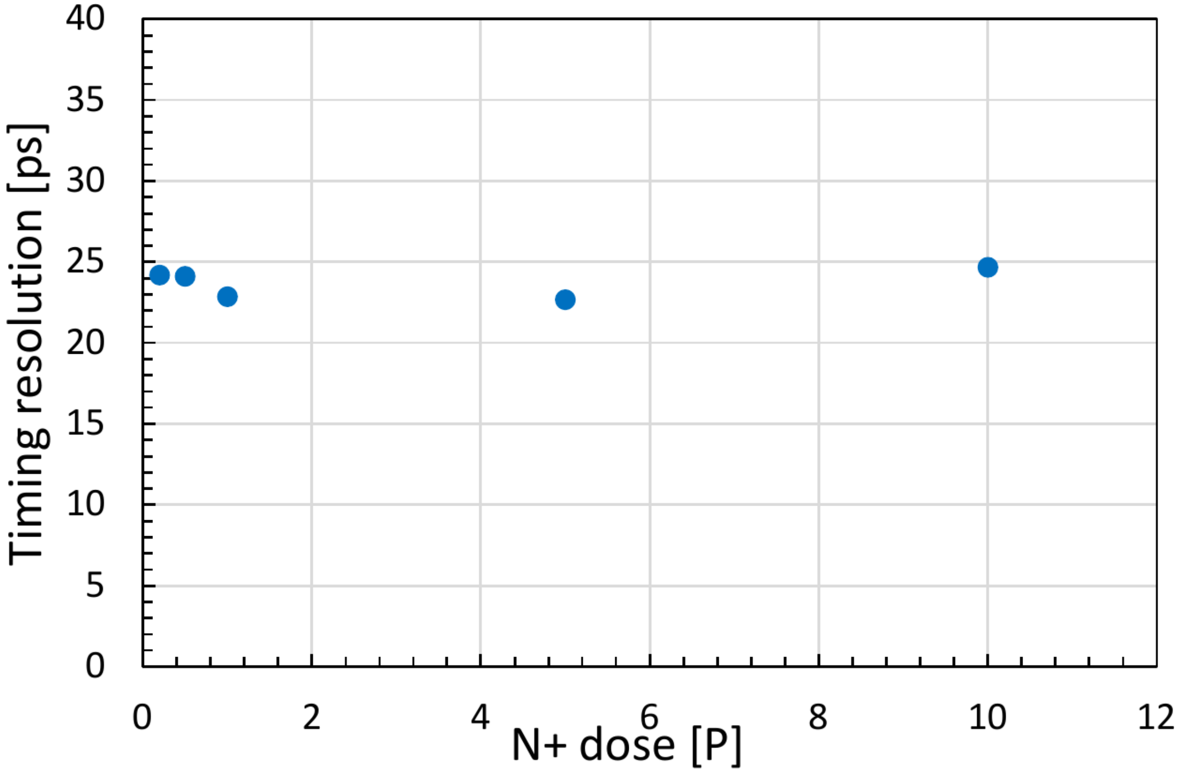
4 channels readout board designed by IHEP



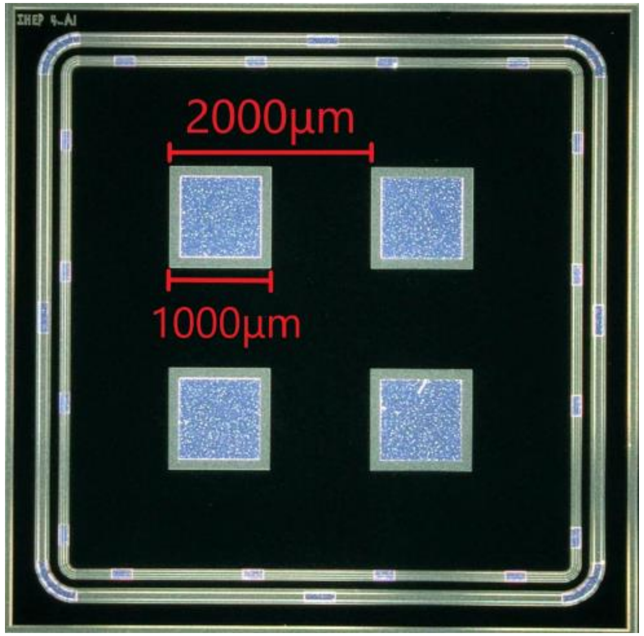
Timing resolution of AC-LGAD

- **Timing resolution of AC-LGAD with different N+ dose**
  - **22~25ps**
  - N+ very slightly affects the time performance

Timing resolution of AC-LGAD with different N+ dose



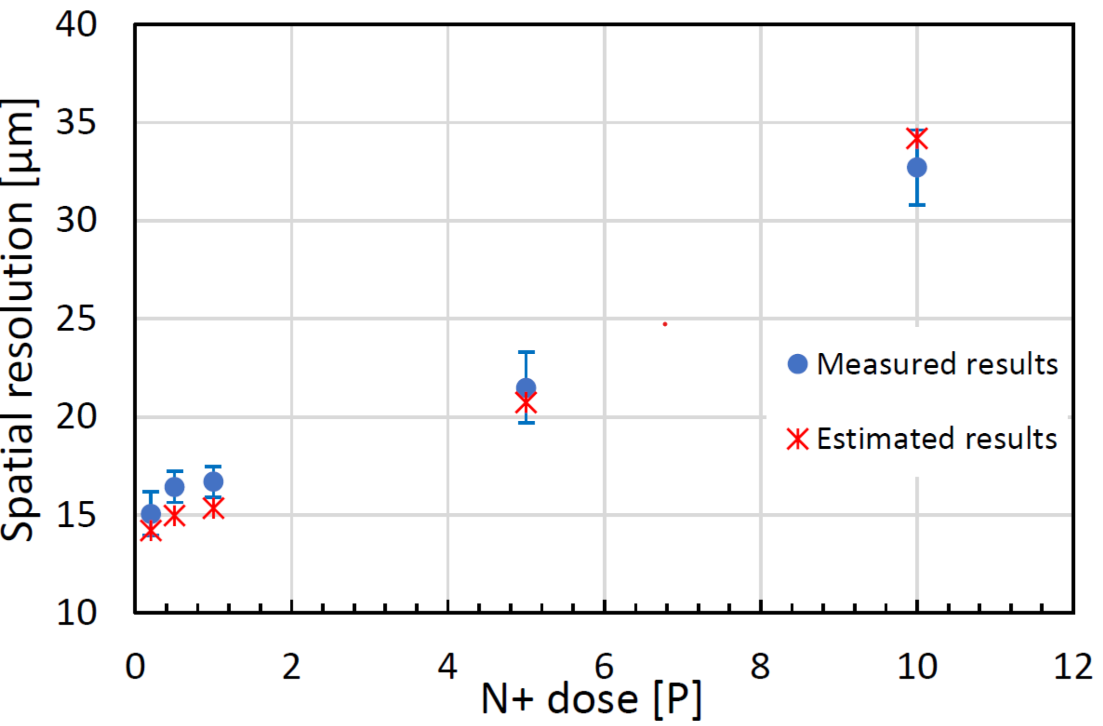
Tested AC-LGAD



Spatial resolution of AC-LGAD

Spatial resolution Vs N+ dose

- 10 P → 0.2 P, spatial resolution ⬆ 15μm (minimum)
- Estimated laser point positions fit the measured well
- **Better than the FBK design** even with 2 times larger pitch



Sensors	Pitch size [μm]	Spatial resolution [μm]	Time resolution [ps]
IHEP AC-LGAD	2000	15	22 （laser）
FBK AC-LGAD	500	11	32 （laser）
BNL AC-LGAD	100	-	45 （beta source）

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IHEP-IME LGAD: Version3 Design

- **The design parameters: IHEP-IME Version3 W12 and Version2 W7Q2**
  - The same designed doping
  - Edge distance is different :V2(V3): 500 μm(500 μm)x500 μm(300 μm),
  - IP : V2(V3) 120 μm(90 μm)

IHEP_IMEv2 LGAD design

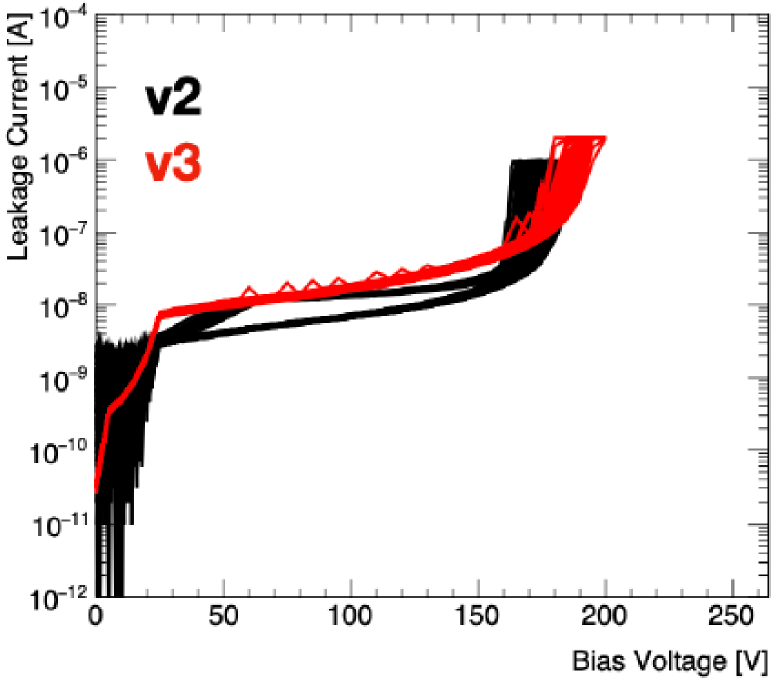
Sensor		Diffuse*	C dose(a.u.)	C factor (x10^16 cm2)
W4	Q1	CLBL	0.2	2.57
	Q2	CLBL	1	1.77
	Q3	CLBL	5	1.60
	Q4	CLBL	10	1.50
W7	Q1	CHBL	0.2	1.62
	Q2	CHBL	0.5	1.14
	Q3	CHBL	1	1.18
	Q4	CHBL	3	1.34
W8	Q1	CHBL	6	1.30 1.32
	Q2	CHBL	8	1.32
	Q3	CHBL	10	1.23
	Q4	CHBL	20	1.29

BEST

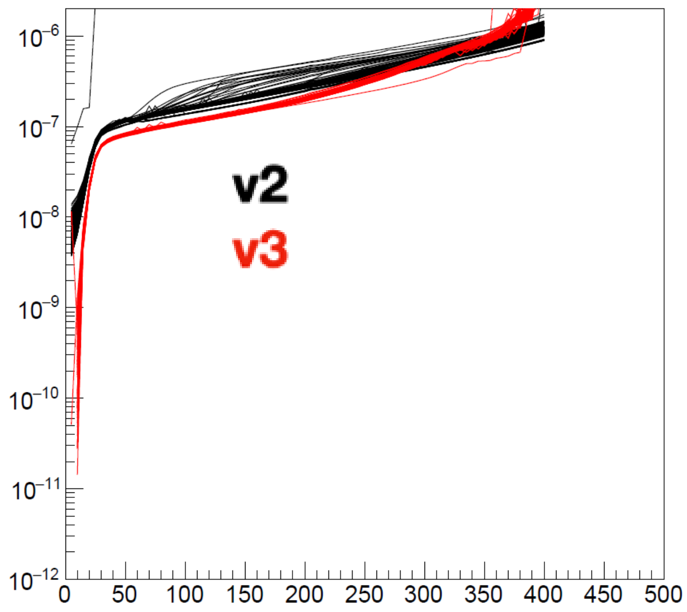
number	Type
12	repeat v2 w7_II
13	repeat v2 w7_II
14	repeat v2 w4_II
15	change B dose, 0.5 unit C(low thermal load)
16 ,17	change C dose (high thermal load)
18	C with median thermal load
19	repeat v2 w1_I
20,21,22	high energy C implantation
23	thick EPI(65um) without C implantation
24	thick EPI(65um) , 0.5 unit C(high thermal load)
25	thick EPI(80um) without C implantation
26	thick EPI(80um), 0.5 unit C(high thermal load)

Consistency of the 15x15 sensor for IHEP

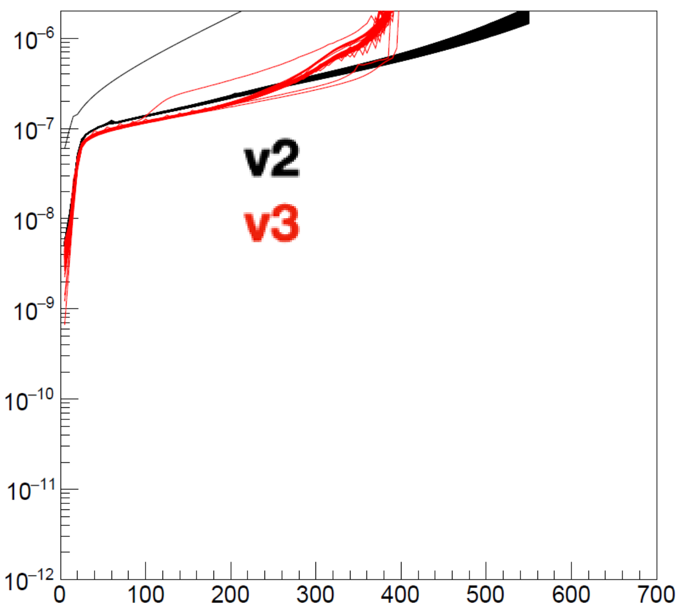
Before irradiation



1e15 neq/cm2



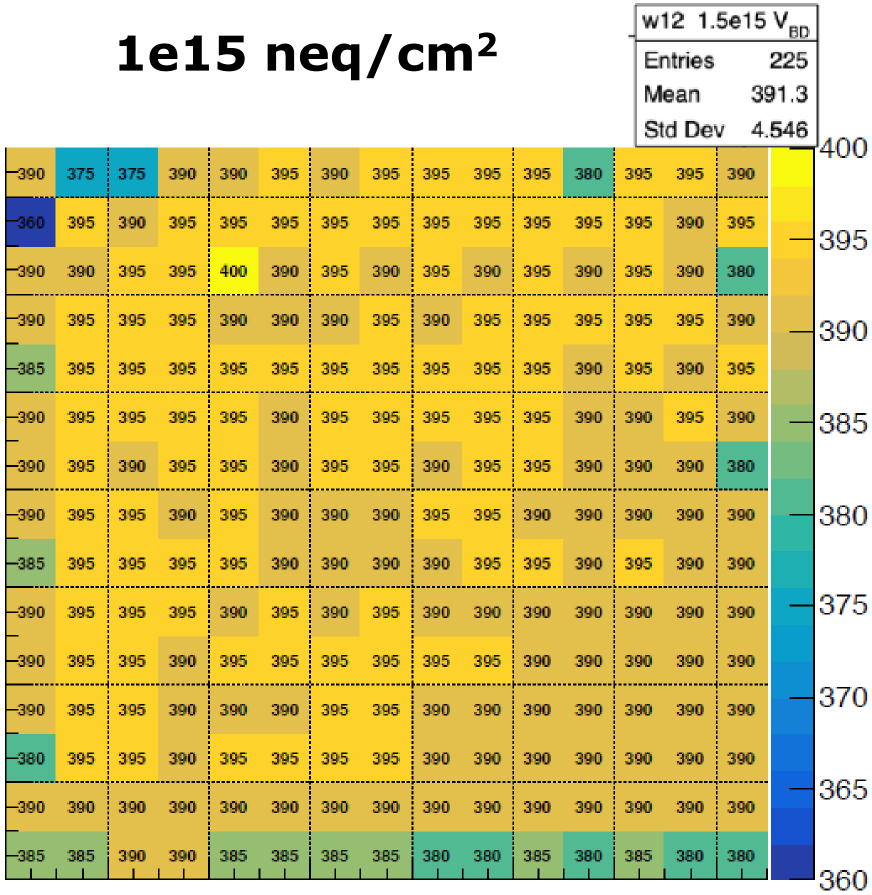
2.5e15 neq/cm2



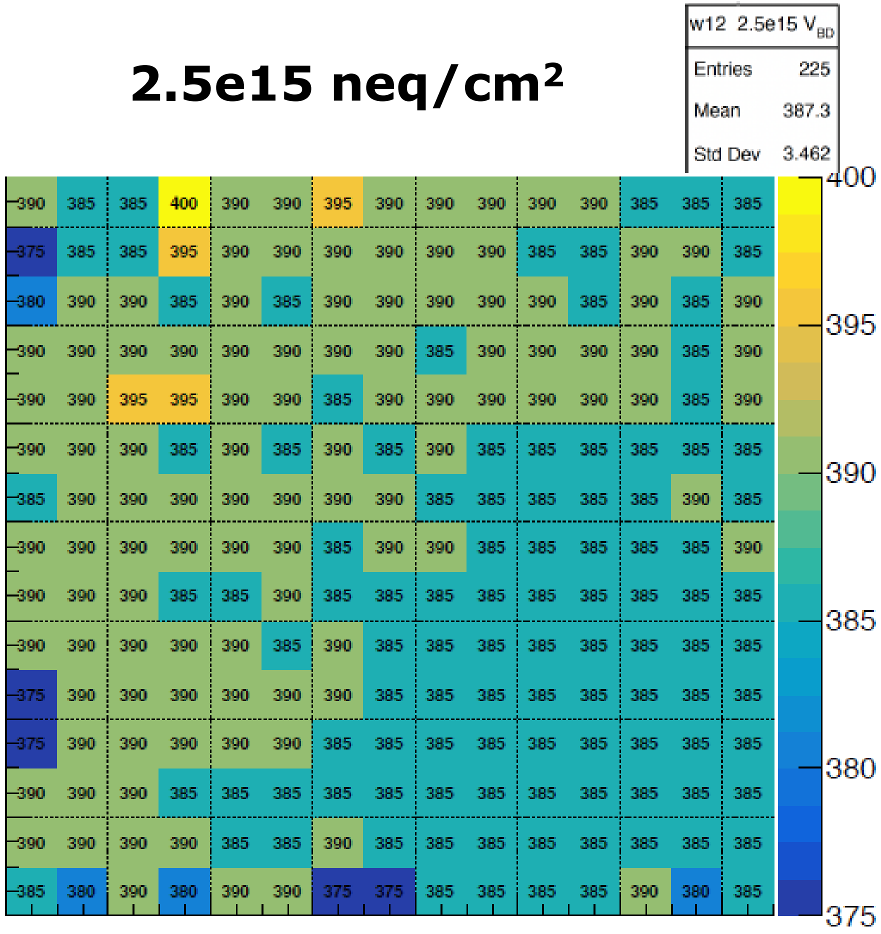
- Good consistency of IV for the 15x15 sensors
- Before irradiation, smaller leakage current in V3
  - may caused by differences in fluence/accepter removal coefficients of V3 is larger than v2.

Breakdown Voltage of the IME version3 15 x 15

1e15 neq/cm²



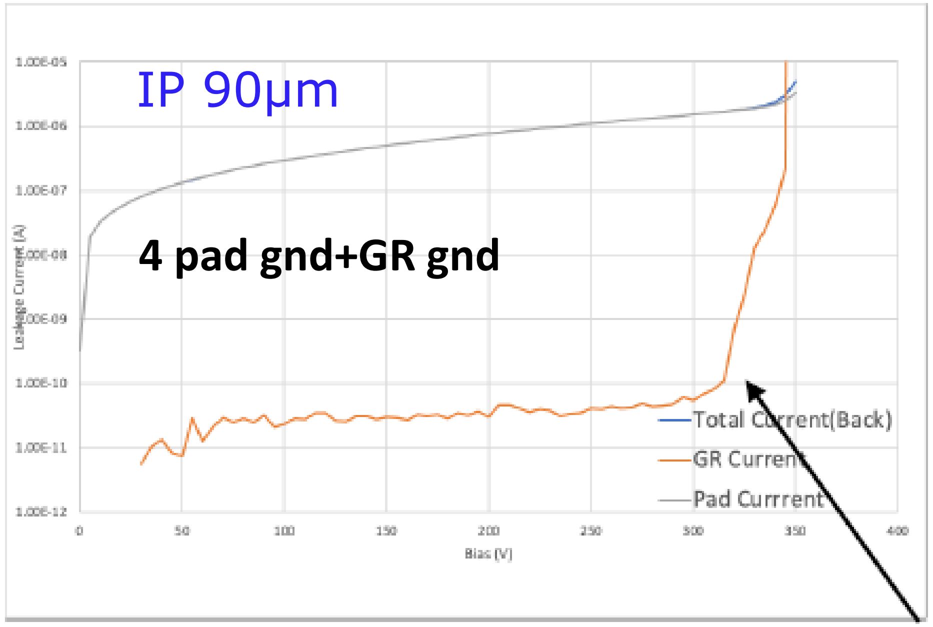
2.5e15 neq/cm²

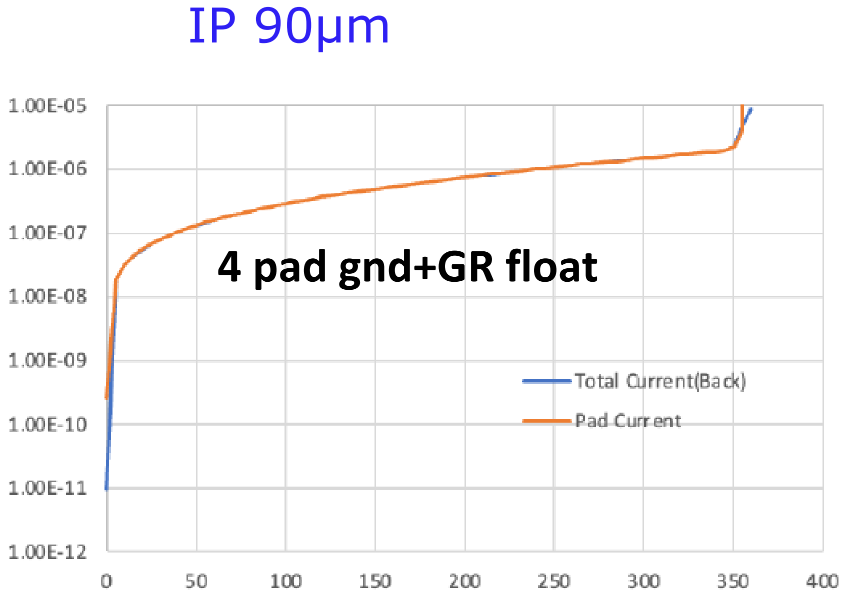


- **After irradiation, uniformity becomes better: std 4.5V -> 3.4V**
- **breakdown voltage decrease: 391V -> 387 V**

IV for Version3 W12 2x2

IV before irradiation for IP 90 μm





GR breakdown earier than pads. Vbd around 340V

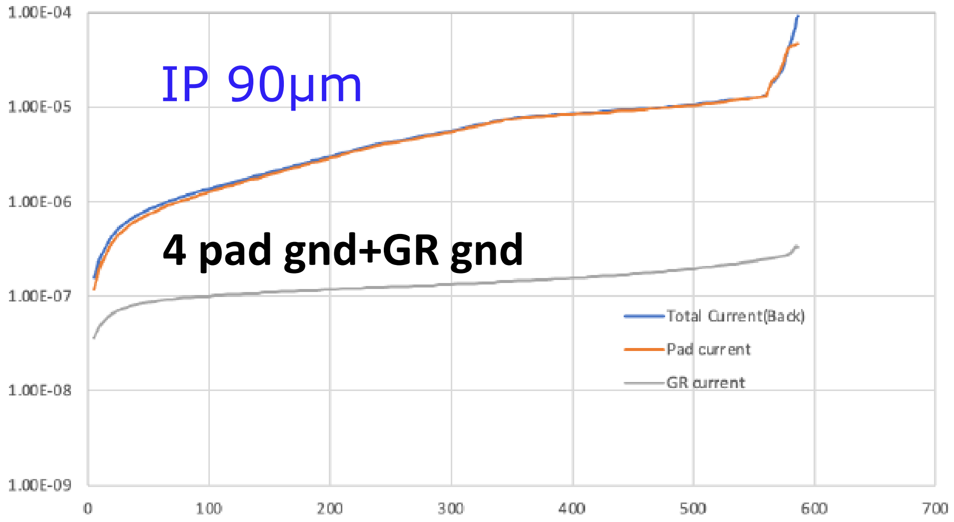
In these 2 configurations, the guard ring is gnd or float:

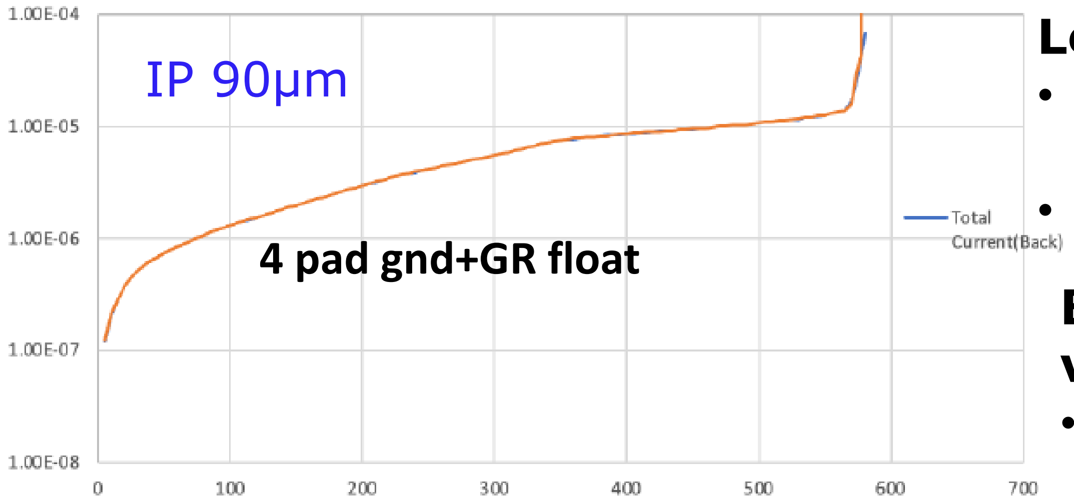
GR ground could reduce the breakdown voltage

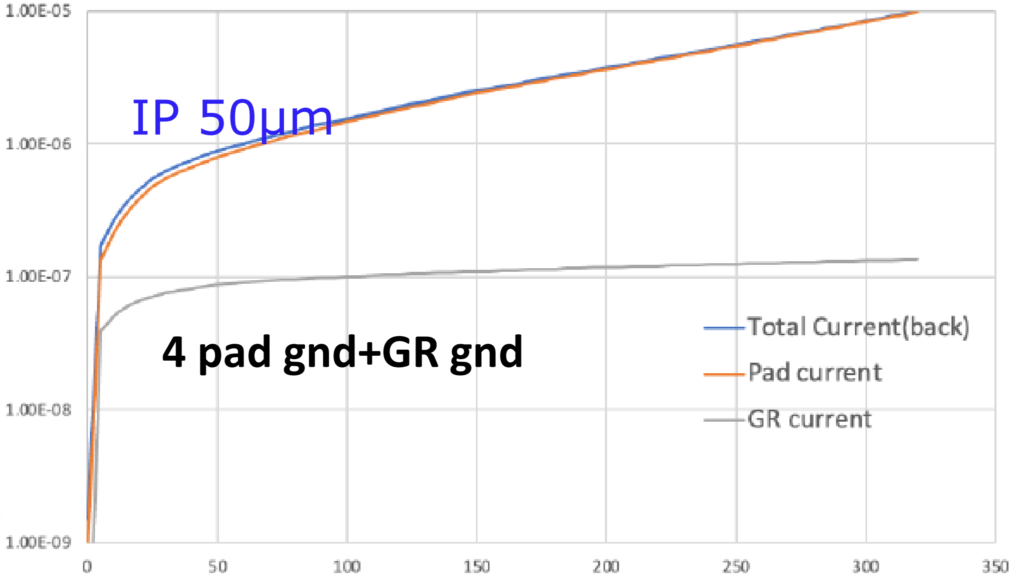
Vbd: **4 pad gnd+GR gnd (~340 V) < 4 pad gnd+GR float (~351 V)**

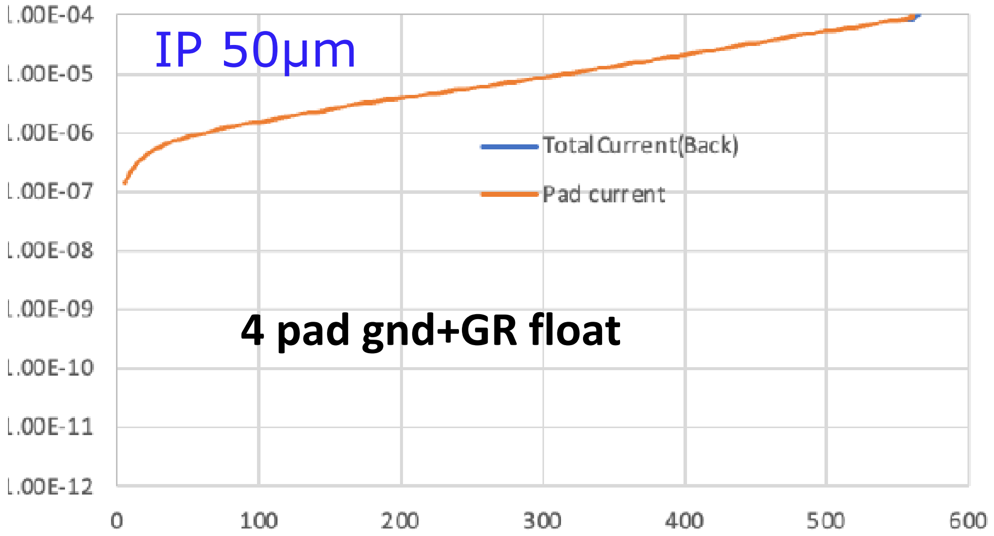
IV for V3 W12 2x2 with different IPs

IV after 2.5e15 neq/cm2 irradiation









Leakage current:
- increase about 10 times
- IP 50 **>** IP 90

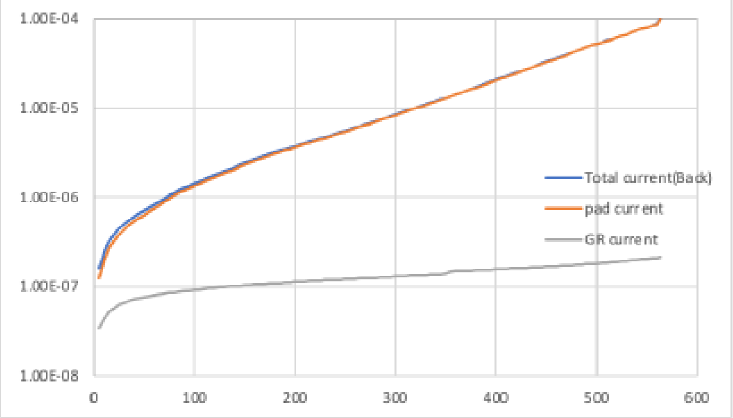
Breakdown voltage increase:
- IP 90:340 V-> 570 V
- IP 50: No obvious breakdown

In these 2 configurations, sensors breakdown near 570V. GR connections don't affect the Vbd.

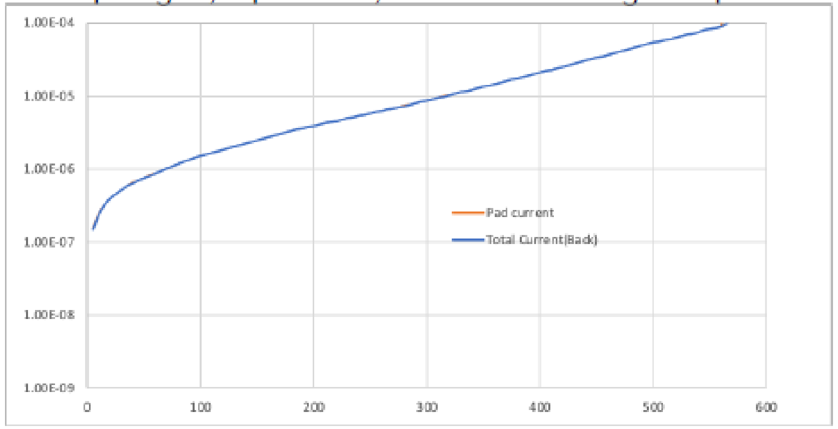
IV for V3 W12 2x2 with different IPs

IHEP-IME Version3 W12: **IP 50 μm after 2.5e15 neq/cm2 irradiation**

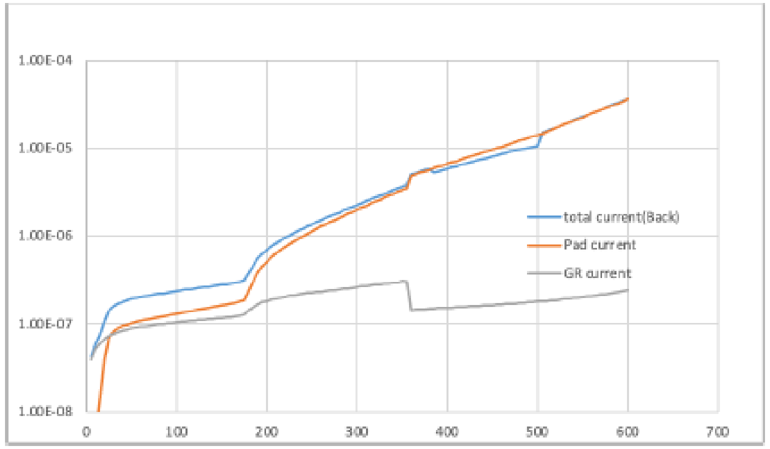
- 3pad gnd, 1 pad float, GR gnd signal:3 pad



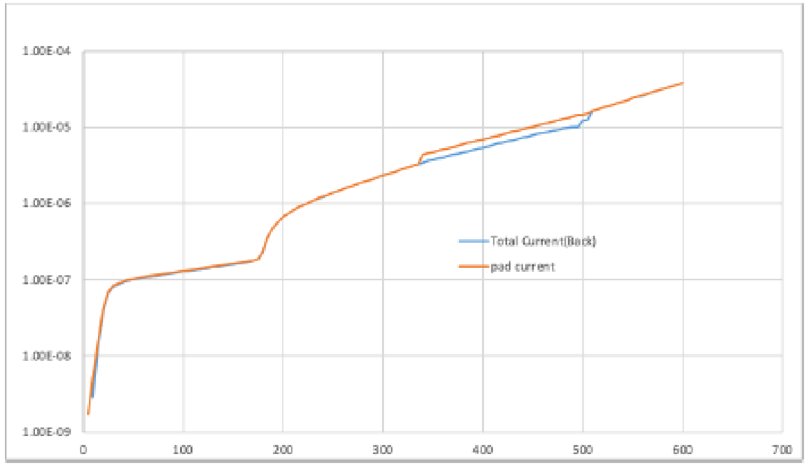
- 3pad gnd, 1 pad float, GR float signal:3 pad



- 3pad float, 1 pad gnd, GR gnd signal:1 pad



- 3pad float, 1 pad gnd, GR float signal:1 pad



- In the upper 2 conditions, sensors don't breakdown, similar to the last page when all 4 pads are GND.
- Soft breakdown was observed in the lower 2 conditions, when testing 1 pad with 3 pads floating.
- In the 3rd condition, both GR and pad current have a bump near 200V.

ATLAS EXPERIMENT

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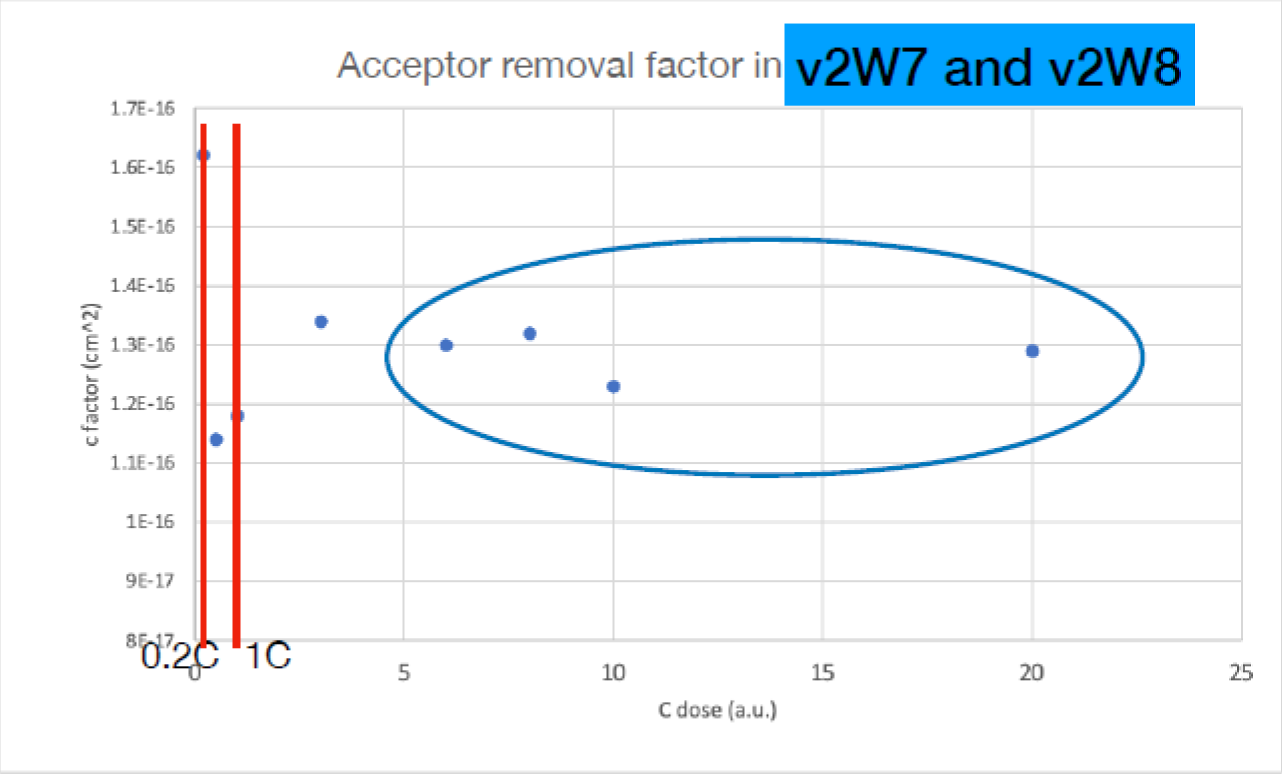
Acceptor removal factors of version3 with different carbon doses



IHEP_IMEv3 LGAD NEW deigns

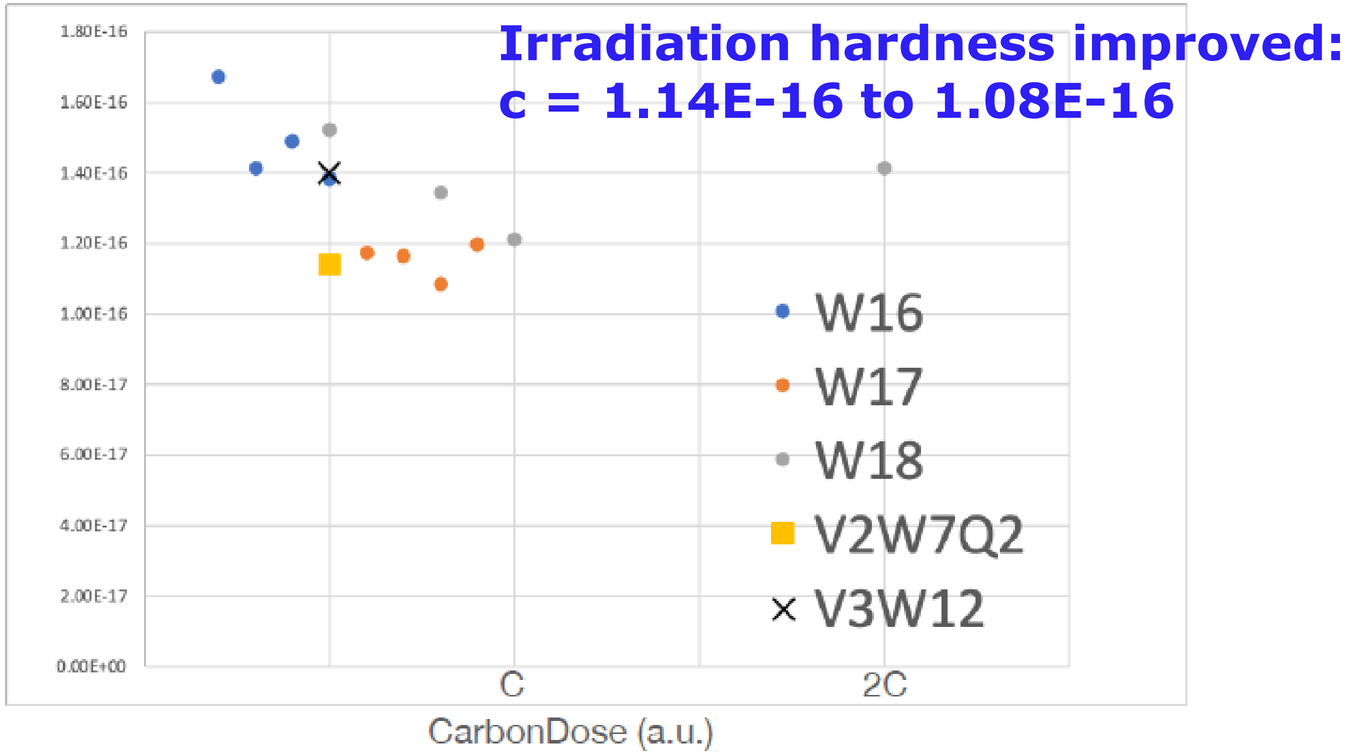
Sensor		Diffuse	C dose(a.u.)	
W15		CLBL	0.5	Different B dose
W16 W17	W16Q1	CHBL	0.2	Interpolate v2w7 to minimize the C factor.
	W16Q2		0.3	
	W16Q3		0.4	
	W16Q4		0.5	
	W17Q1		0.6	
	W17Q2		0.7	
	W17Q3		0.8	
	W17Q4		0.9	
W18		CMBL	0.5, 0.8, 1, 2	Change c thermal load

- 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.

Acceptor removal factors of version3 with different carbon doses

- **V3 W16 W17:** high carbon thermal load, shallow carbon penetration depth (same as V2W7 V2W8)
- **V3 W18**: median carbon thermal load, shallow carbon penetration depth
- Comparison: V3 W12, V3 W16 Q4 and V2W7Q2 (same design)

Carbon dose	type	C value
0.2C	W16_I	1.67E-16
0.3C	W16_II	1.41E-16
0.4C	W16_III	1.49E-16
0.5C	W16_IV	1.38E-16
0.6C	W17_I	1.17E-16
0.7C	W17_II	1.17E-16
0.8C	W17_III	1.08E-16
0.9C	W17_IV	1.20E-16
0.5C	W18_I	1.52E-16
0.8C	W18_II	1.34E-16
C	W18_III	1.21E-16
2C	W18_IV	1.41E-16



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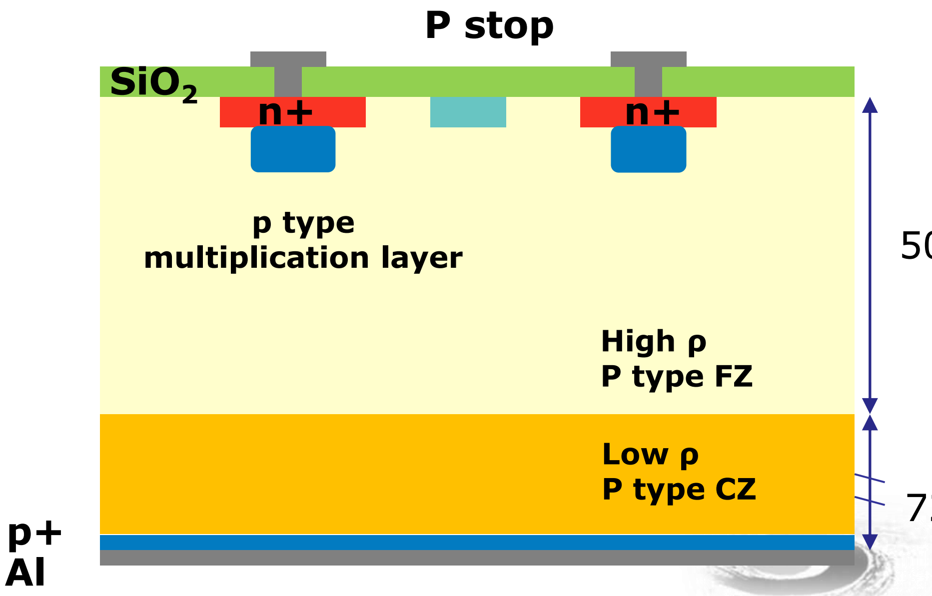
Total Ionization Dose of LGAD

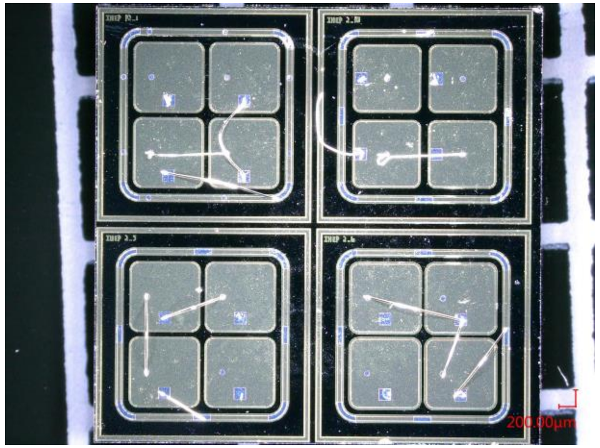
- **Study the TID damage of LGAD :**
  - optimize the design of LGAD surface properties such as the inter-pad distance and the gap between the active edge and the edge
  - Maximum the fill factor
- **Total ionizing dose experiment to study the TID: 2MGy**
  - surface damage at the SiO2 and the Si - SiO2 interface by inducing oxide charges and interface traps
  - Points defects in silicon sensors by Compton electrons and photoelectrons



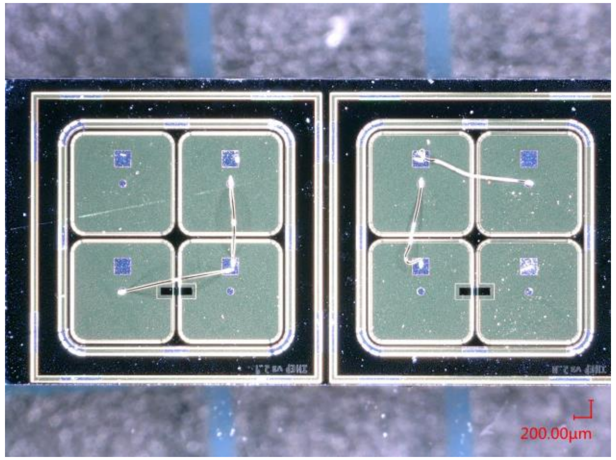
TID study of IHEP-IME version3/2 sensors

- **Quad LGADS with Shallow carbon were produced with six different inter-pad spacings (50 µm – 100 µm)**
  - IMEV3_2-5< IMEV3_2-6 < IMEV3_2-7 < IMEV3_2-8 < IMEV3_2-9 <IMEV3_2-10
- **Co60 irradiated up to 2 MGy**

IMEv2 W7 Q2
(most radiation
hardness)



IMEv3 W12



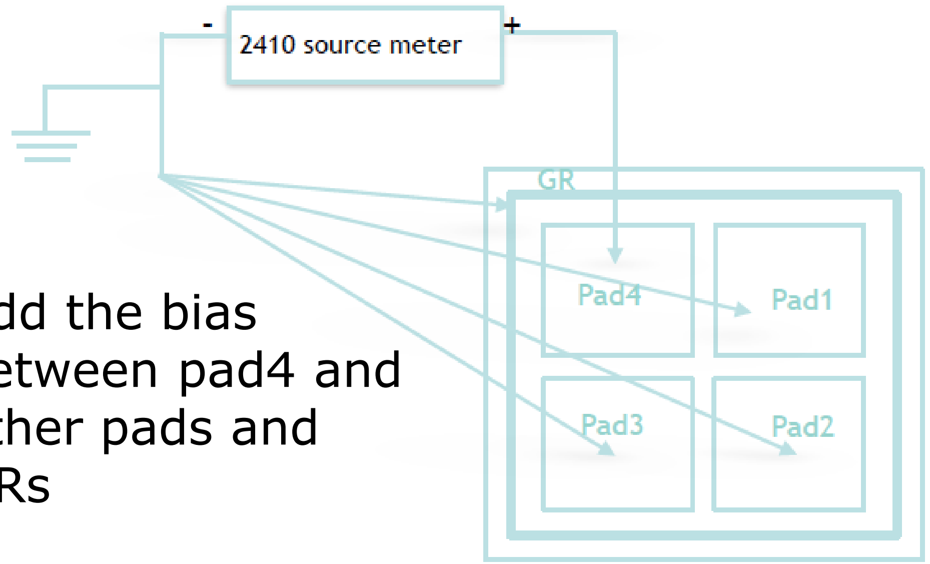
Cylinder Co60
source

Inter-pad R Measurement

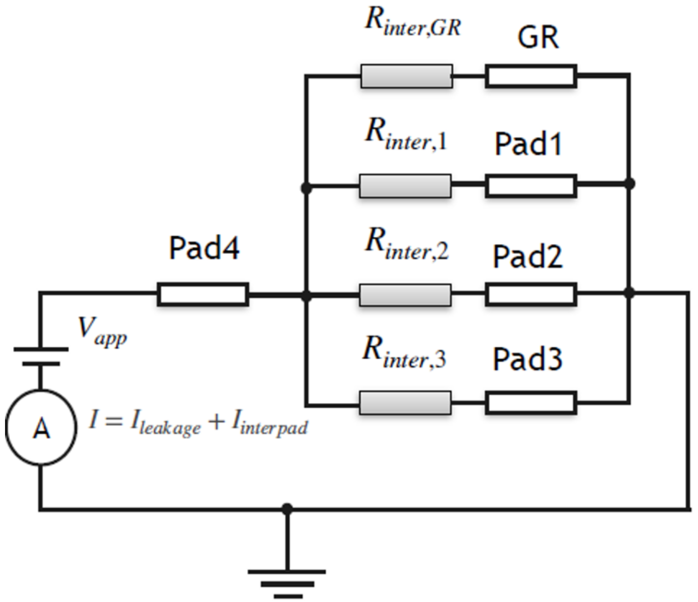
Apply the extra bias voltage ($\Delta\, U_i$) between the tested pads (pad4) and the other pads and GR while the sensor is biased on the backside with a bias voltage (U).

$$R_I \approx \frac{\Delta U_i}{\Delta I}$$

Δ I: $I_{Ui} - I_{Ui=0}$ the increase of the leakage current on pad4 while the bias voltage increase ,
$\Delta \boldsymbol{U_i}$: the change of biased voltage on pad4.
The pad1-3 and GR are grounded.

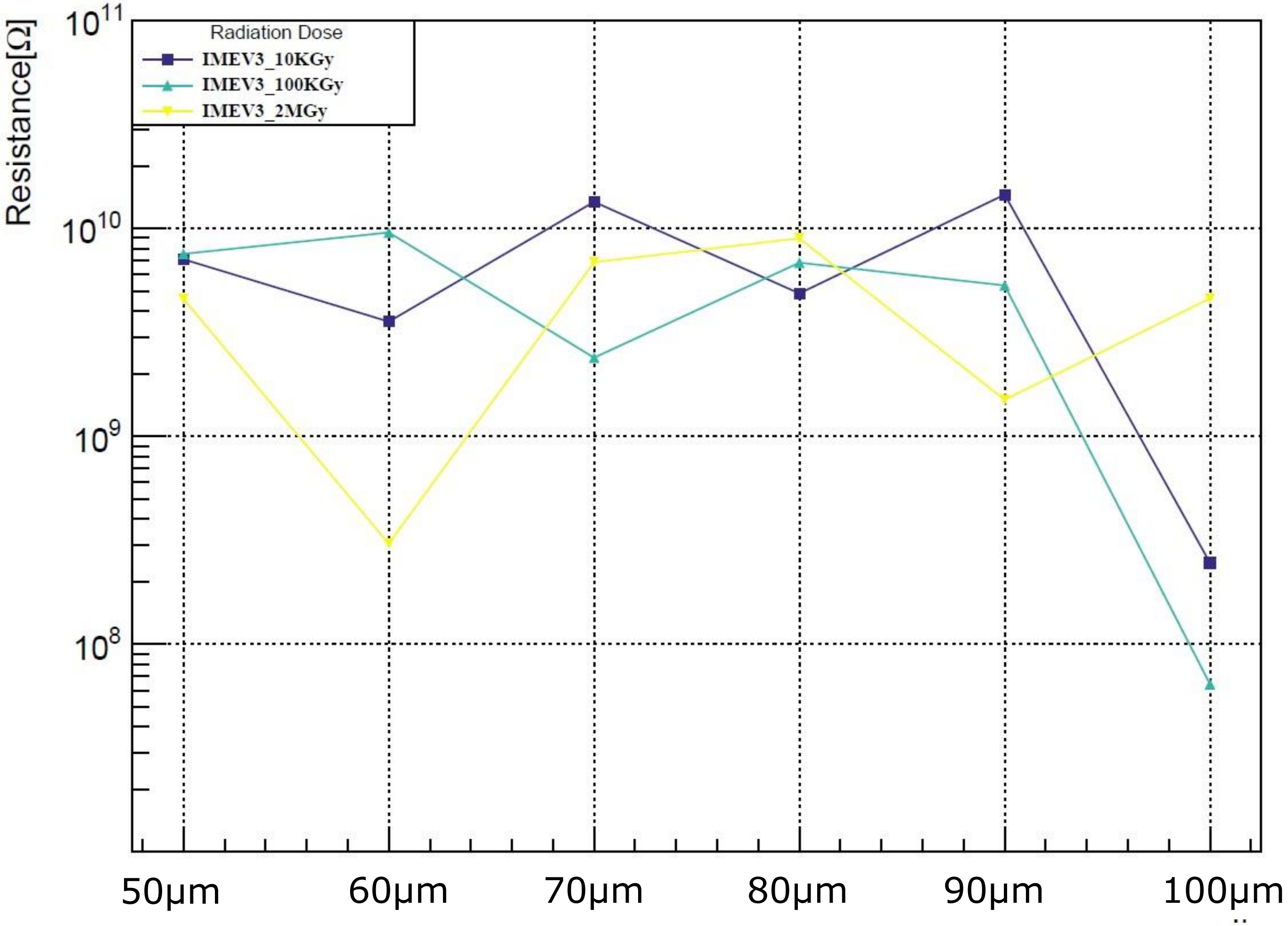


Add the bias between pad4 and other pads and GRs



Inter-pad R

The inter-pad resistance of IHEP-IME v3 sensors when Bias = 85 V



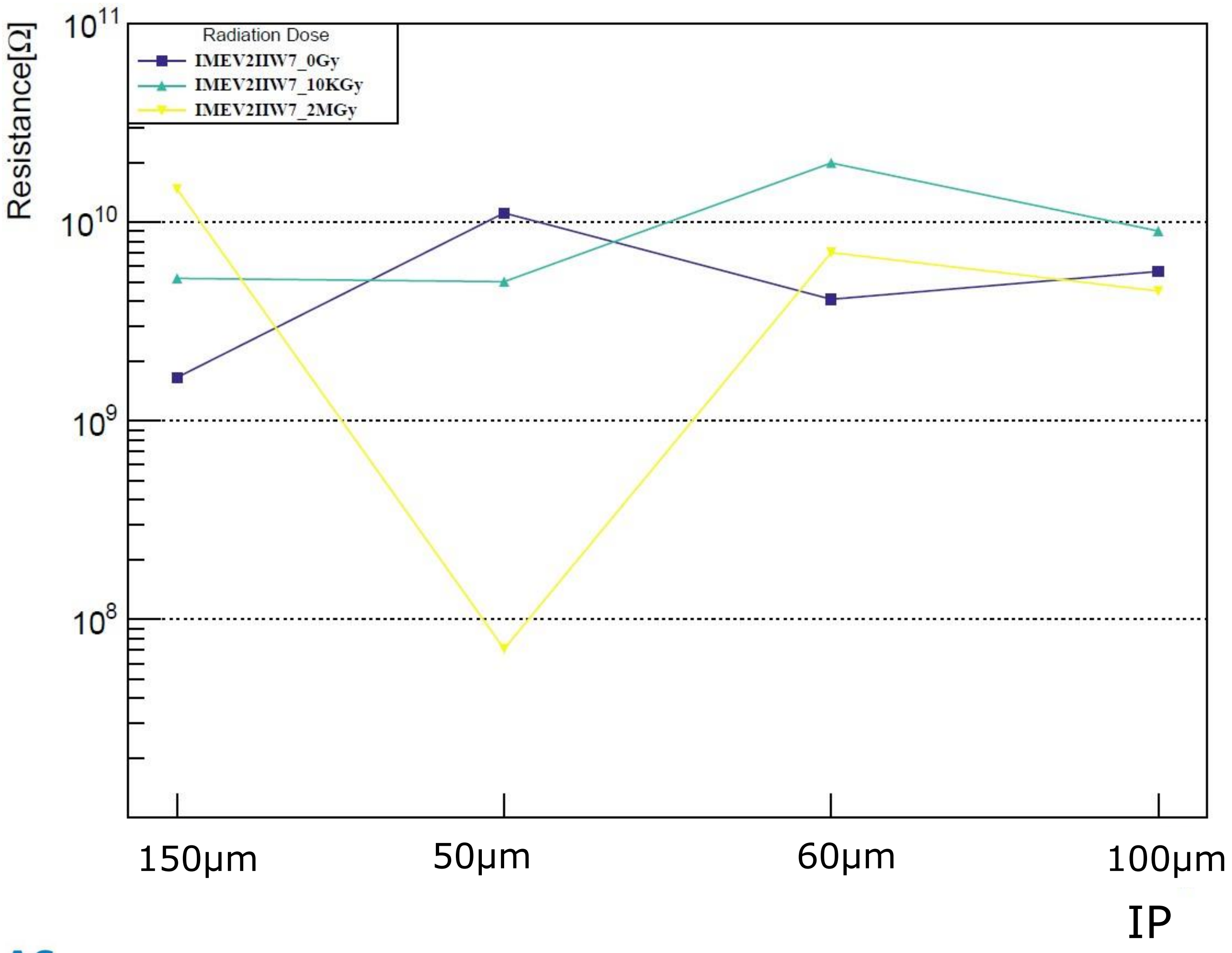
IMEV3_2-5, IMEV3_2-6, IMEV3_2-7, IMEV3_2-8 , IMEV3_2-9, IMEV3_2-10

10 MΩ < R after 2 MGy irradiation

No regular pattern was observed. Will study the reason further.

Inter-pad R

The inter-pad resistance of IHEP-IME v2 W7 sensors when Bias = 85 V

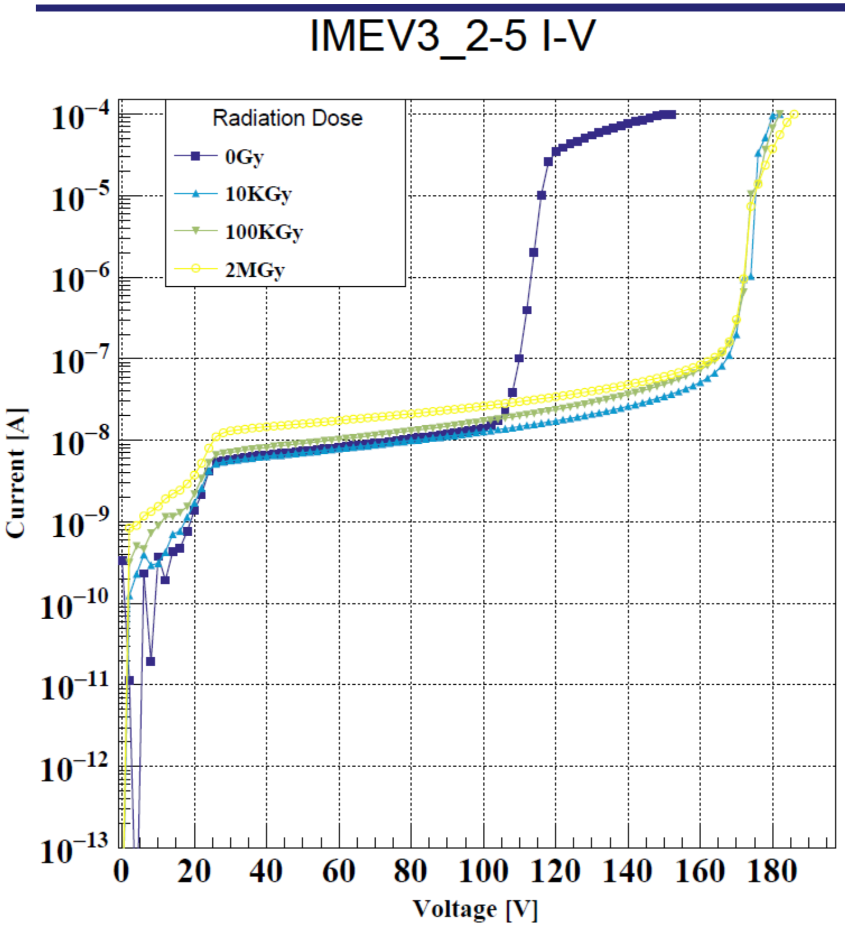


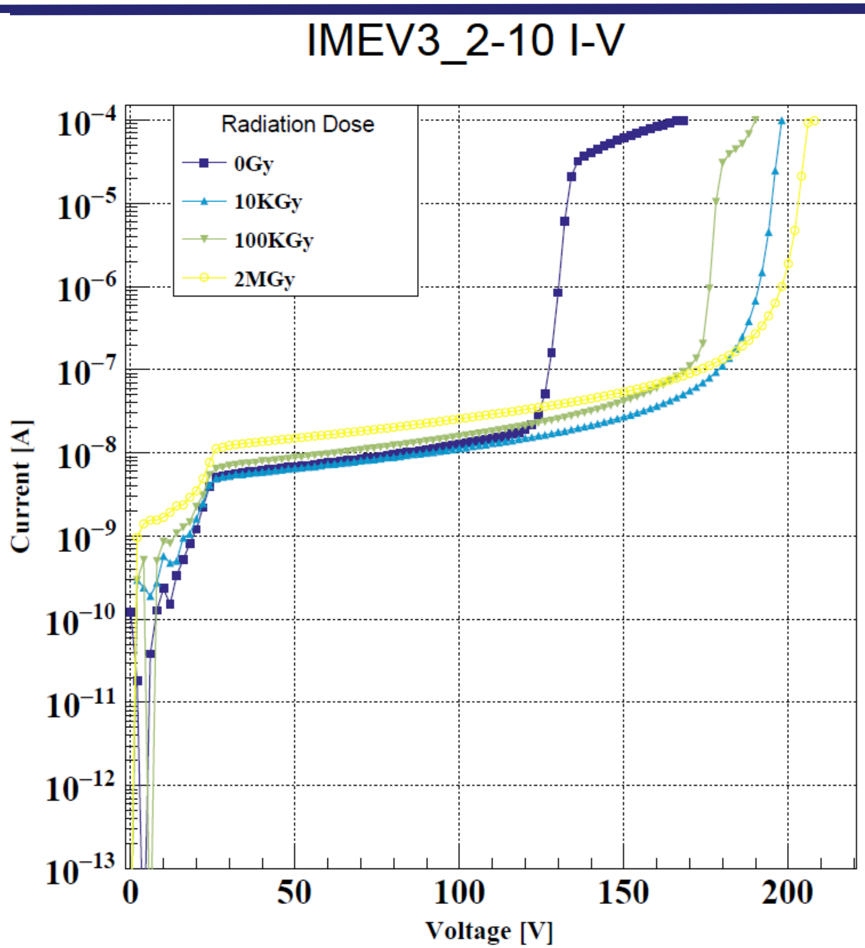
IMEV2_2-1, IMEV2_2-5
IMEV2_2-6, IMEV2_2-10

10 MΩ < R after 2 MGy irradiation

No regular pattern was observed. Will study the reason further.

IV of IHEP-IME v3





IV test setup:
1 pad gnd+3 pad float+GR gnd

- Breakdown voltage: increase **60V-70V ⬆**
- The leakage currents of pad4 increase slightly with the increase of the TID dose

Summary

- **AC-LGAD：23ps, 15μm （better than FBK small pitch ）**
- **LGAD design**

Neutron irradiation for IHEP IME version3

- IME version 3 15x15 sensors showed good consistency of IME version 2 sensors.
- Different IPs affects the neutron irradiation performance.
- Different connecting configurations of 2x2 sensors with 90/50 μm IPs shows floating pads might cause early breakdown. （**need further study**）
- 0.8C W17_III showed the **smallest c value: 1.08E-16** , which is the same condition except the carbon dose.

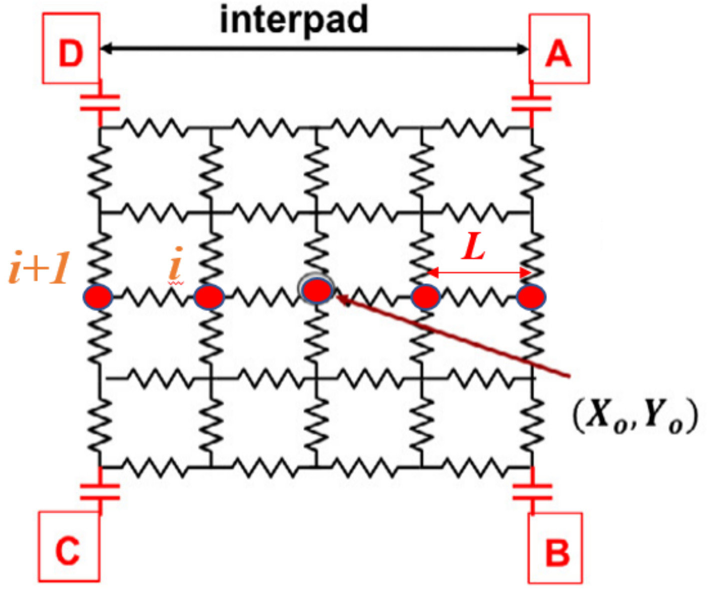
TID for IHEP IME version3

- **LGAD with shallow carbon， The interpad-R of IHEP-IME v2 W7 II is 1GΩ < R < 10 MΩ， and show excellent TID radiation hardness than the uncarbonated LGAD**
- **Larger IP resolution slightly affects the leakage current and the TID radiation hardness**

Thanks for your attention!

- **Back up**

The calculation of the timing and spatial resolution



$$X = X_0 + k_x\left(\frac{q_A + q_B - q_C - q_D}{q_A + q_B + q_C + q_D}\right) = X_0 + k_x m$$

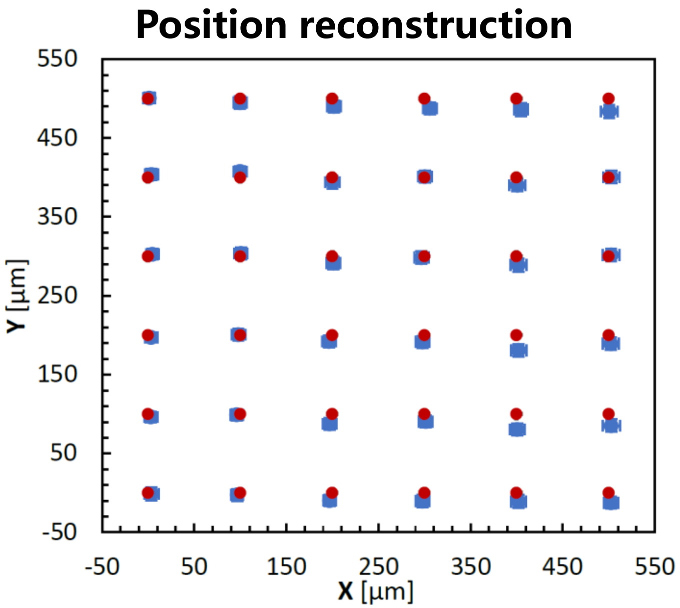
$$Y = Y_0 + k_y\left(\frac{q_A + q_D - q_B - q_C}{q_A + q_B + q_C + q_D}\right) = Y_0 + k_y n$$

$$k_x = L\frac{\sum(m_{i+1} - m_i)}{\sum(m_{i+1} - m_i)^2} \qquad k_y = L\frac{\sum(n_{i+1} - n_i)}{\sum(n_{i+1} - n_i)^2}$$

Discretized Positioning Circuit model (DPC)

- **Assuming resistan**

Position reconstruction with the center mass method



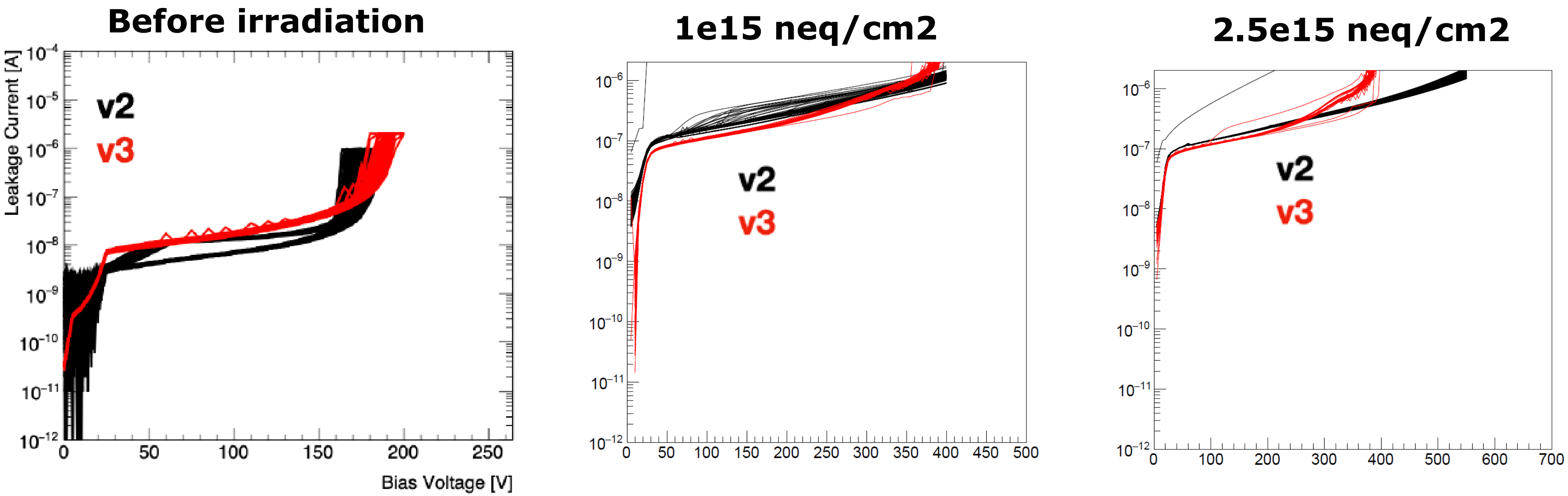
Spatial resolution

$$\sigma^2_{spatial} = \sigma^2_{reconstruction} - \sigma^2_{platform}$$

Timing resolution：

$$\sigma_t = \sigma_{t1+t2+t3+t4}$$

Consistency of the 15x15 sensor for IHEP



- Good consistency of IV for the 15x15 sensors
- smaller leakage current in V3
- 20 ℃ (before irradiation), -30 ℃(after irradiation), 1 pad gnd others and GR floating

differences in fluence/accepter removal coefficients of V3 is larger than v2.

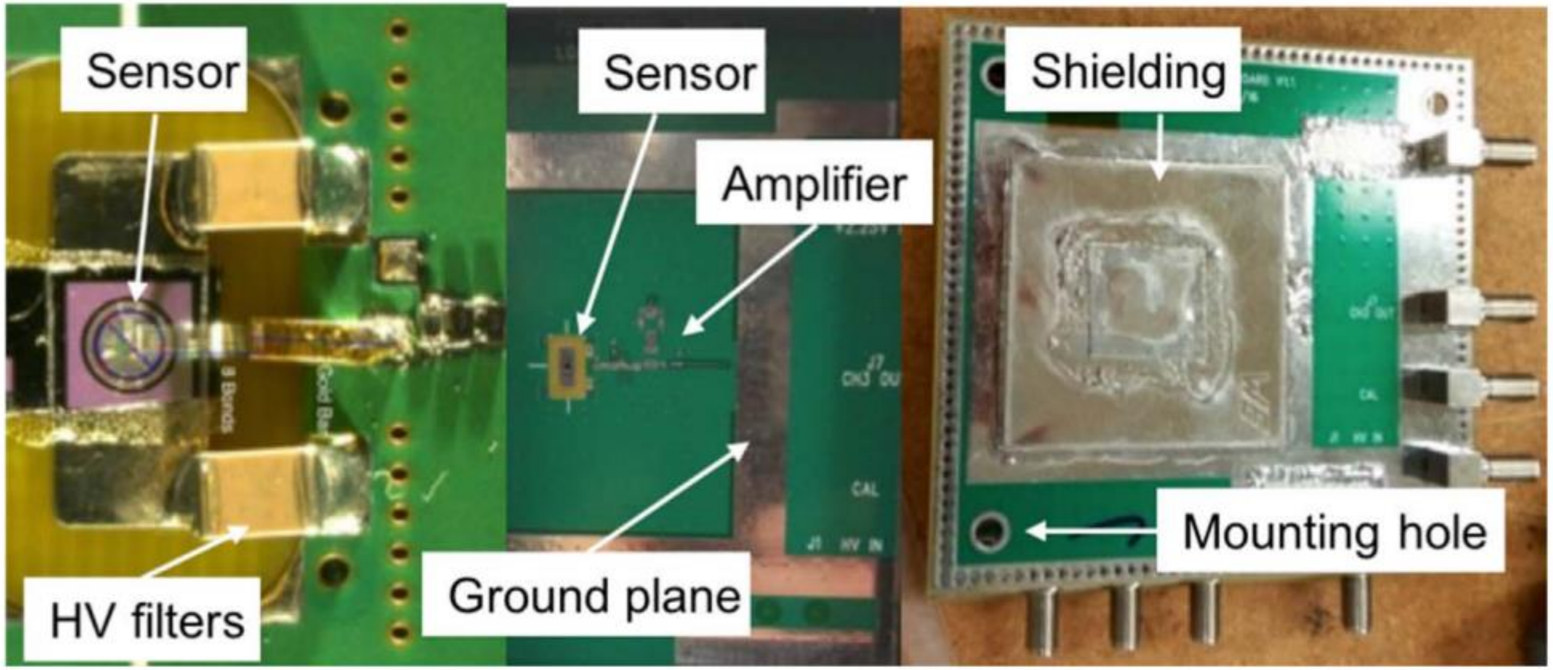


Fig. 2. Read-out board: connections to the UFSD (left), board without shielding (centre), board with shielding (right).