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Performance of IHEP-IME LGAD sensors before and after irradiation

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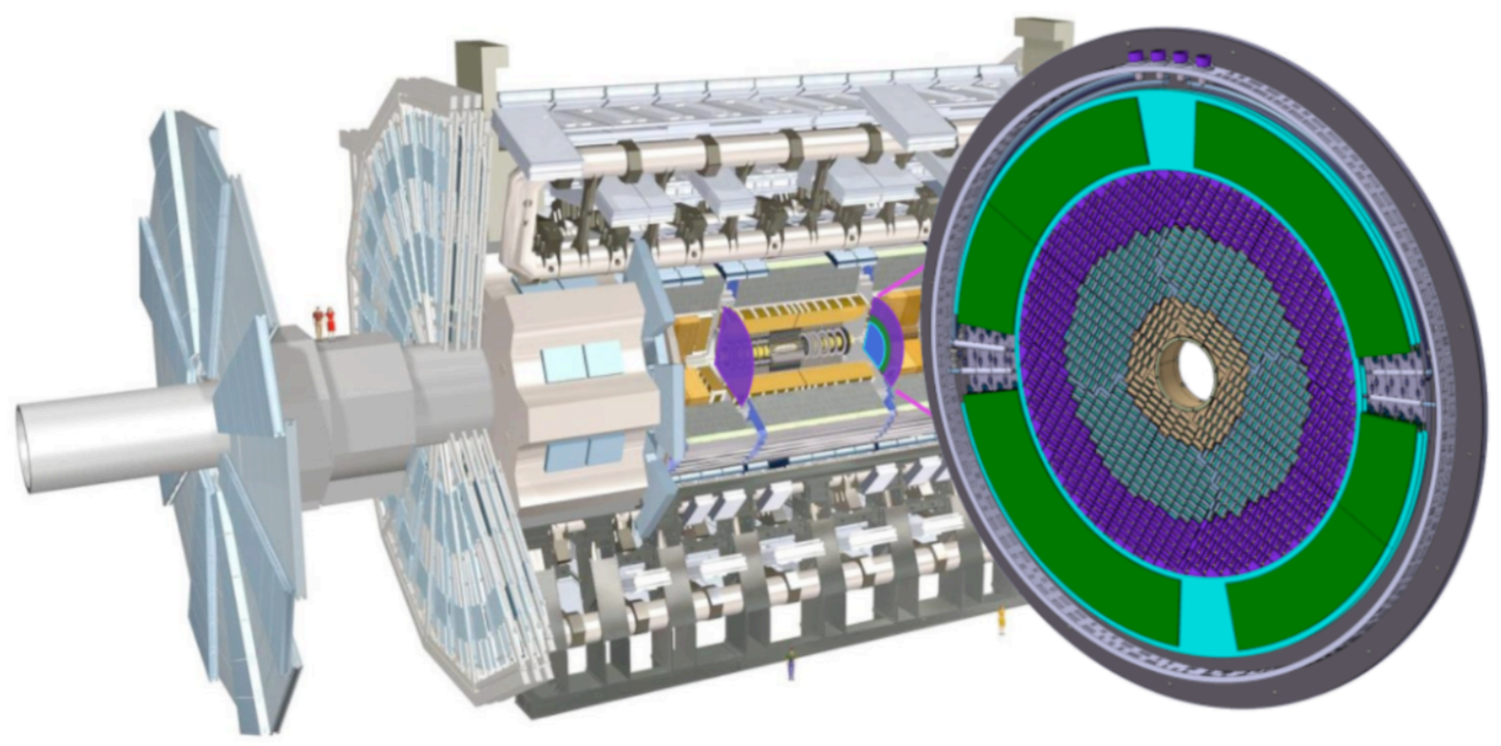
on behalf of IHEP HGTD sensor group
2022/06/23

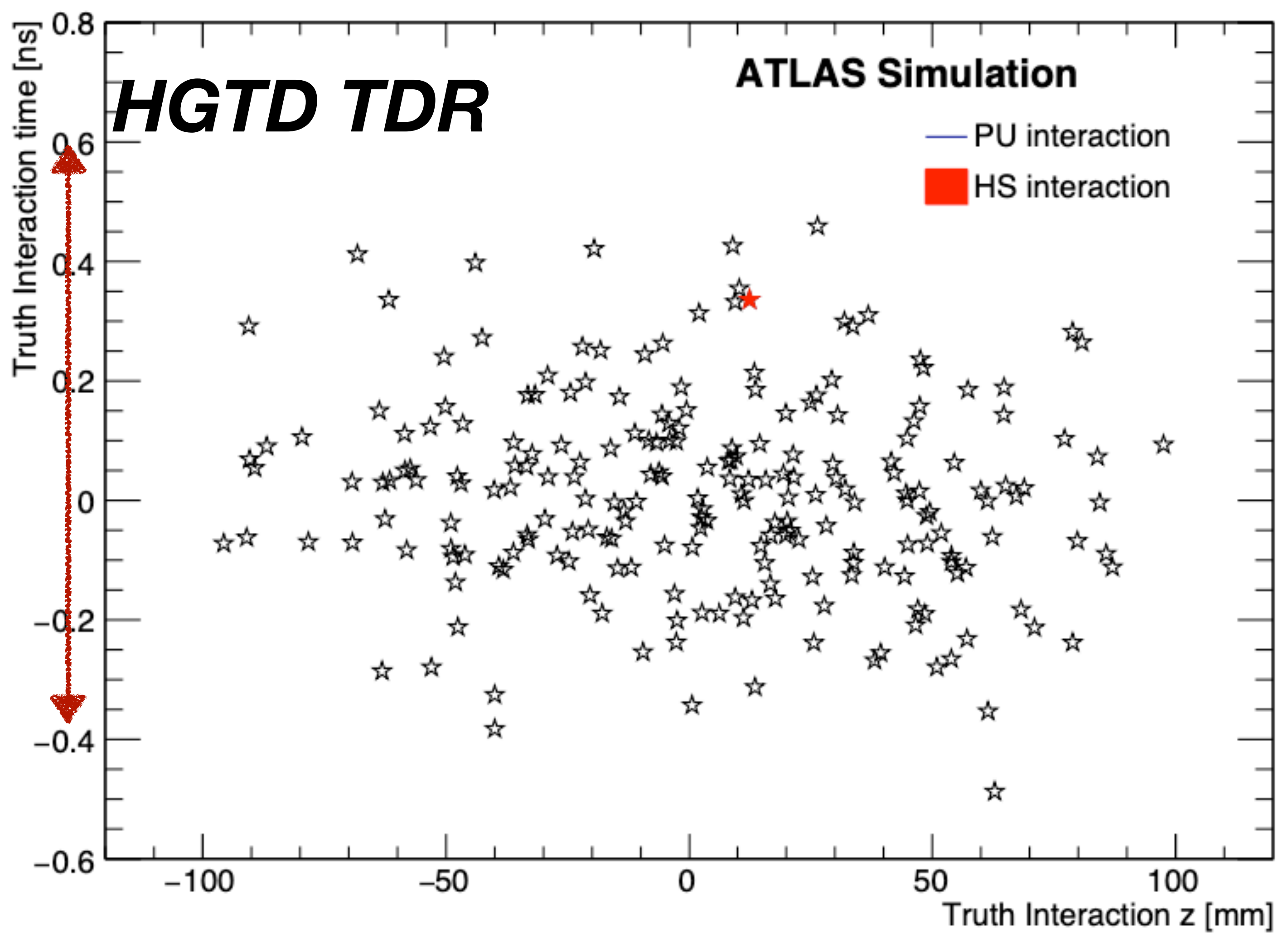
Outline

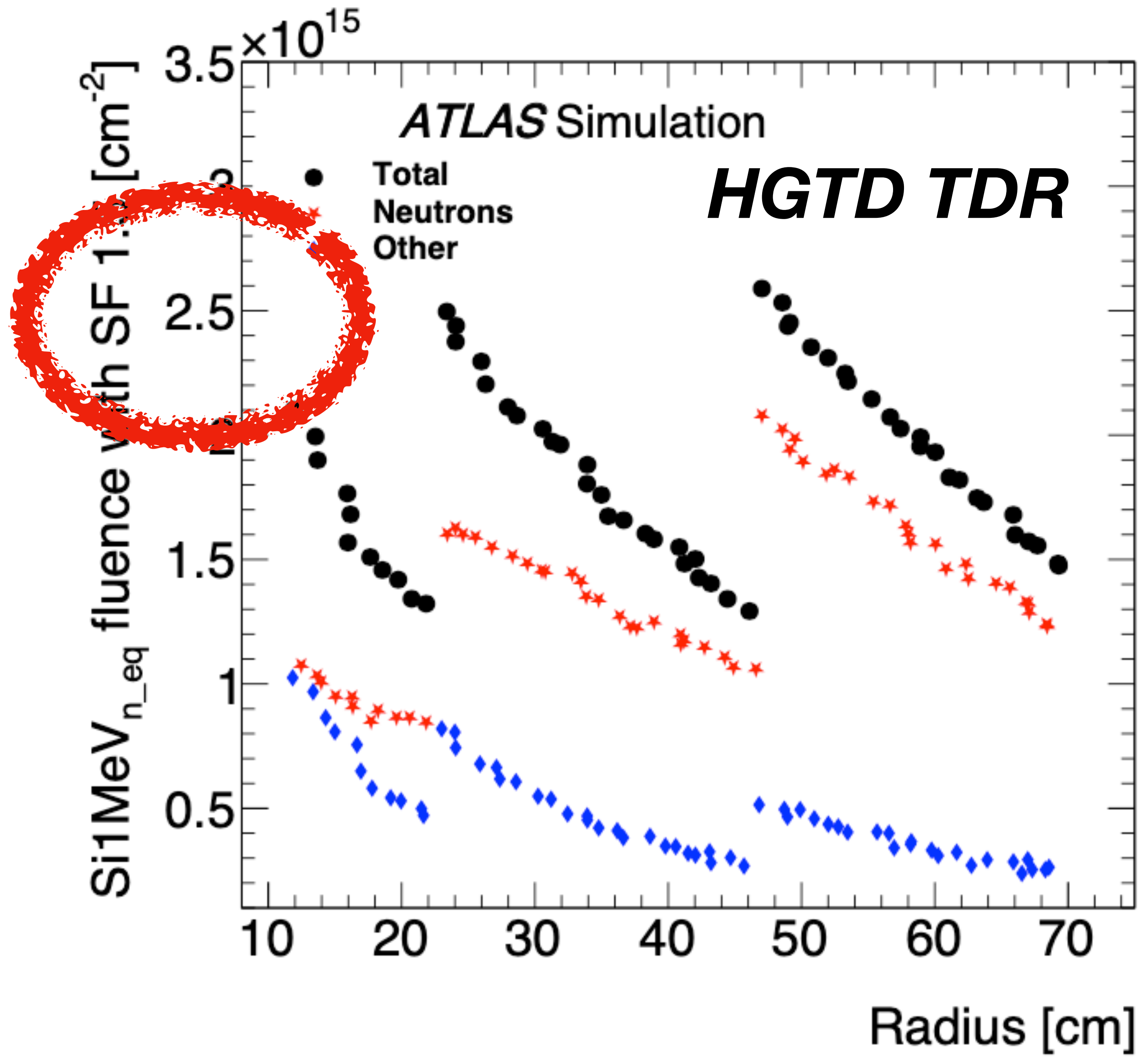
- 1. IHEP-IME LGAD for the ATLAS HGTD
- 2. IHEP-IME LGAD sensor performance
  - Before radiation
  - After radiation
- 3. Summary

HGTD introduction and sensor requirements

- High-Granularity Timing Detector (HGTD) : proposed for ATLAS phase II upgrade, to reduce the pile-up effect. Better time resolution to resolve primary vertex.
- Aiming at 30~50 ps per track.
- LGAD will be used as its sensing technology to provide the good time resolution, segmented into 1.3 × 1.3 mm^2 pads, with a total of 15x15 pads per sensor. The sensor need survive in high irradiation environment.







Introduction of IHEP-IME LGAD

- IHEP-IME: Designed by IHEP, fabricated by the Institute of Microelectronics of Chinese Academy of Sciences(IME) for the HGTD project
- So far three versions of IHEP-IME has been produced.
  - IHEP-IMEv1 was submitted in May 2020,

    finished in September
  - **IHEP-IMEv2** was produced in January 2021

    finished June 2021, outstanding results, especially on the radiation hardness.
  - IHEP-IMEv3 first batch was produced in March 2022, to further confirm and repeat what we achieved

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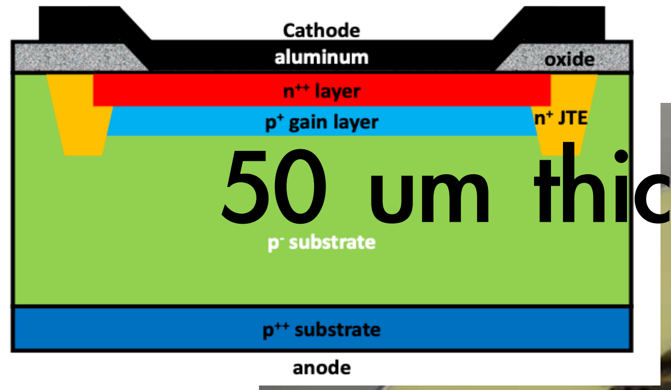
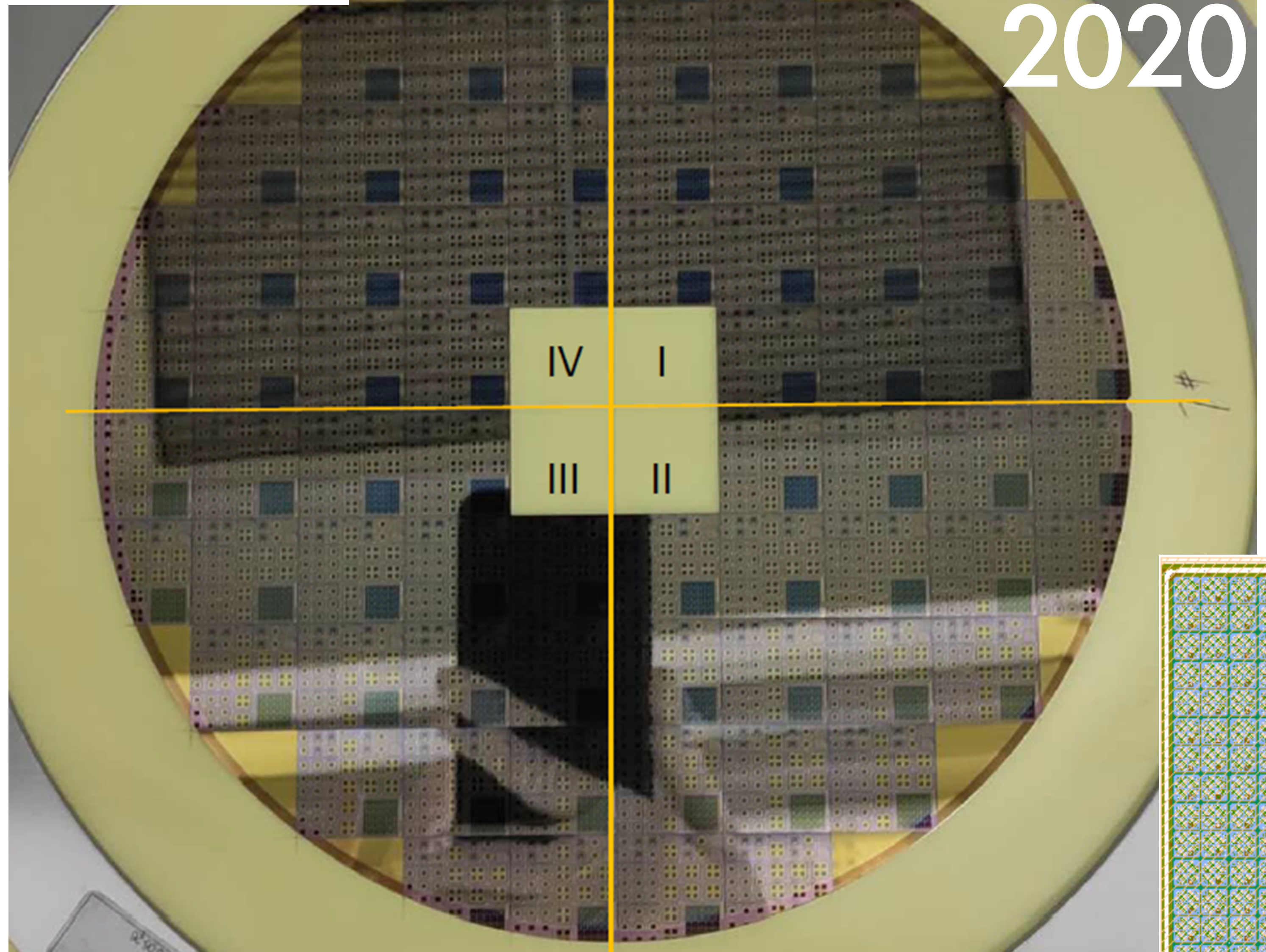
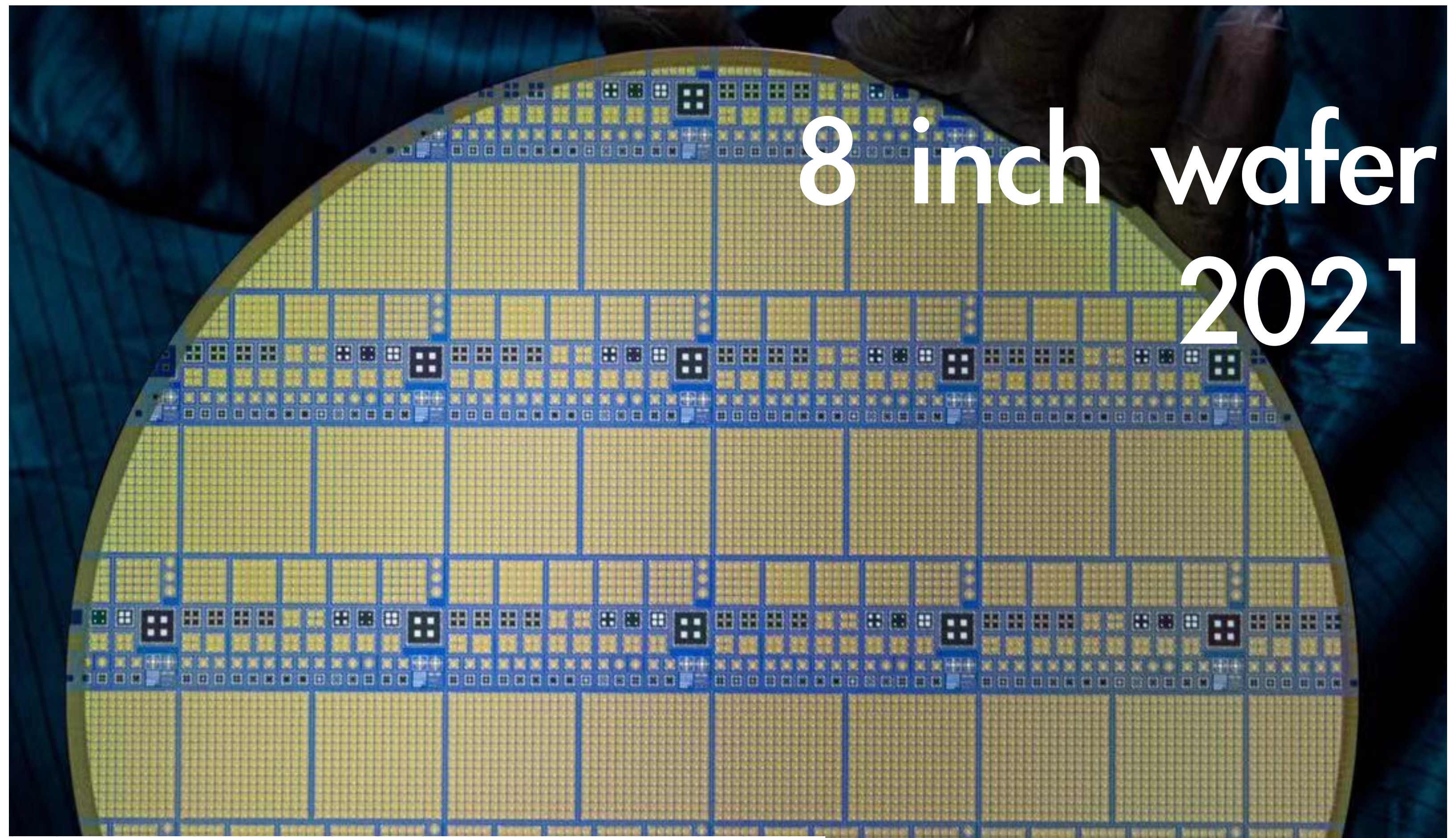
Introduction of IHEP-IME LGAD



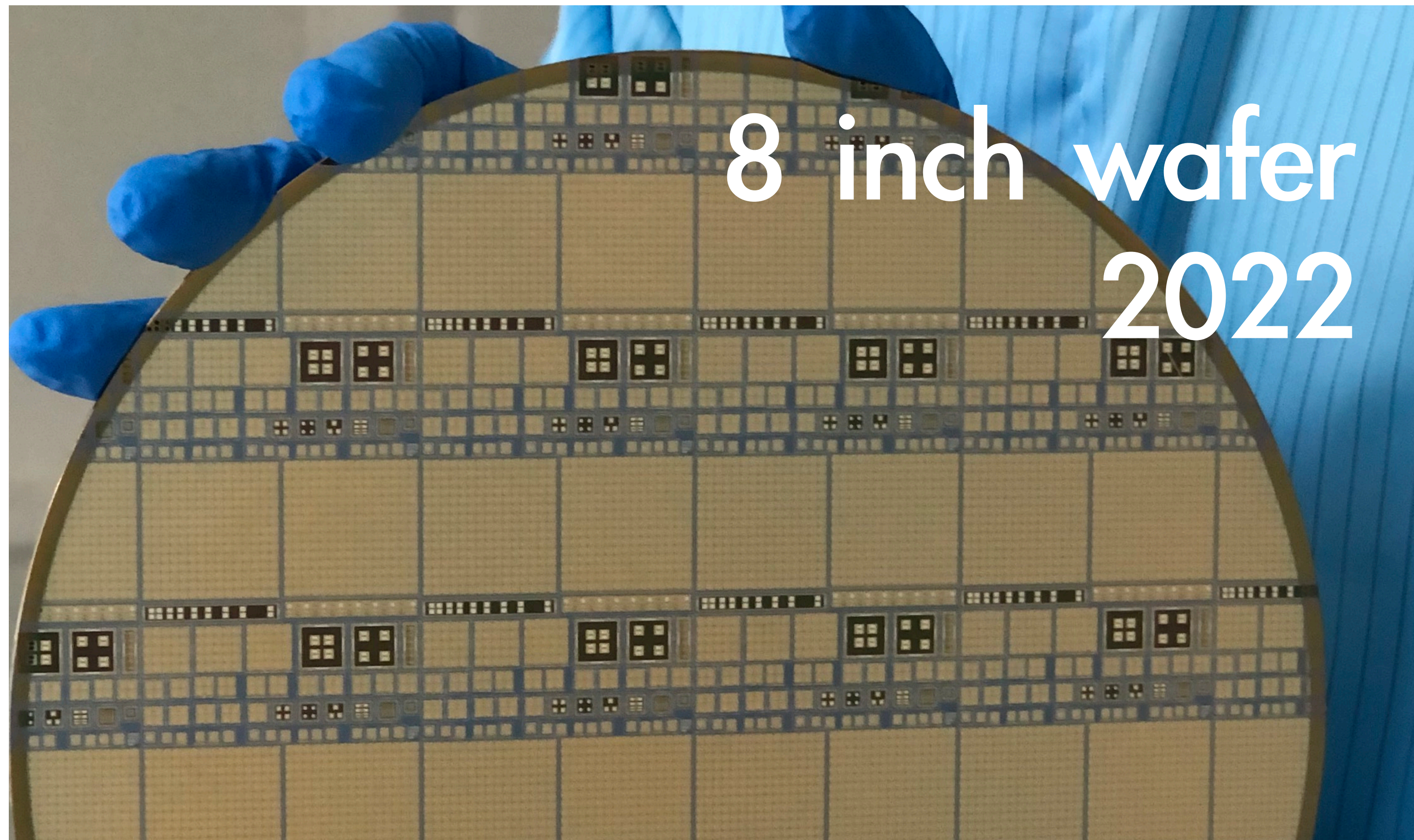
50 um thick LGAD



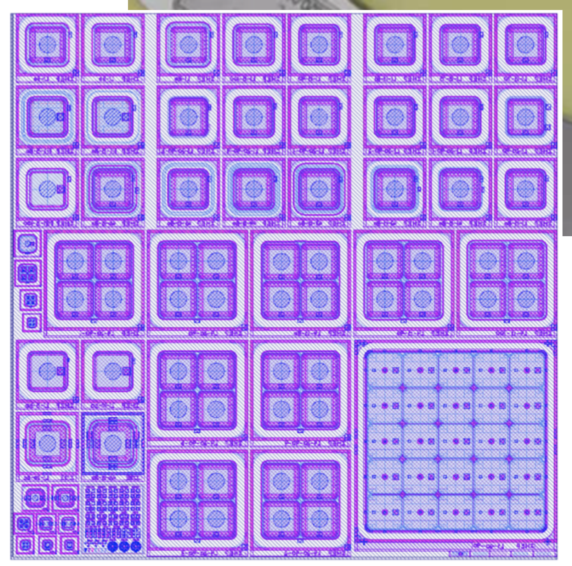
8 inch wafer
2020



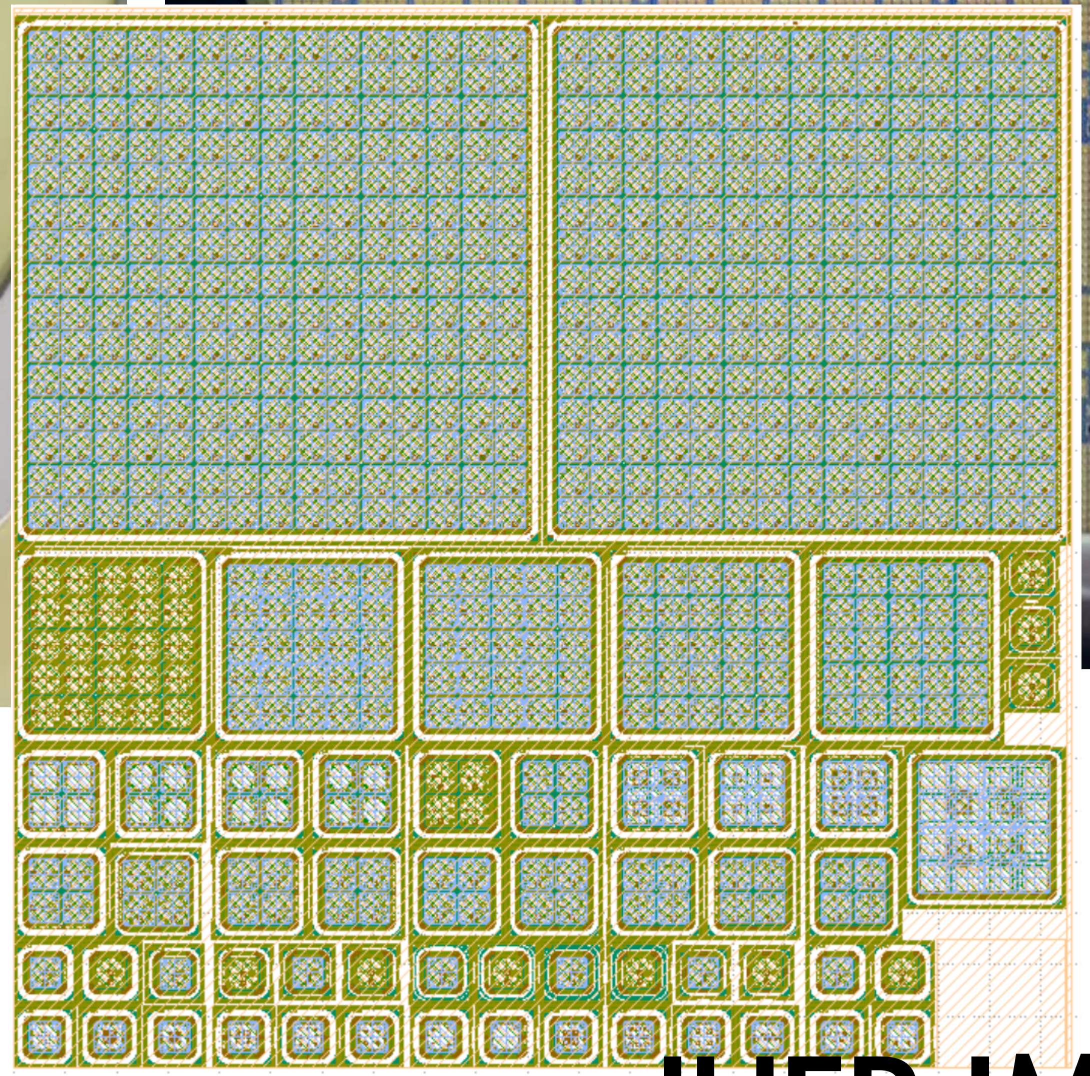
8 inch wafer
2021



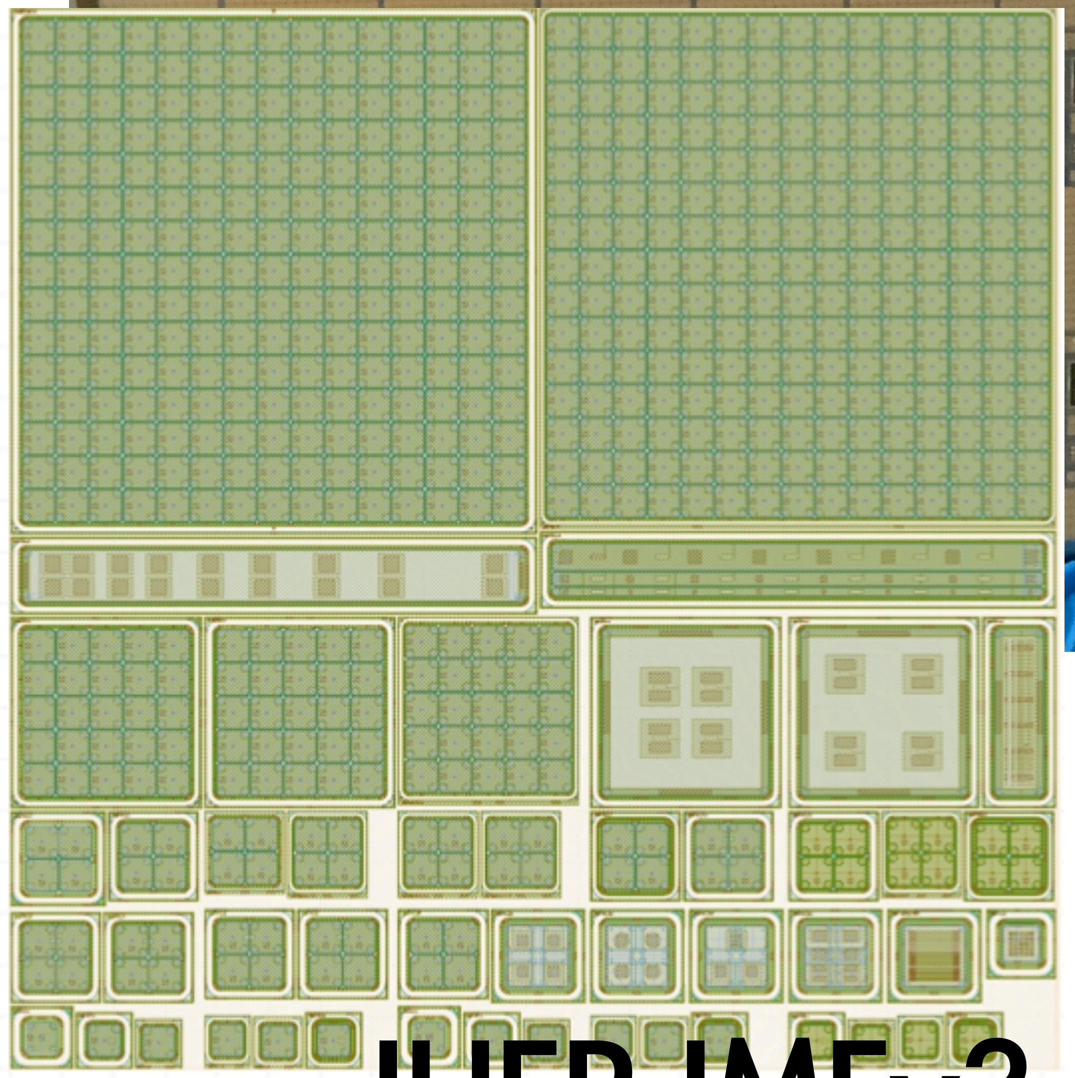
8 inch wafer
2022



IHEP-IMEv1 layout



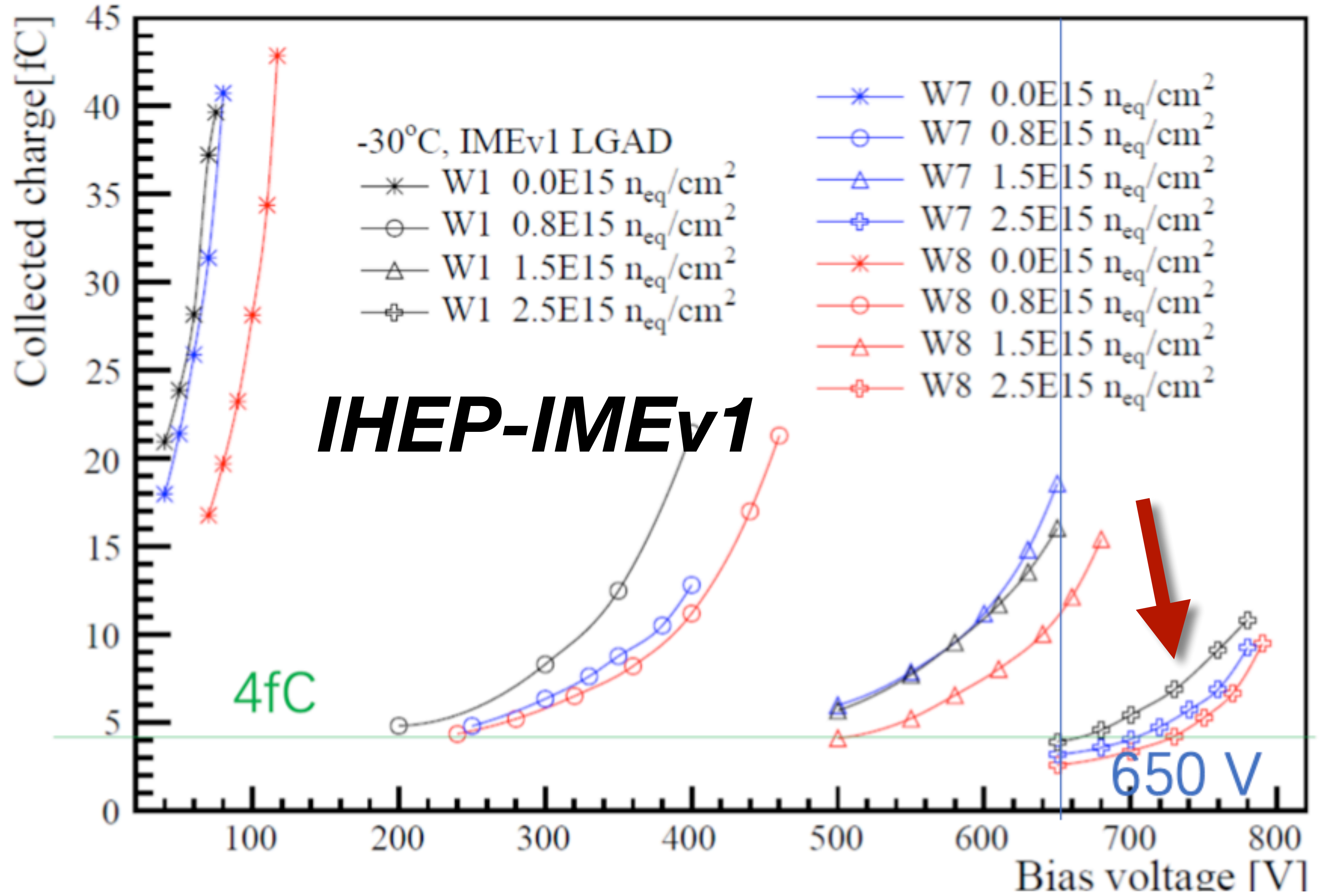
IHEP-IMEv2 layout



IHEP-IMEv3 layout

Carbon implantation

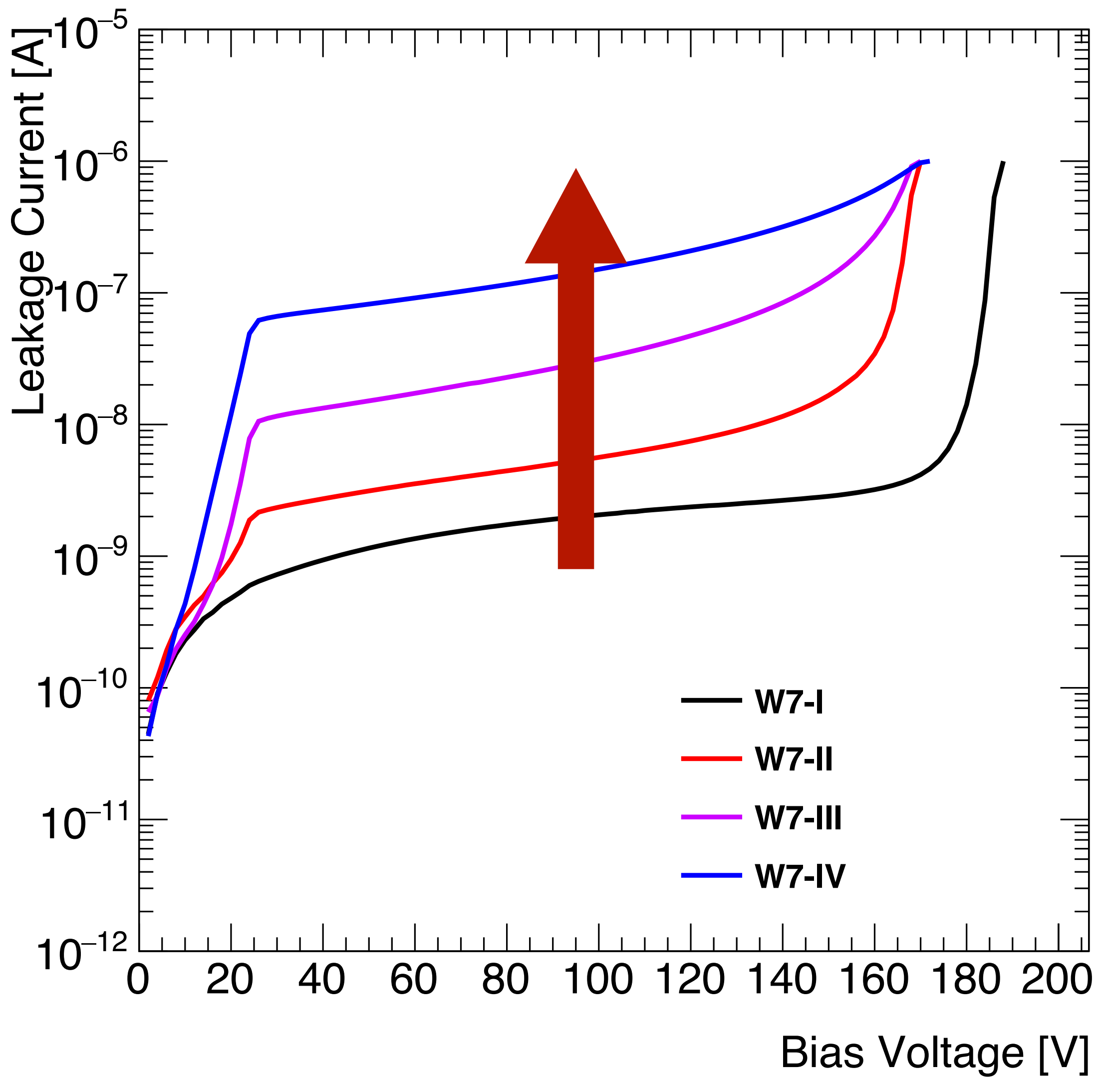
- In IHEP-IMEv1, Wafer 1 was implanted with carbon with low dose and low energy. Better radiation hardness observed than the ones without.
- In IHEP-IMEv2, various carbon dose and thermal process were studied to improve the sensors' radiation hardness.

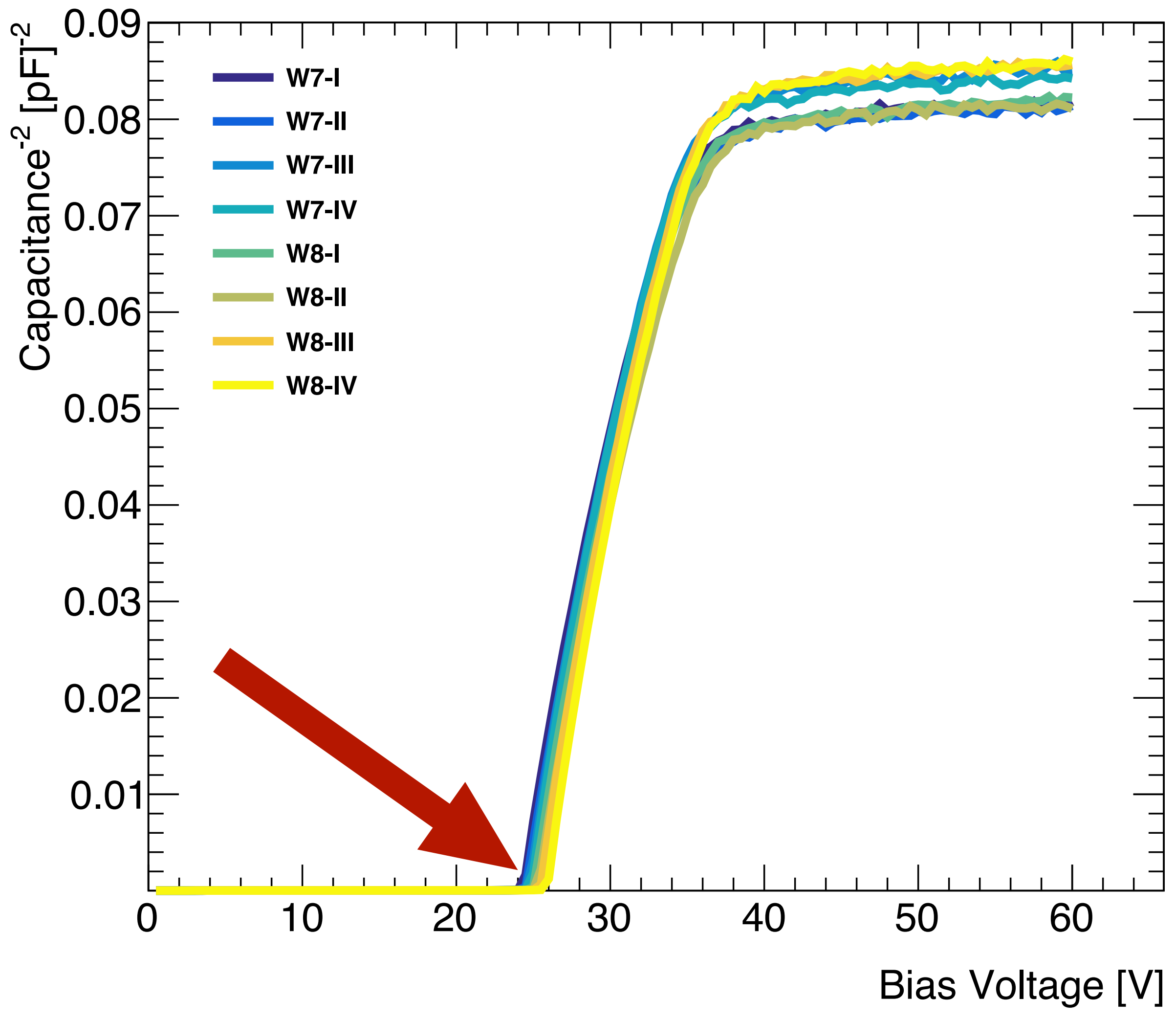


IHEP-IMEv2	I	II	III	IV
W4 (fast annealing)	0.2	1	5	10
W7 (long annealing)	0.2	0.5	1	3
W8 (long annealing)	6	8	10	20

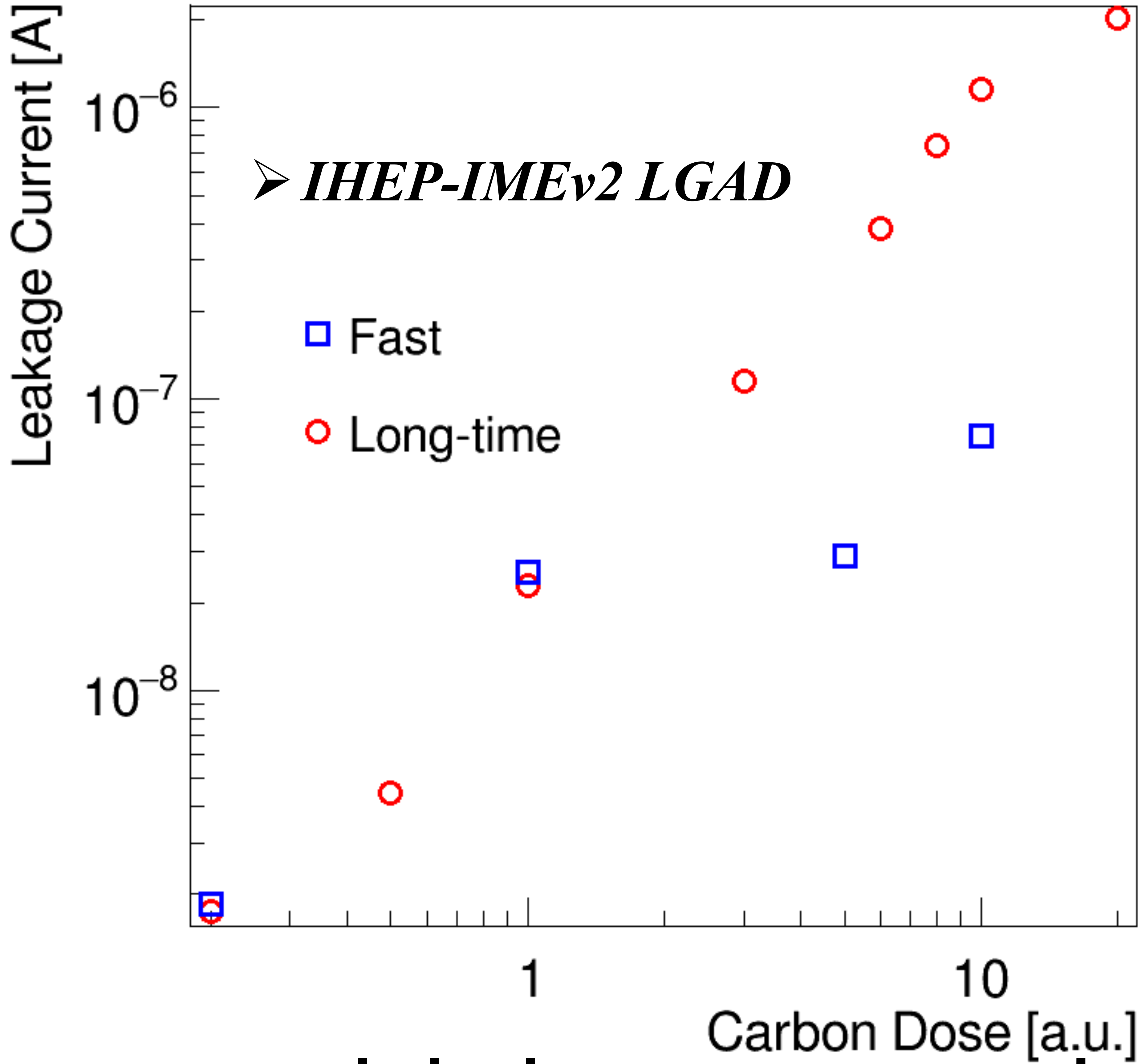
Carbon dose [a.u.] (noted as "C")

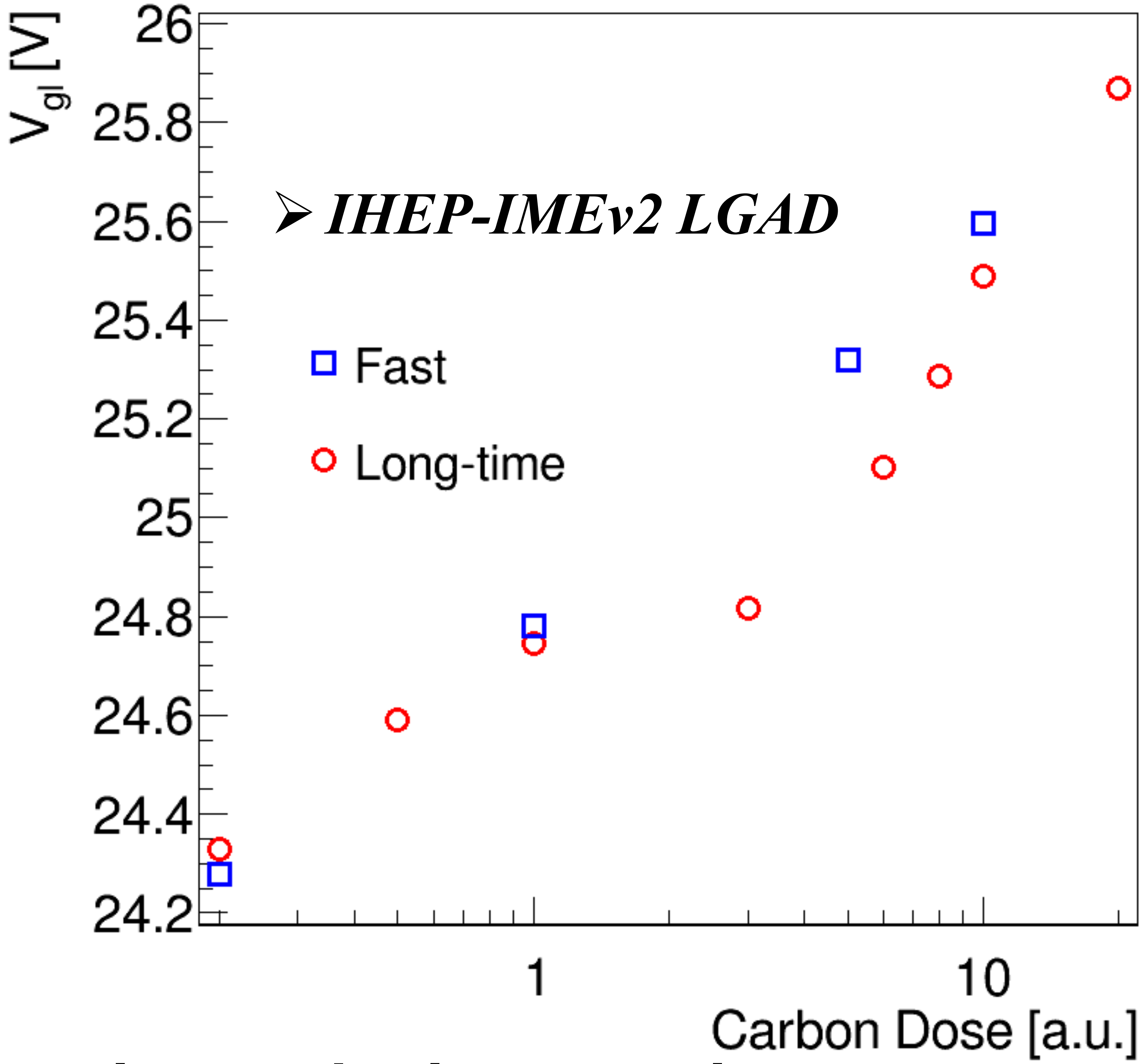
Before radiation – single pad





From single pad measurement with the same design.





Both <u>leakage current</u> and <u>gain layer depletion voltage</u> increase with the carbon dose.

Large array sensor before radiation

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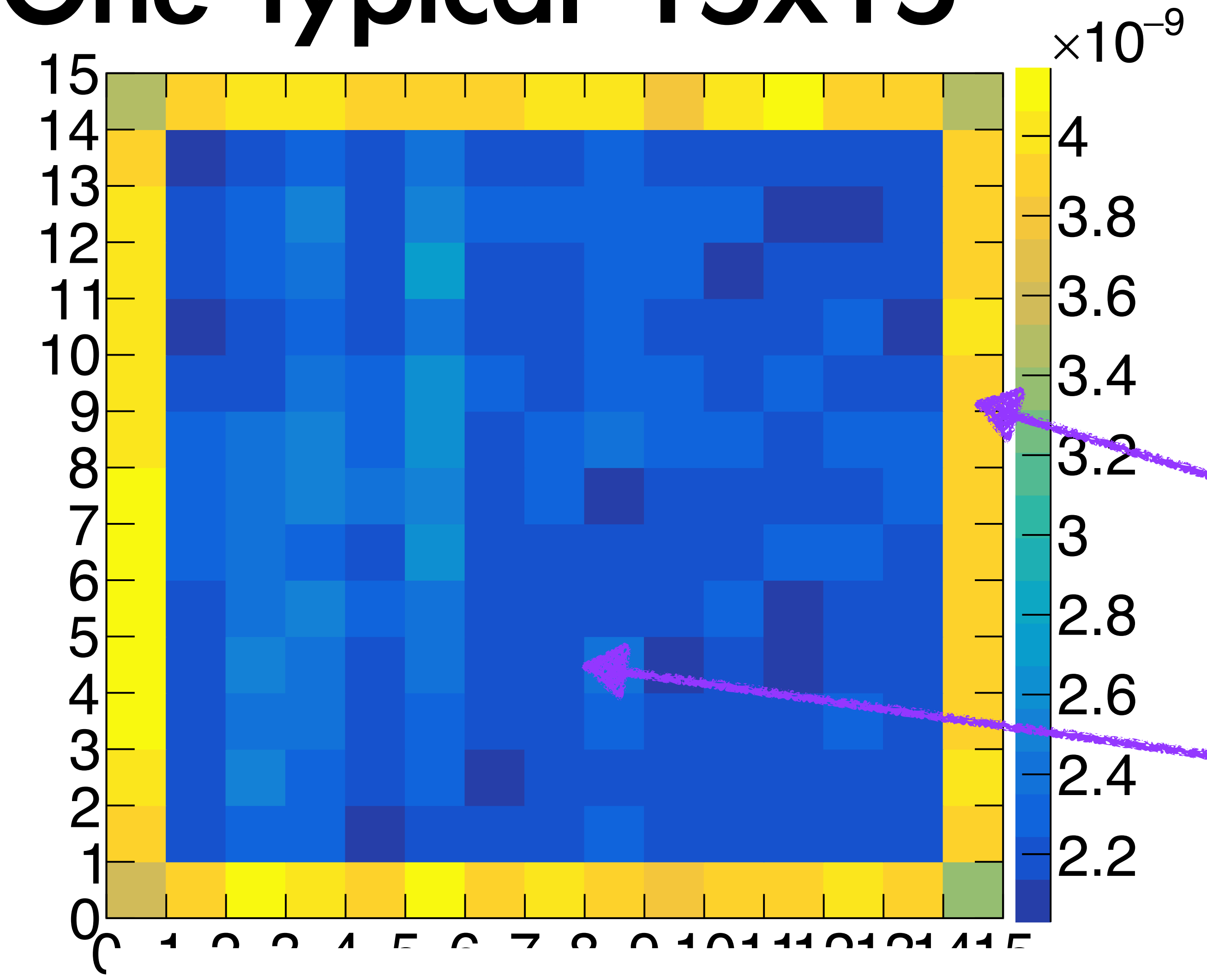
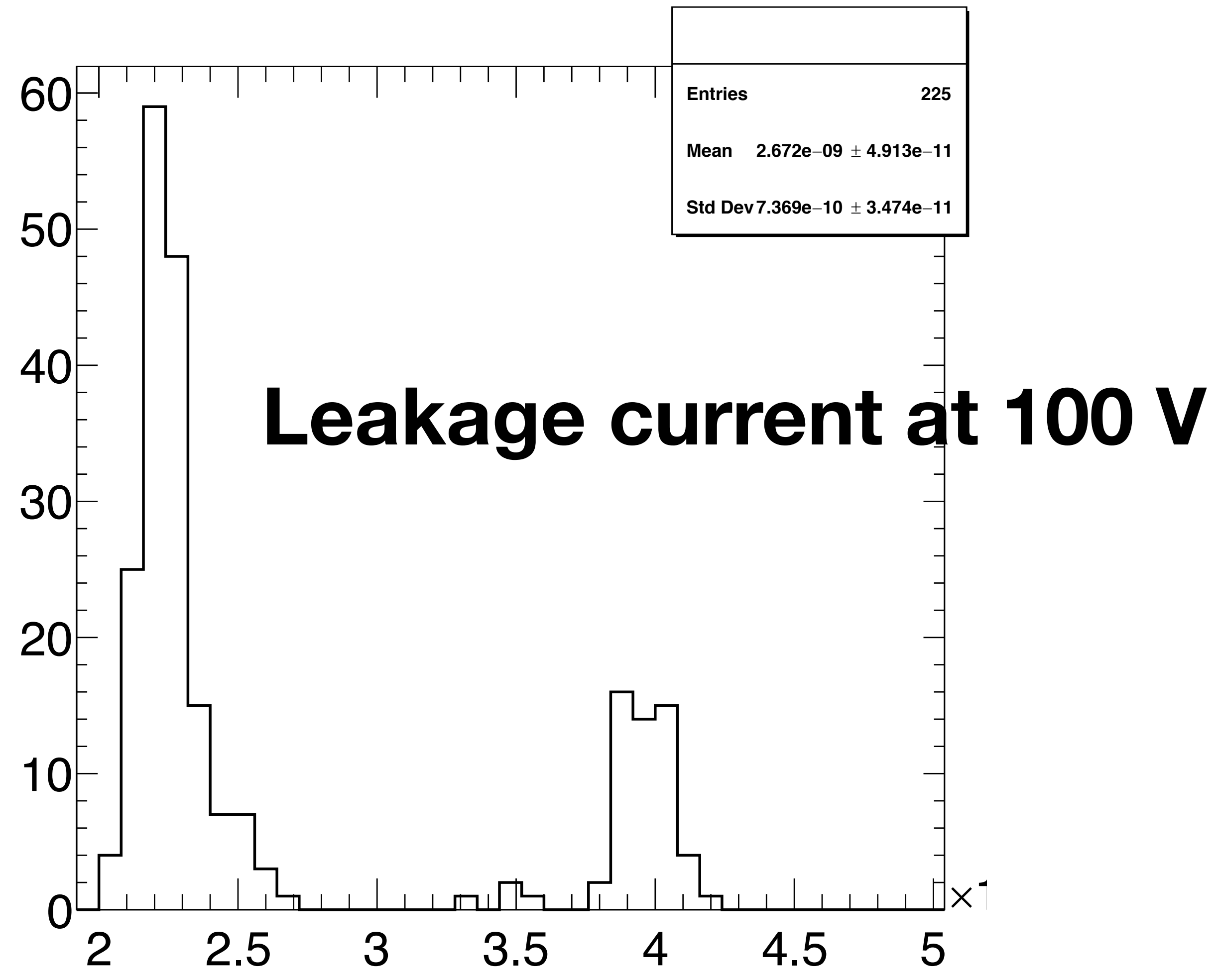
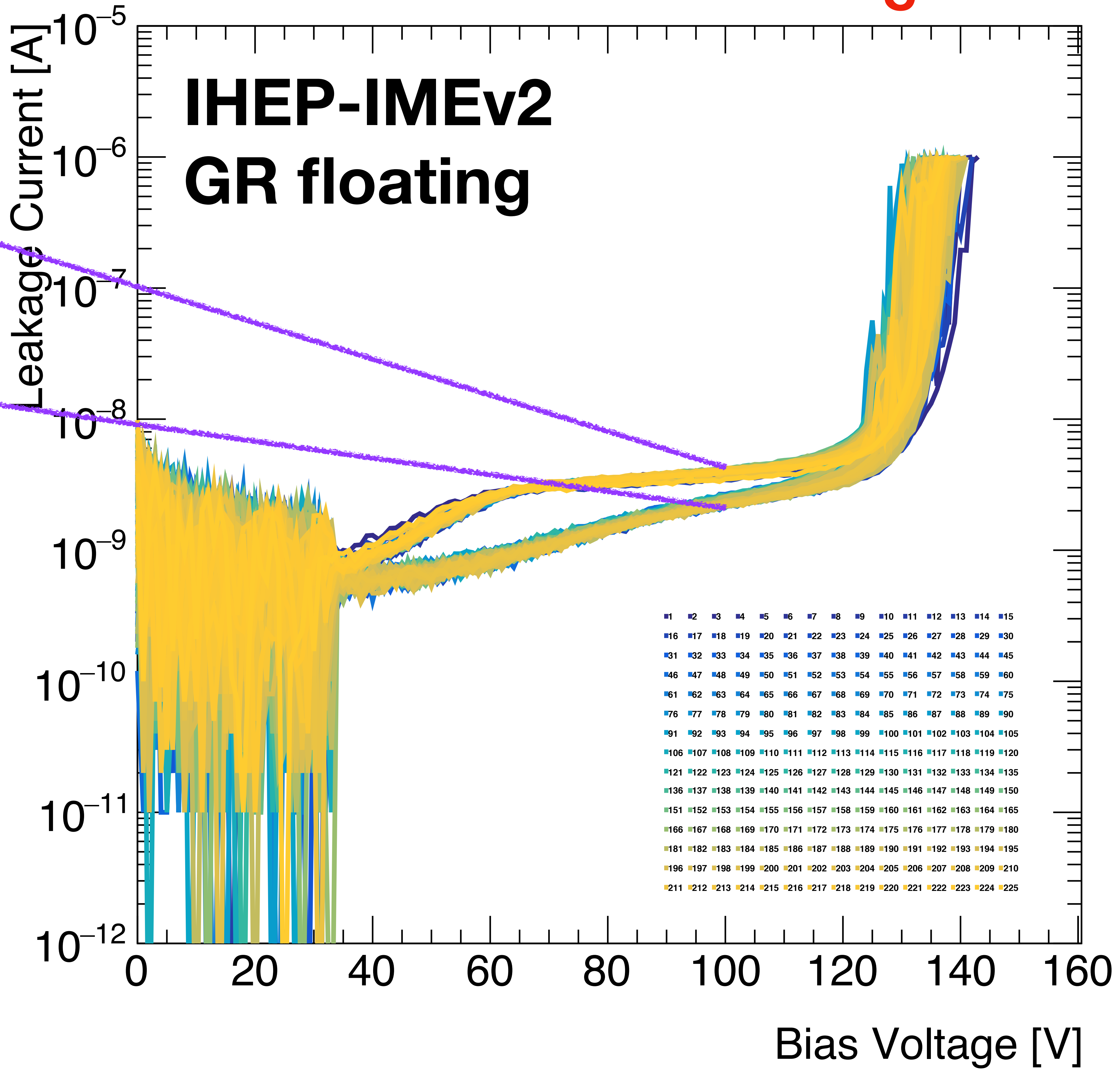
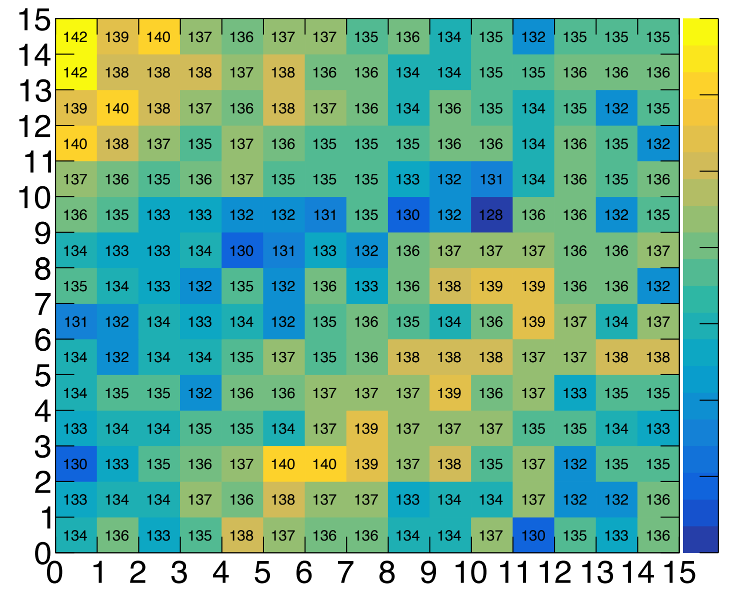
One typical 15x15

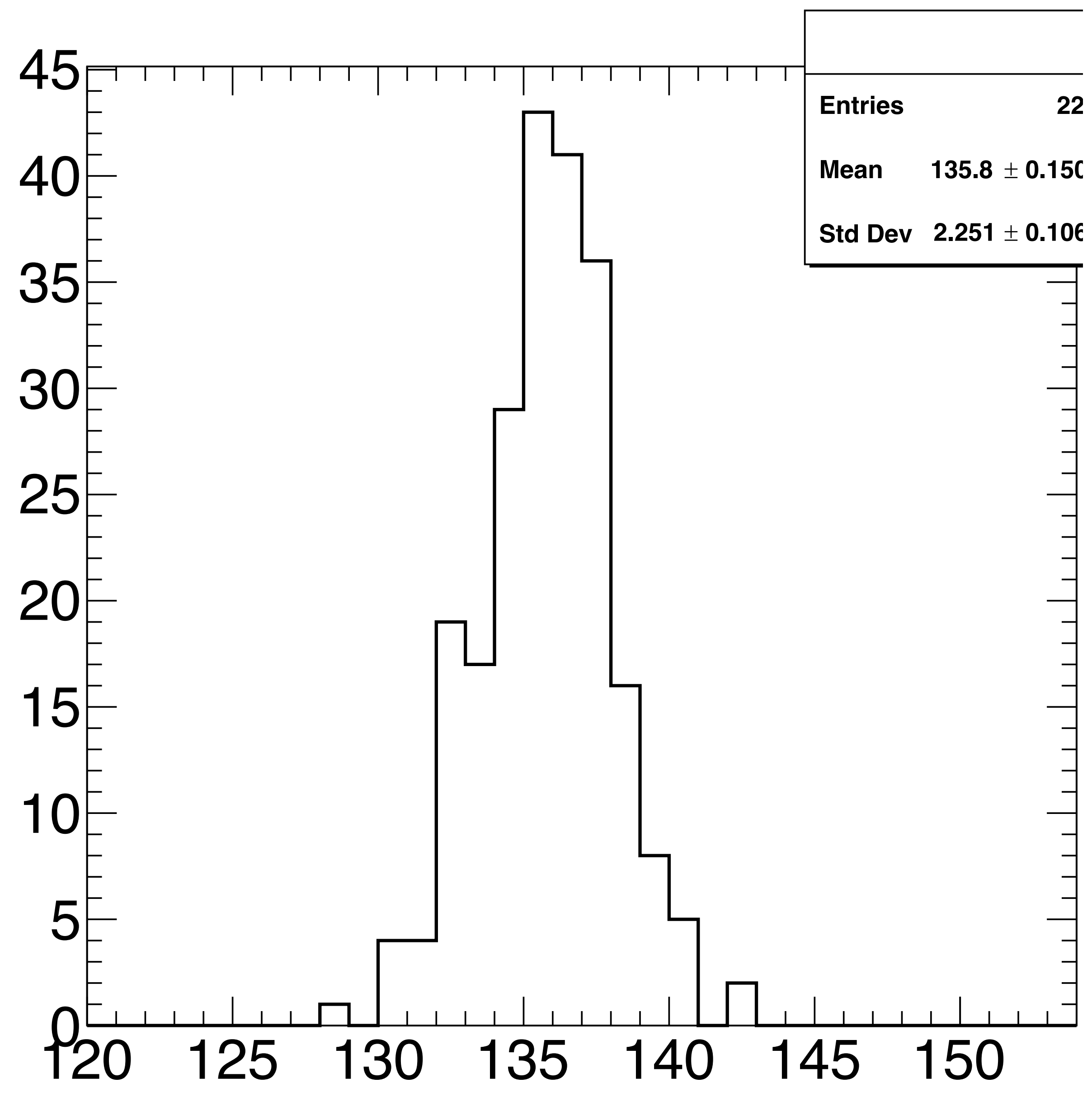




Breakdown voltage and leakage current of full size sensor showed good uniformity







Large array sensor before radiation

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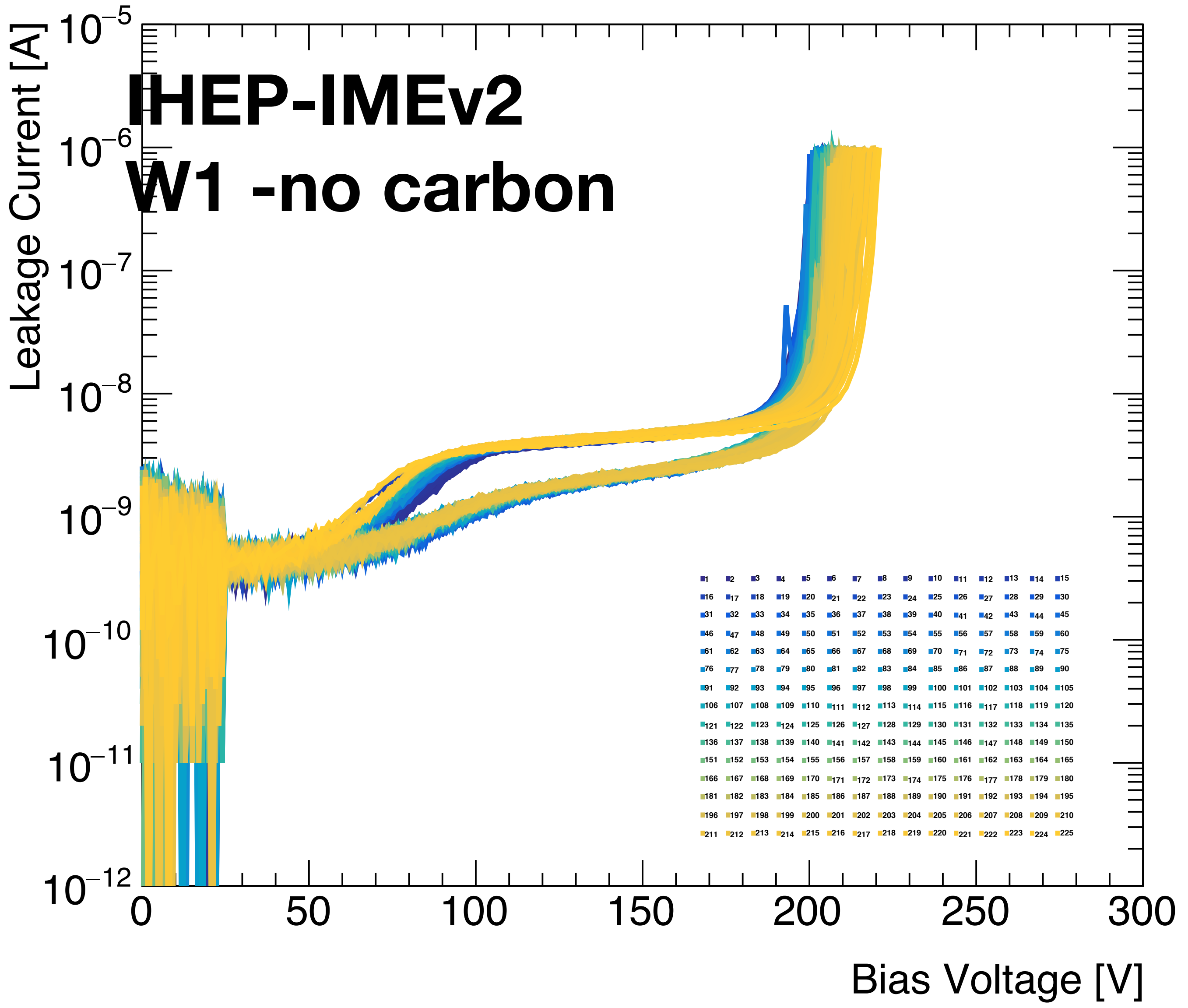
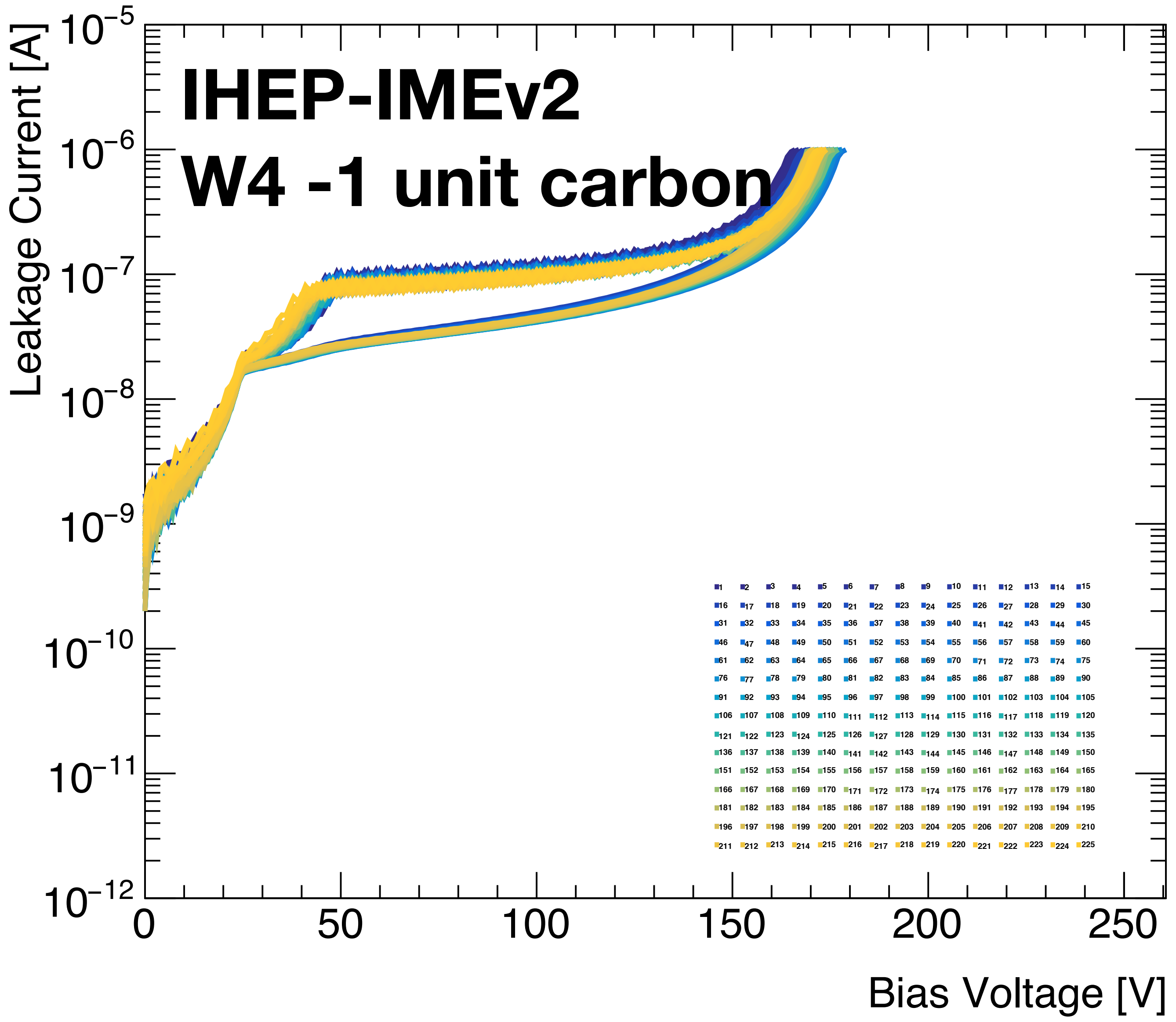
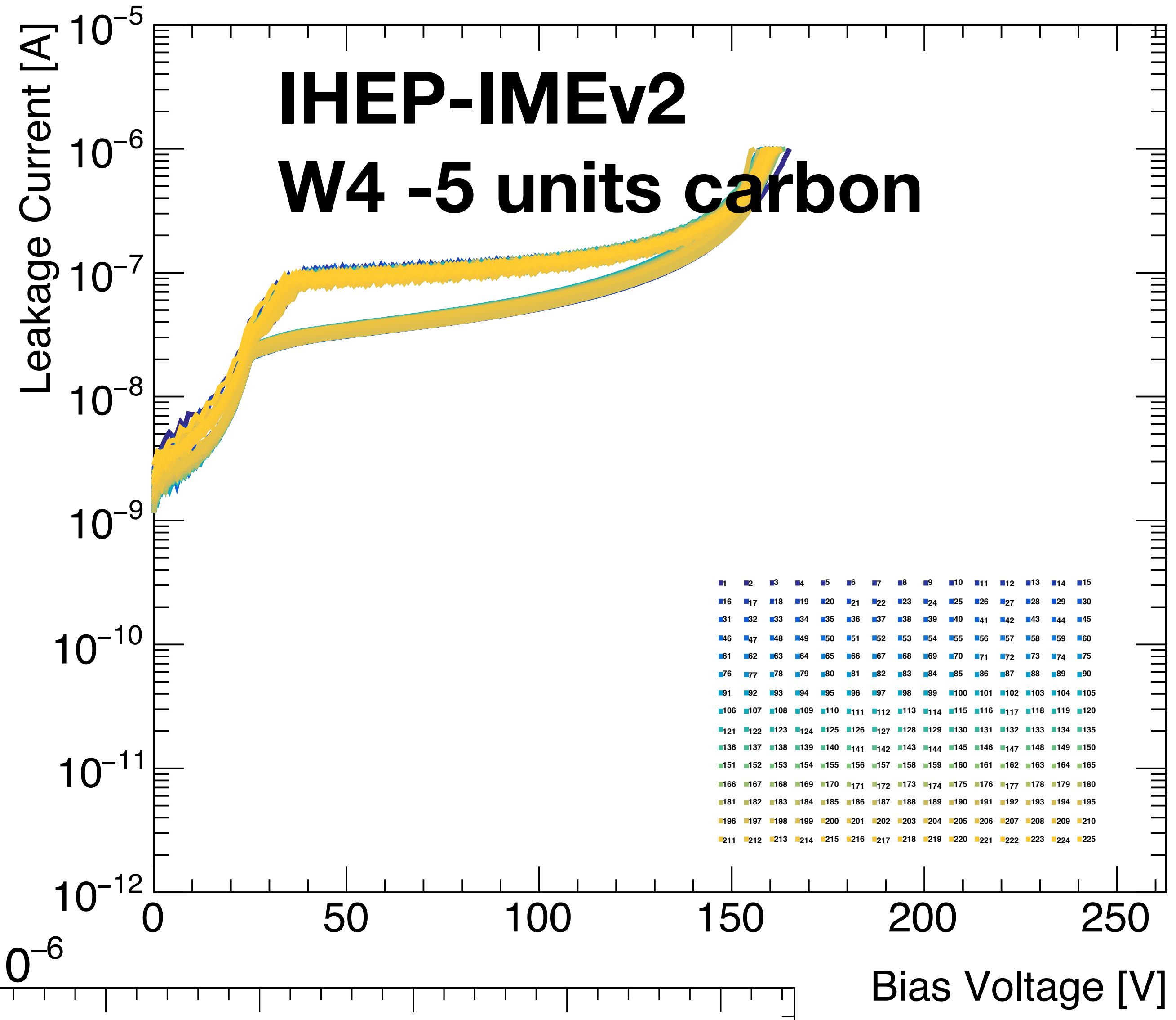
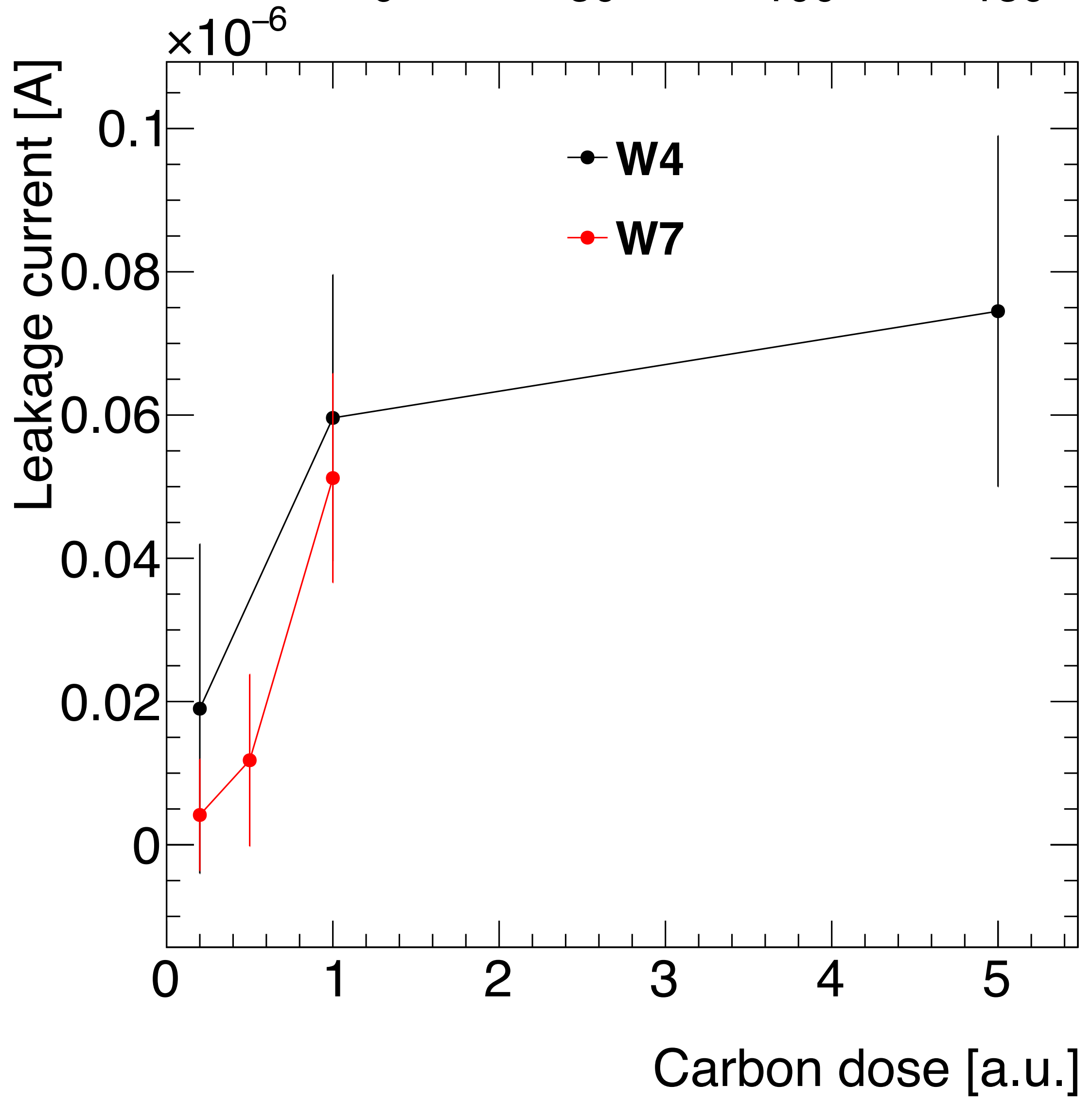
Before irradiation 15x15:





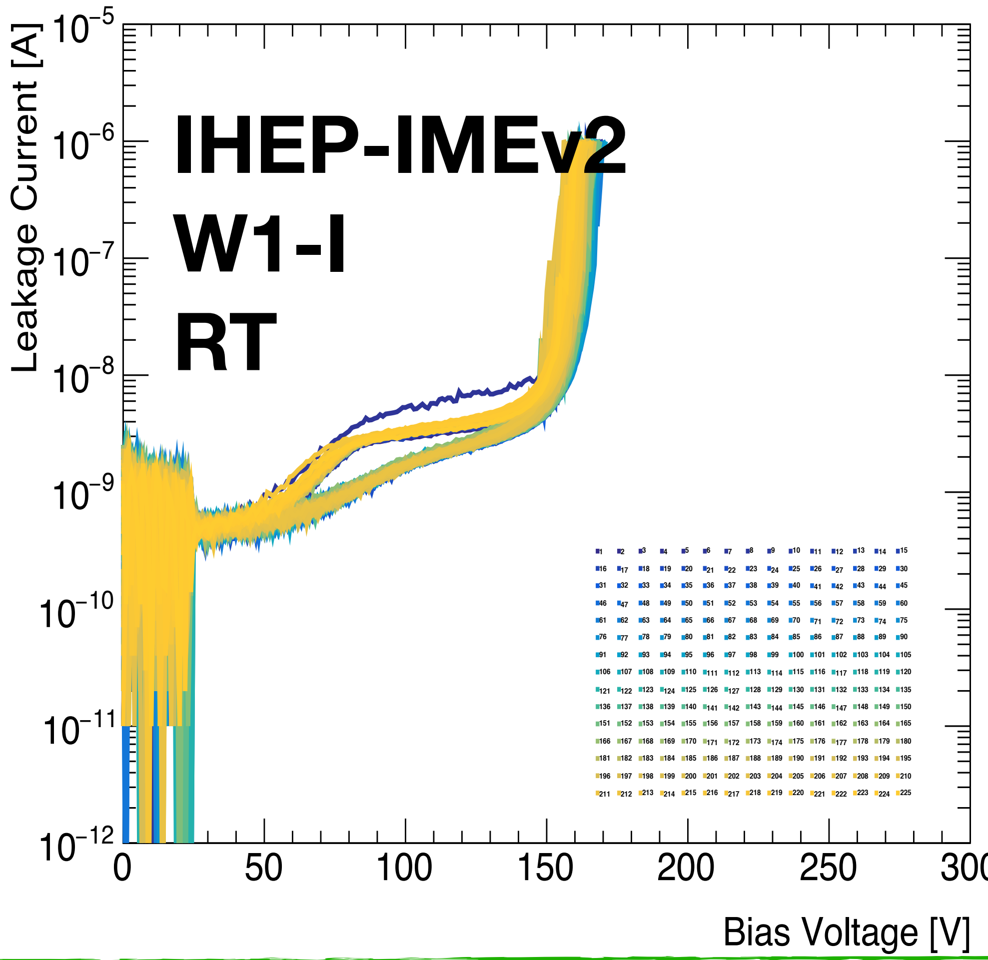


When carbon dose increase, the breakdown voltages decrease and the leakage currents increase.



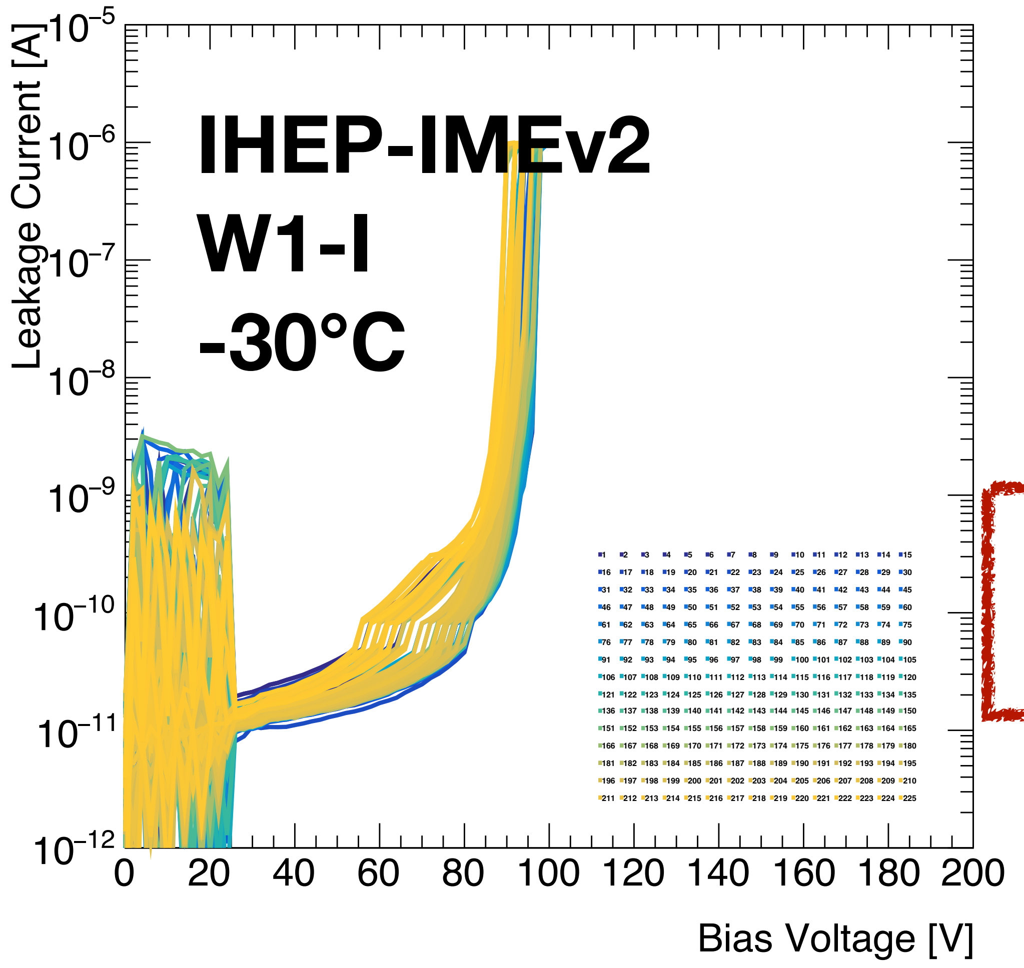
Large array sensor before radiation

- Lower leakage current and breakdown voltage at -30˚C
- Better uniformity at -30˚C
- At -30˚C, carbon implanted sensor still has higher leakage current.



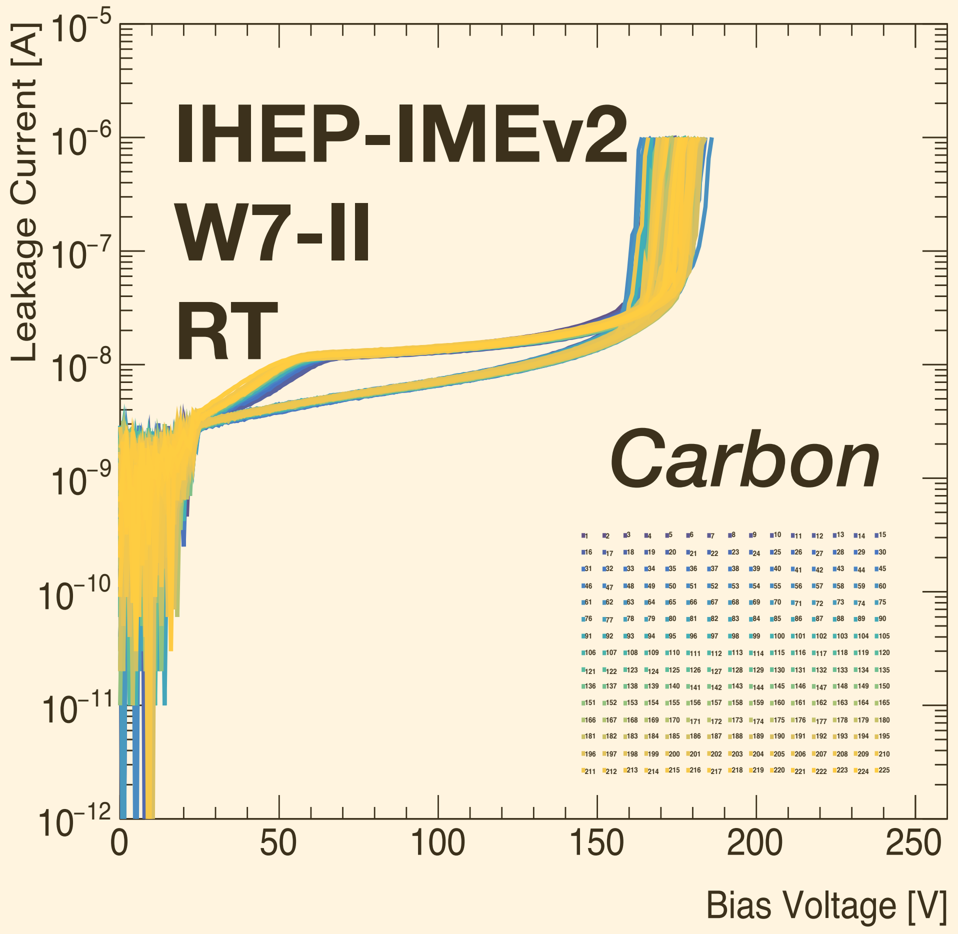
Mean: 162.3 V
RMS: 2.8 V

Mean: 6.9e-10 A
RMS: 1.2e-10 A



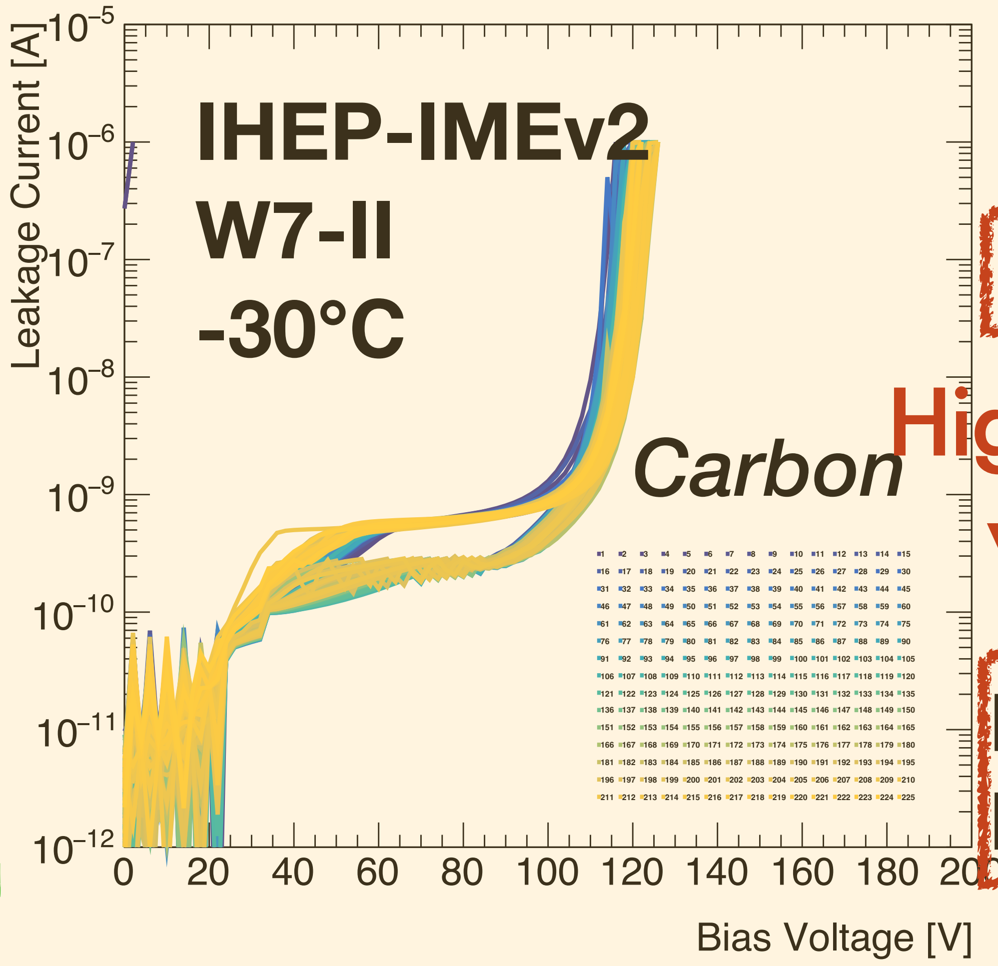
Mean: 93.5 V
RMS: 2.3 V

Mean: 2.7e-11 A
RMS: 1.4e-11 A



Mean: 175.0 V
RMS: 4.1 V

Mean: 6.2e-9 A
RMS: 2.7e-9 A



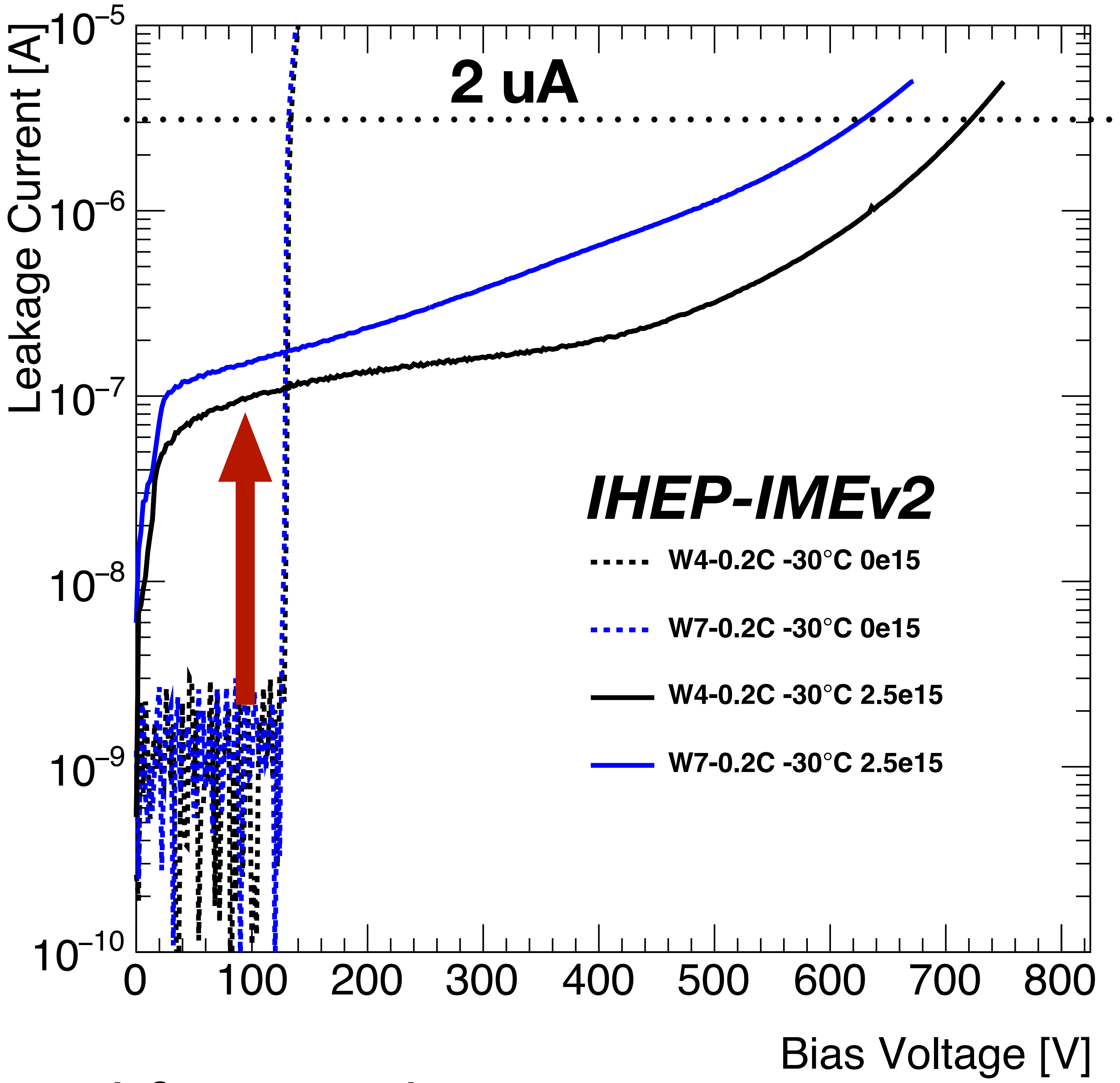
Mean: 120.5 V
RMS: 2.2 V

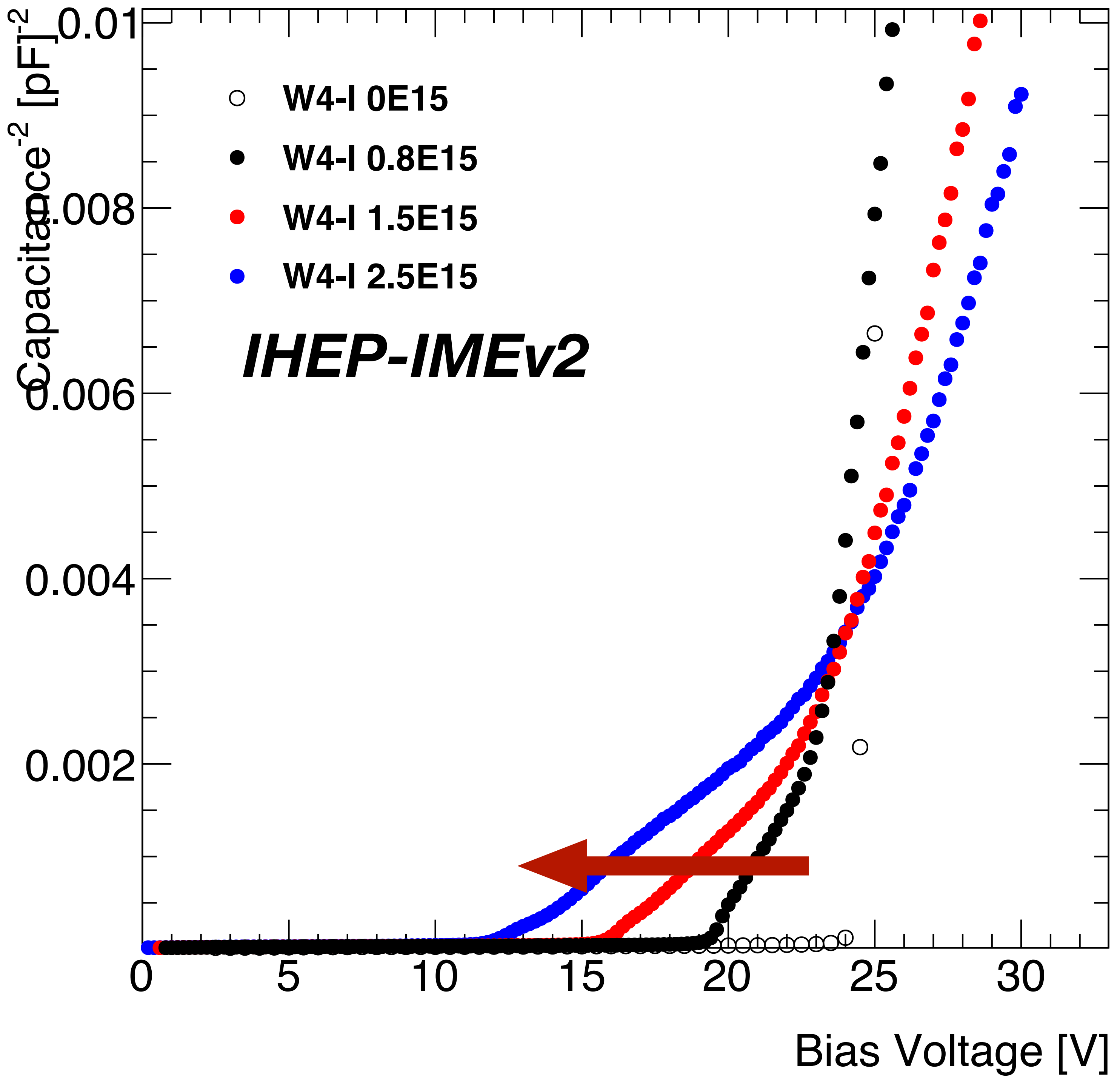
Higher than sensors without carbon

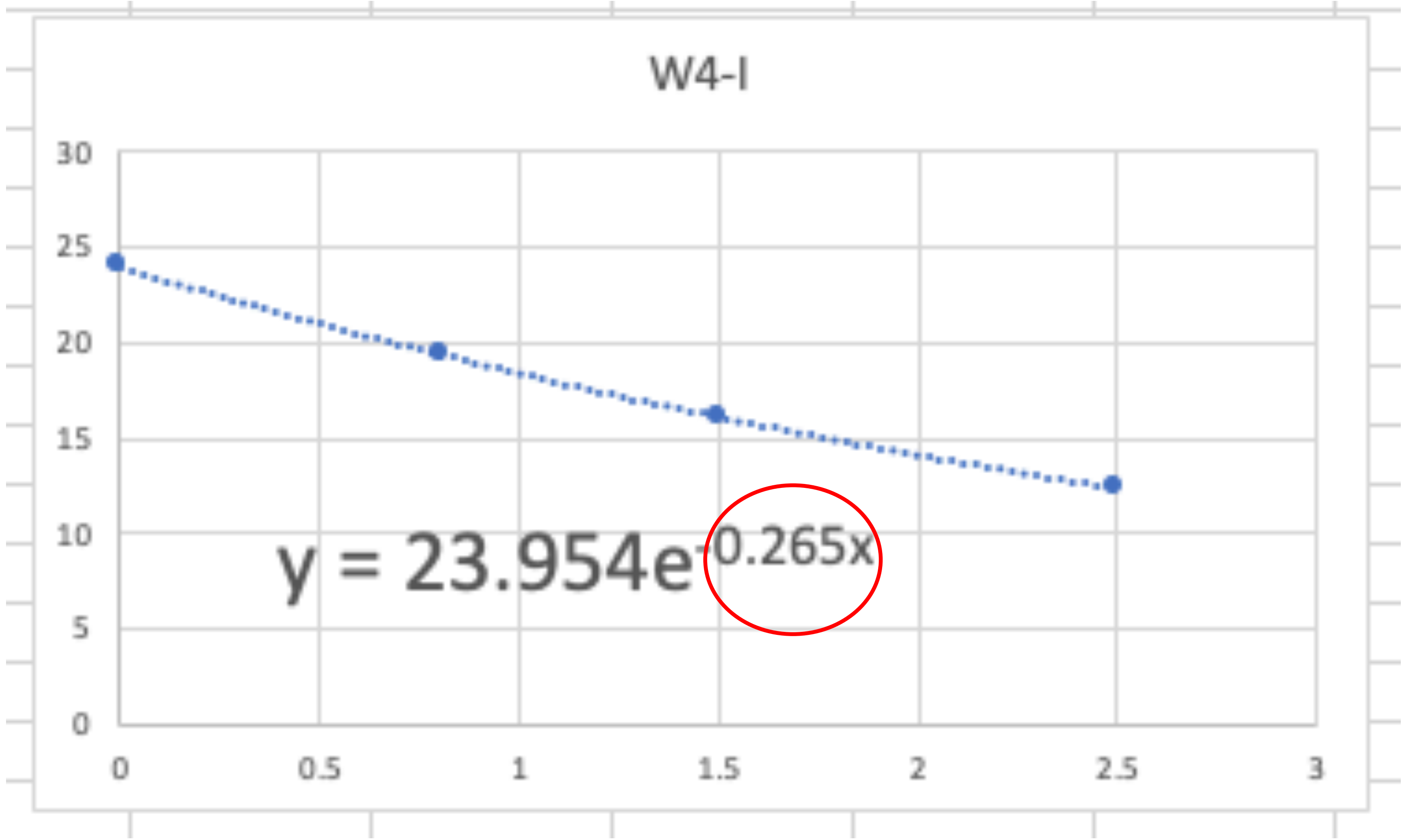
Mean: 2.6e-10 A
RMS: 1.3e-10 A

After radiation

IHEP-IMEv2





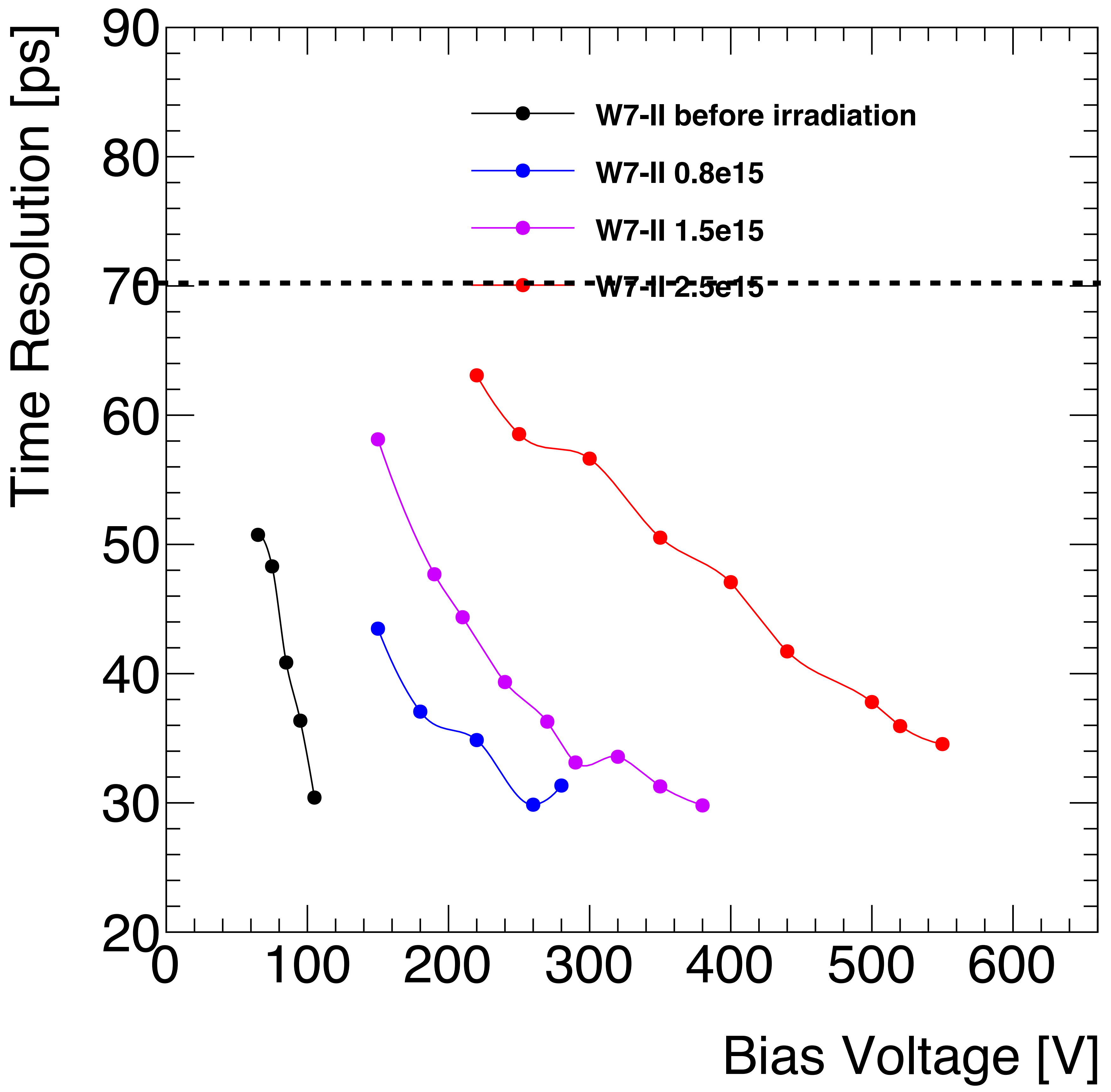


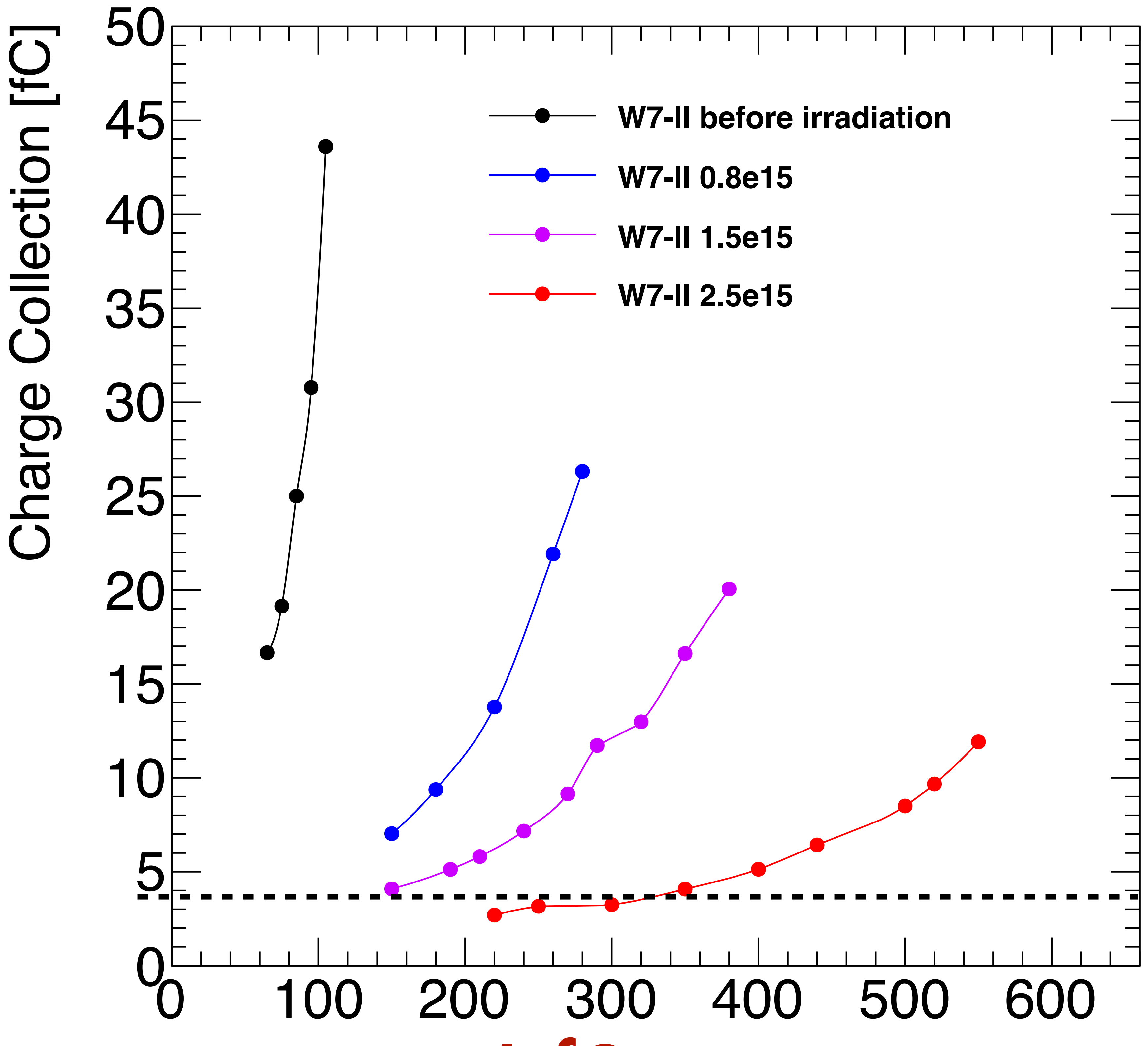
Gain layer acceptor removal constant

After irradiation:

- The leakage current increase nA->100nA
- The acceptor concentration is reduced
  - Vgl decrease with the irradiation fluence (Acceptor removal constant)
- The sensor needs to be operated at higher voltage, higher power consumption (I<2 uA)

After radiation - Timing and charge



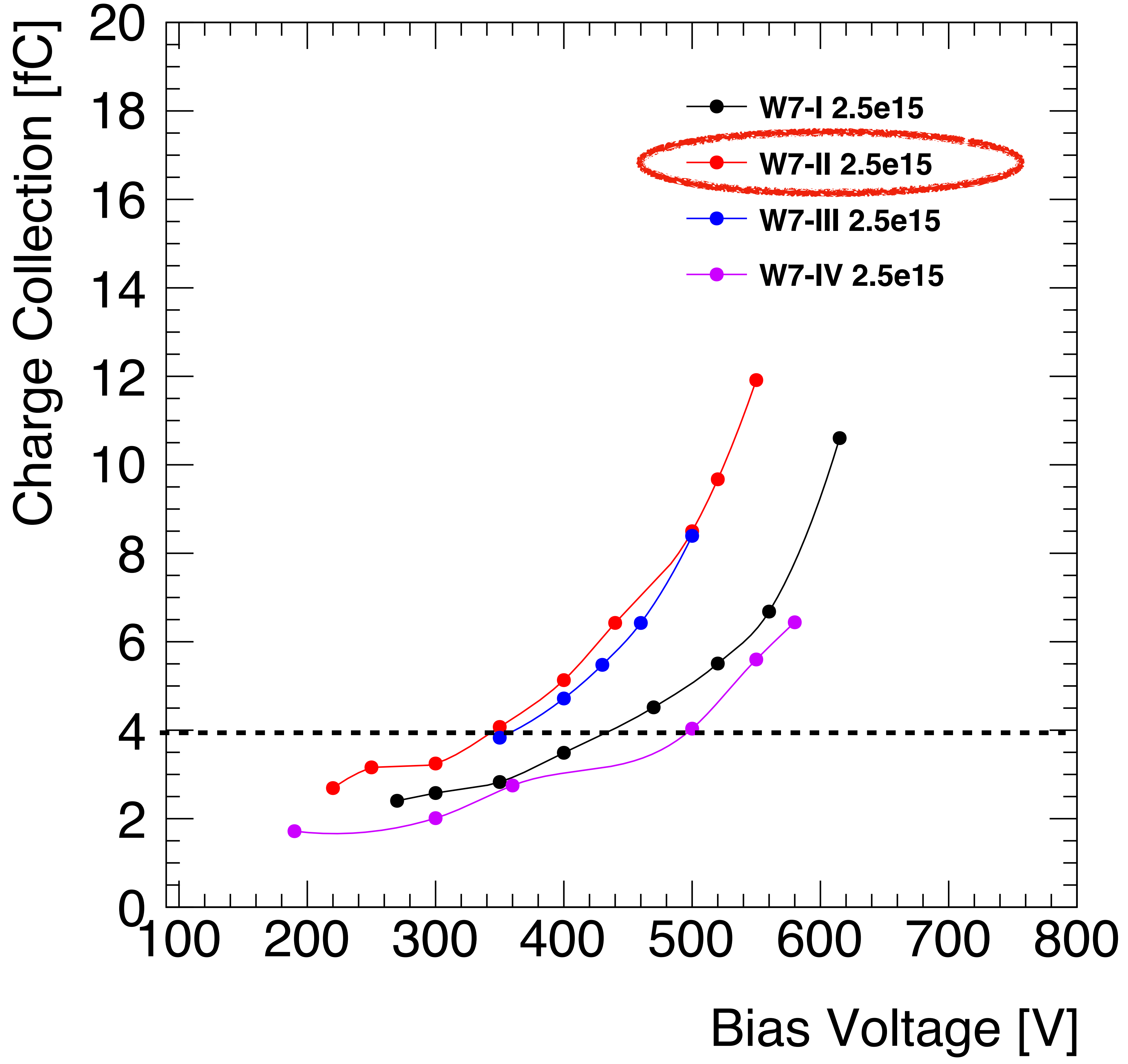


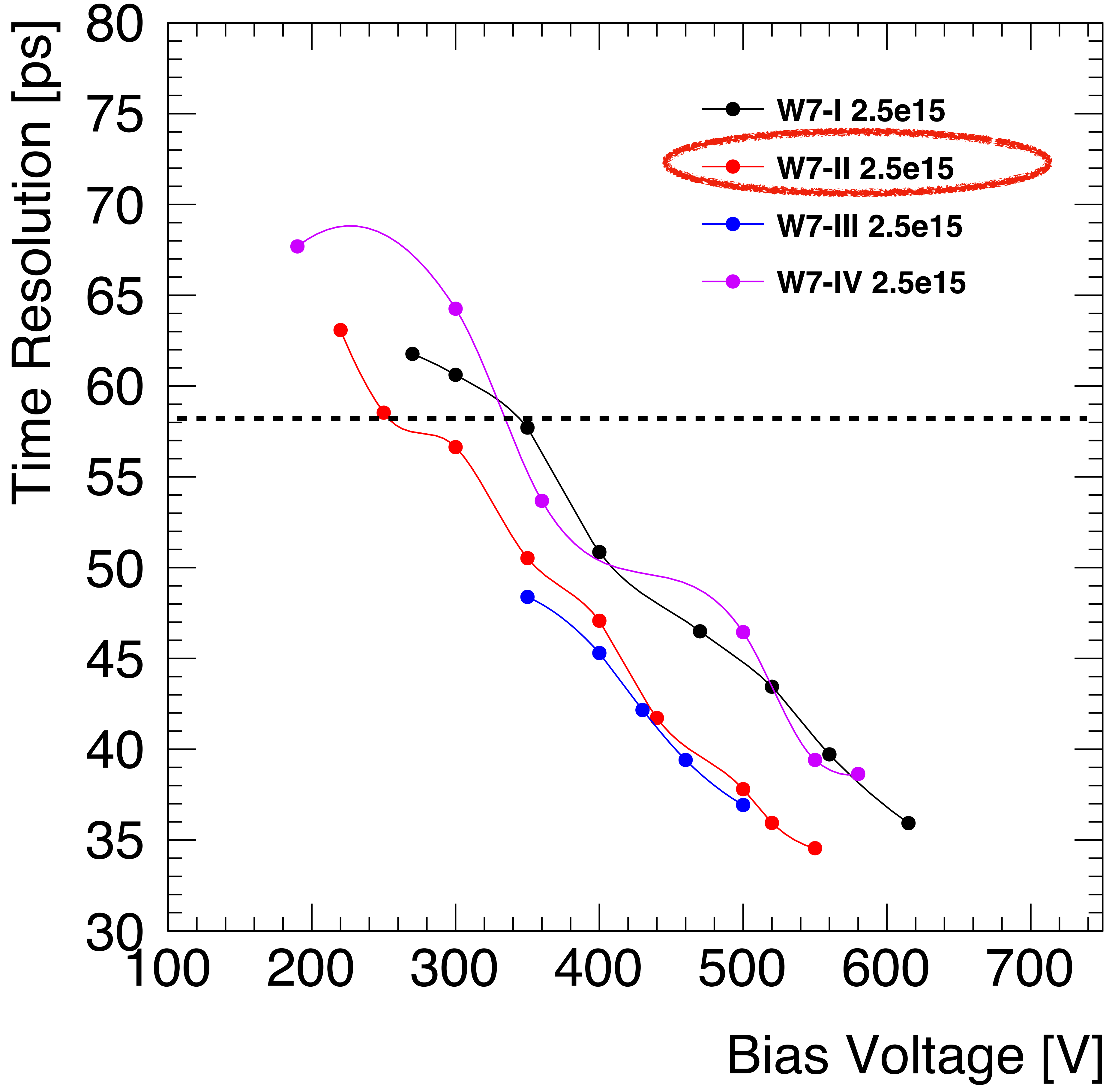
4 fC at:
W7-II(0.5C): 350 V 50.5 ps

- Time resolution and charge collection after radiation

After radiation - Carbon dose

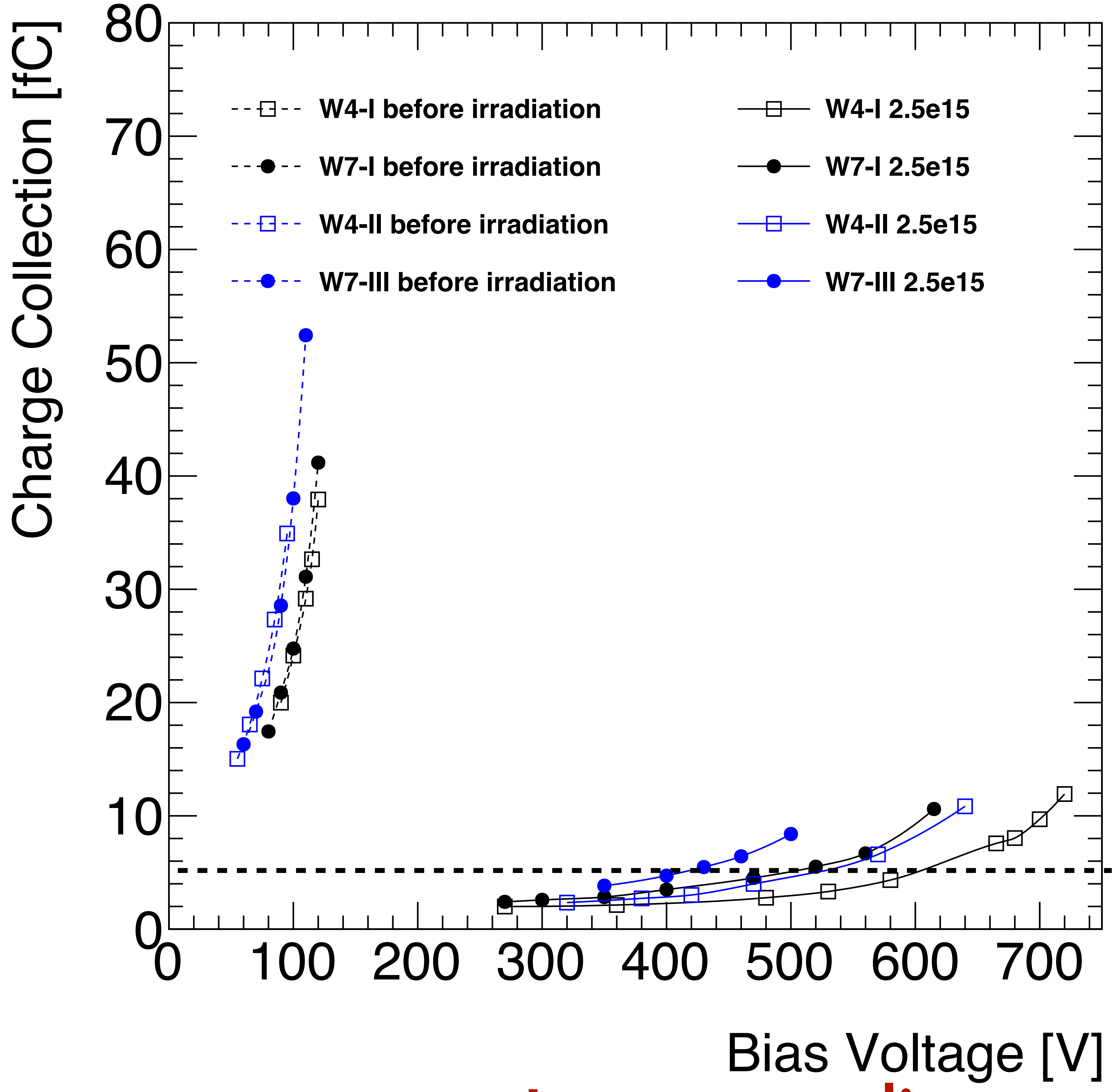
- Time resolution and charge collection of sensors with different carbon dose

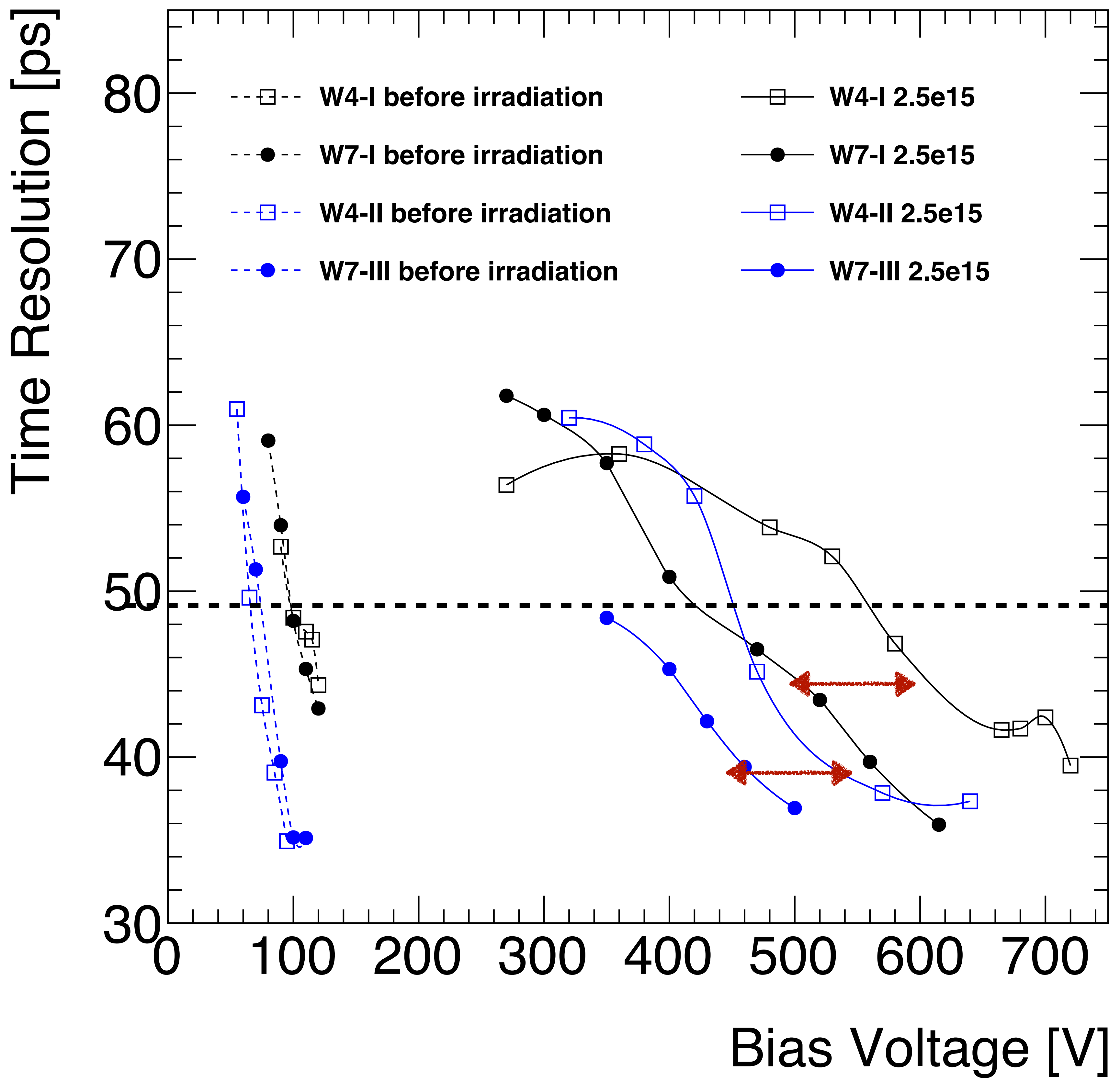




After radiation - Thermal load

Time resolution and charge collection of sensors with same carbon dose but different thermal load





Long annealing sensors have better performance

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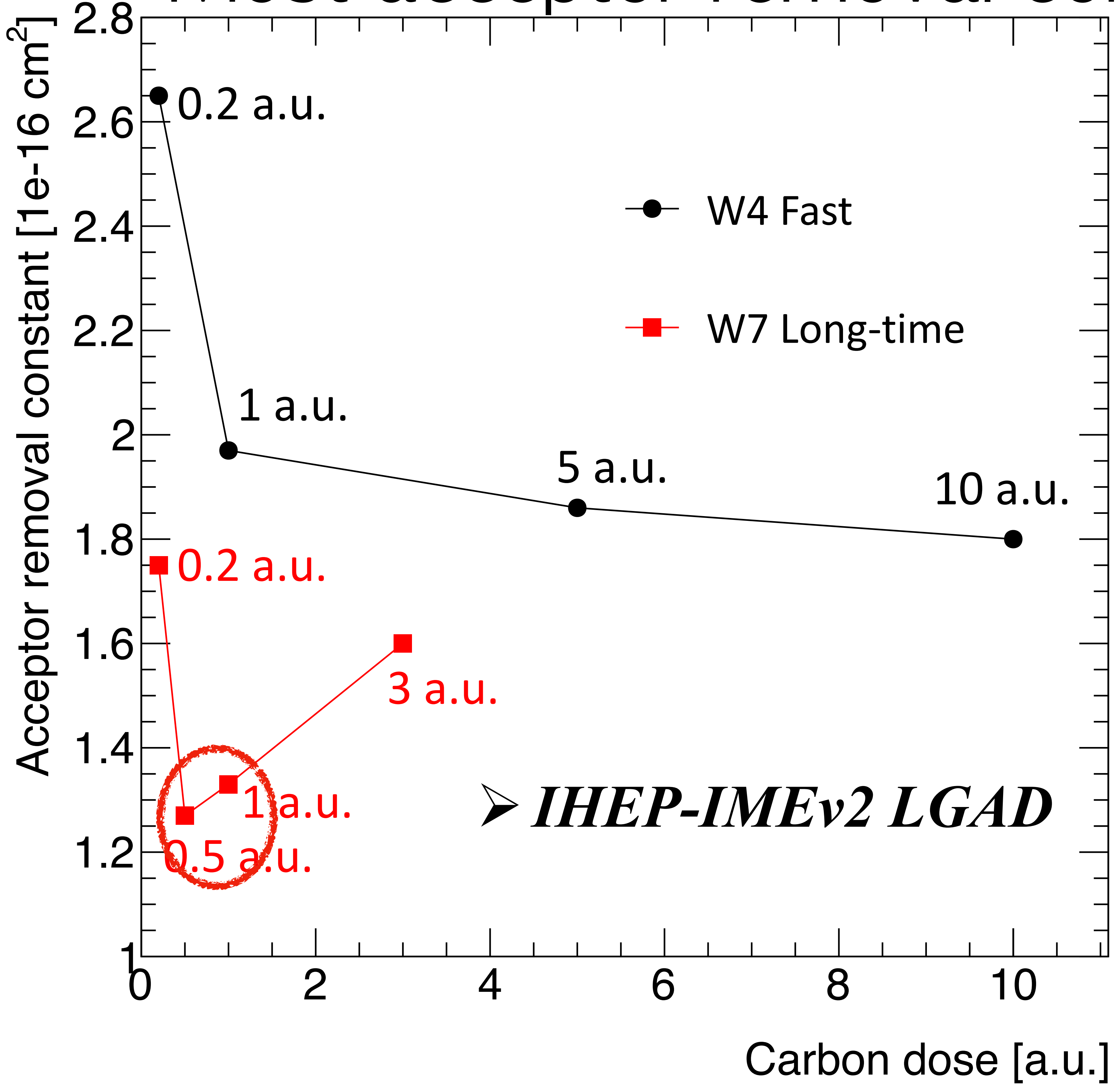
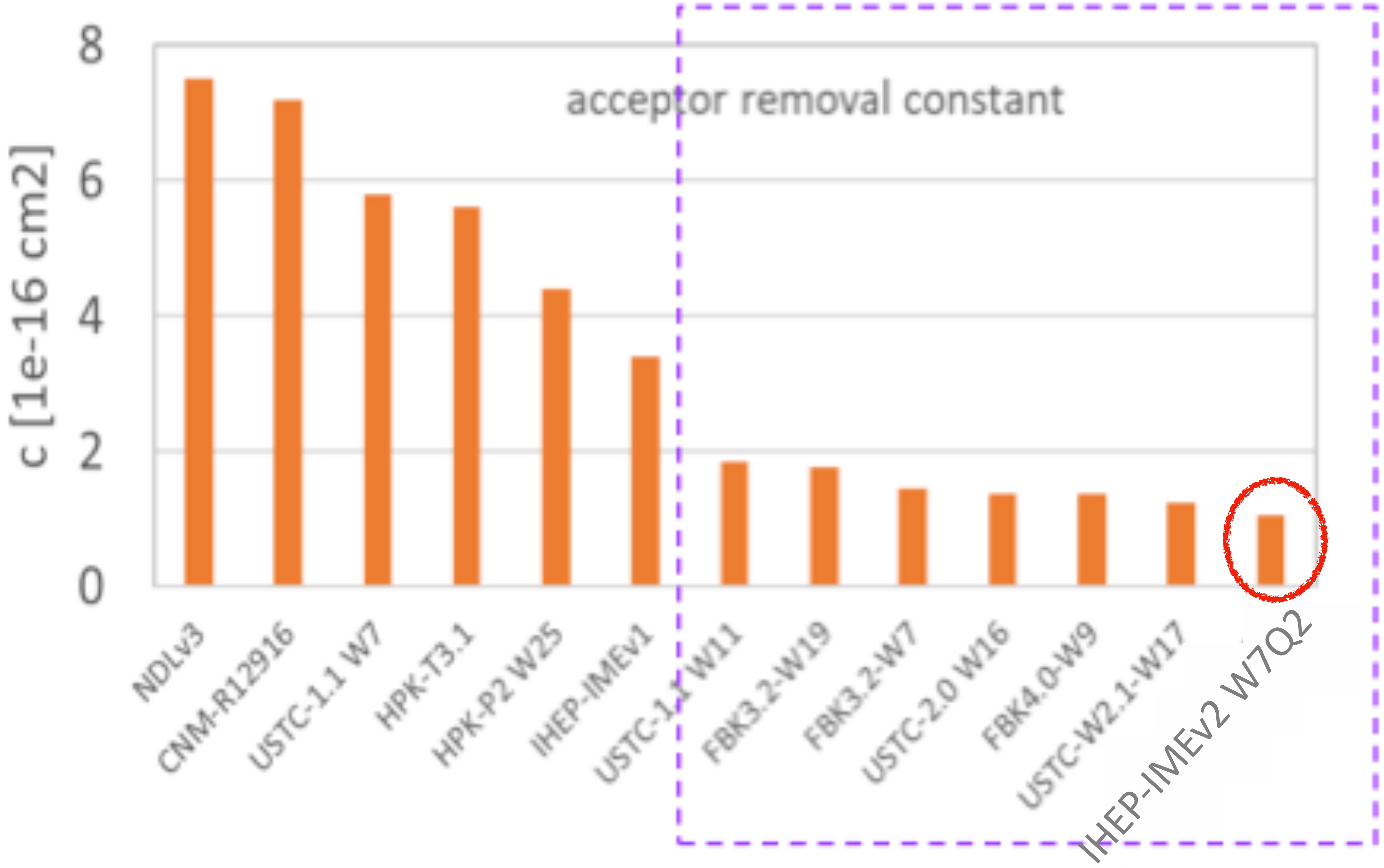
After radiation

IHEP-IMEv2

- Most acceptor removal constant below 2, the best (W7-II) is about 1.27.





Between 0.2C and 1C, long time annealing the best recipe for irradiation hardness.

Large array sensor after irradiation

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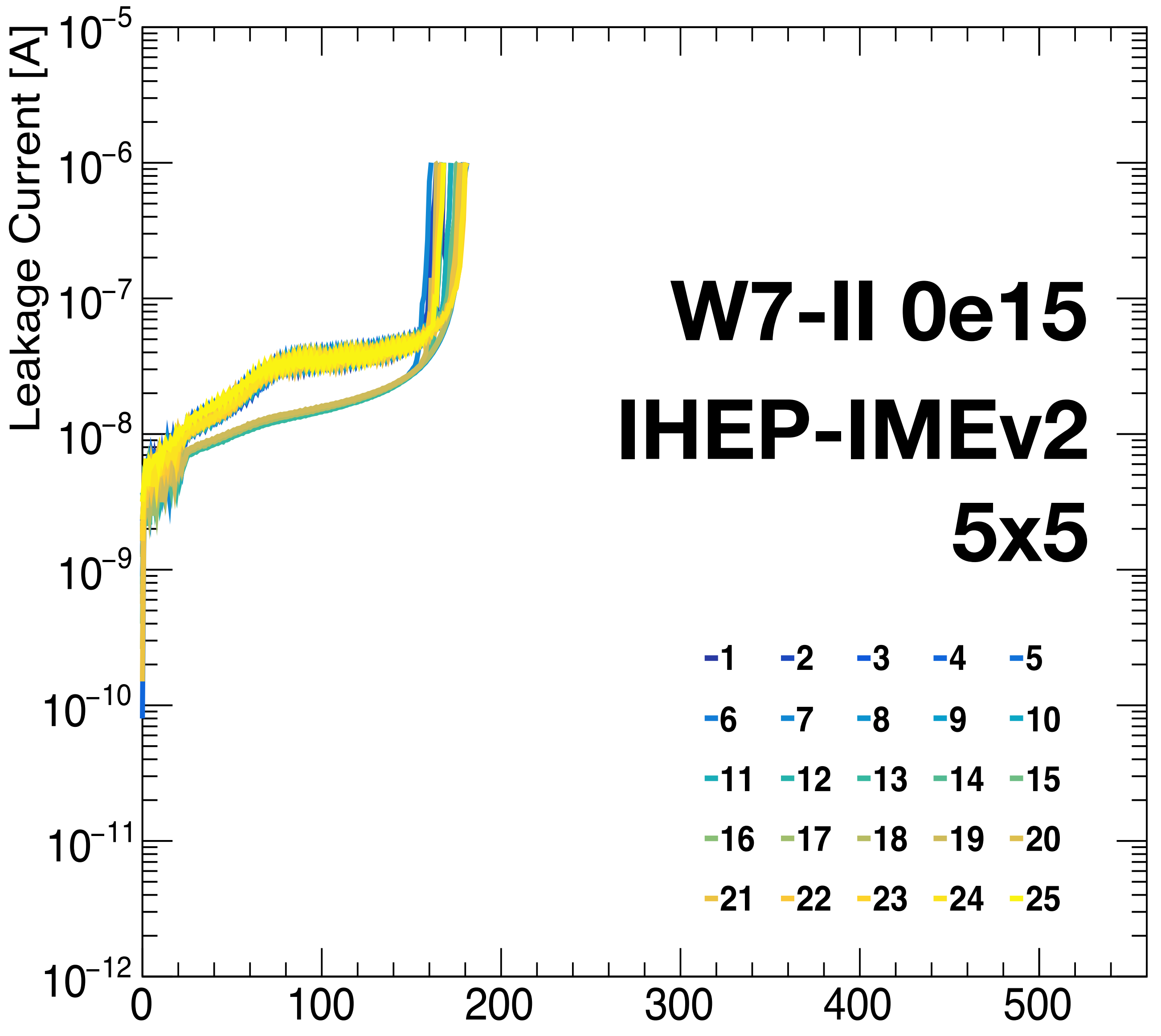
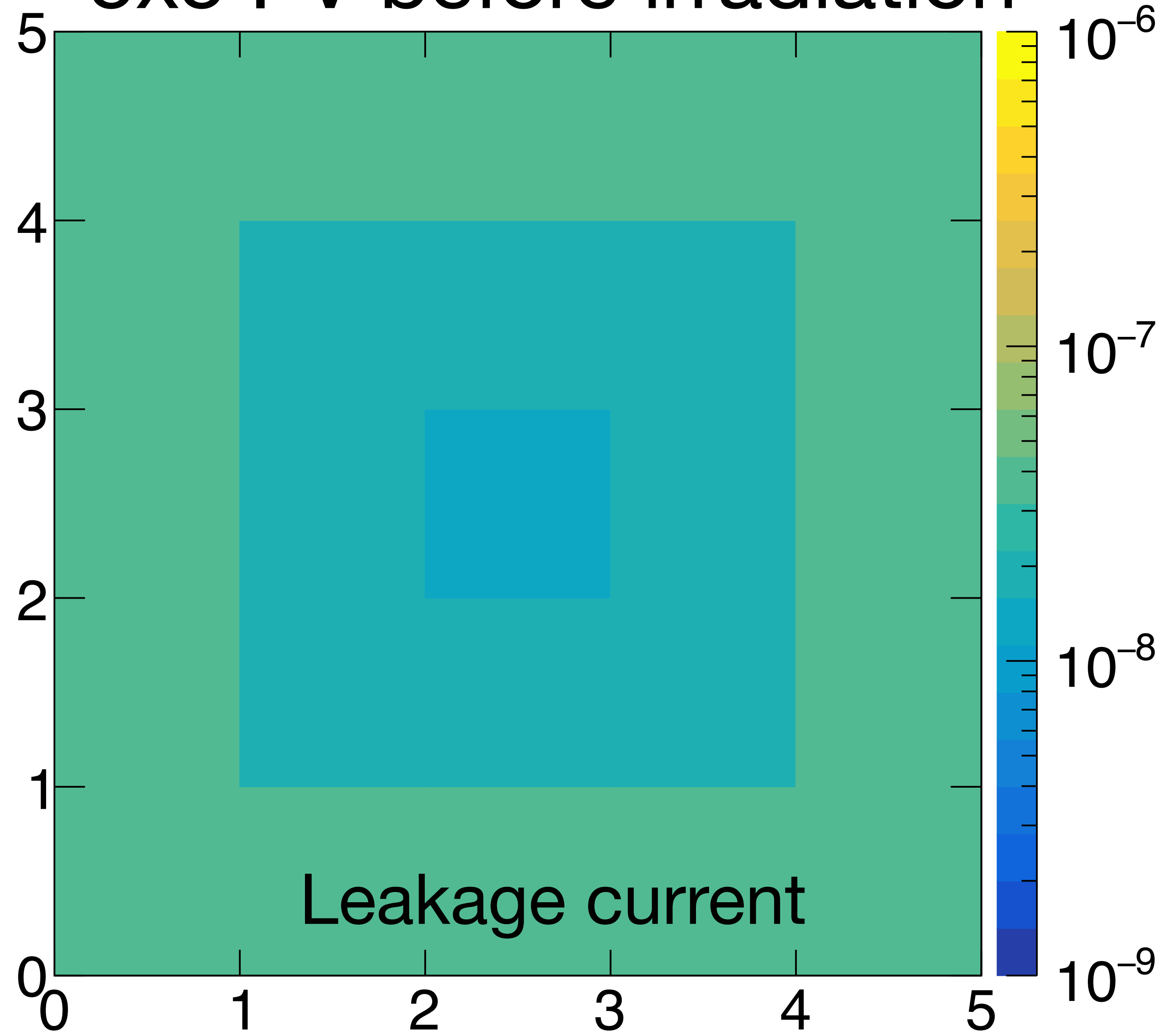
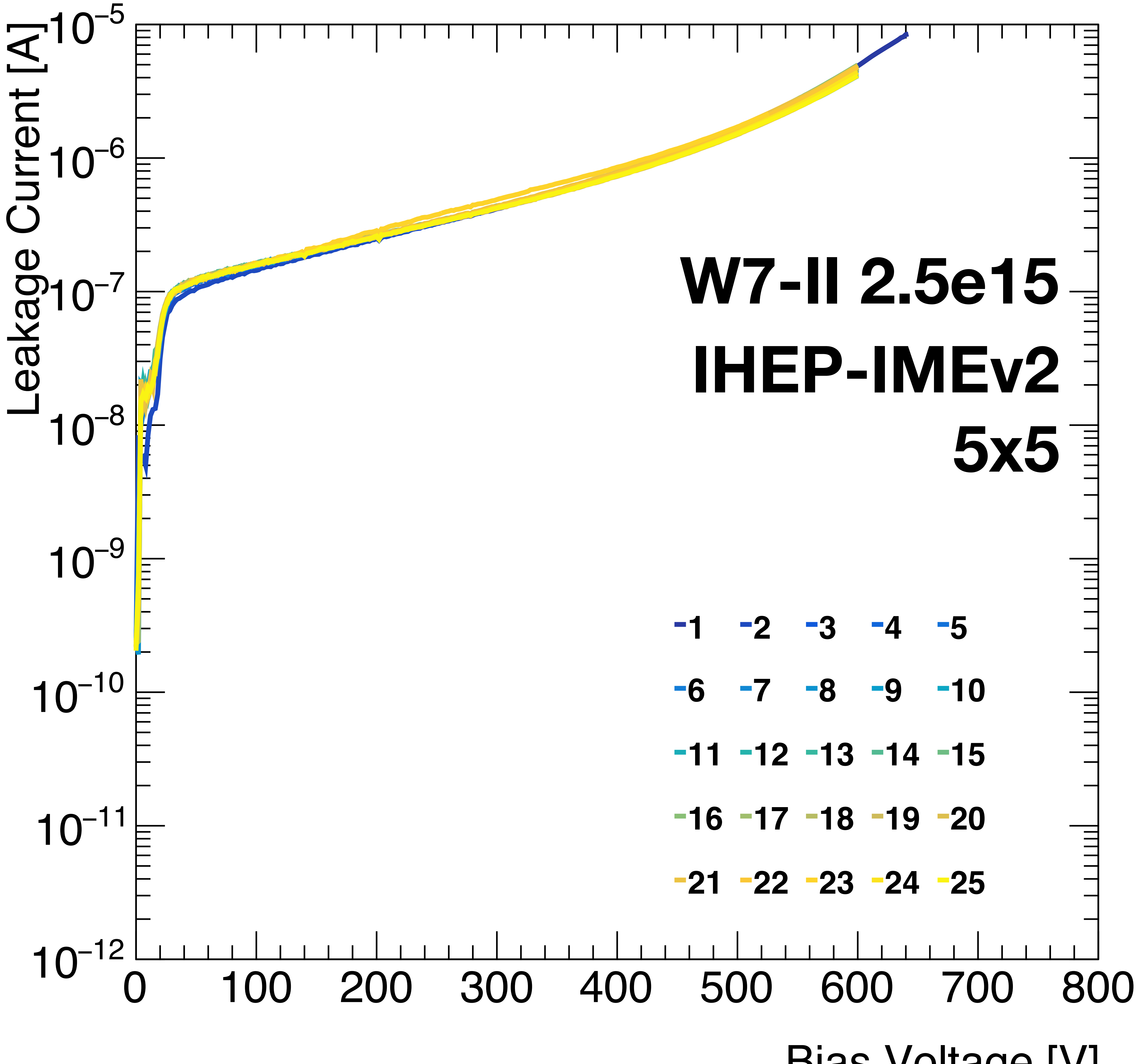


5x5 I-V before irradiation



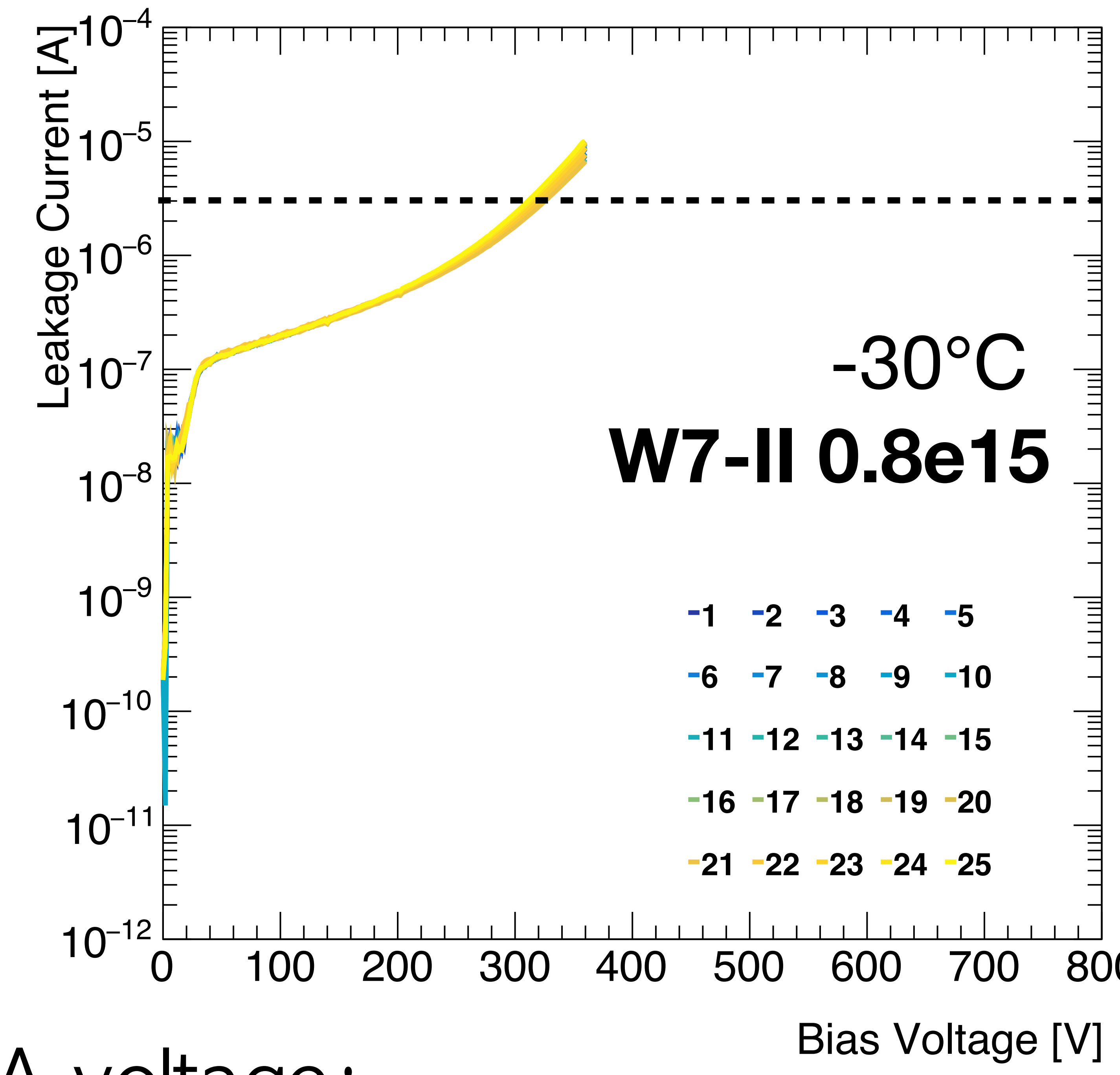


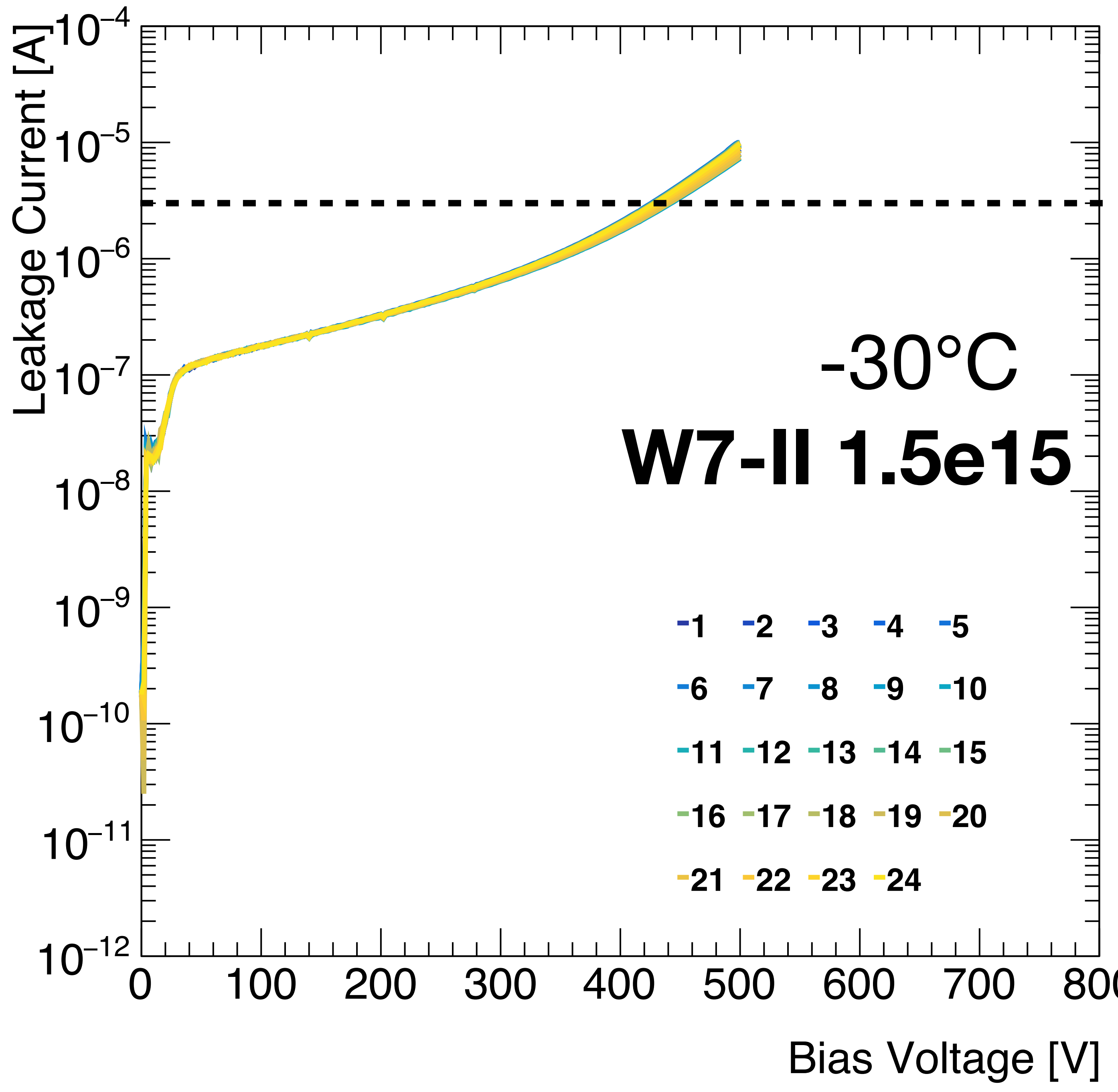
2 μA voltage:
Mean: 525 V
RMS: 4.7 V

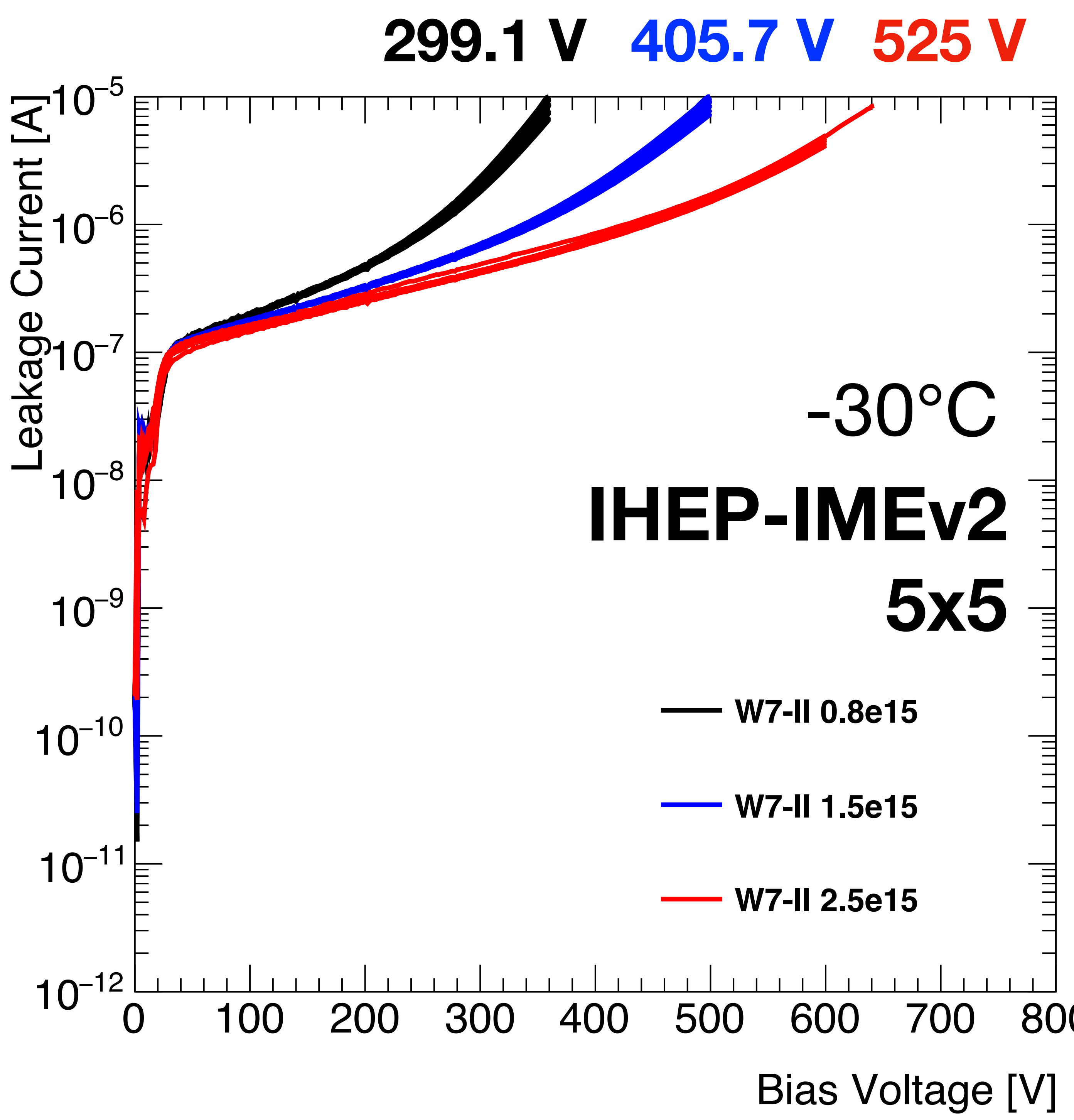
Very uniformed I-V after irradiation

Large array sensor after radiation

Uniformed I-V after irradiation







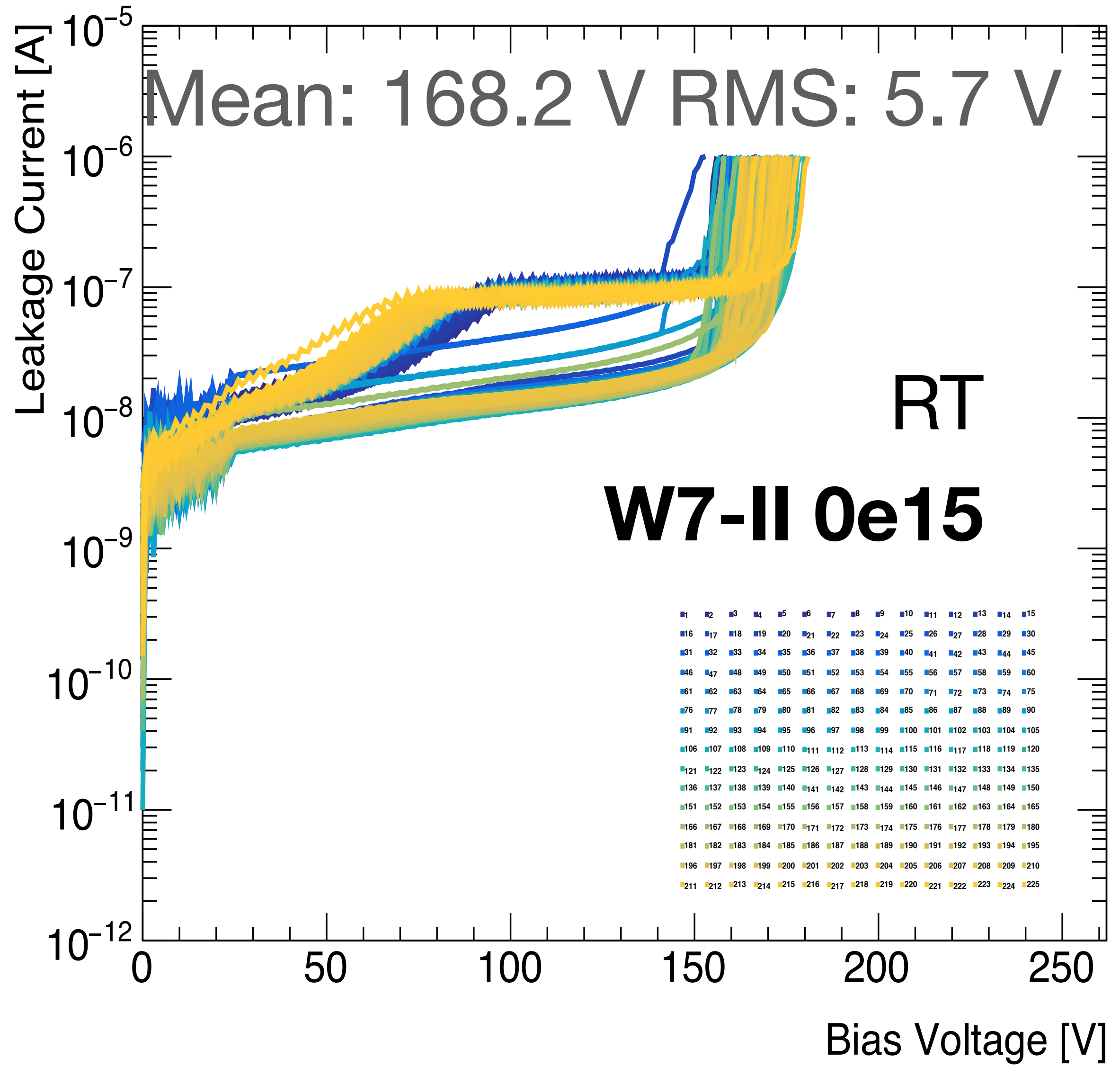
2 uA voltage:

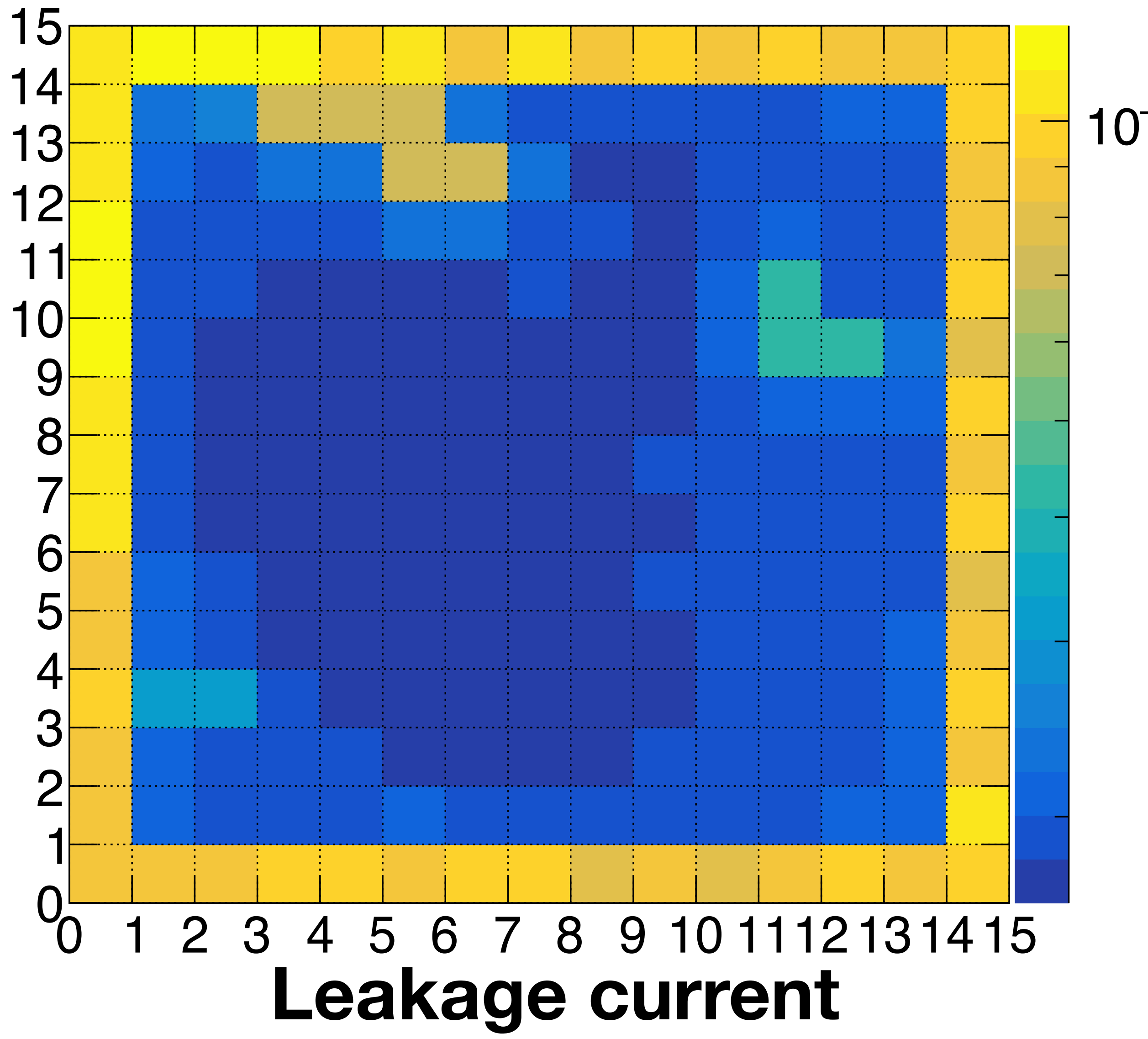
Mean: 299.1 V
RMS: 3.5 V

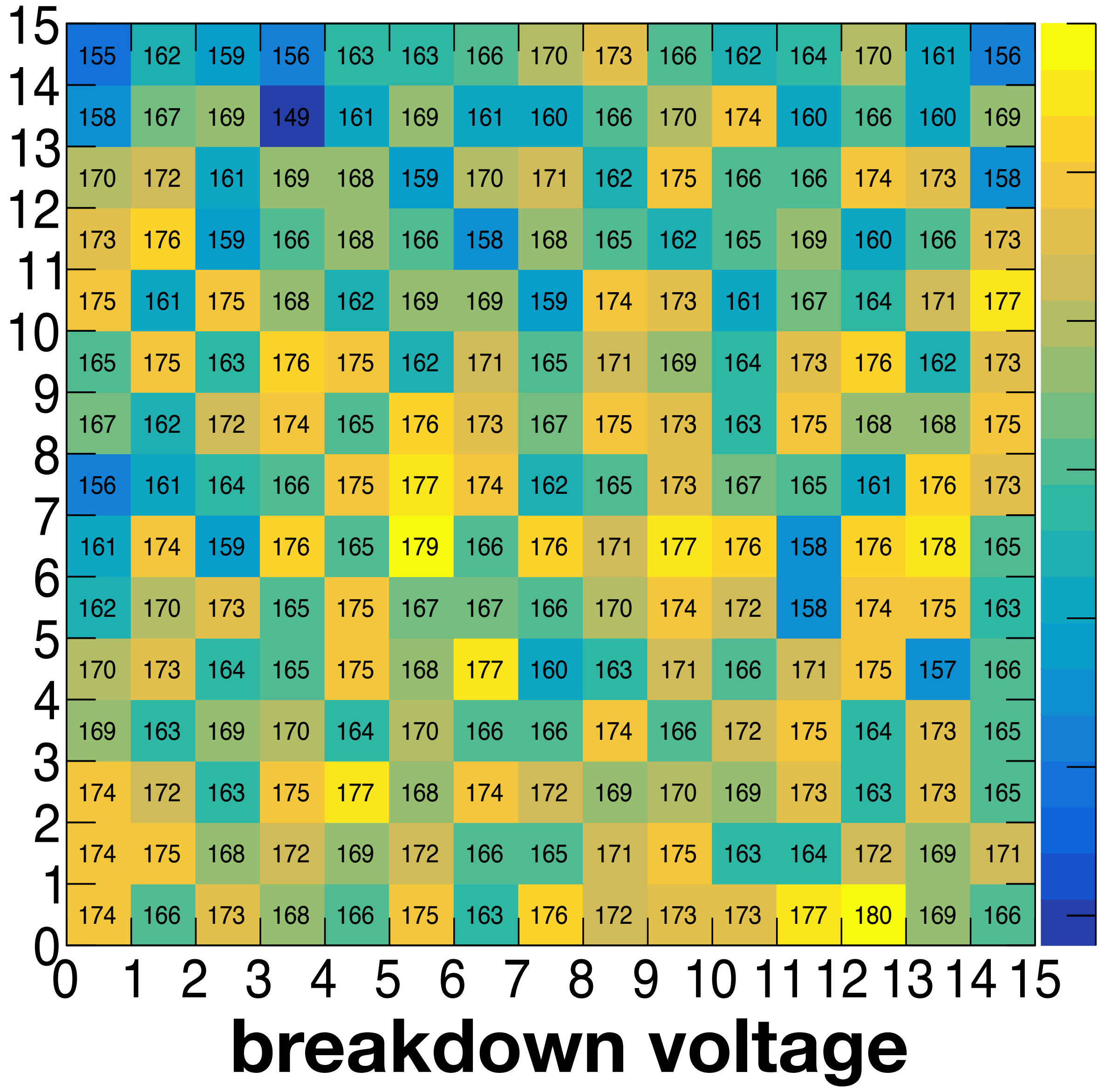
Mean: 405.7 V
RMS: 4.8 V

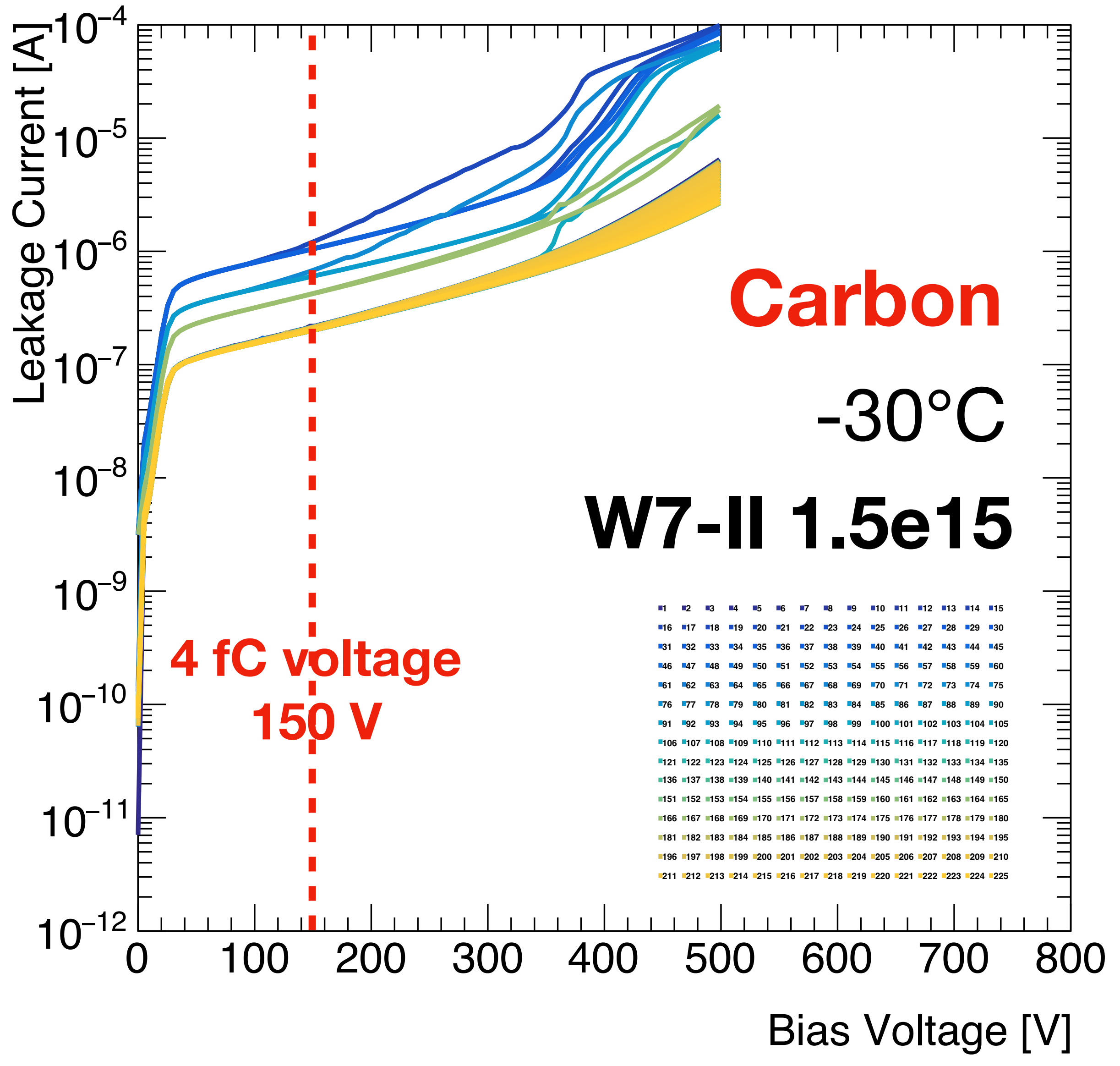
5x5 I-V after
different irradiation fluence

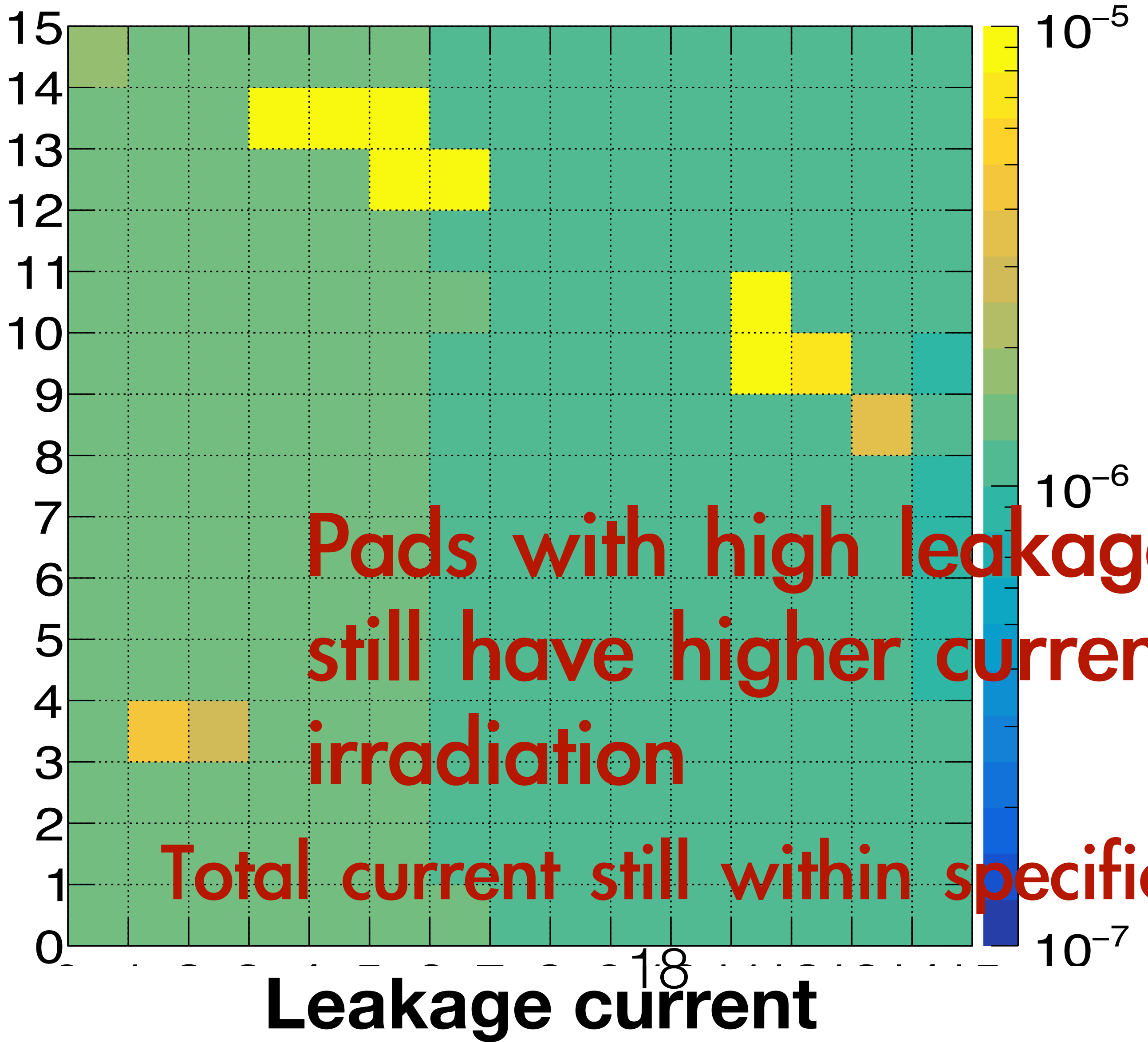
Large array sensor after radiation





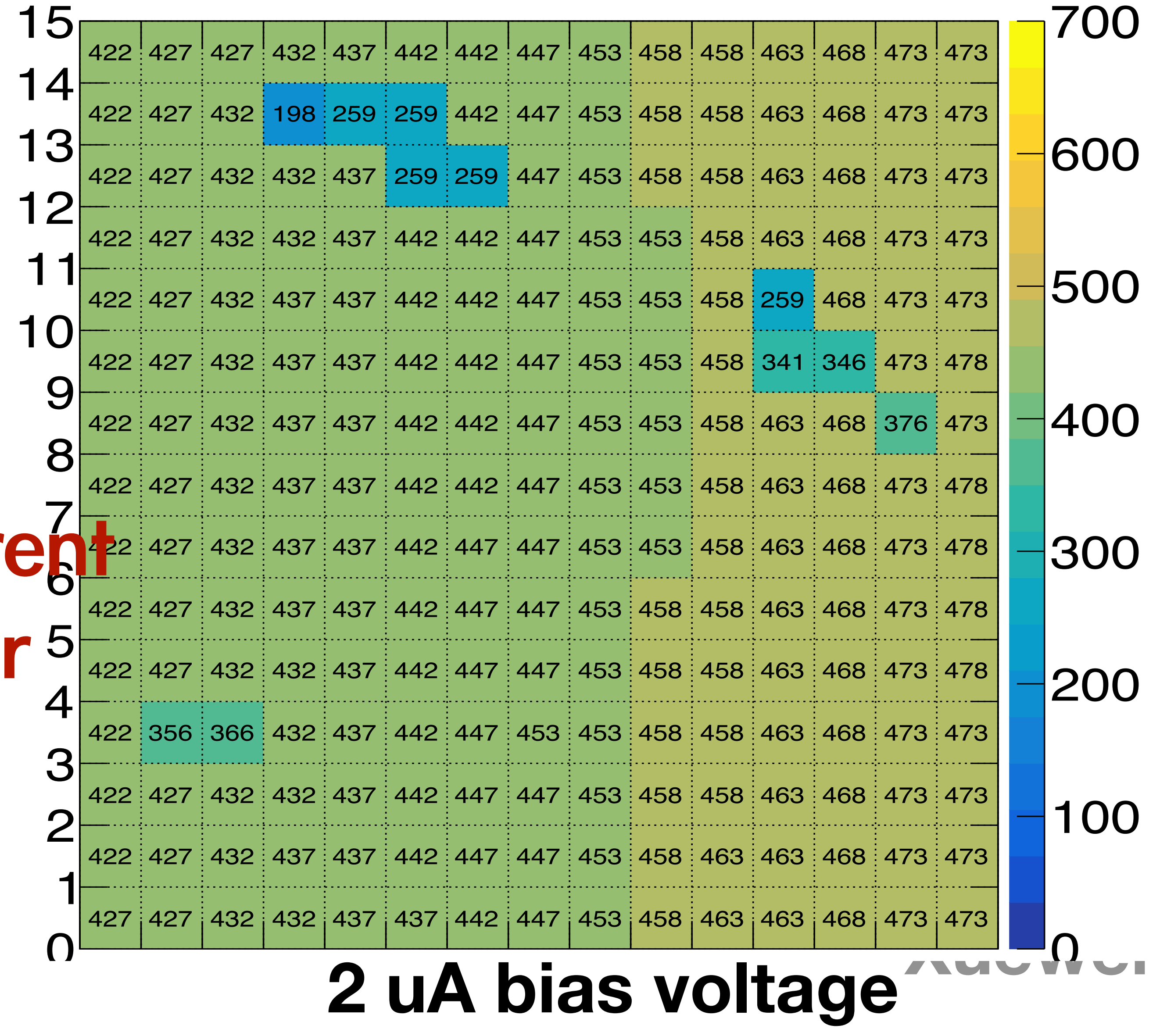






Pads with high leakage current still have higher current after irradiation

Total current still within specification



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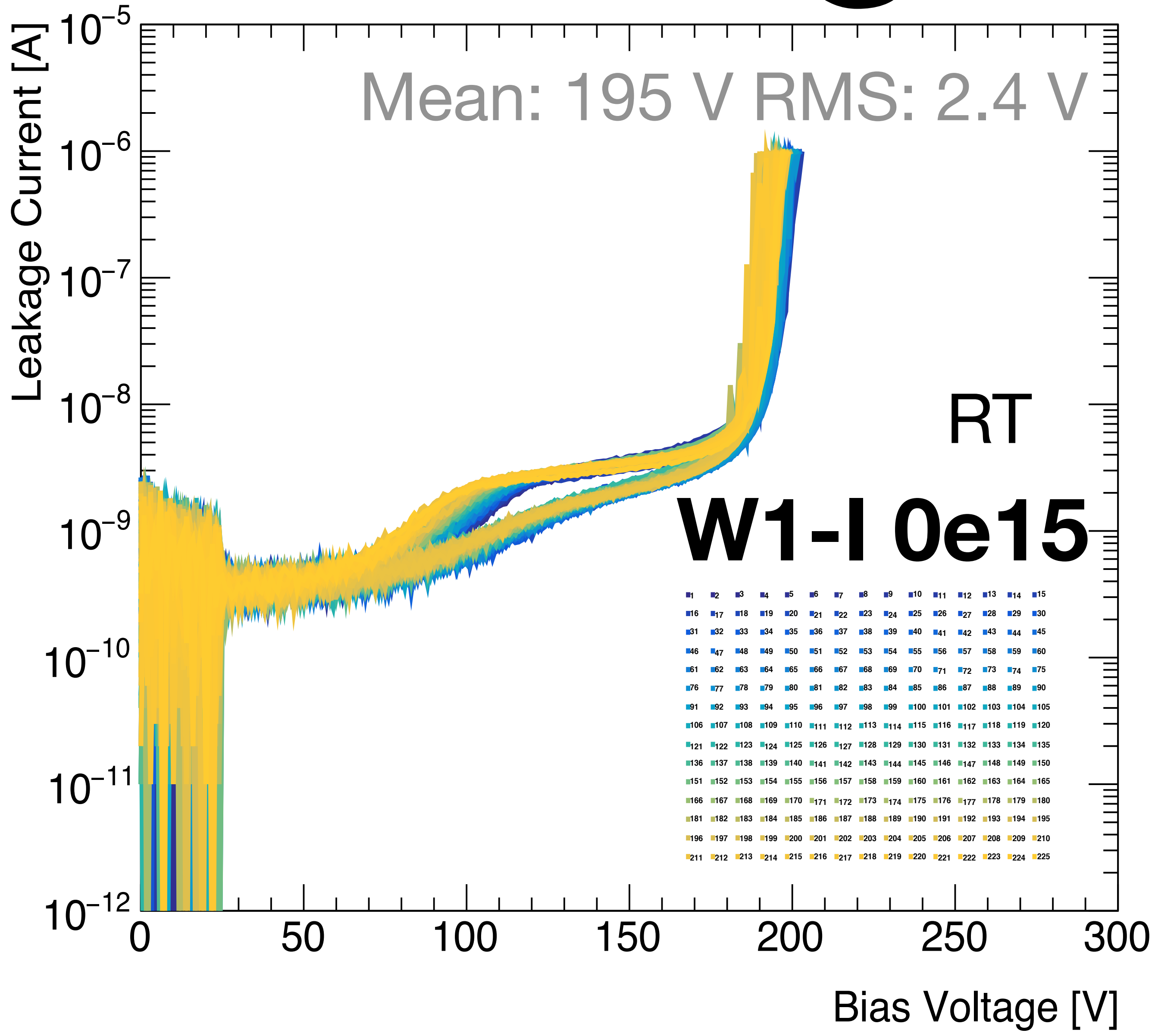
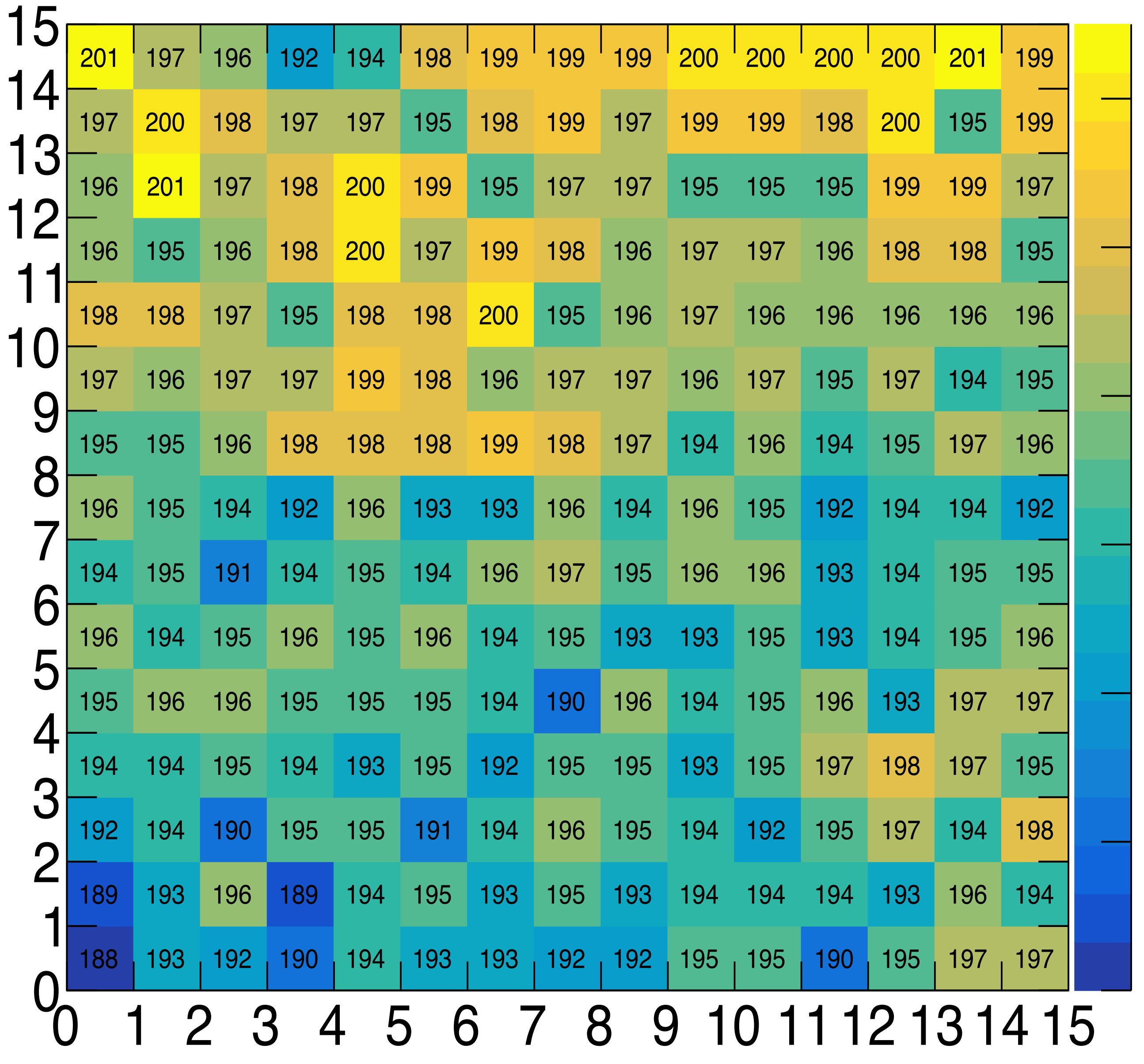
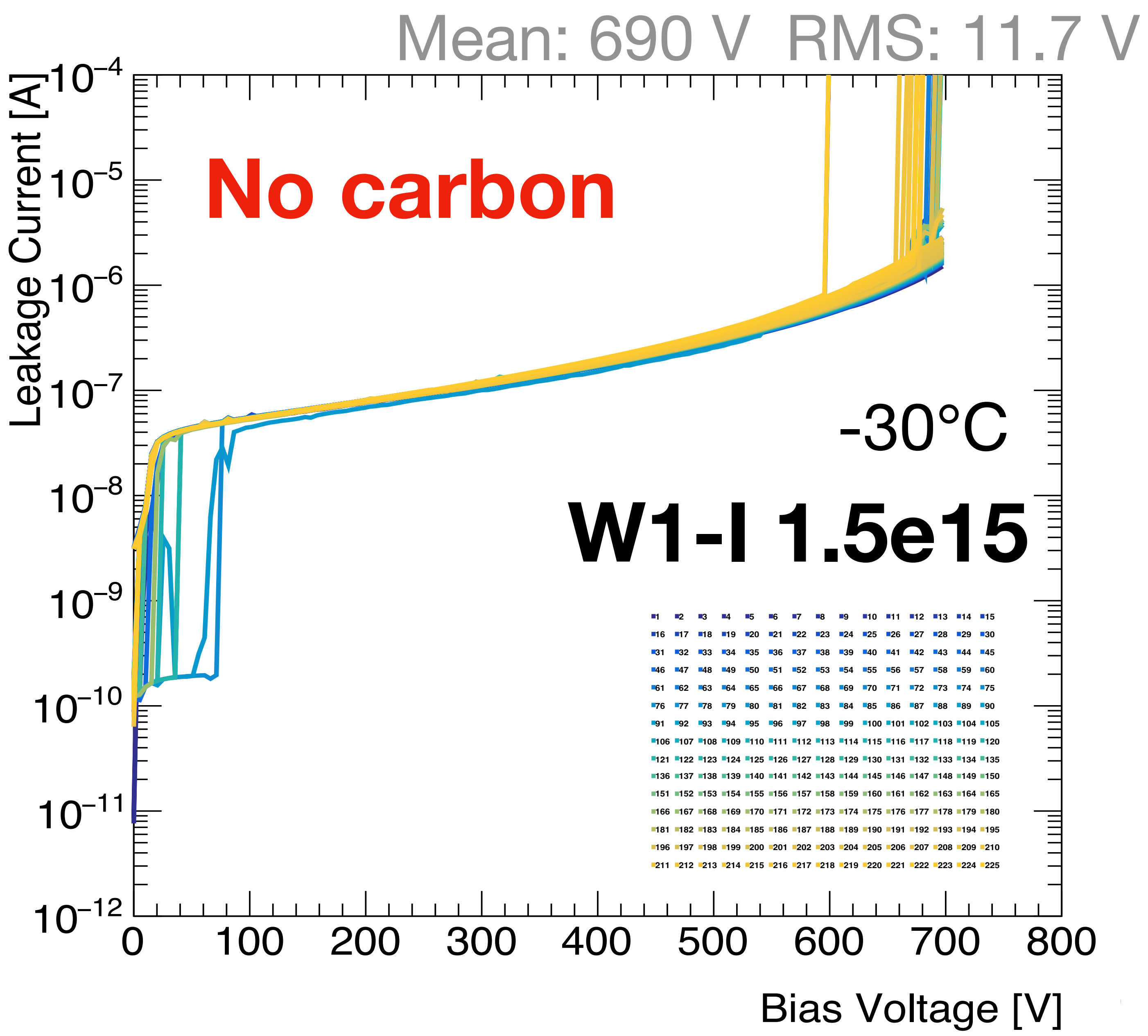
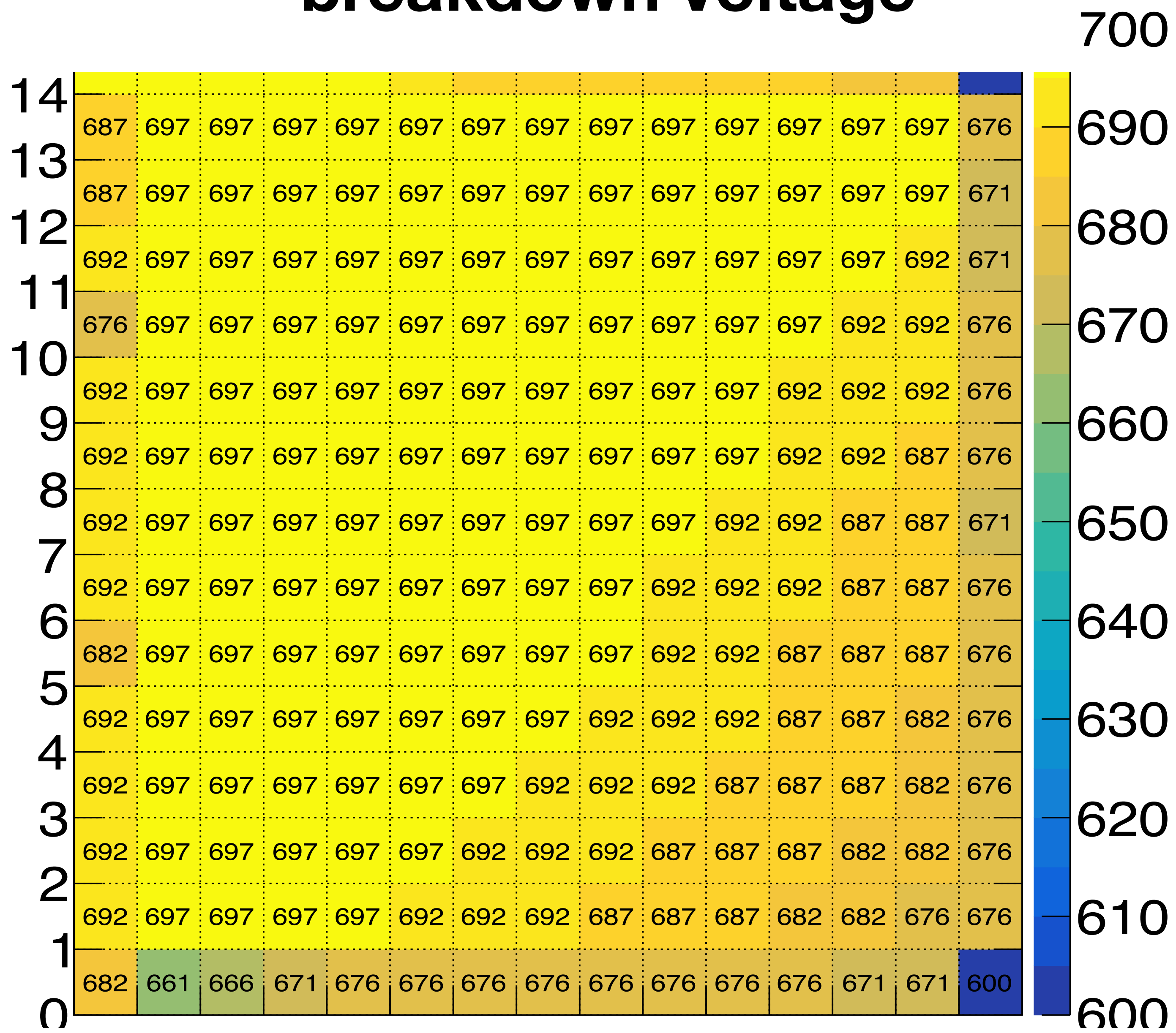
Large array sensor after radiation





breakdown voltage





- After 1.5e15, compared with the W7-II 2uA@405 V, shows that carbon makes the sensor more radiation hard.
- More uniformed I-V after irradiation. 2 uA@~700 V

Xuewei Jia

Large array sensor after radiation

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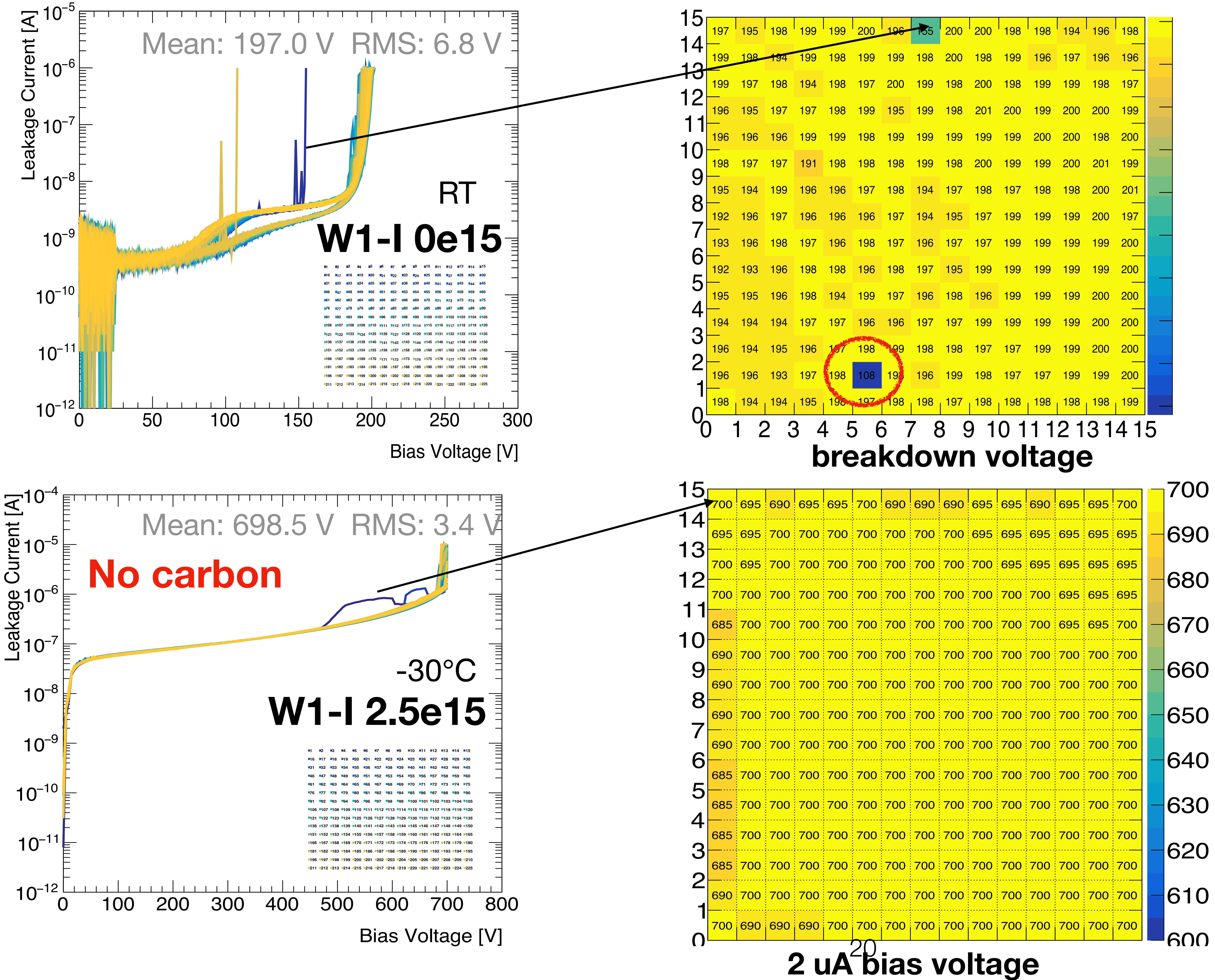

- After irradiation I-V curves became more uniformed because of the acceptor removal. The sensor requires higher voltage to operate. (~700 V)
- After 2.5e15, compared with the W7-II 2uA@525 V, shows that carbon implantation make the sensor more irradiation hard.

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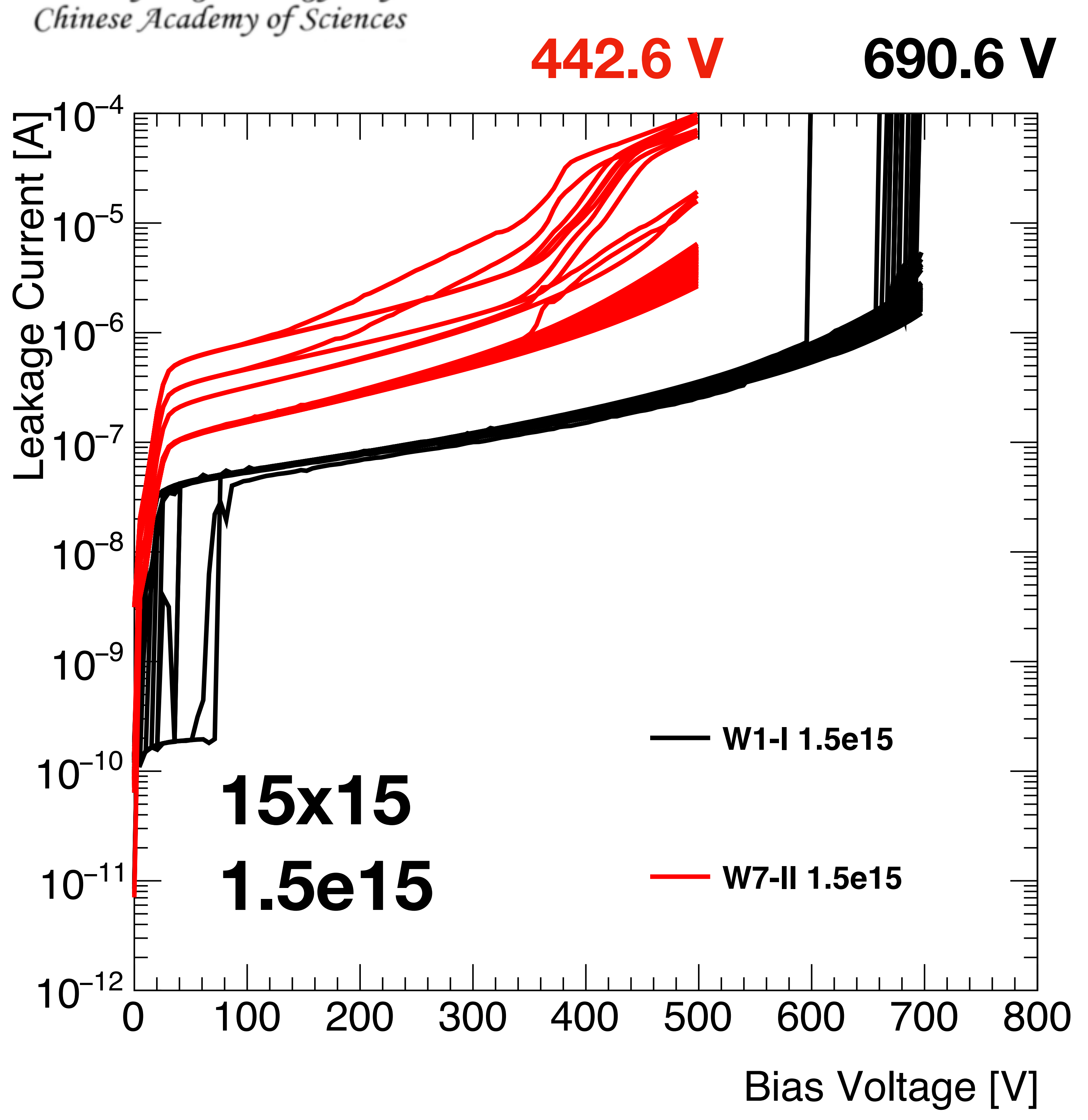
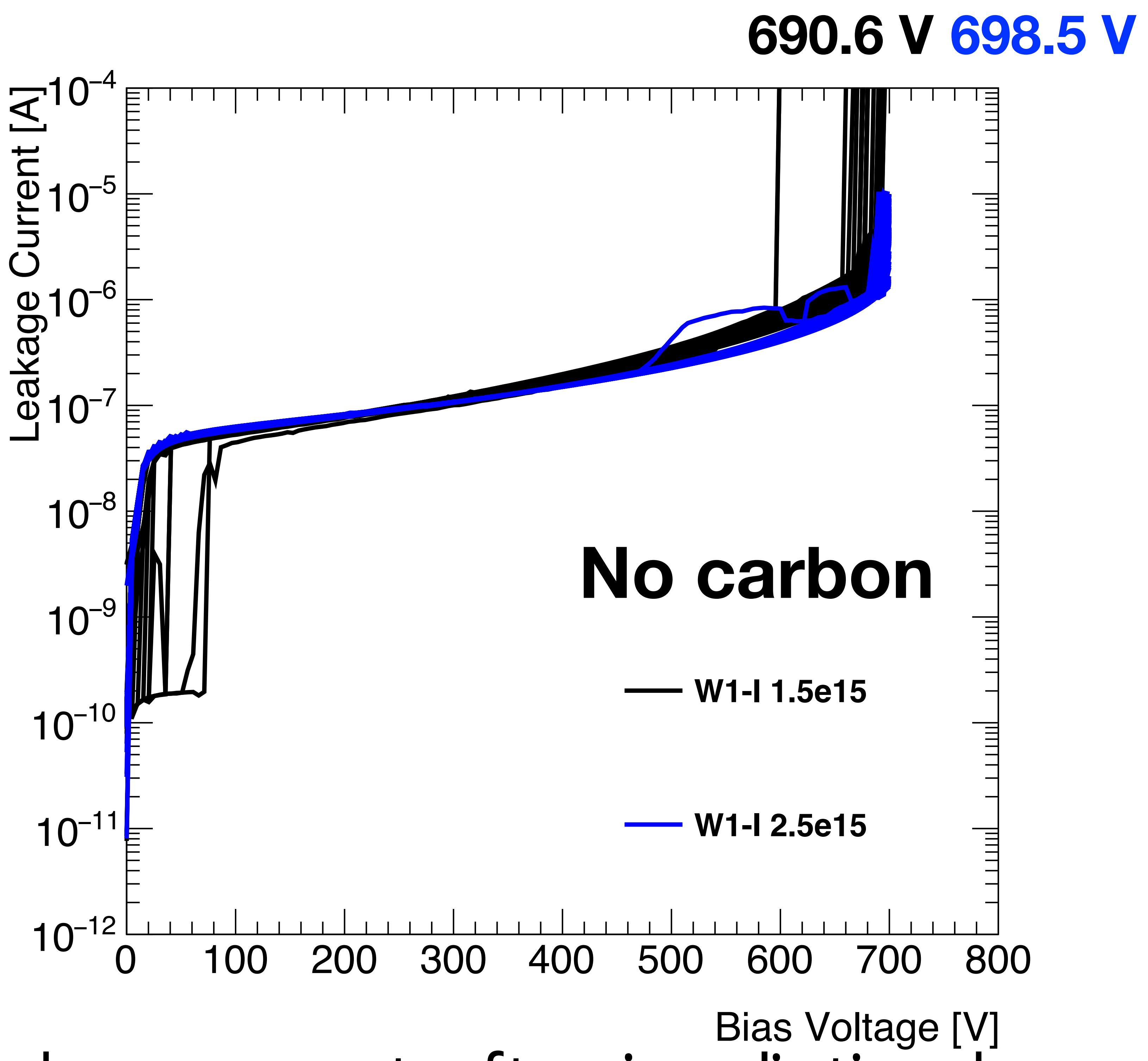
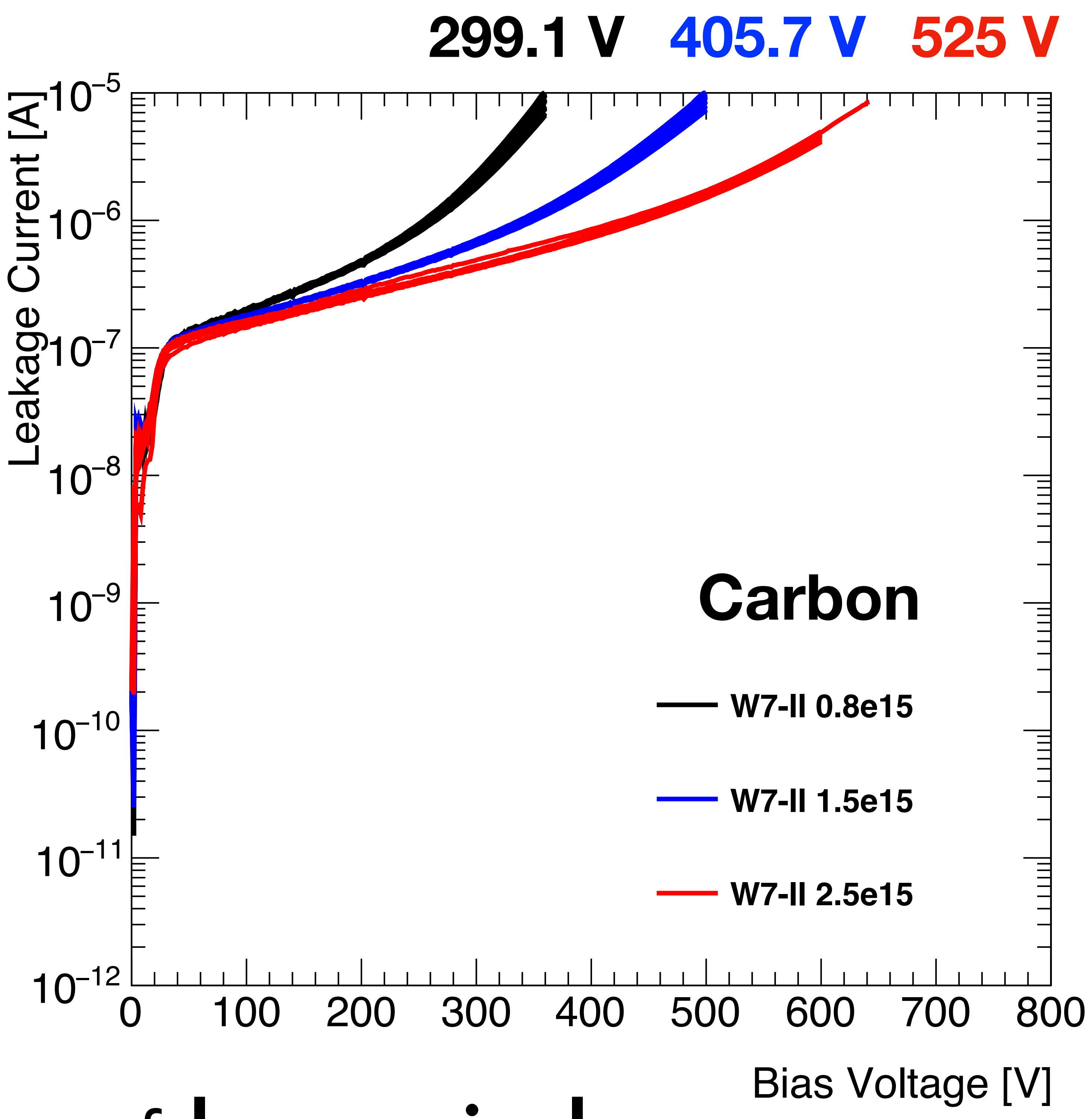
Large array sensor after radiation







- Carbon implanted sensor have higher current after irradiation because of **less gain loss**.
- The working voltage of carbon implanted sensor is much lower.
- Sensor without carbon after different fluence radiation, the I-V difference is small, since most of the gain was lost.
- While the sensor with carbon implantation after different fluence radiation are quite different, since the more gain was kept after radiation. ⟷ Radiation hard

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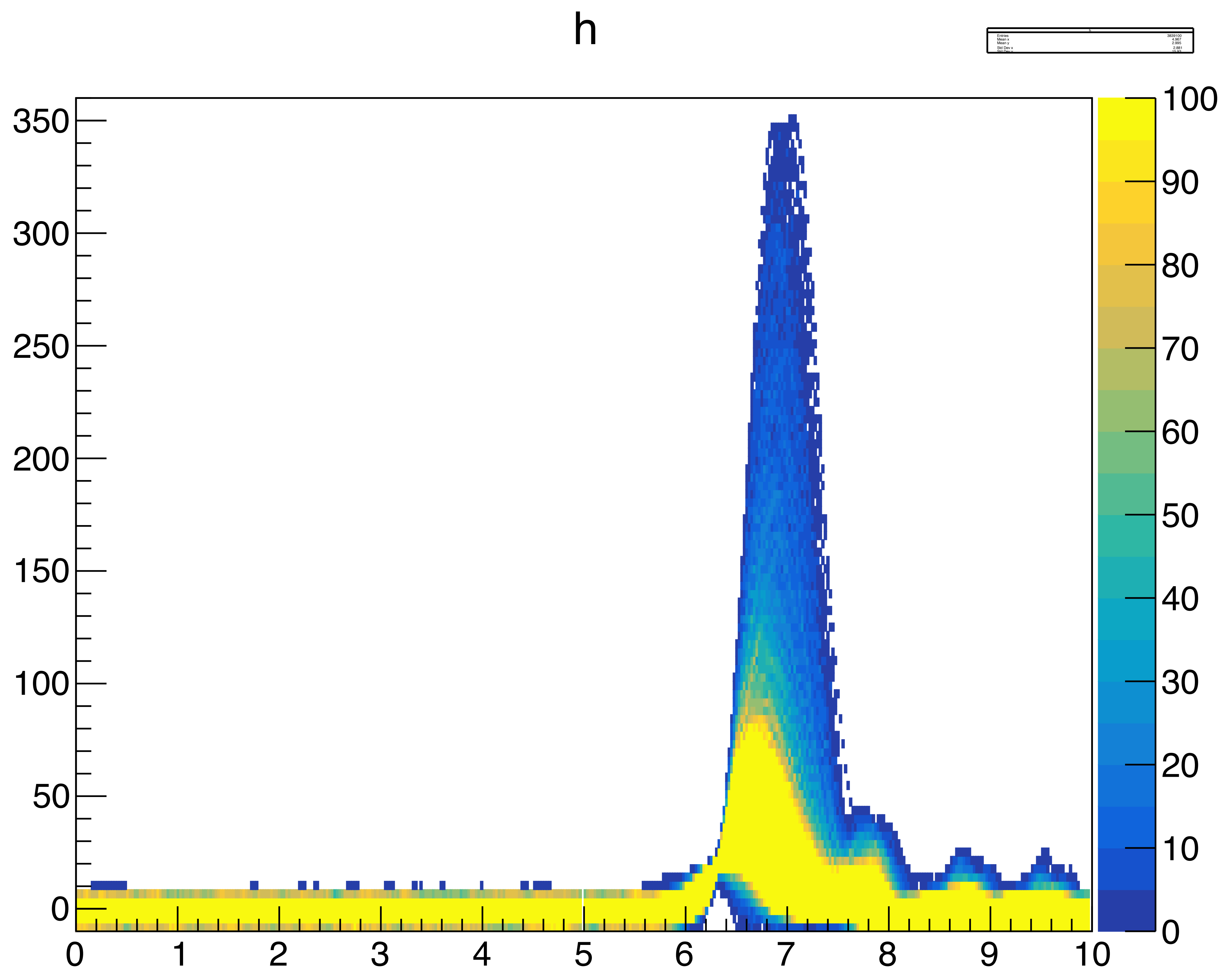
Summary

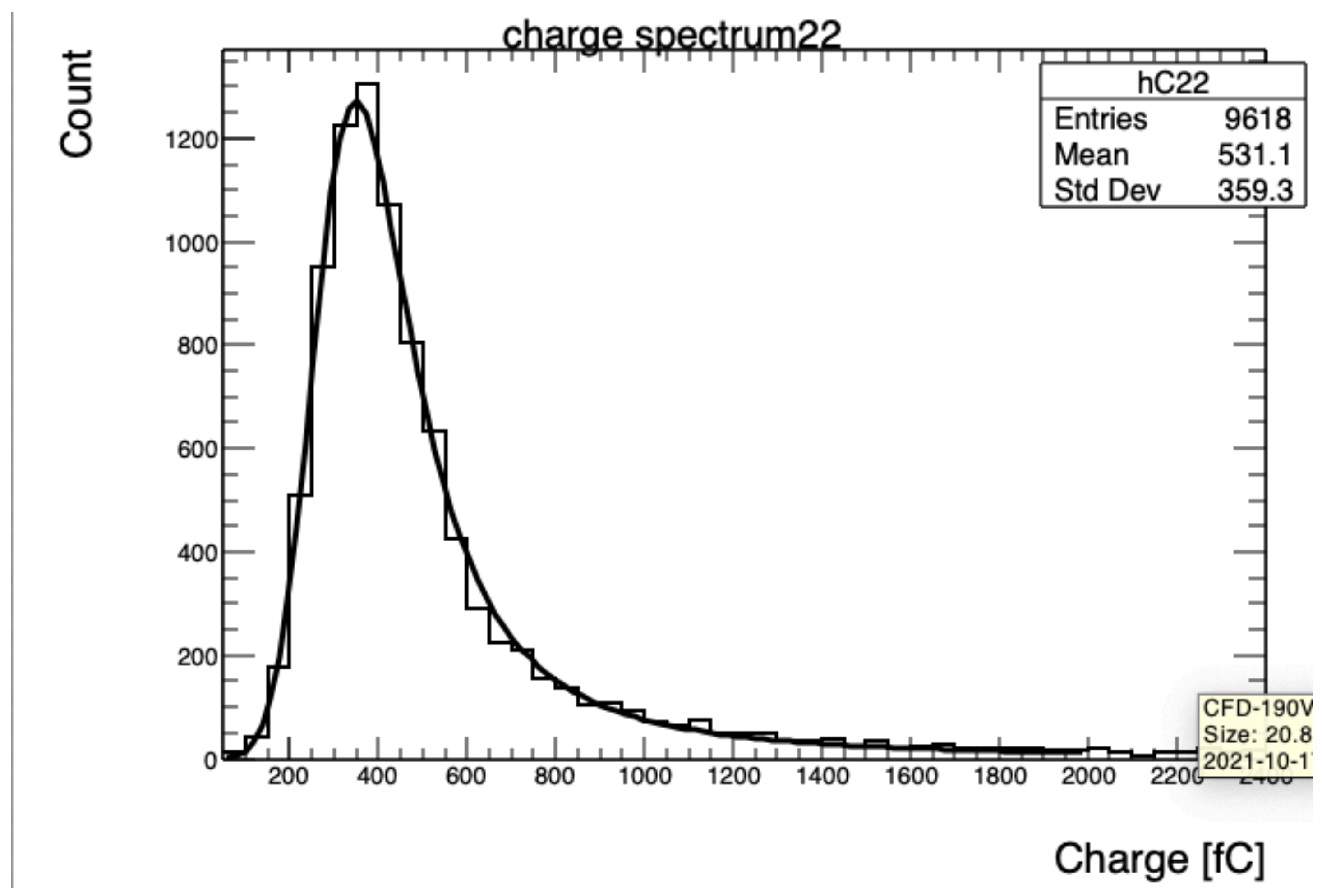
- IHEP-IME LGAD sensors showed promising results for the ATLAS HGTD project before and after irradiation. **Carbon implantation for the irradiation hardness was optimized.**
- Before irradiation:
  - When carbon dose increase:
    - the leakage current increase
    - the breakdown voltage decrease
    - the Vgl increase
  - Best time resolution ~ 40 ps, charge collection 〉35 fC
  - Large array sensor satisfy the HGTD requirements
- After irradiation:
  - IHEP-IMEv2 W7-II has the best performance
    - with acceptor removal 1.2.
    - 4 fC@350V(2.5e15)/150V(1.5 e15), ~50 ps.
    - Satisfied all the requirements for HGTD including the SEB one, within safety margin
  - Long annealing overall more radiation hard than fast annealing though before irradiation they are close.
  - Large array sensor have more uniformed I-V because of the gain loss, however the ones with carbon implantation can still keep some characteristics, validating the carbon's role in improving the radiation hardness.

Back-up

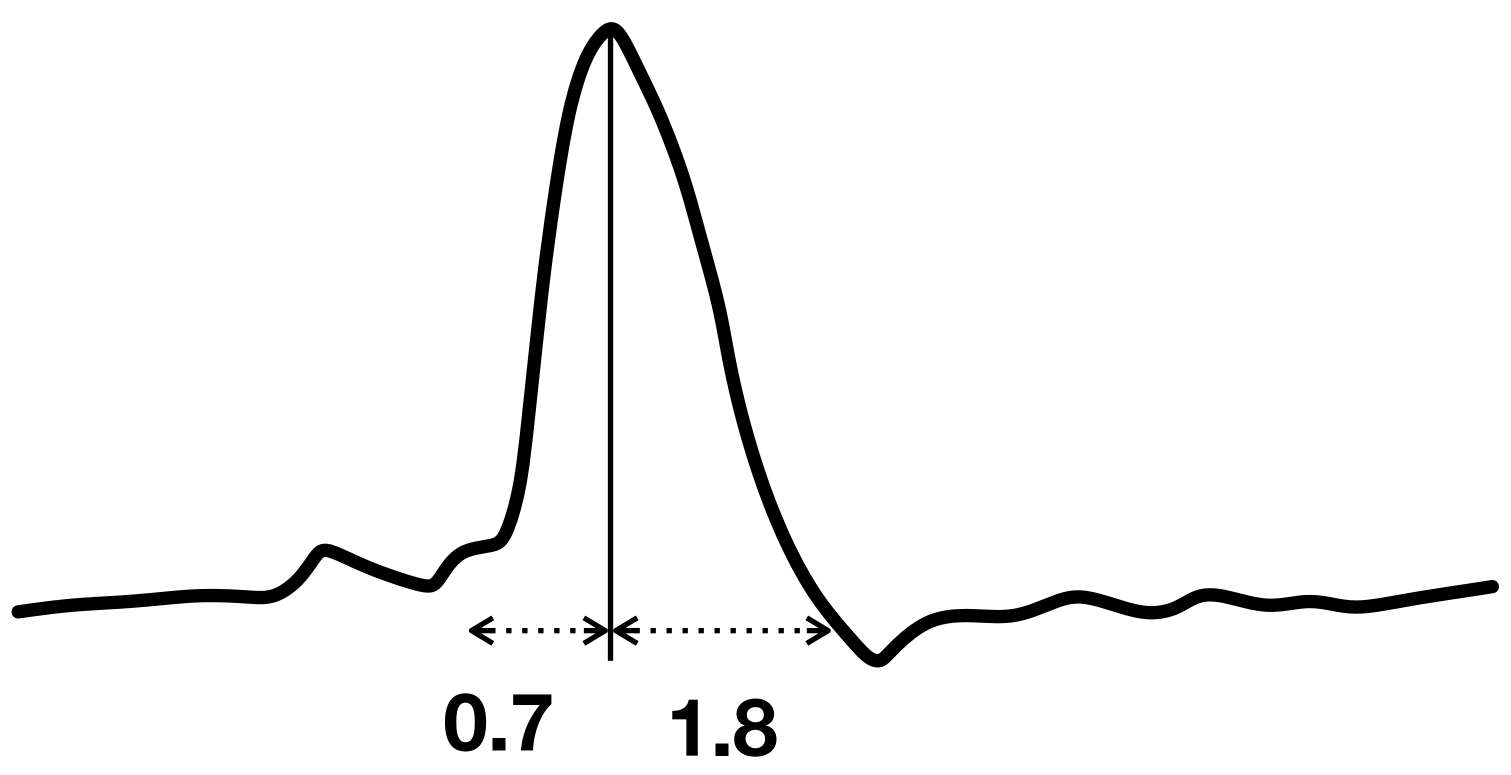
Charge



h
350
300
250
200
150
100
50
0
0 1 2 3 4 5 6 7 8 9 10
100
90
80
70
60
50
40
30
20
10
0



charge spectrum22
Count
hC22
Entries 9618
Mean 531.1
Std Dev 359.3
1200
1000
800
600
400
200
0
200 400 600 800 1000 1200 1400 1600 1800 2000 2200
Charge [fC]

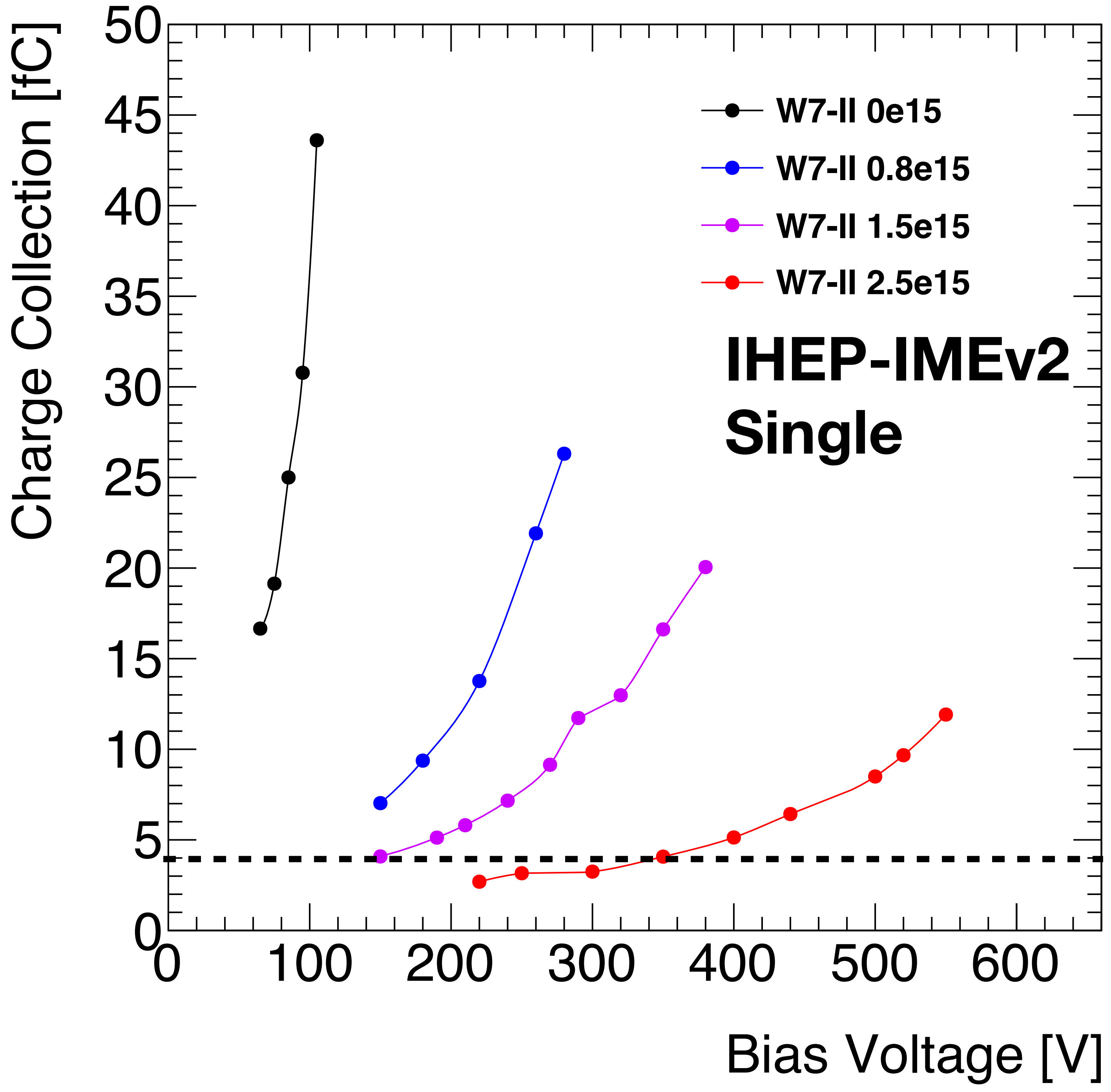


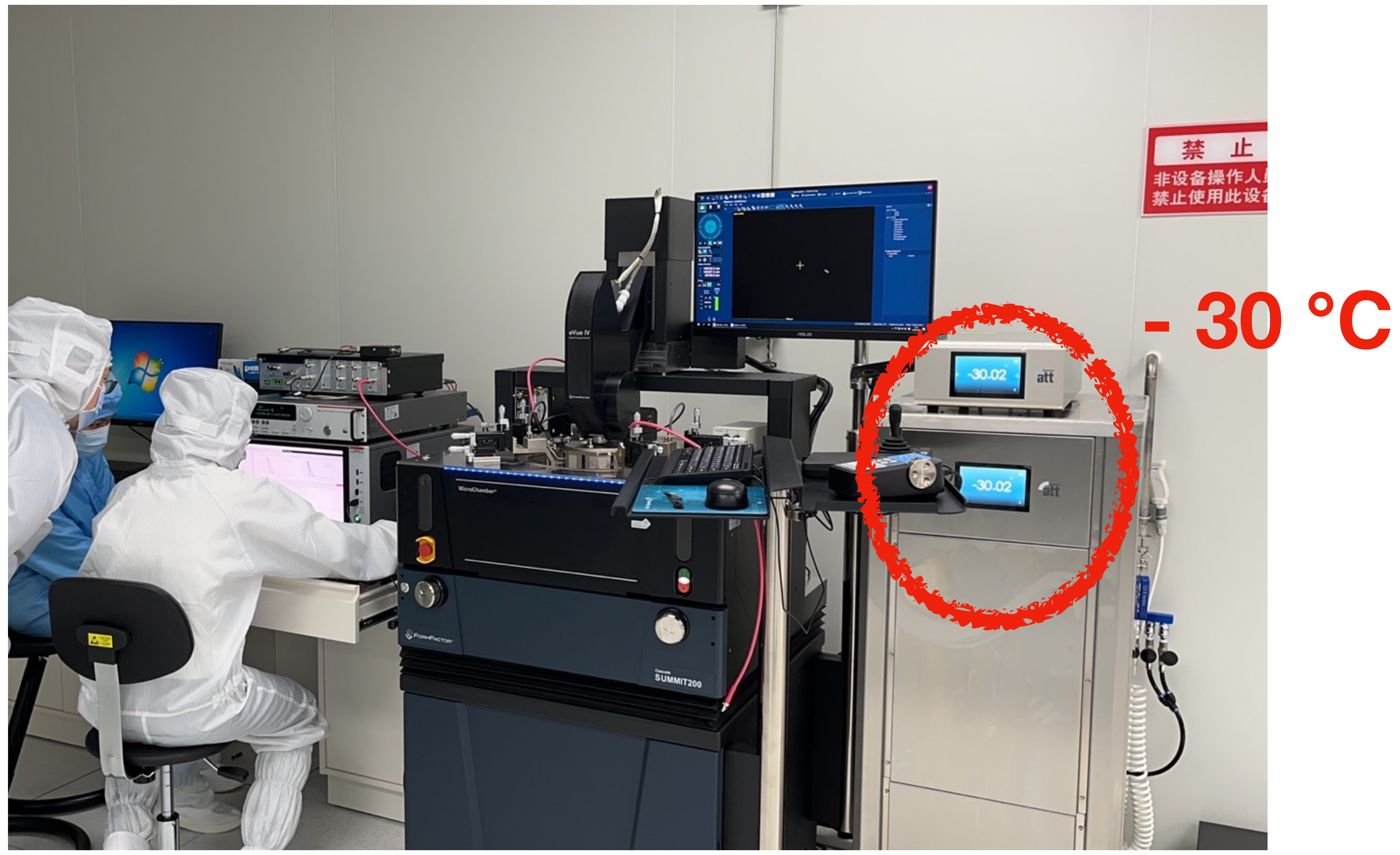
0.7
1.8

IHEP-IMEv2 Introduction

- IHEP-IMEv2:
  - W1 without carbon implantation
  - W7 carbon long annealing

W7-II(0.5C) 4 fC@
~100 V (0.8e15); 150 V (1.5e15); 350 V (2.5e15)





Carbonated sensor performance after irradiation

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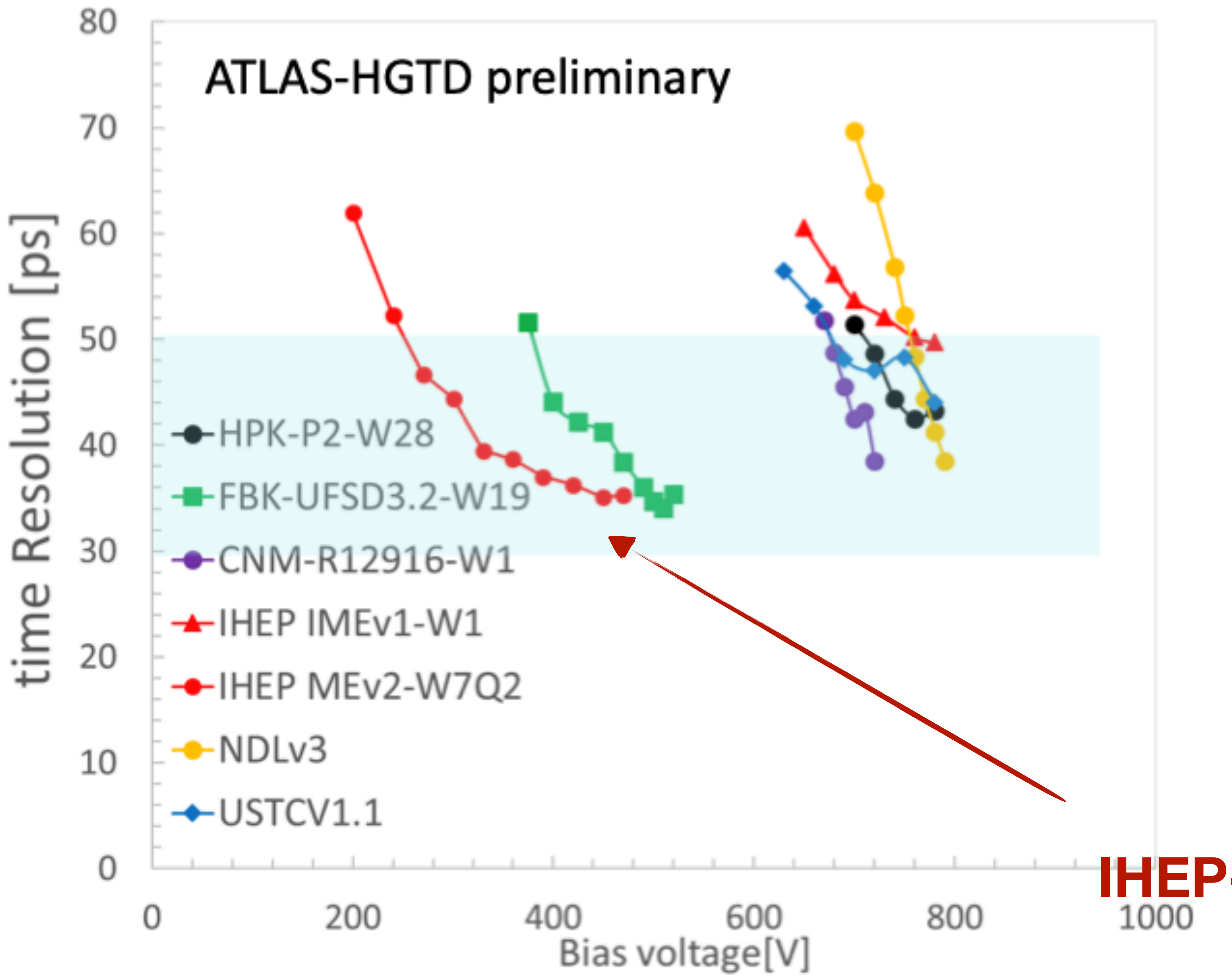
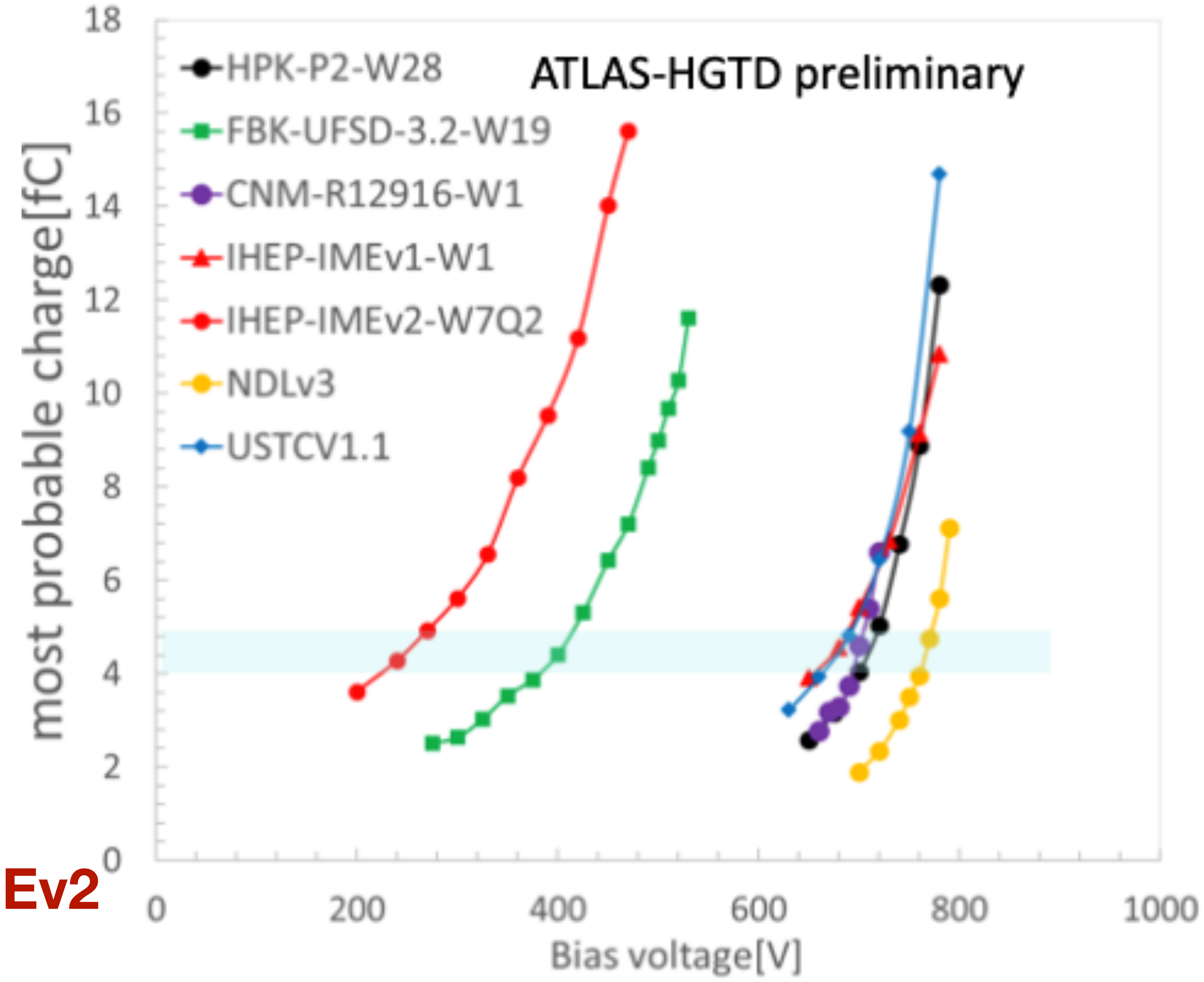
After 2.5e15 irradiation:



IHEP-IMEv2



Lower operation voltage save more power.
Also good for mortality in the testbeam.

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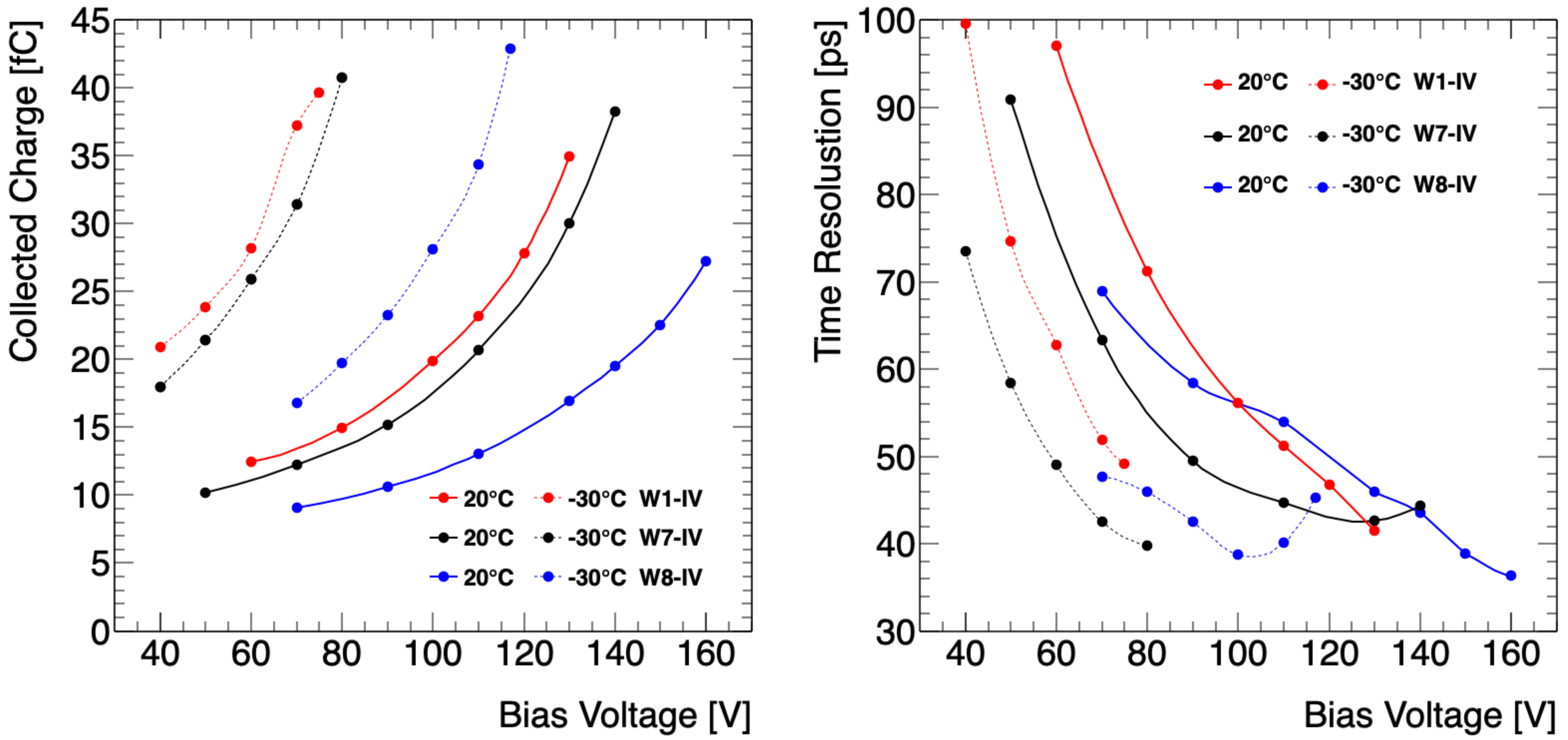

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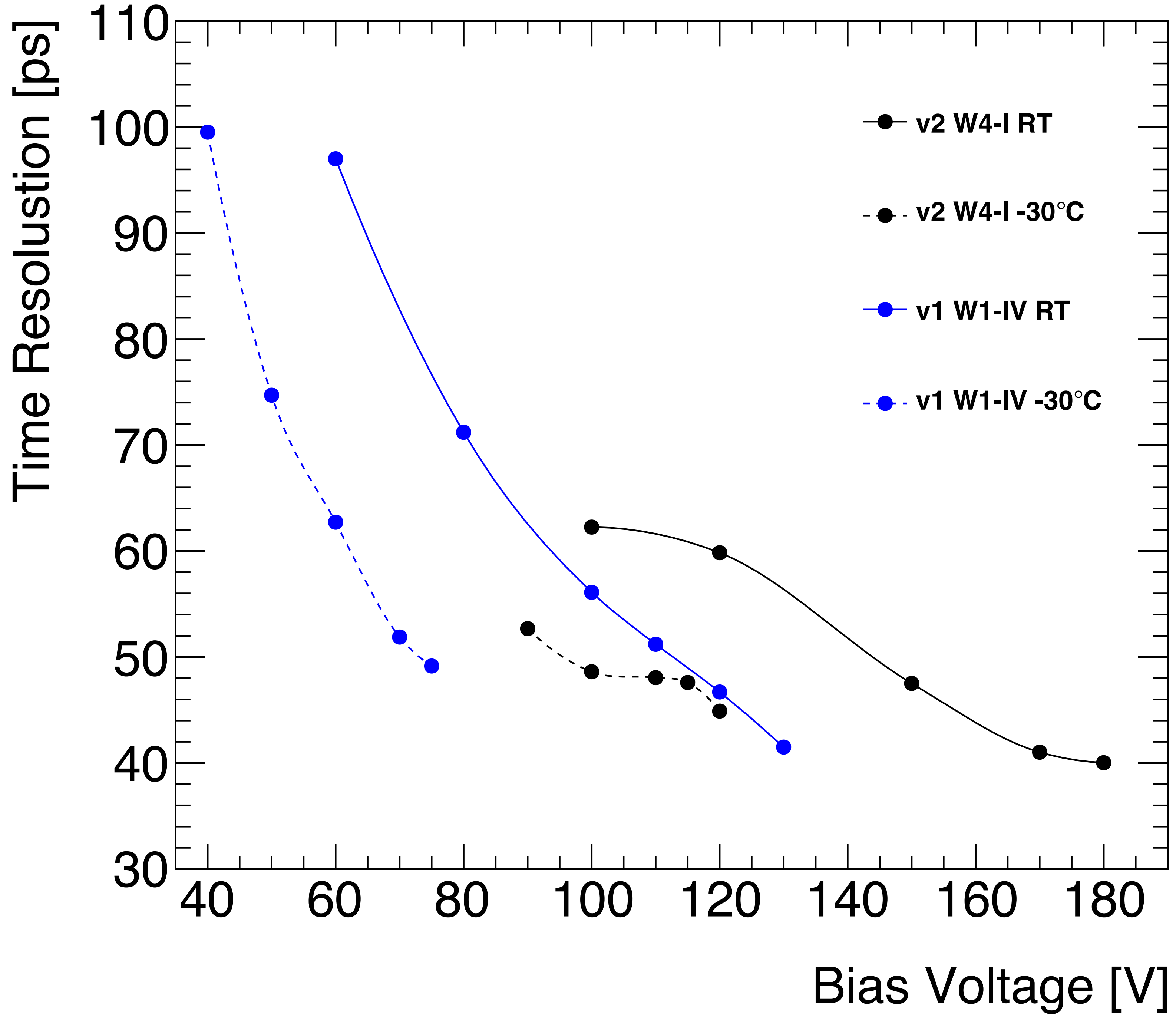
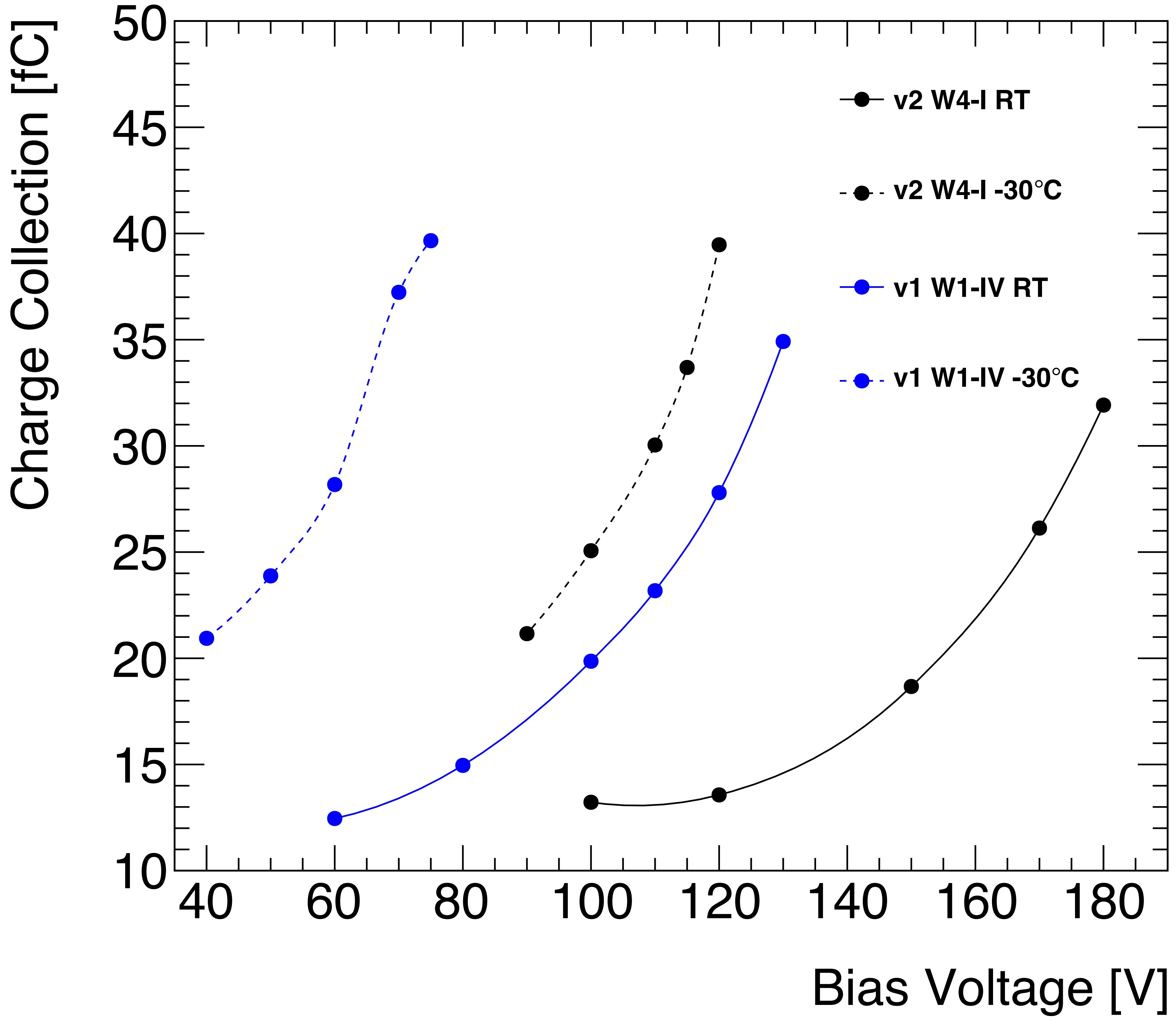
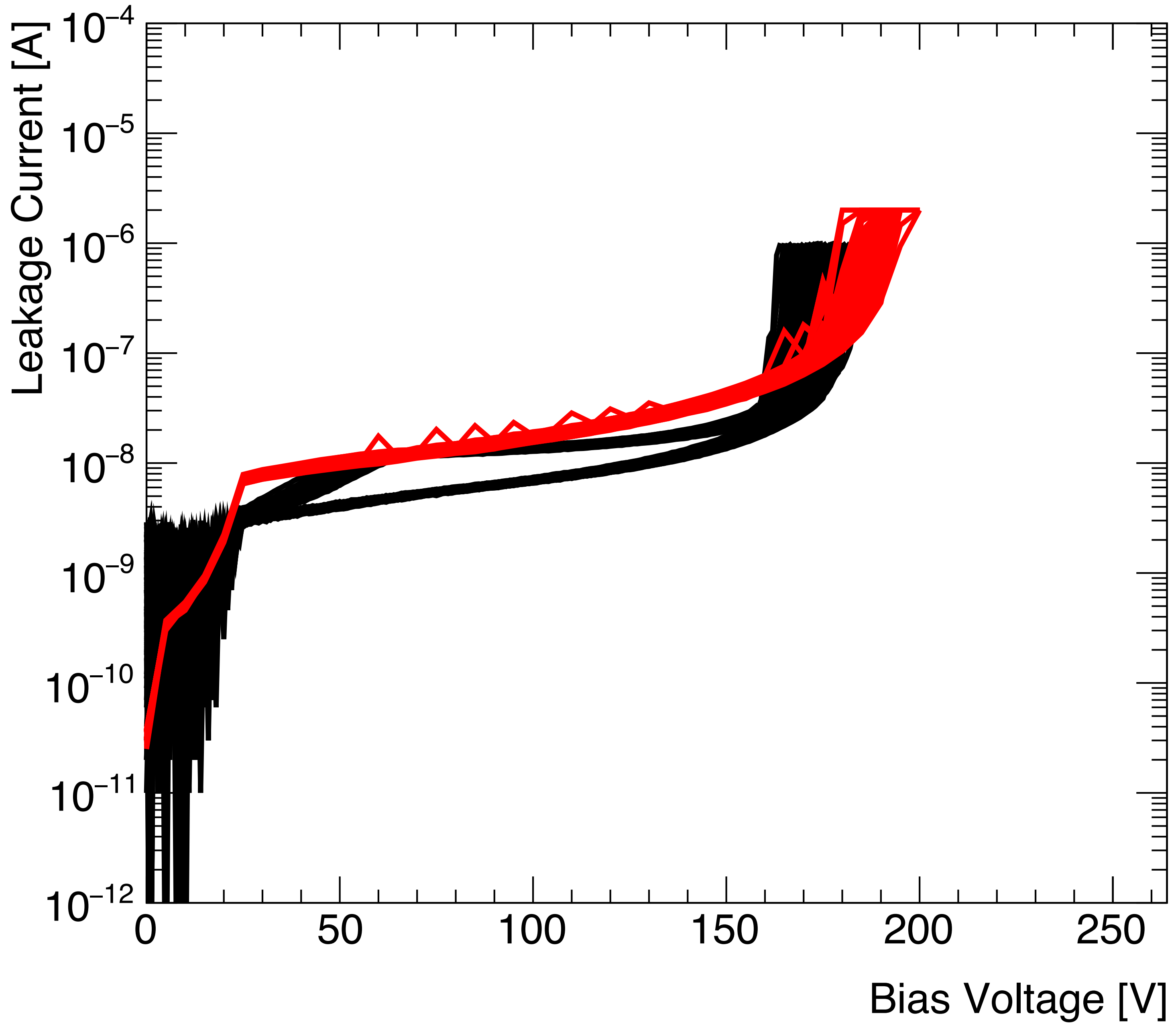
Before irradiation



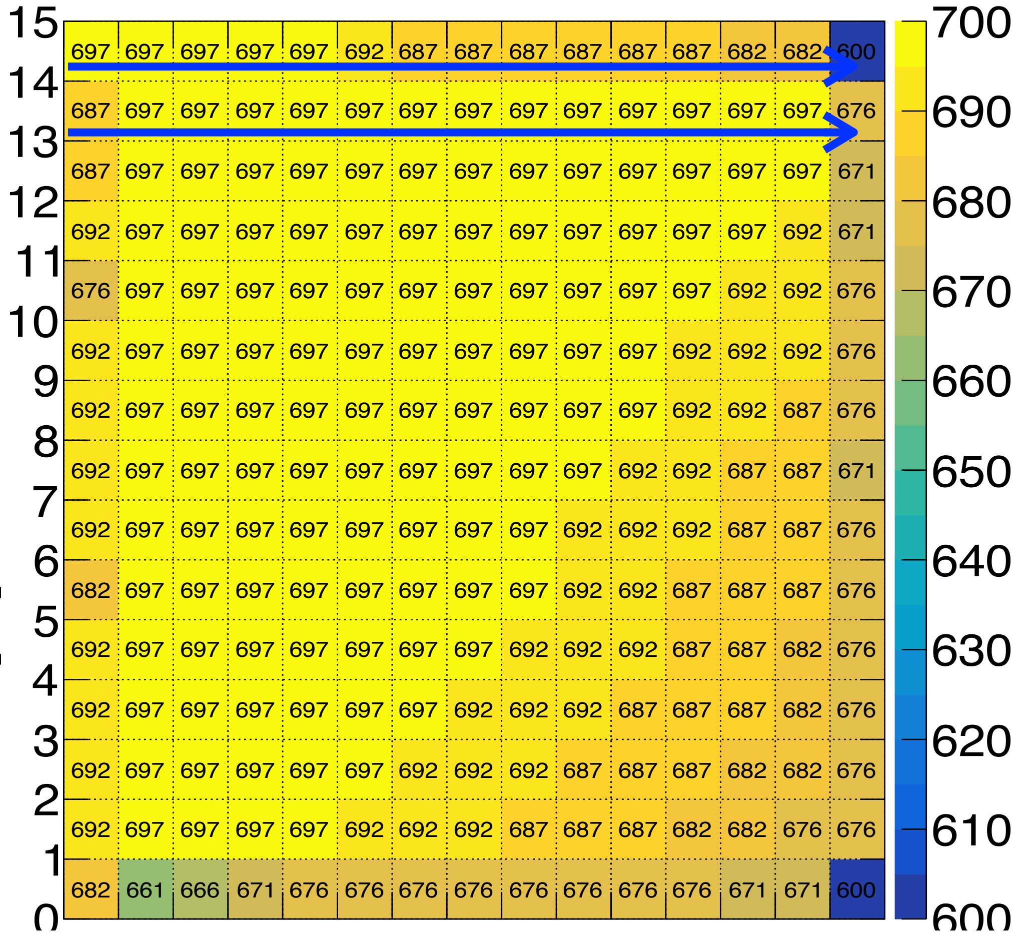
Before irradiation

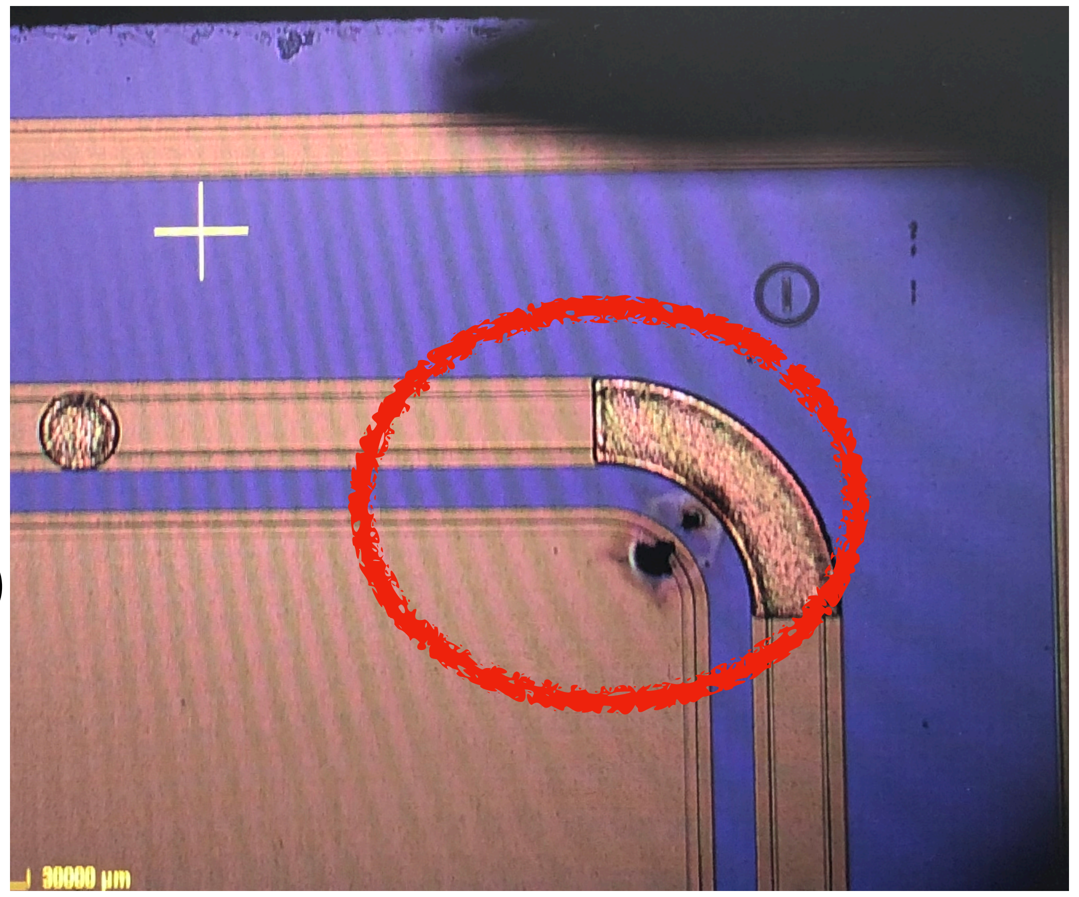


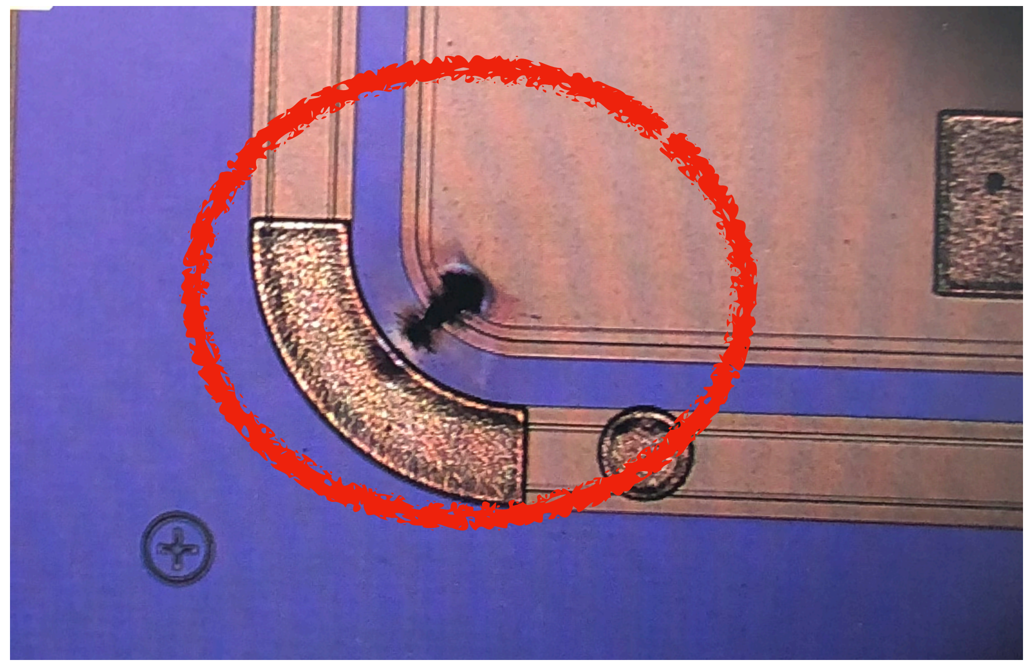


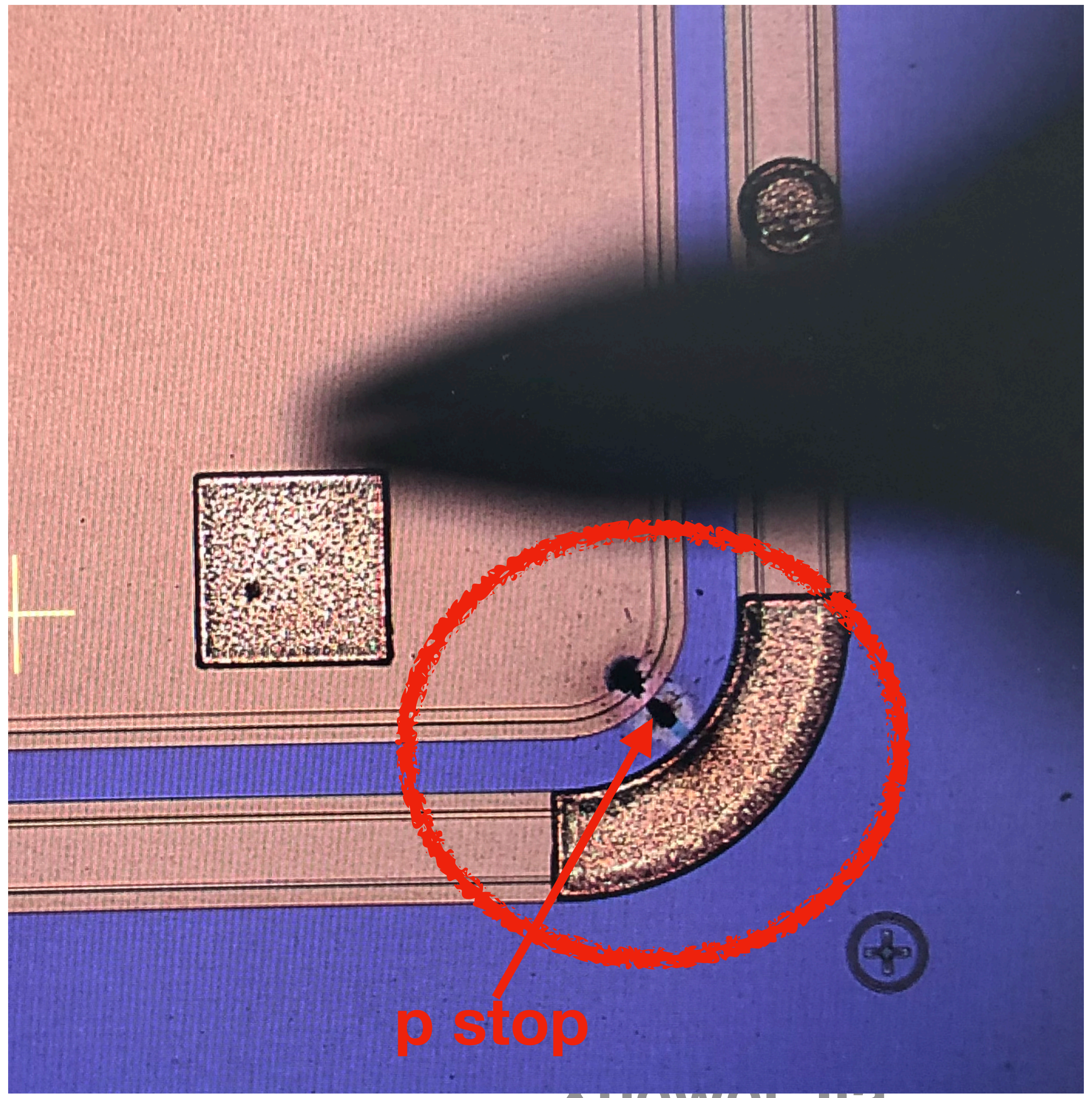
15x15 I-V after irradiation

- W1-I, without carbon, after 1.5e1
- The test started from the up left co … to corner row by row.
- 〔0,700V〕 5V step
- In total took 2h13min
- Burn marks in the corner

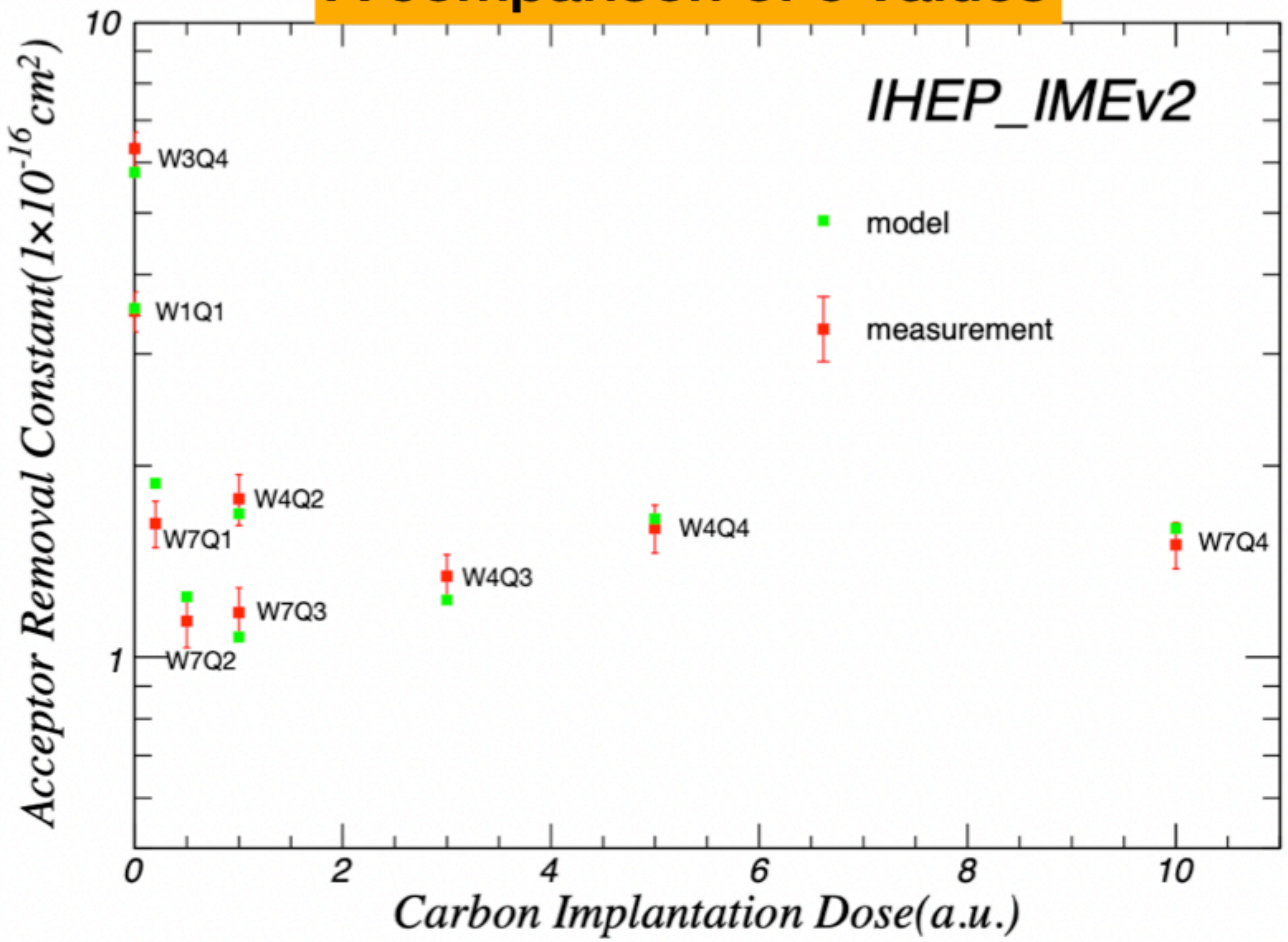








A comparison of c values



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