

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Before and after irradiation test results of the LGAD sensors developed by IHEP

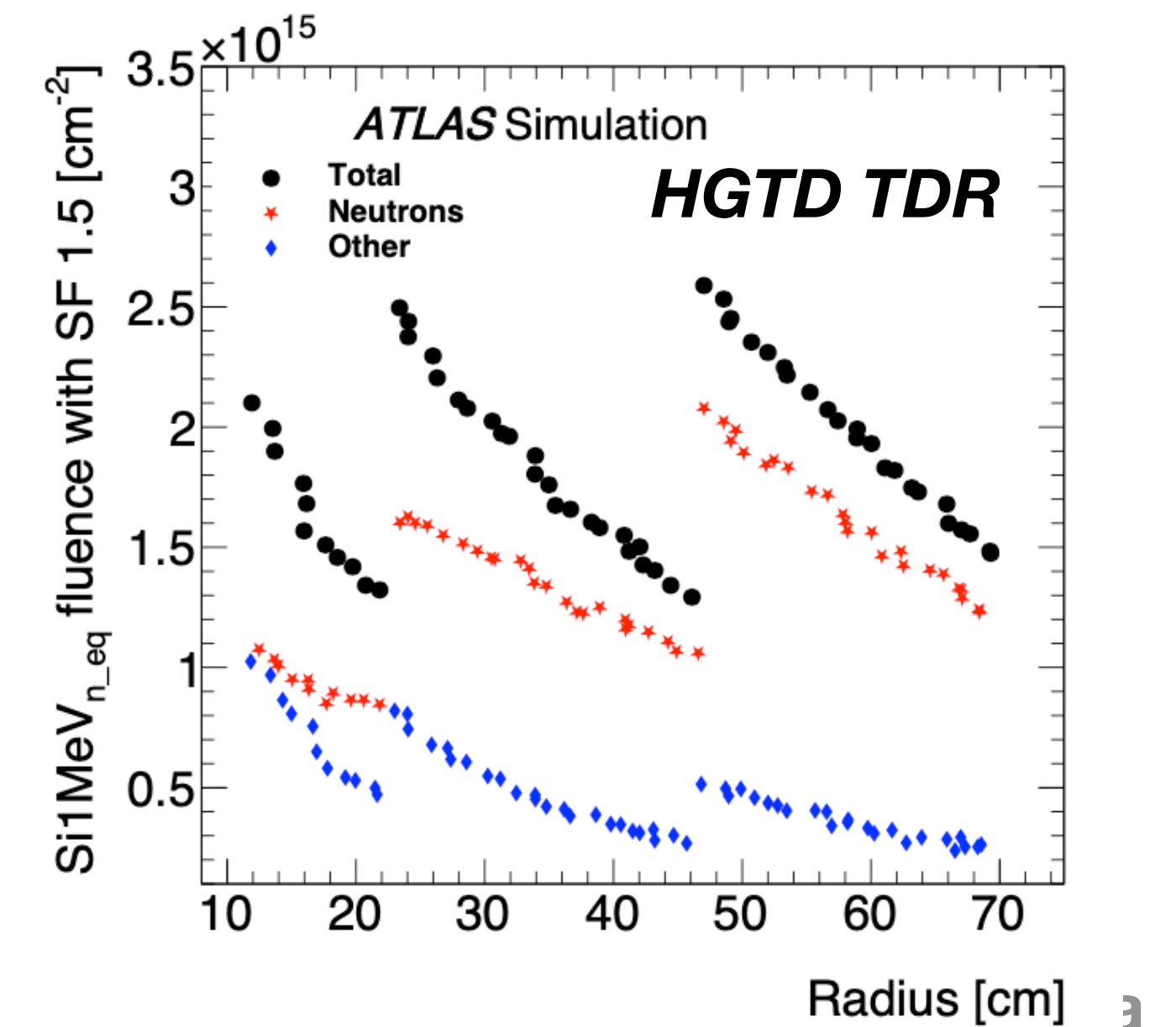
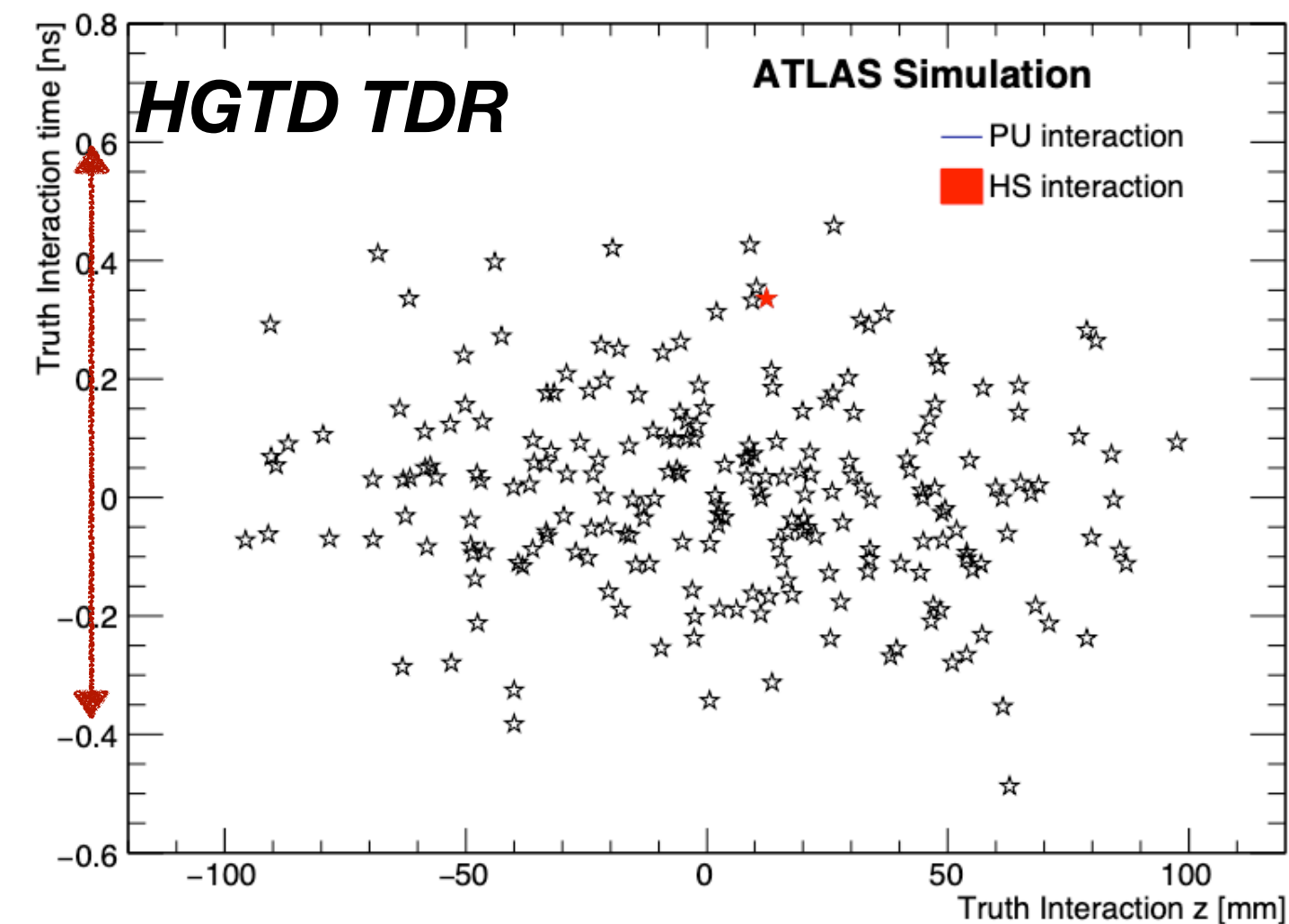
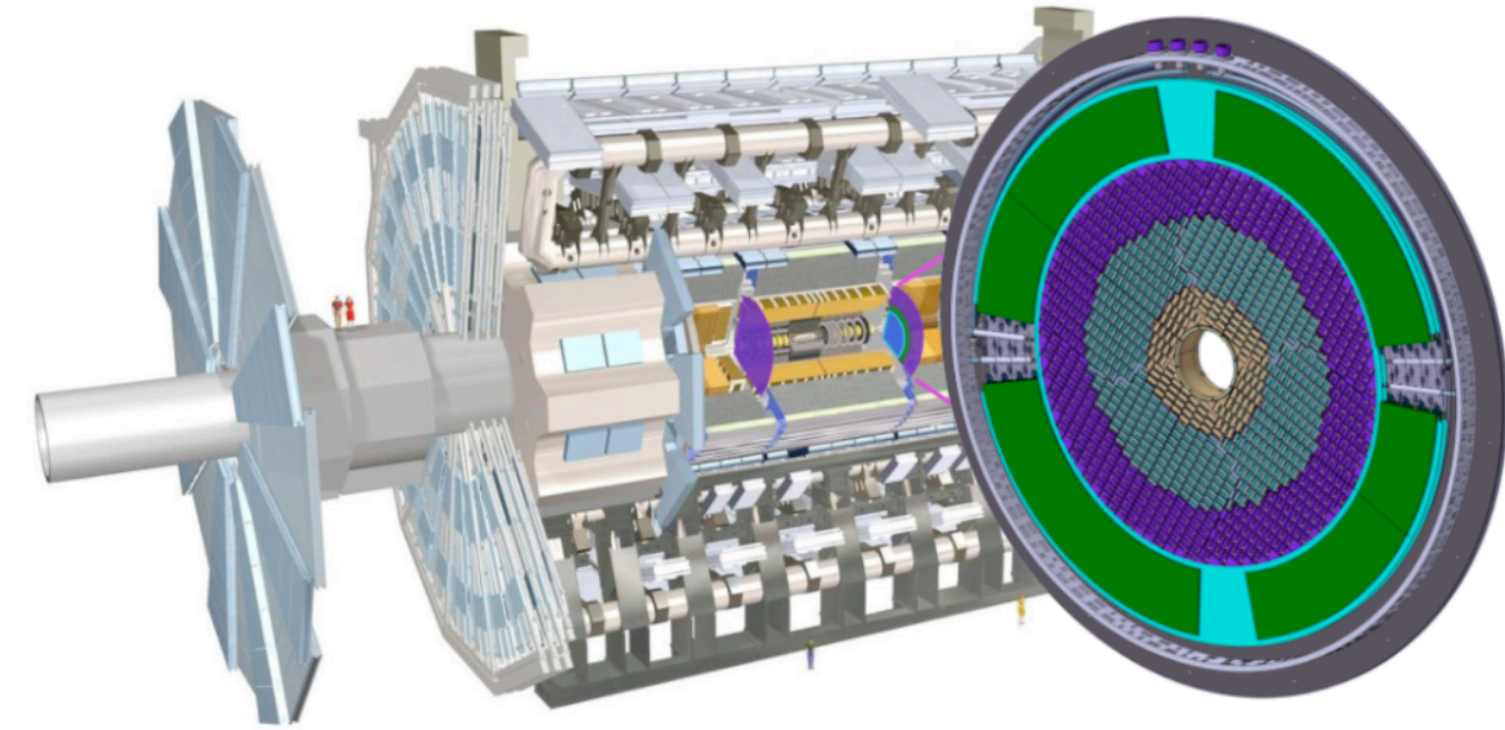
Xuwei Jia
2021/11/18

Outline

1. IHEP-IME LGAD sensors for the ATLAS HGTD
2. Carbon implanted sensors — IHEP-IMEv1
 - before and after irradiation
3. Carbon implanted sensors — IHEP-IMEv2
 - before and after irradiation
4. Summary

HGTD introduction and sensor requirements

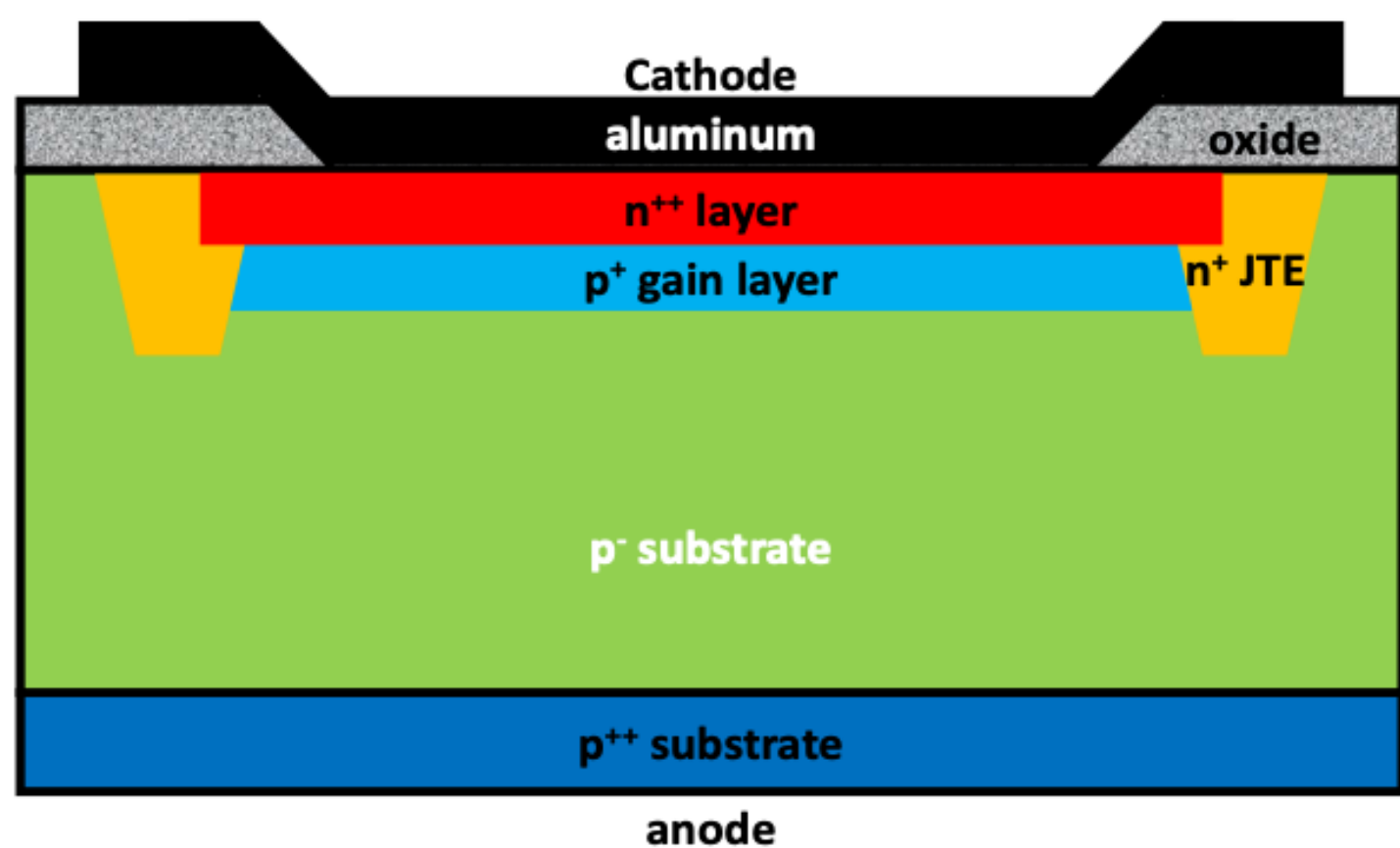
- **High-Granularity Timing Detector (HGTD)**: proposed for ATLAS phase II upgrade, to reduce the pile-up effect. Better time resolution to resolve primary vertex.
- Aiming at 30~50 ps per track.
- LGAD will be used as its sensing technology to provide the good time resolution, segmented into $1.3 \times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



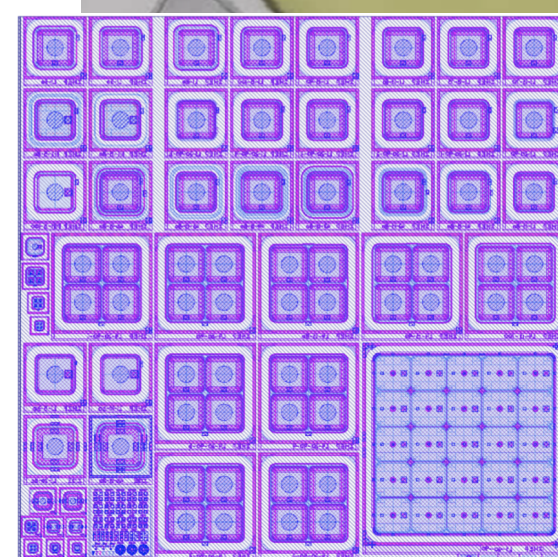
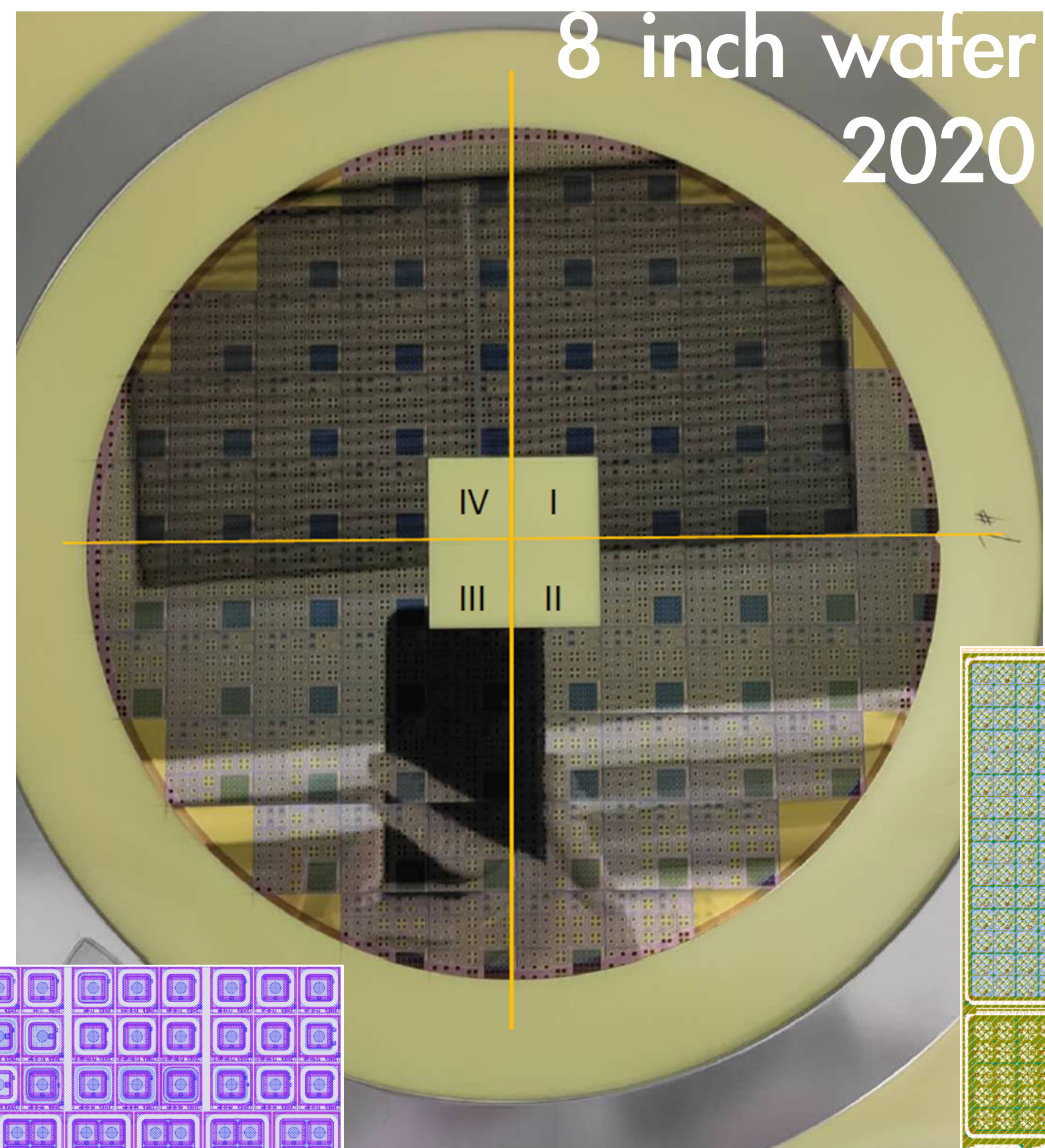
Introduction of IHEP-IME LGAD

- **IHEP-IME**: Designed by IHEP, fabricated by the Institute of Microelectronics of Chinese Academy of Sciences (IME) for the HGTD project
- So far two 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 April/ June 2021
 - IHEP-IMEv3 production is ongoing.

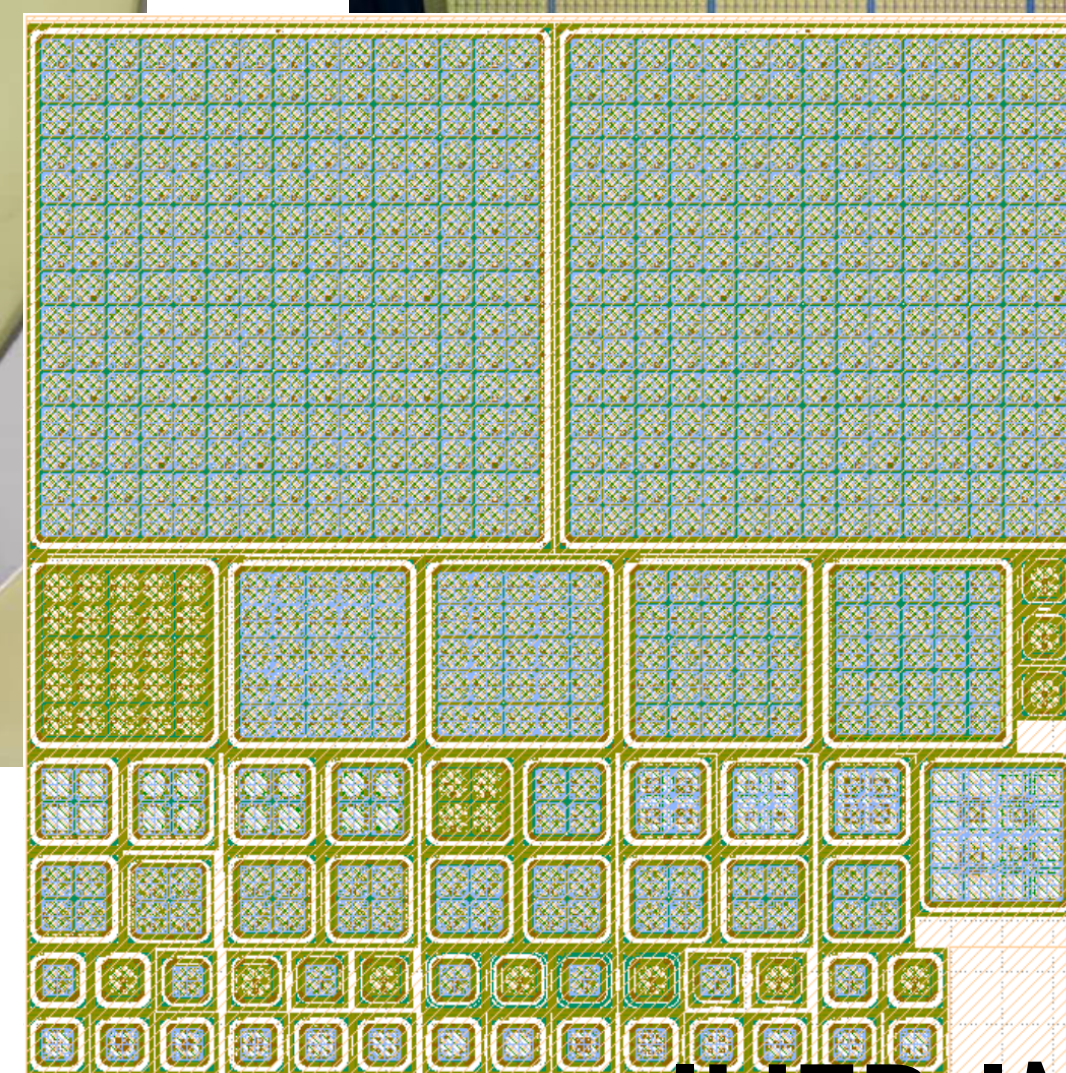
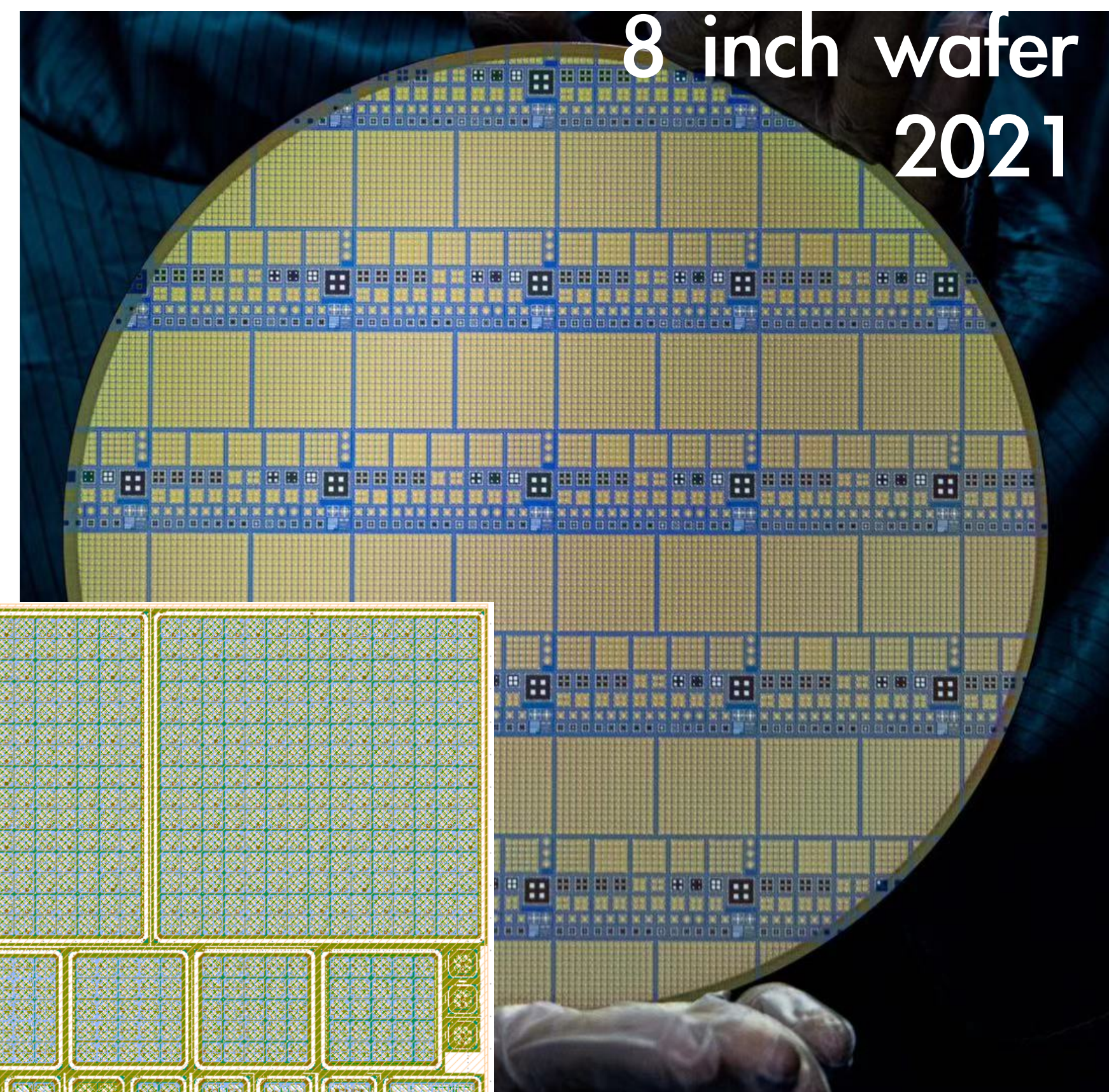
Introduction of IHEP-IME LGAD



50 um thick LGAD



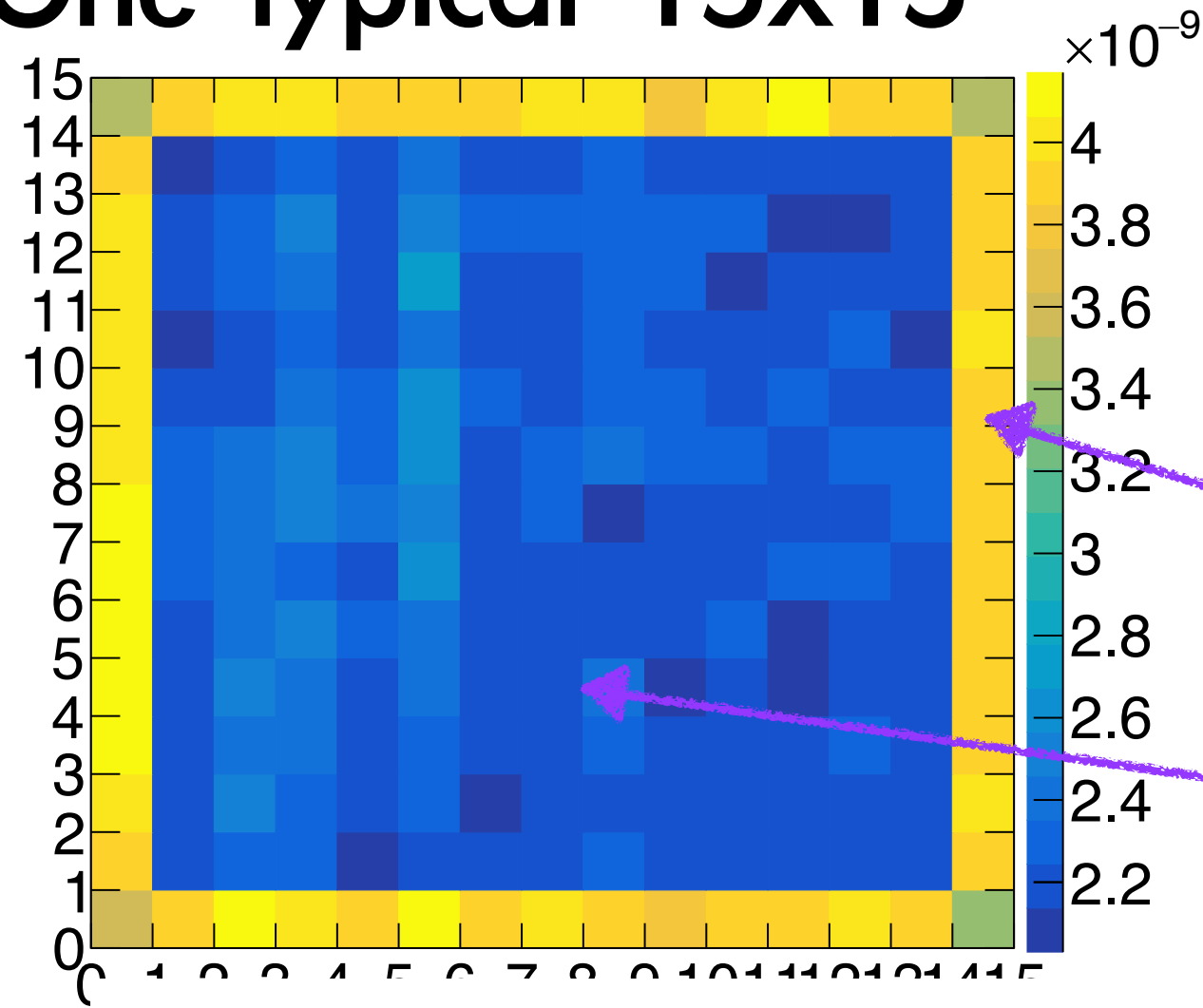
IHEP-IMEv1 layout



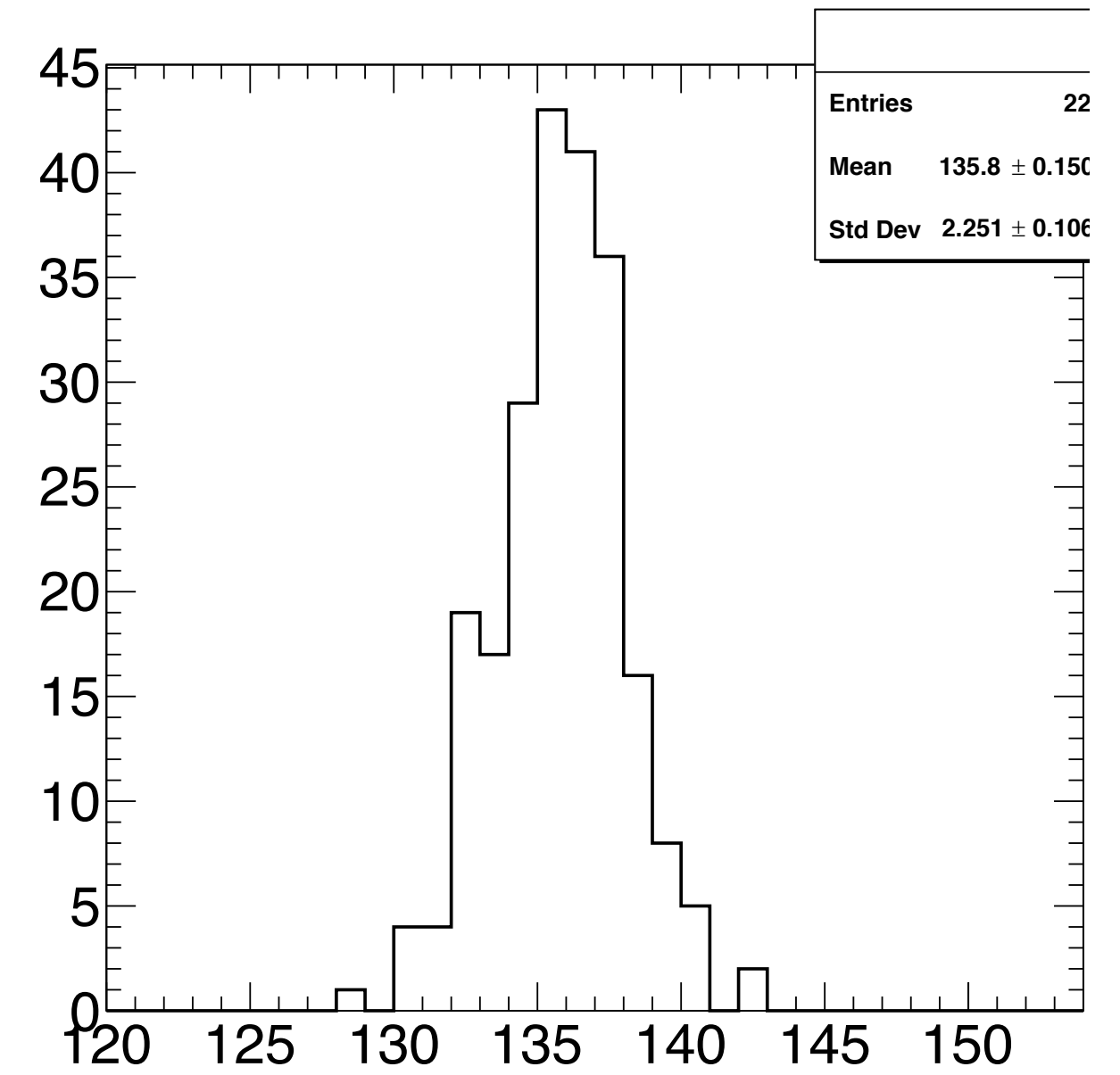
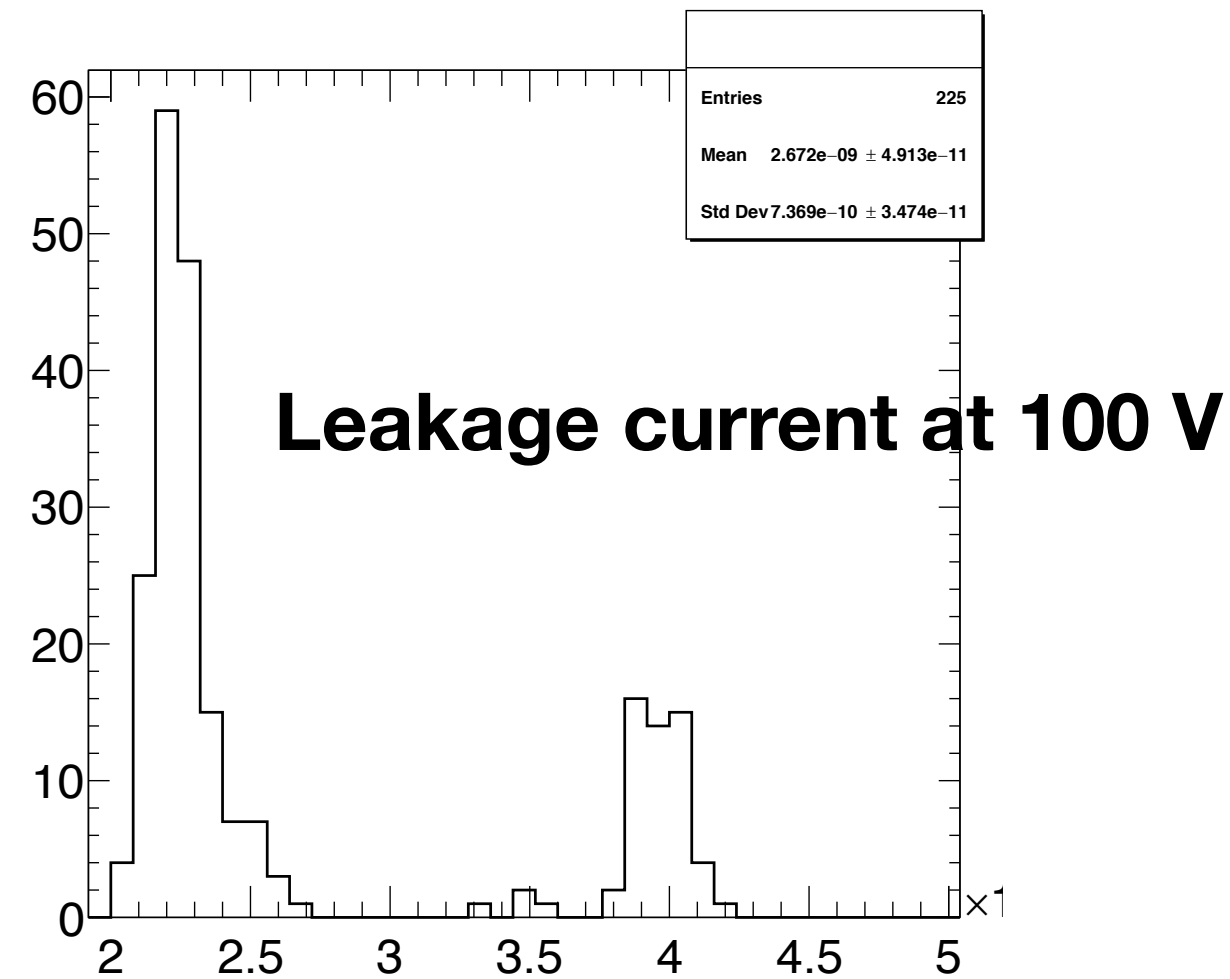
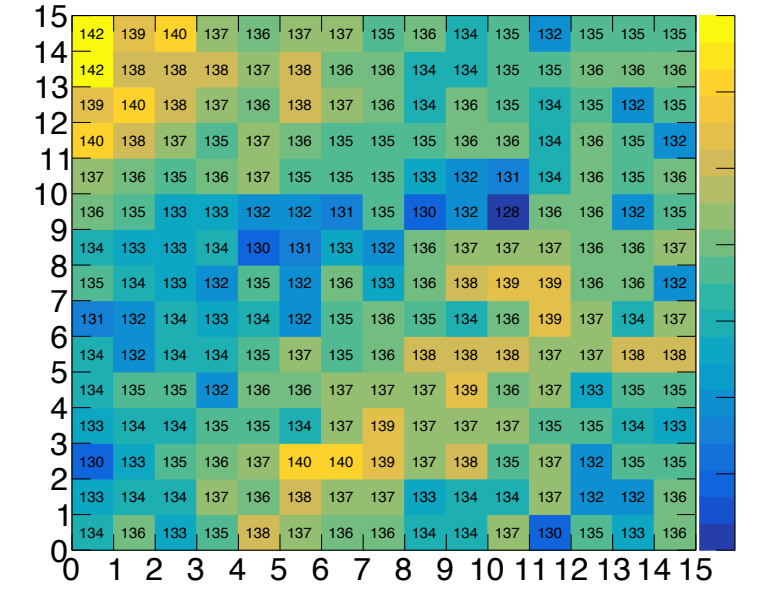
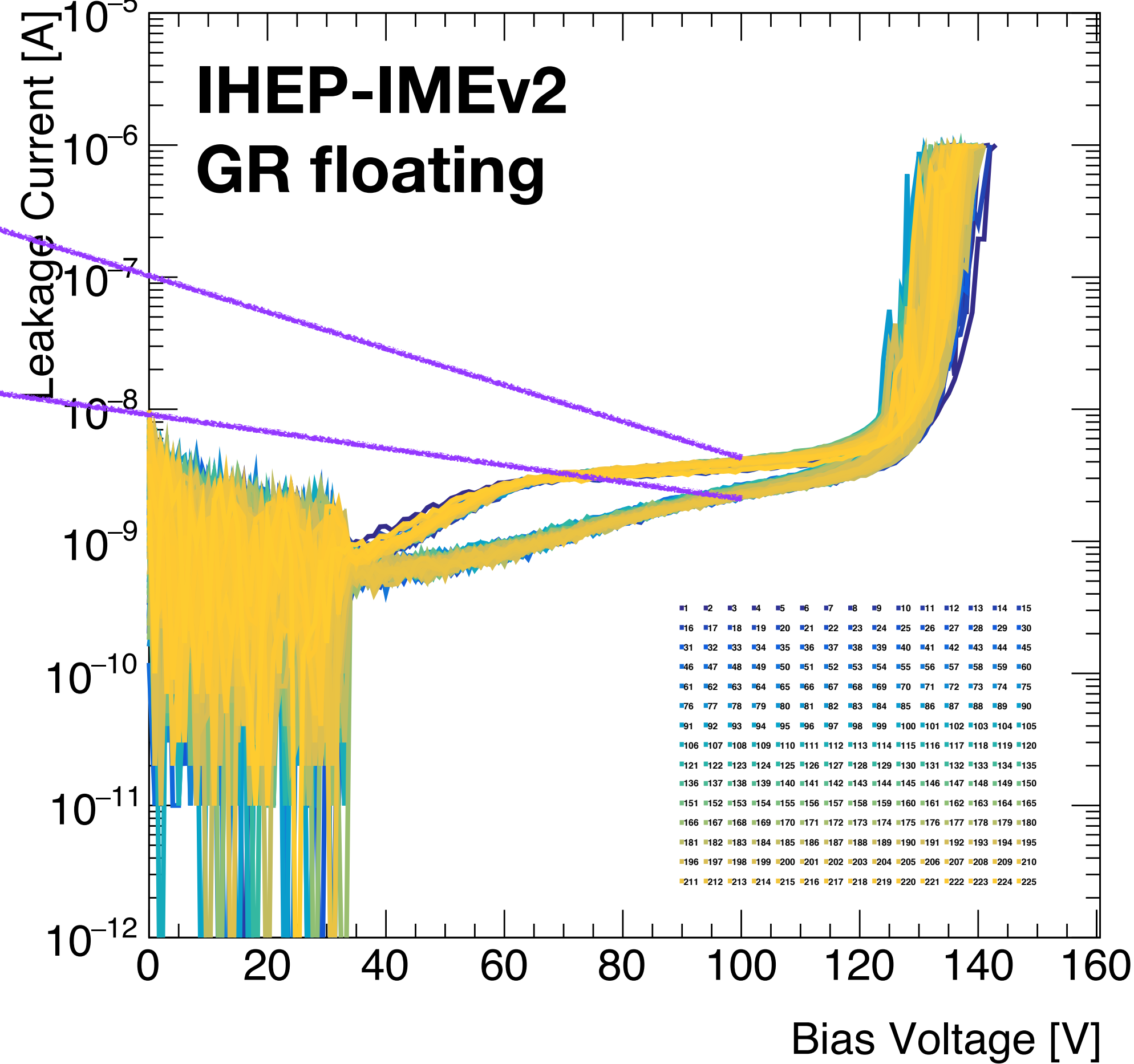
IHEP-IMEv2 layout

Introduction of IHEP-IME LGAD

One typical 15x15



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



Carbon implanted sensors — IHEP-IMEv1

IHEP-IMEv1 before irradiation

Carbon implanted

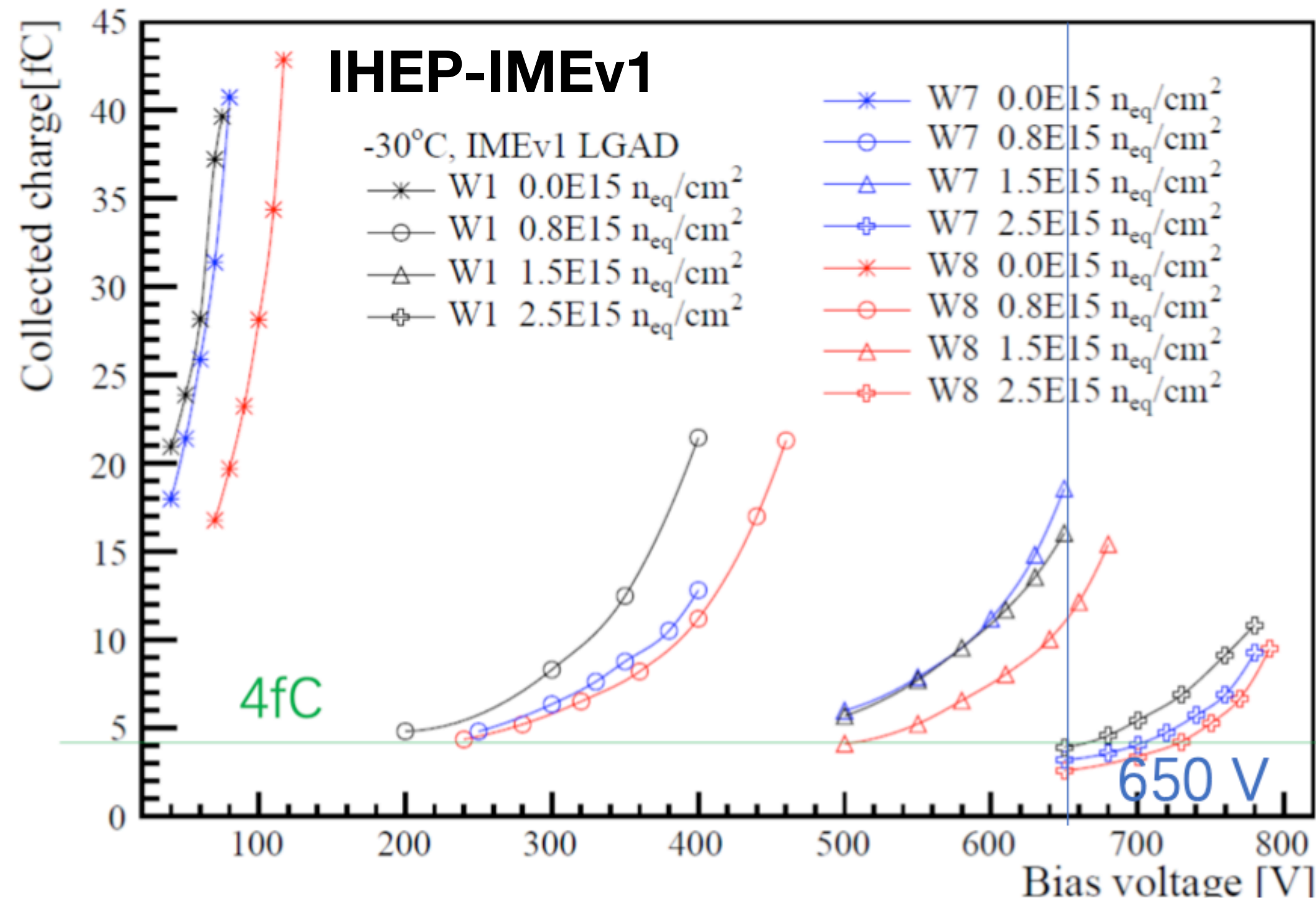
	W7 (mean±std)	W1 (mean±std)	W7 std/mean	W1 std/mean
Breakdown voltage [V]	148.2±5.4	140±7.7	3.6%	5.5%
Leakage current at 110V [A]	5.13e-10±1.52e-10	5.35e-10±2.51e-10	29.6%	46.9%
Vgl [V]	24.7±0.1	25.2±0.2	0.4%	0.8%
Vfd [V]	38.8±1.3	39.0±1.2	3.4%	3.1%
C [pF]	4.82±0.06	4.80±0.05	1.2%	1.0%

W1 was implanted with carbon. Others parameters are the same as W7.

Carbon implantation:

- lower the breakdown voltage
- raise the leakage current
- increase Vgl and Vfd
- capacitance difference not significant
- worsen the uniformity

Carbon implanted sensors — IHEP-IMEv1



After irradiation:
Voltage reach 4fC @2.5e15
650 V (W1), 700 V (W7), 730 V (W8)
W1 < W7 < W8

Time resolution 50 ps

[More in Mengzhao's talk in 38th RD50](#)

- W1 of IHEP-IMEv1 with **carbon implantation** showed good performance after irradiation. Also seen in sensors from other vendors.
- For IHEP-IMEv2 we did more studies on the carbon effect for the irradiation hardness

Carbon implanted sensors — IHEP-IMEv2

IHEP-IMEv2 carbon implantation:

- We have 3 wafers implanted with carbon
- Four quadrants have different carbon dose. (I, II, III, IV)

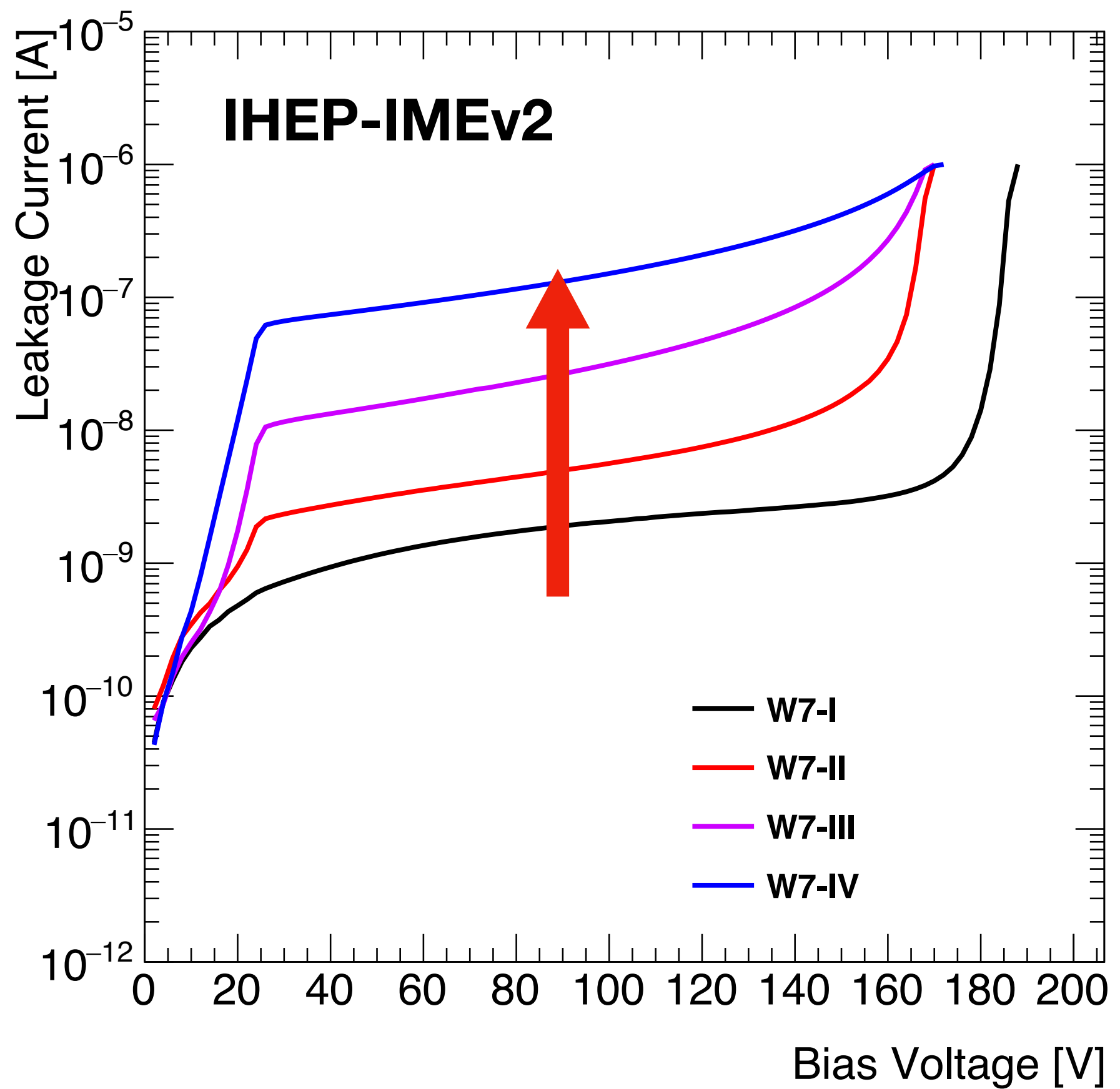
	I	II	III	IV
W4 (fast annealing)	0.2	1	5	10
W7 (long annealing)	0.2	0.5	1	2
W8 (long annealing)	3	6	8	10

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

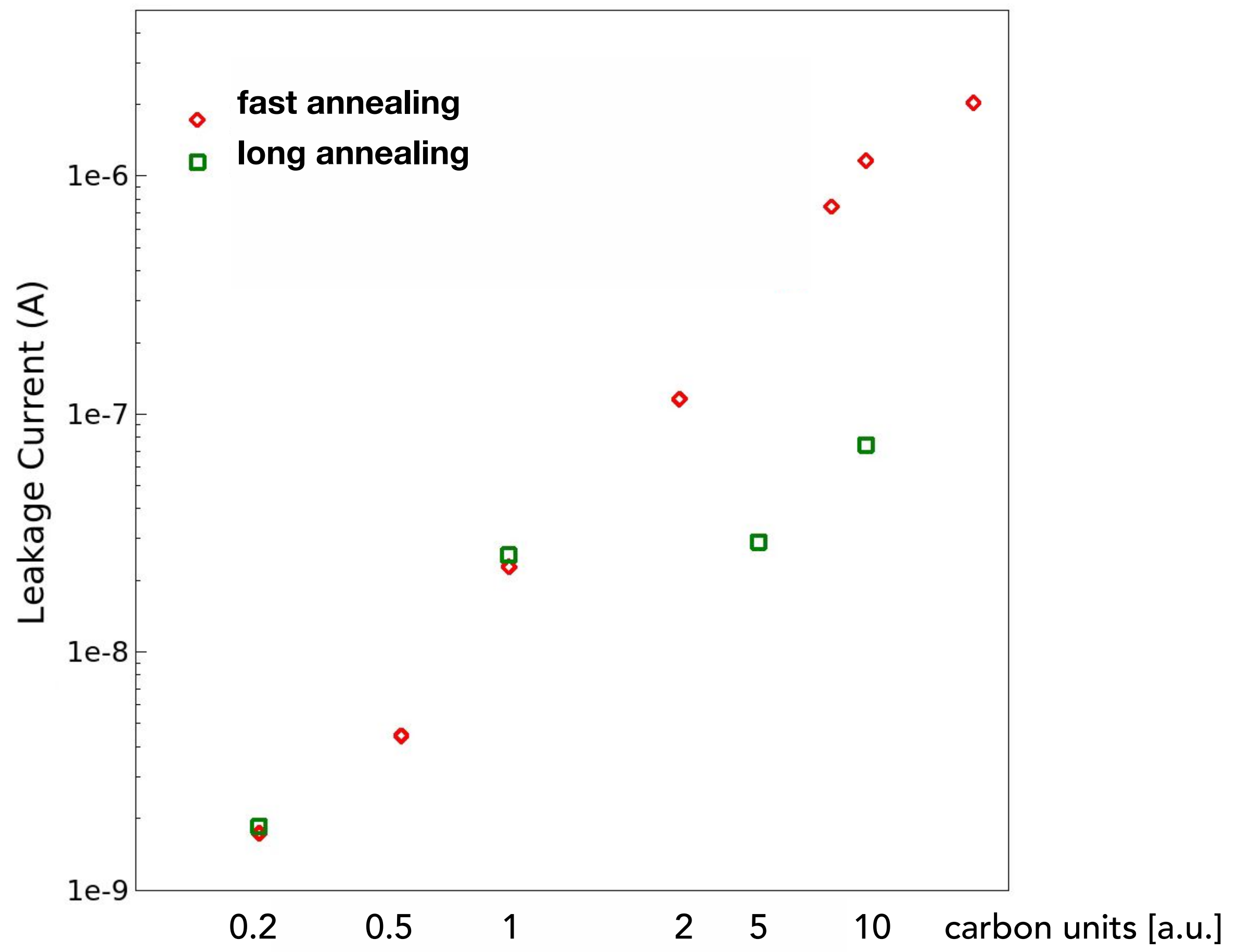
Sent for neutron irradiation

Carbon implanted sensors — IHEP-IMEv2

Before irradiation single pads:



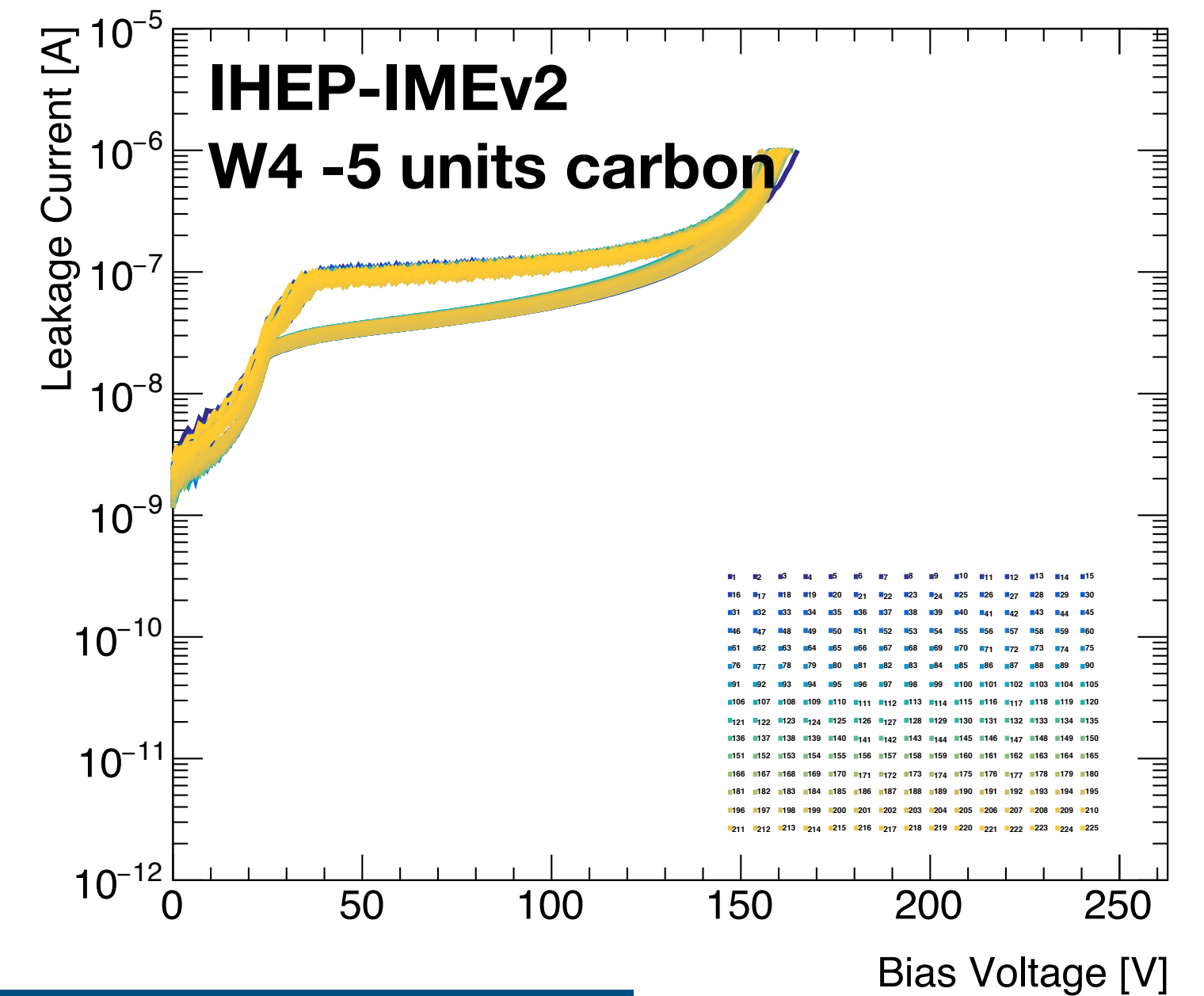
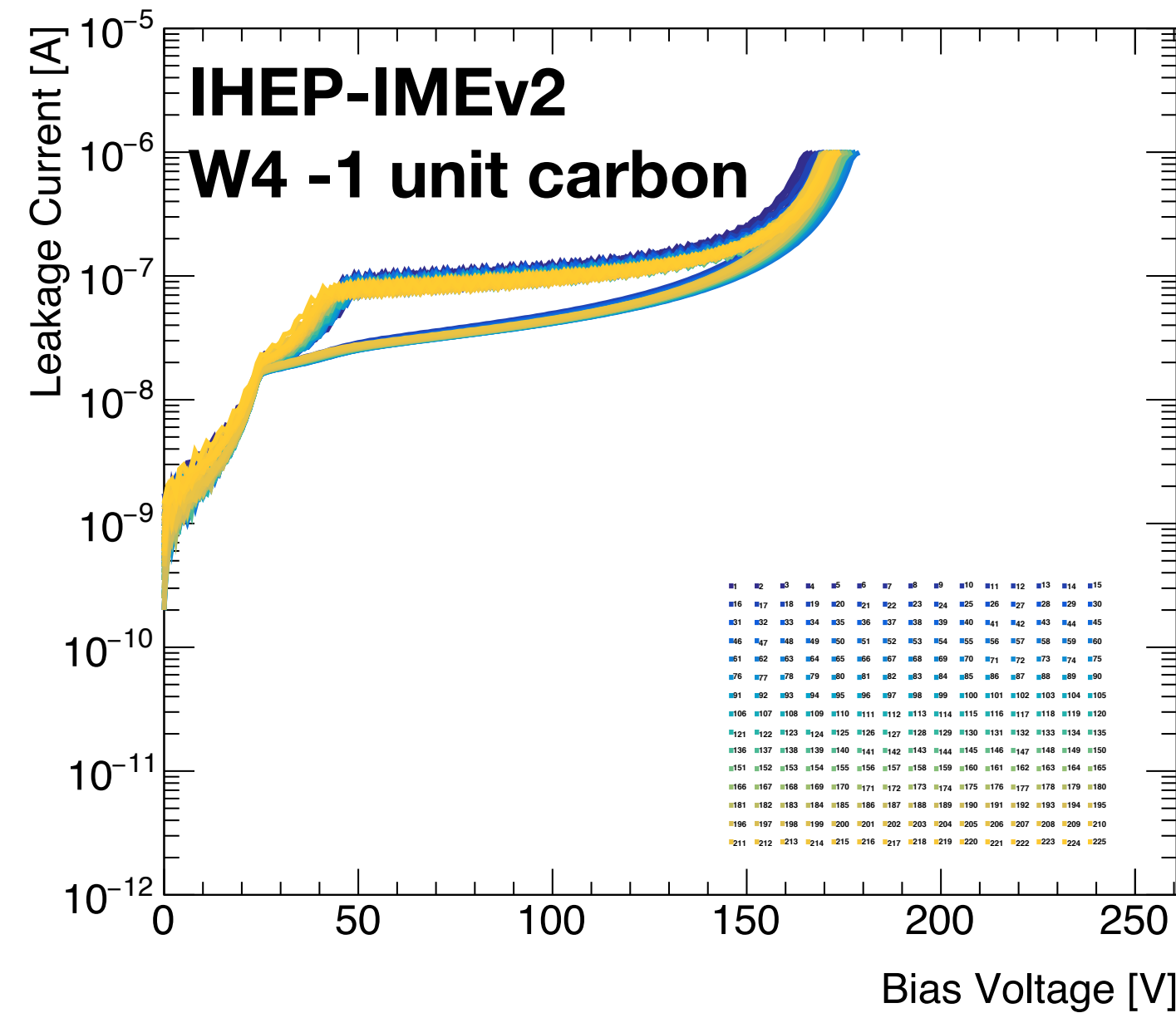
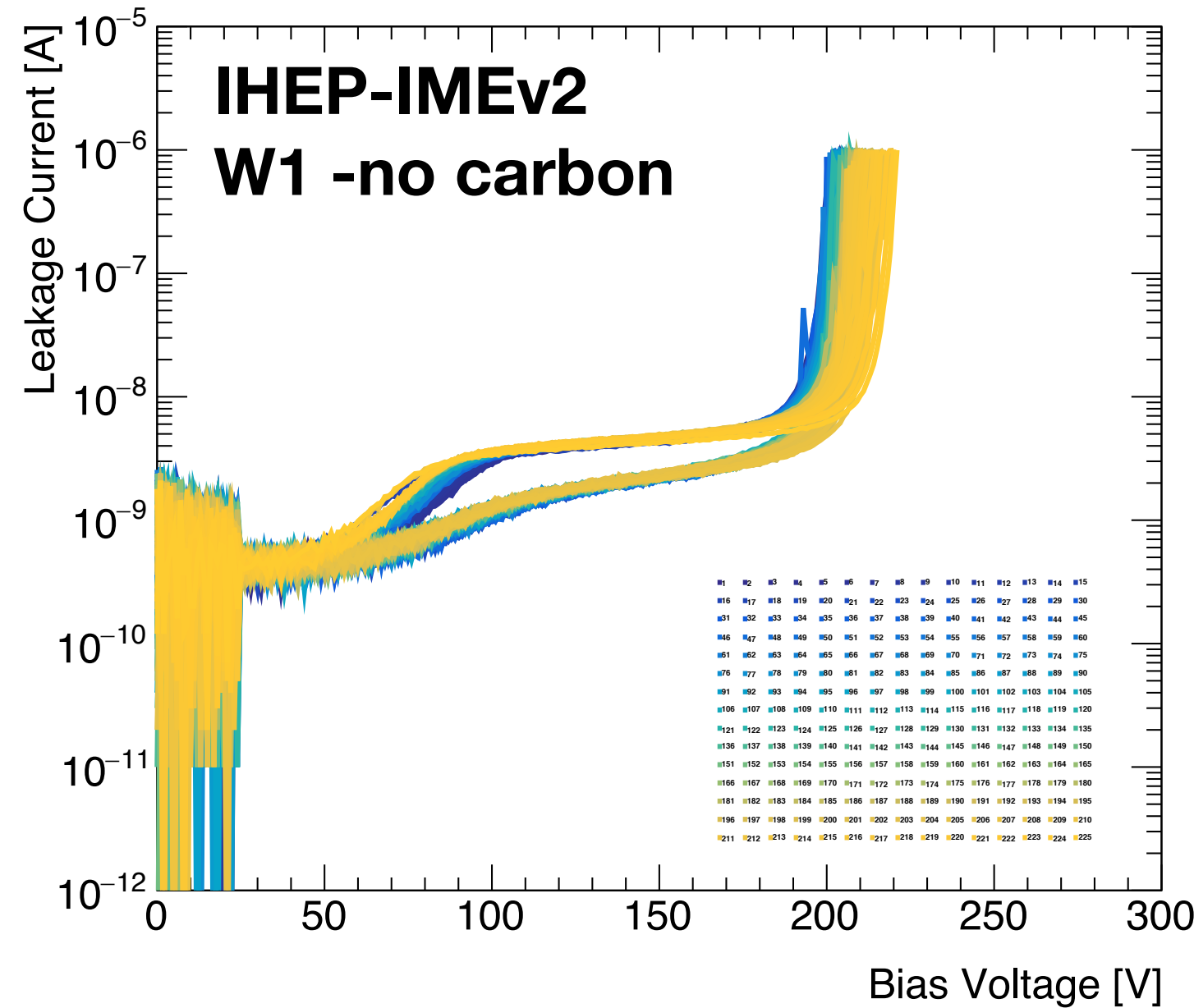
Carbon Leakage Current before Radiation



When carbon dose increase, the leakage current increase from the single pads tests.

Carbon implanted sensors — IHEP-IMEv2

Before irradiation 15x15:

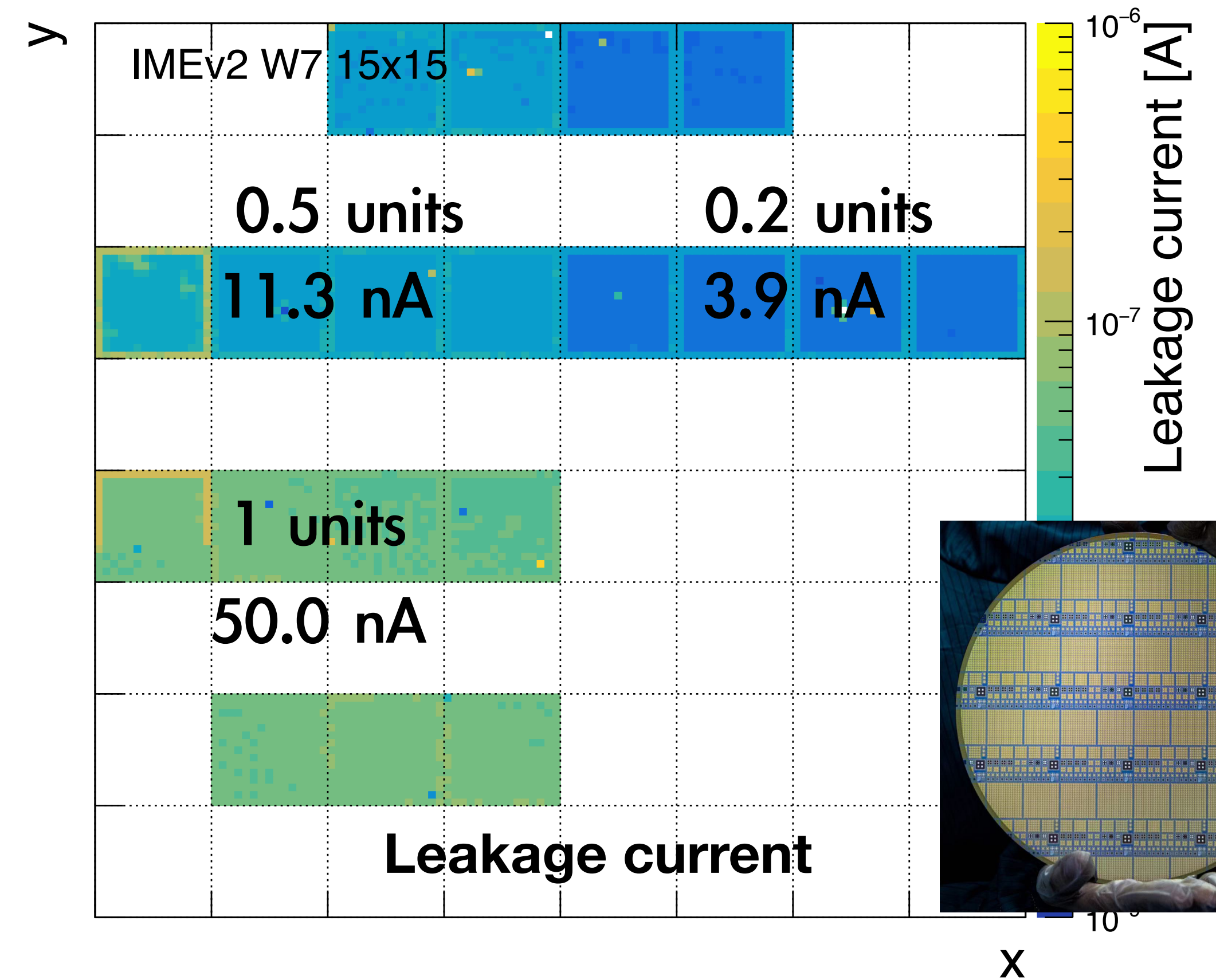
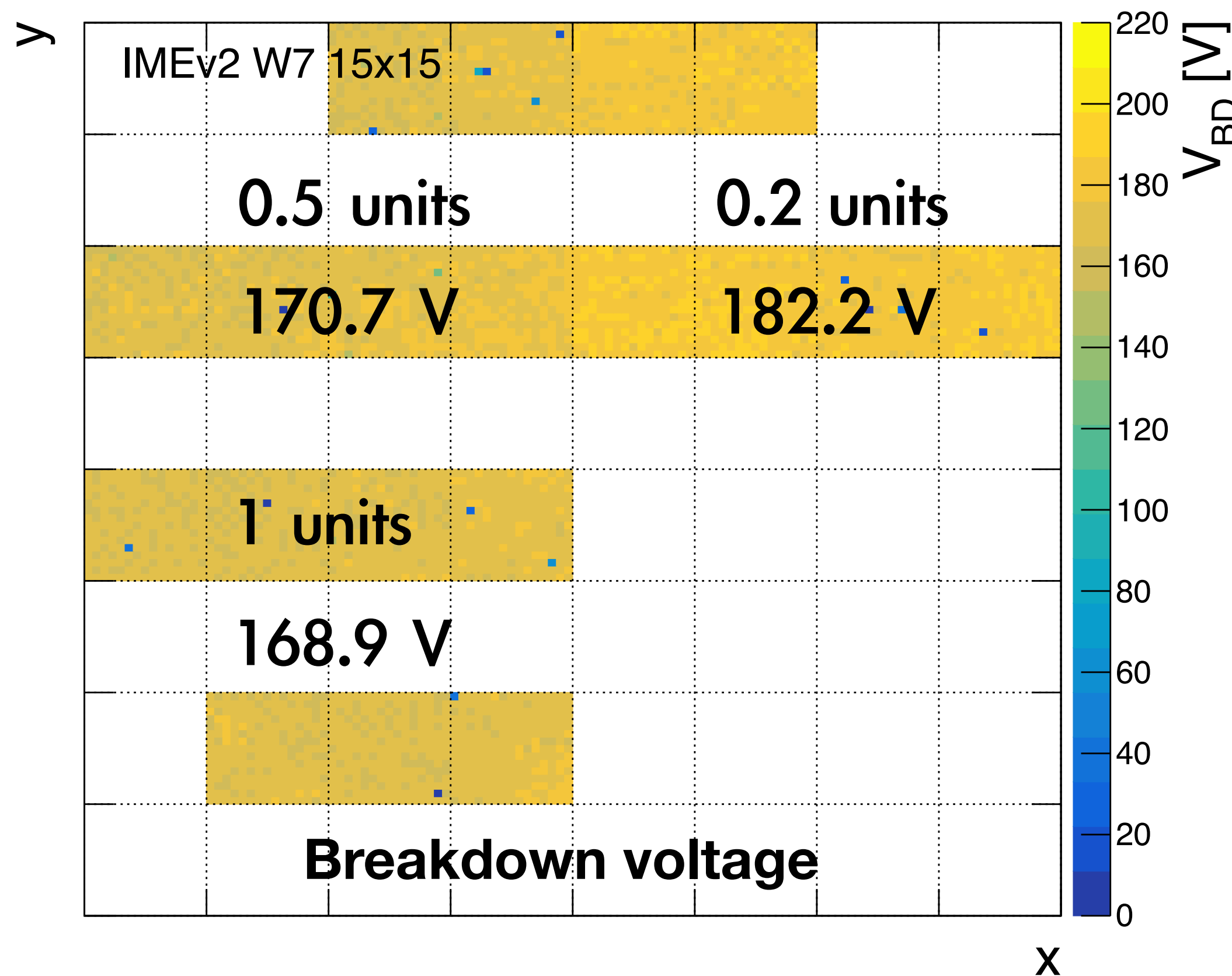


Carbon dose	0	1C	5C
Breakdown voltage [V]	207.6(3.7)	168.8(2.1)	155.0(0.6)
Leakage current [nA]	1.65(0.09)	57.2(2.2)	80.6(7.8)

When carbon dose increase, the breakdown voltages decrease and leakage currents increase from the full size sensor tests of W4 (fast annealing) .

Carbon implanted sensors — IHEP-IMEv2

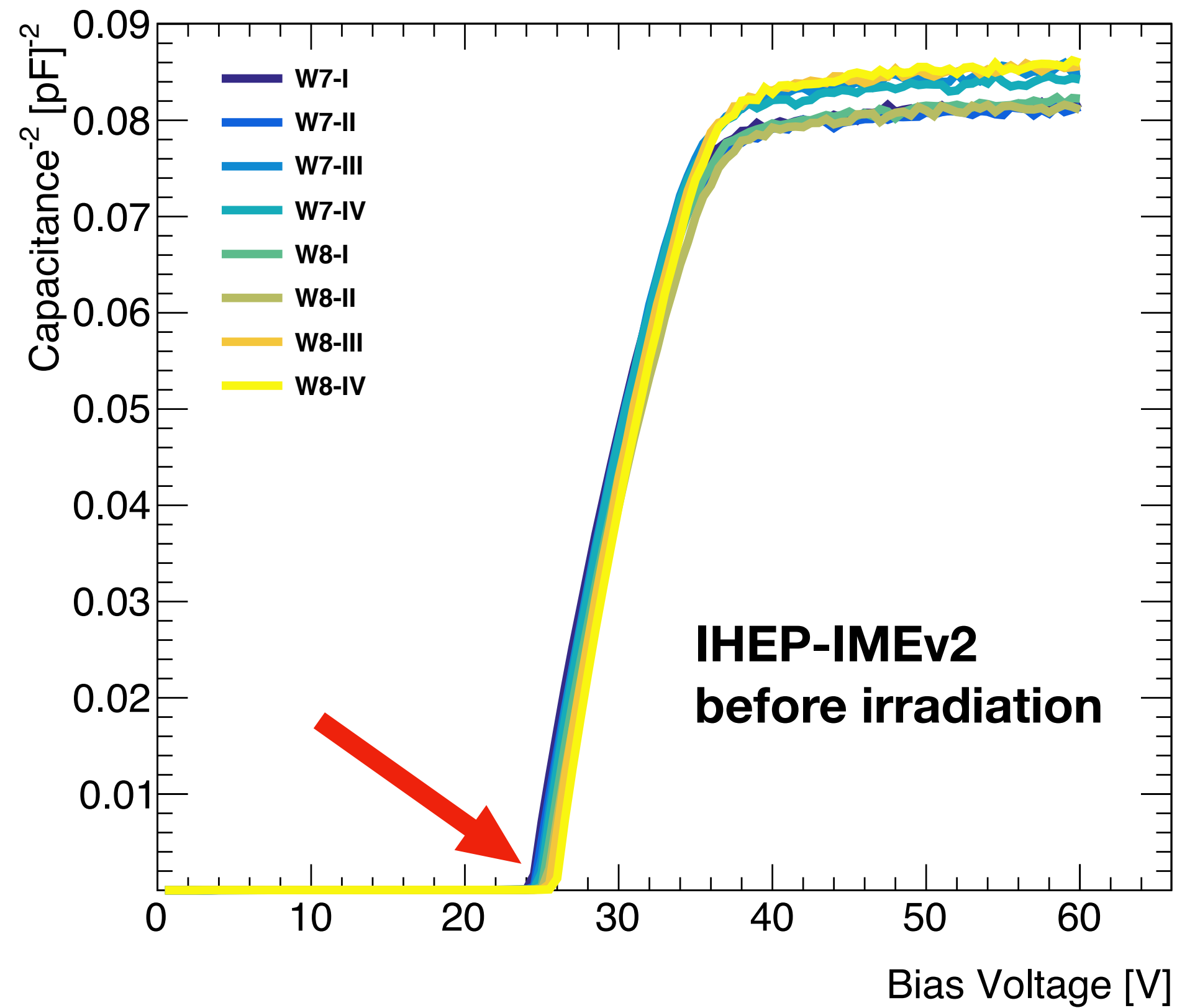
W7 before irradiation:



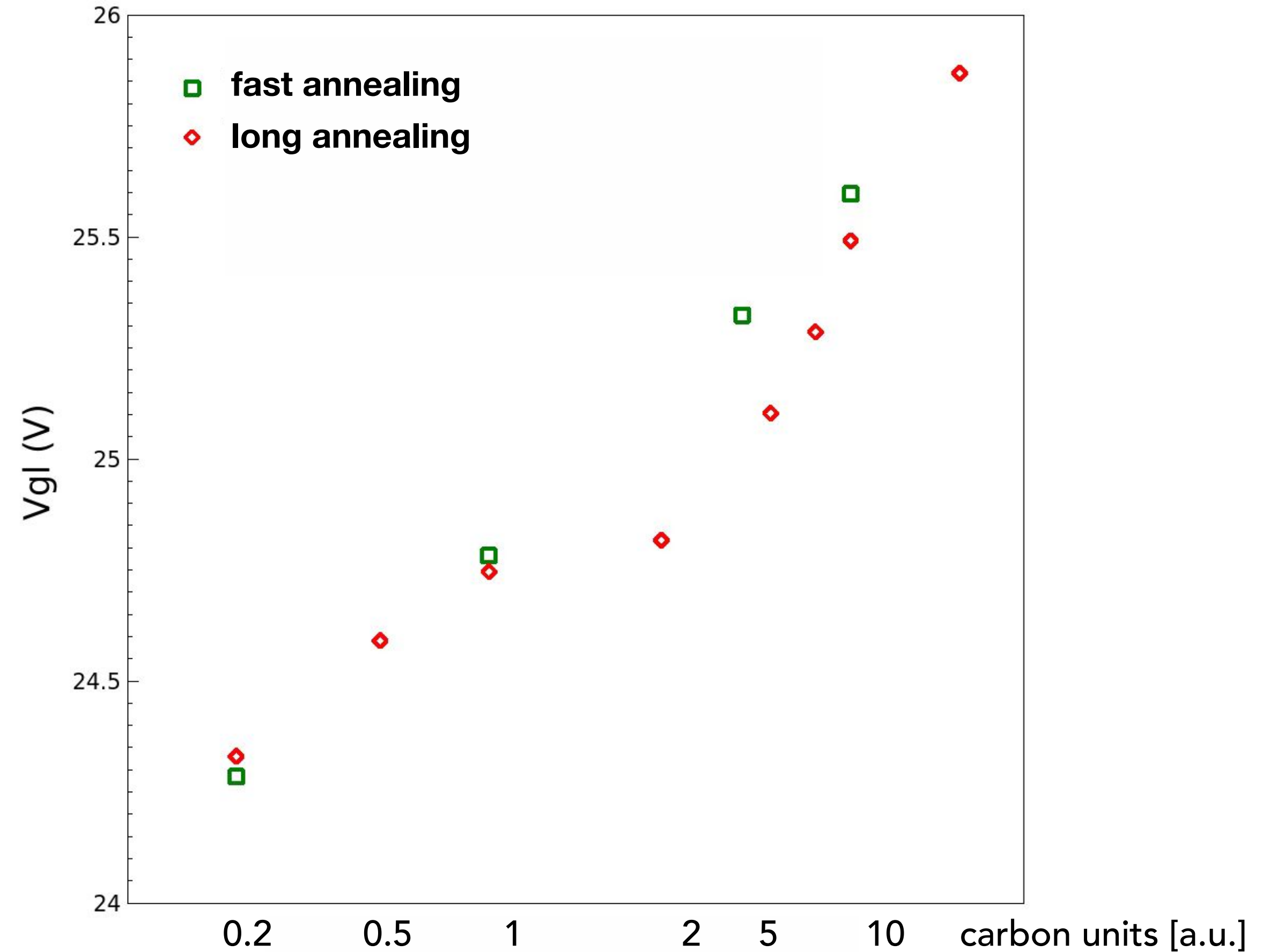
When carbon dose increase, the breakdown voltages decrease and leakage currents increase from larger statistics in W7 (long annealing).

Carbon implanted sensors — IHEP-IMEv2

Vgl before irradiation:



Carbon Dose Vgl

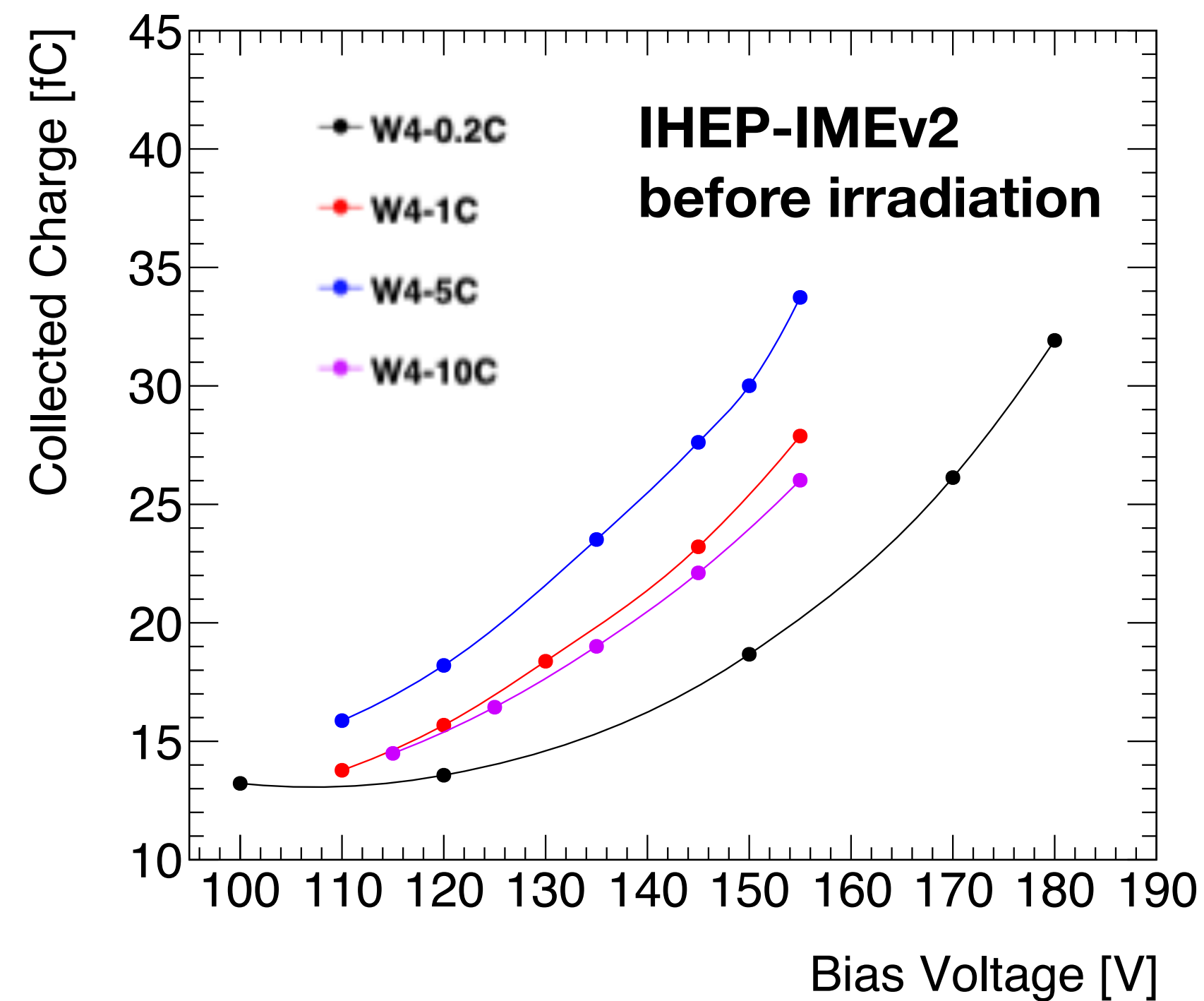
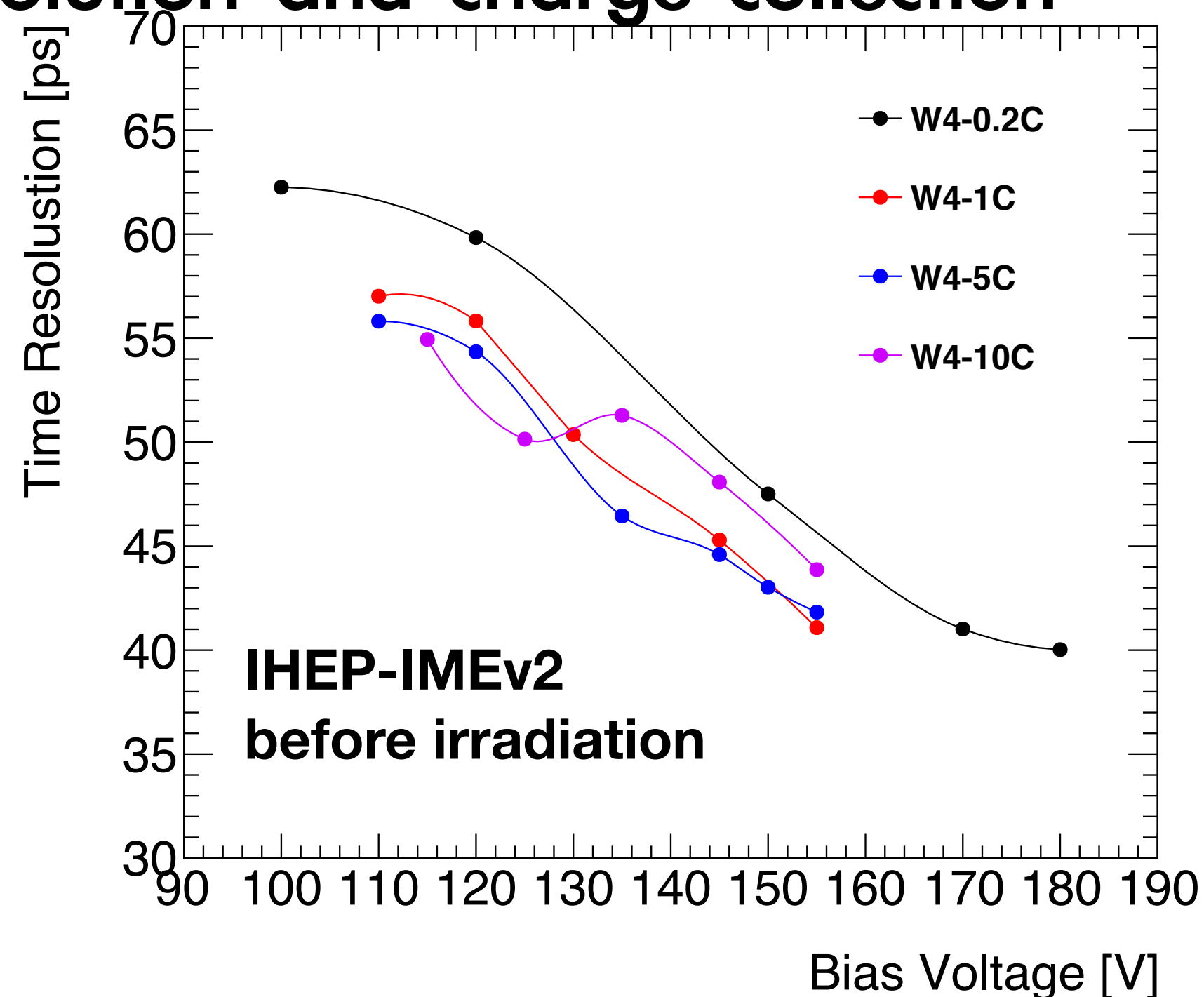


When carbon dose increase, the Vgl also increase.

Carbon implanted sensors — IHEP-IMEv2

W4 fast annealing at RT:

Time resolution and charge collection

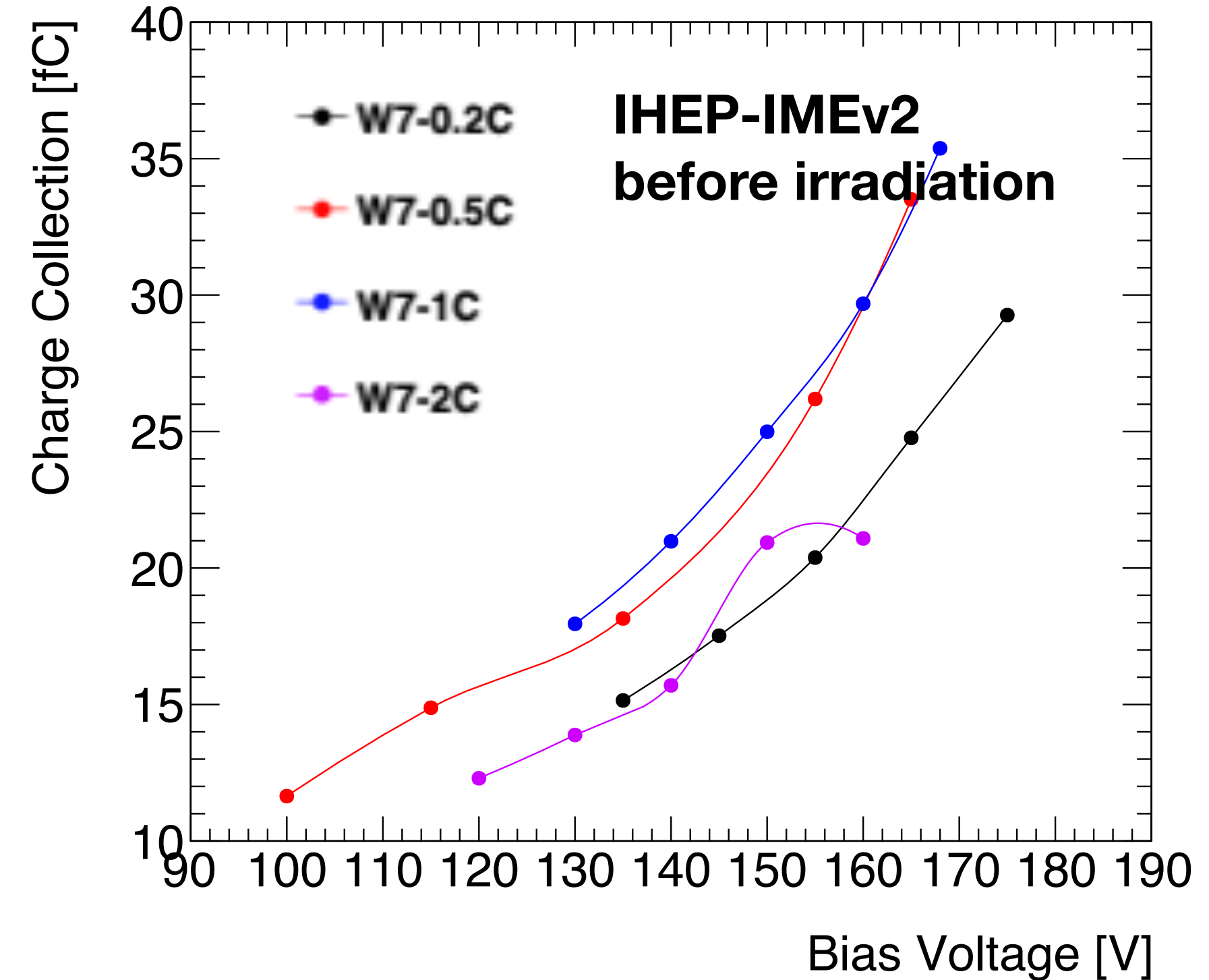
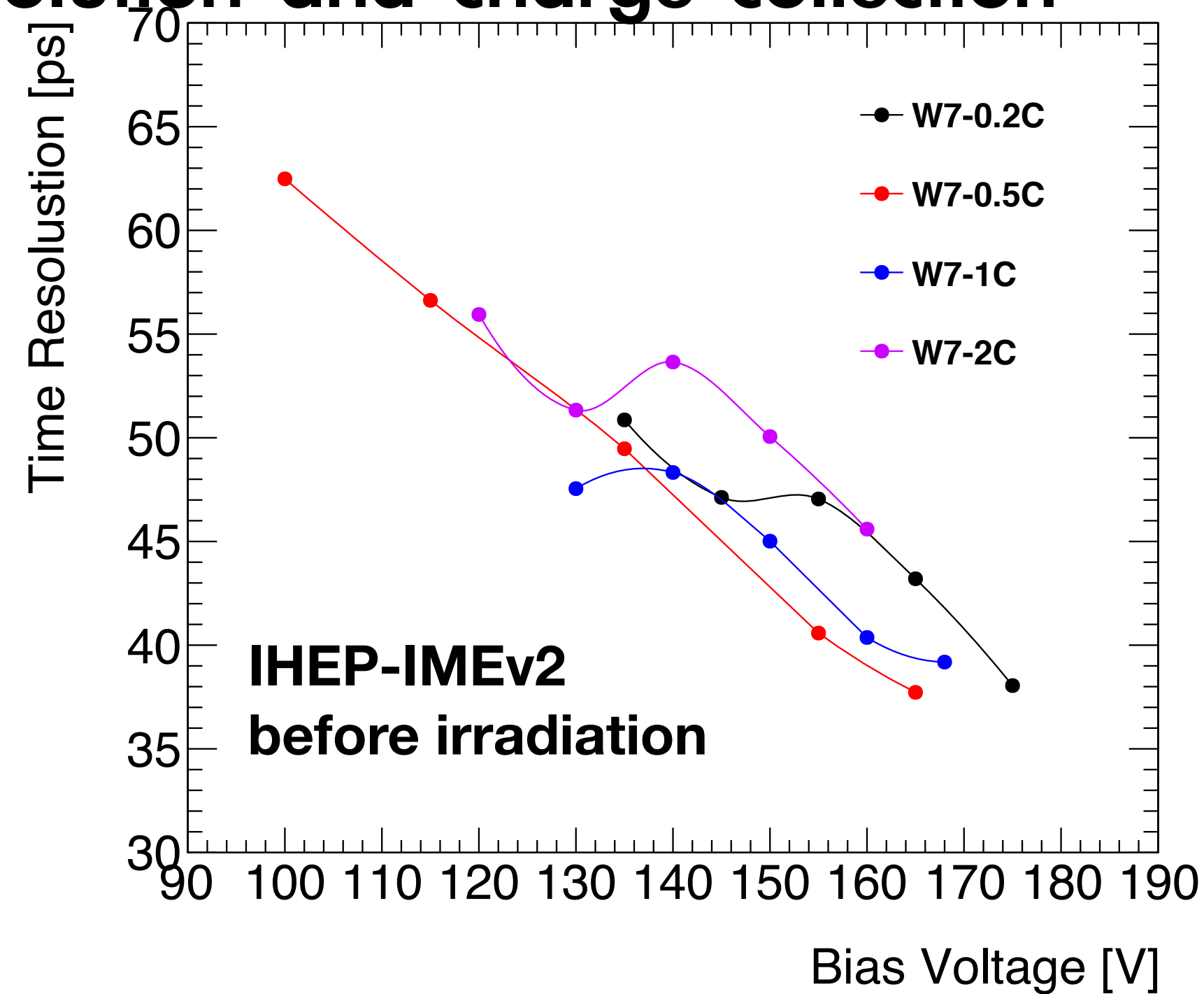


- For each sensor the best time resolution before irradiation ~ 40 ps, charge collection ~ 30 fC.
- W4: carbon dose increase from 0.2C to 5C, the gain increase. But compared with 5C, at 10C the gain decrease and time resolution is worse at high voltage.

Carbon implanted sensors — IHEP-IMEv2

W7 fast annealing at RT:

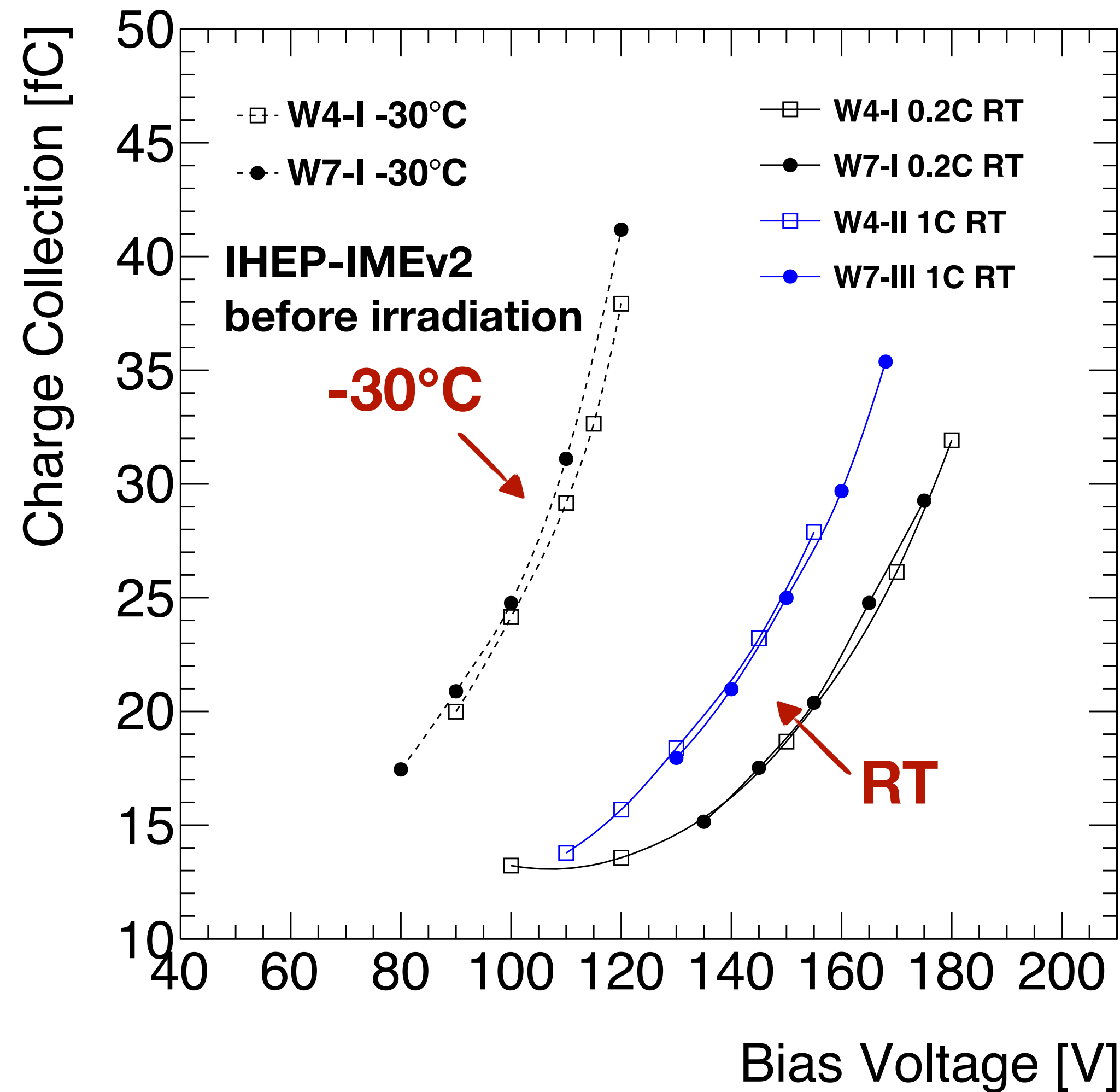
Time resolution and charge collection



- For each sensor the best time resolution before irradiation ~ 40 ps, charge collection ~ 30 fC.
- W7: carbon dose increase from 0.2C to 1C, the gain increase and the time resolution is better (or close). But compared with 1C, at 2C the gain decreases a lot and time resolution is worse.

Carbon implanted sensors — IHEP-IMEv2

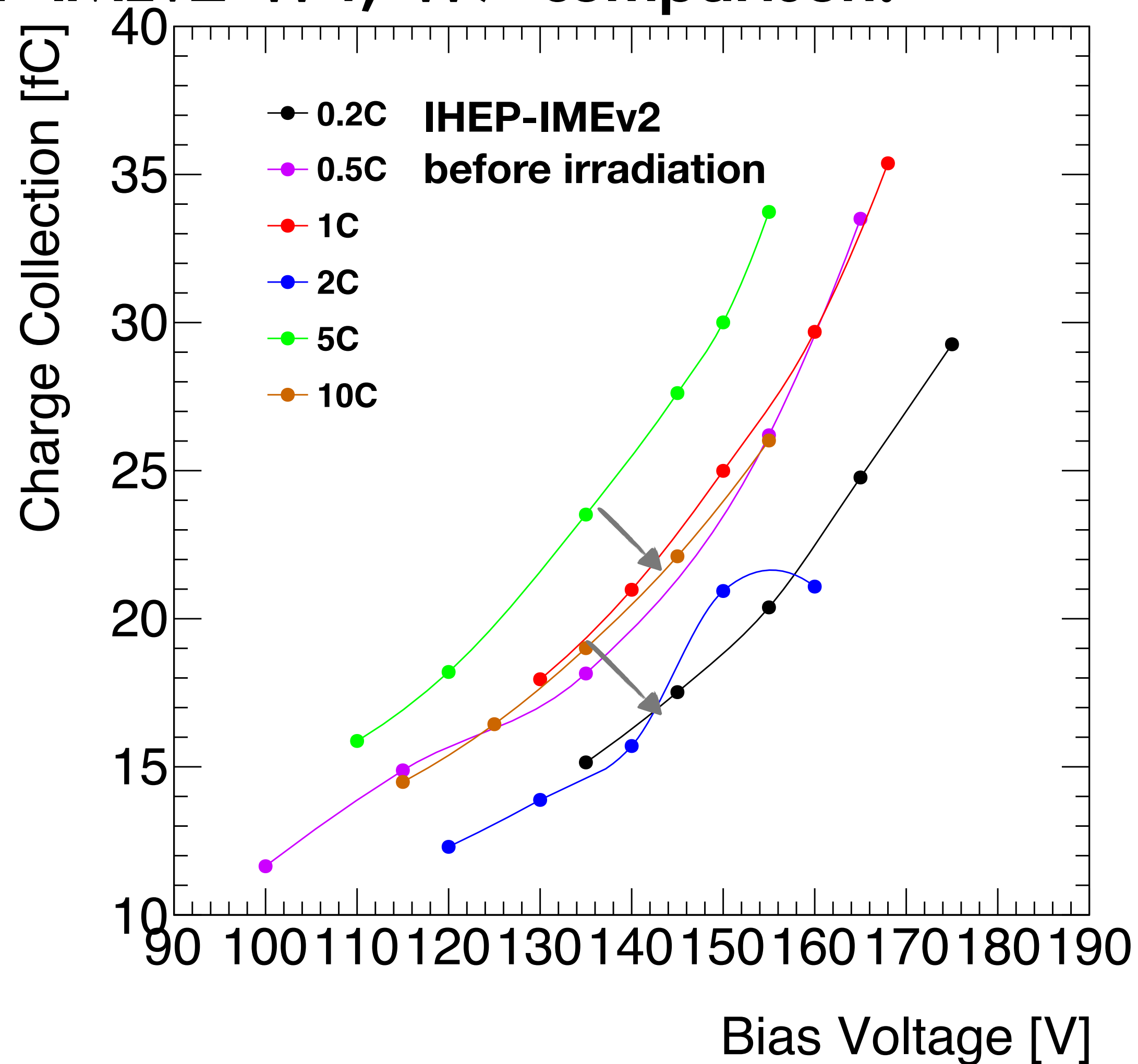
IHEP-IMEv2 W4, W7 comparison



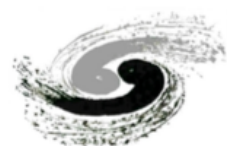
- At -30°C best charge ~40 fC ~40 ps (backup)
- At both room temperature and -30°C, annealing time have small effect on the timing performance and charge collection before irradiation.

Carbon implanted sensors — IHEP-IMEv2

IHEP-IMEv2 W4, W7 comparison:

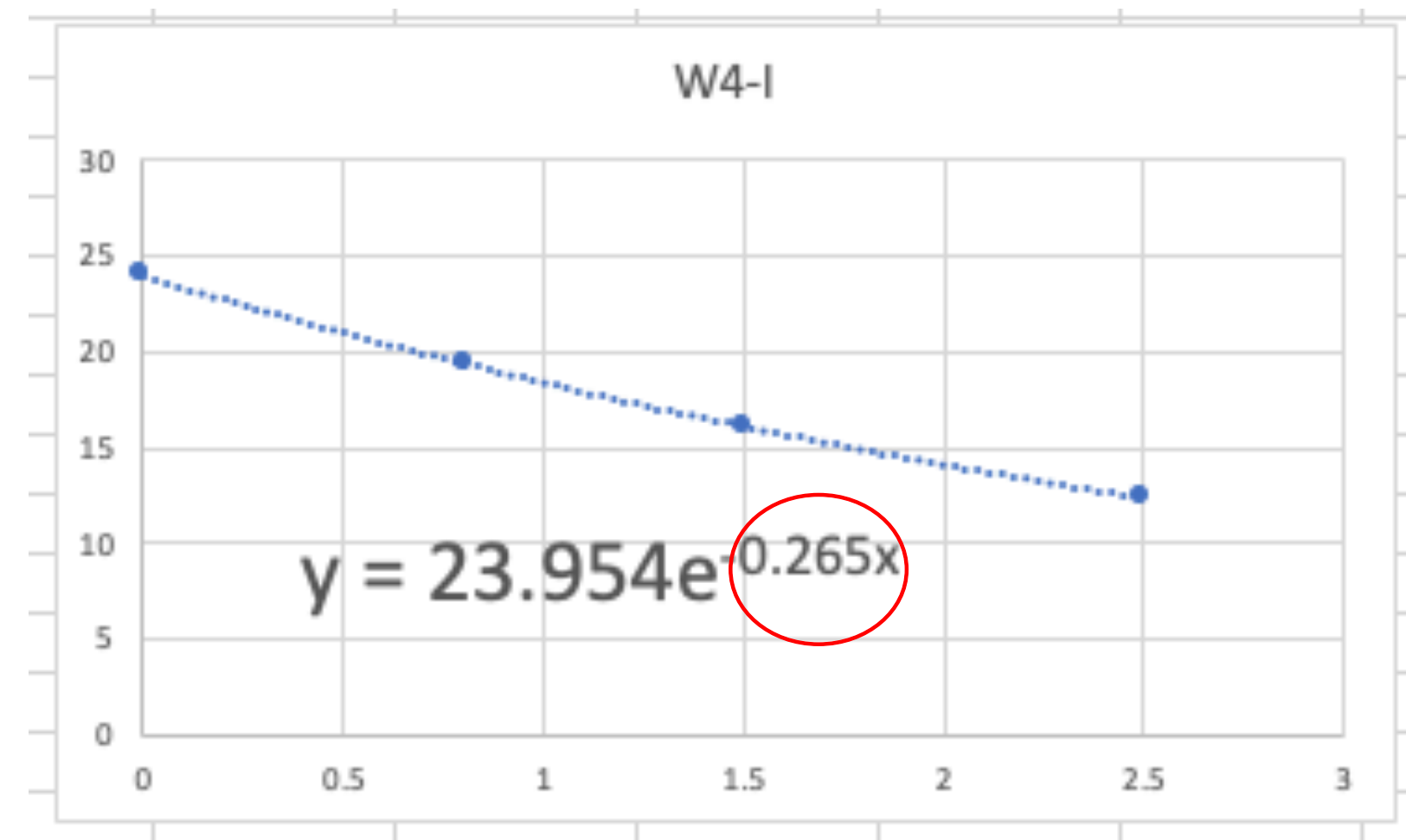
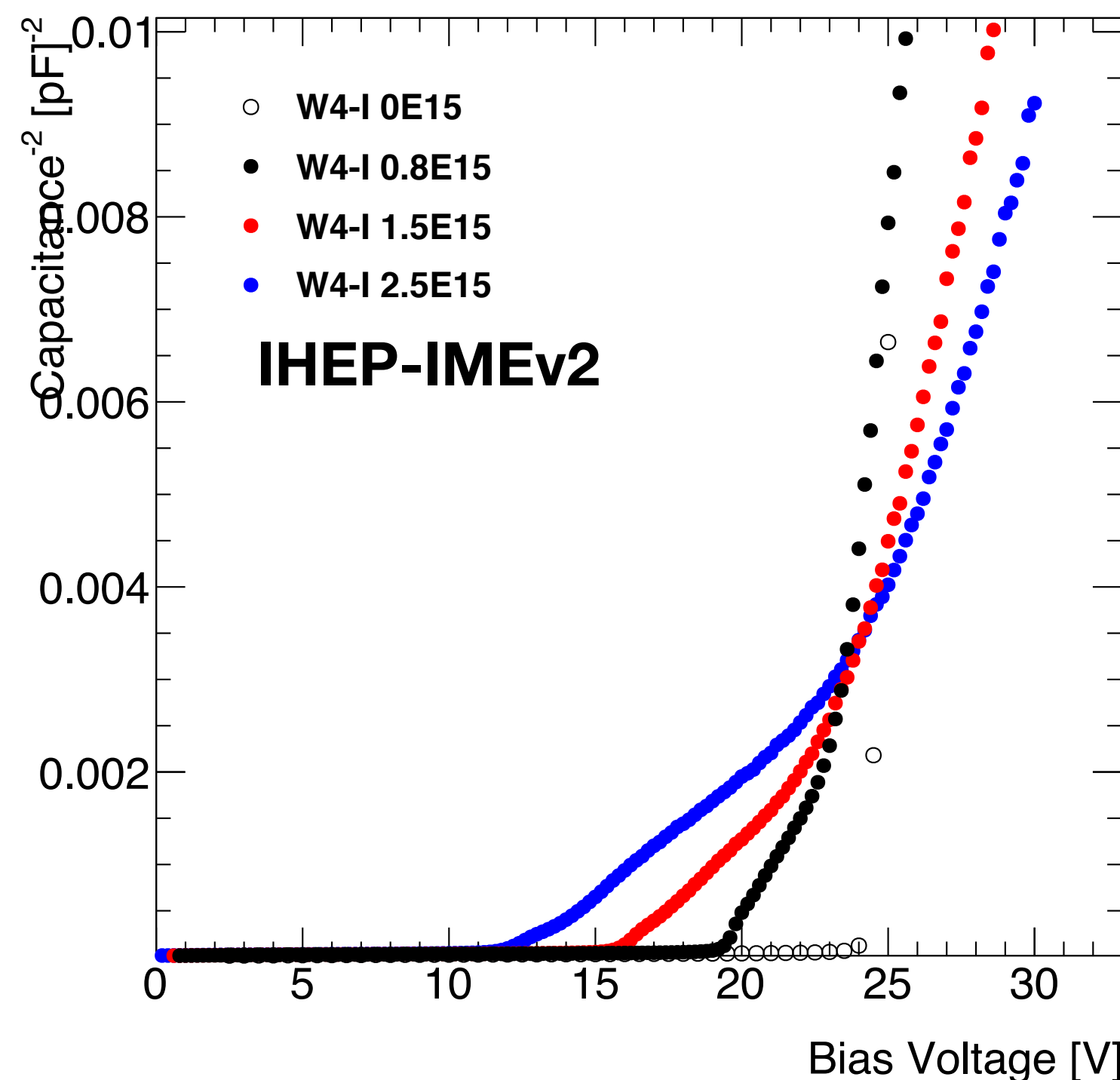
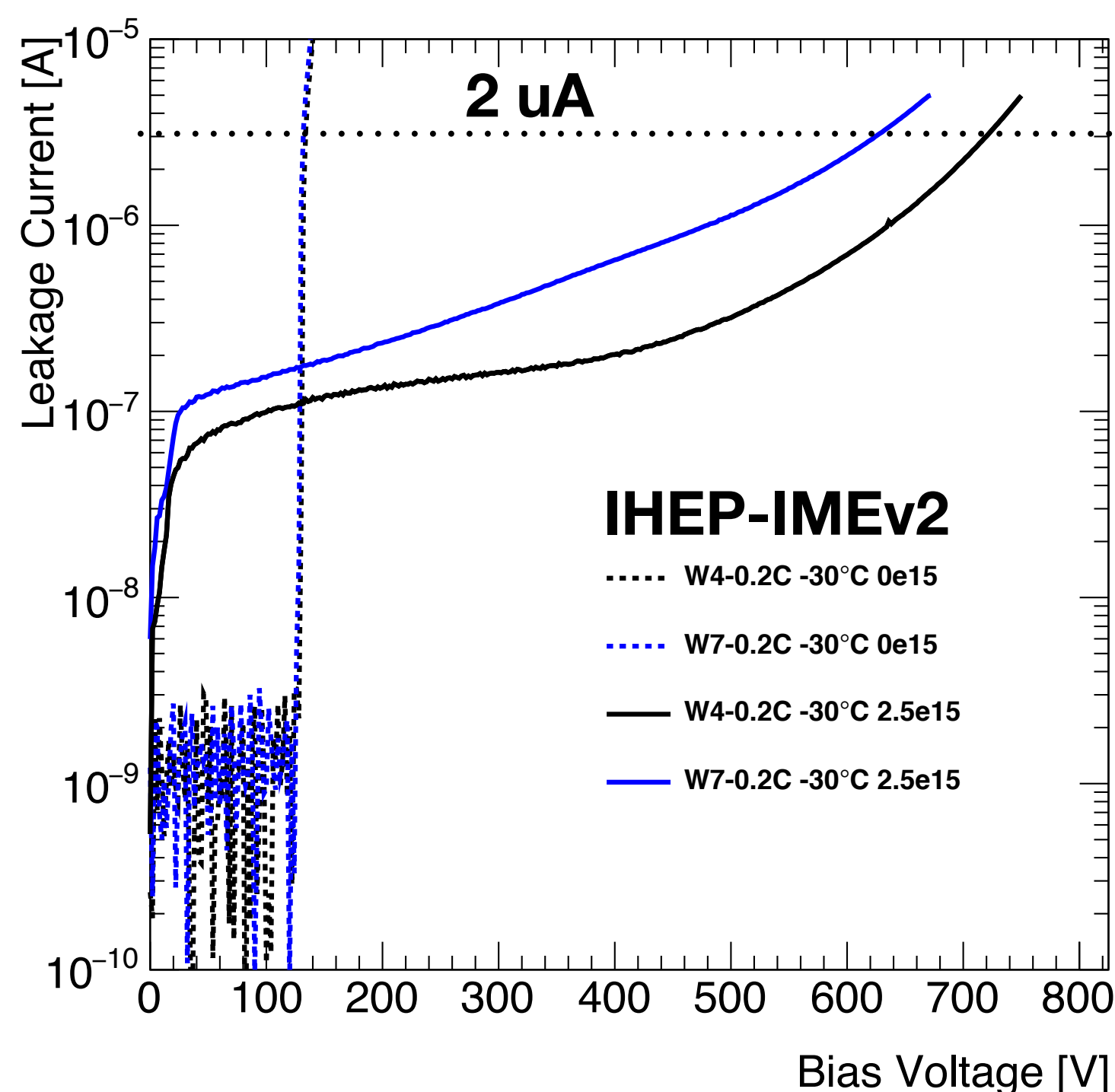


- At 0.2C and 1C, W4 and W7 performance are close.
- For W4 (fast annealing) the gain increase with carbon dose from 0.2C to 5C. 10C has a worth gain.
- For W7 (long annealing) the gain increase with carbon dose from 0.2C to 1C. 2C has a worth gain.



Carbonated sensor performance after irradiation

IHEP-IMEv2



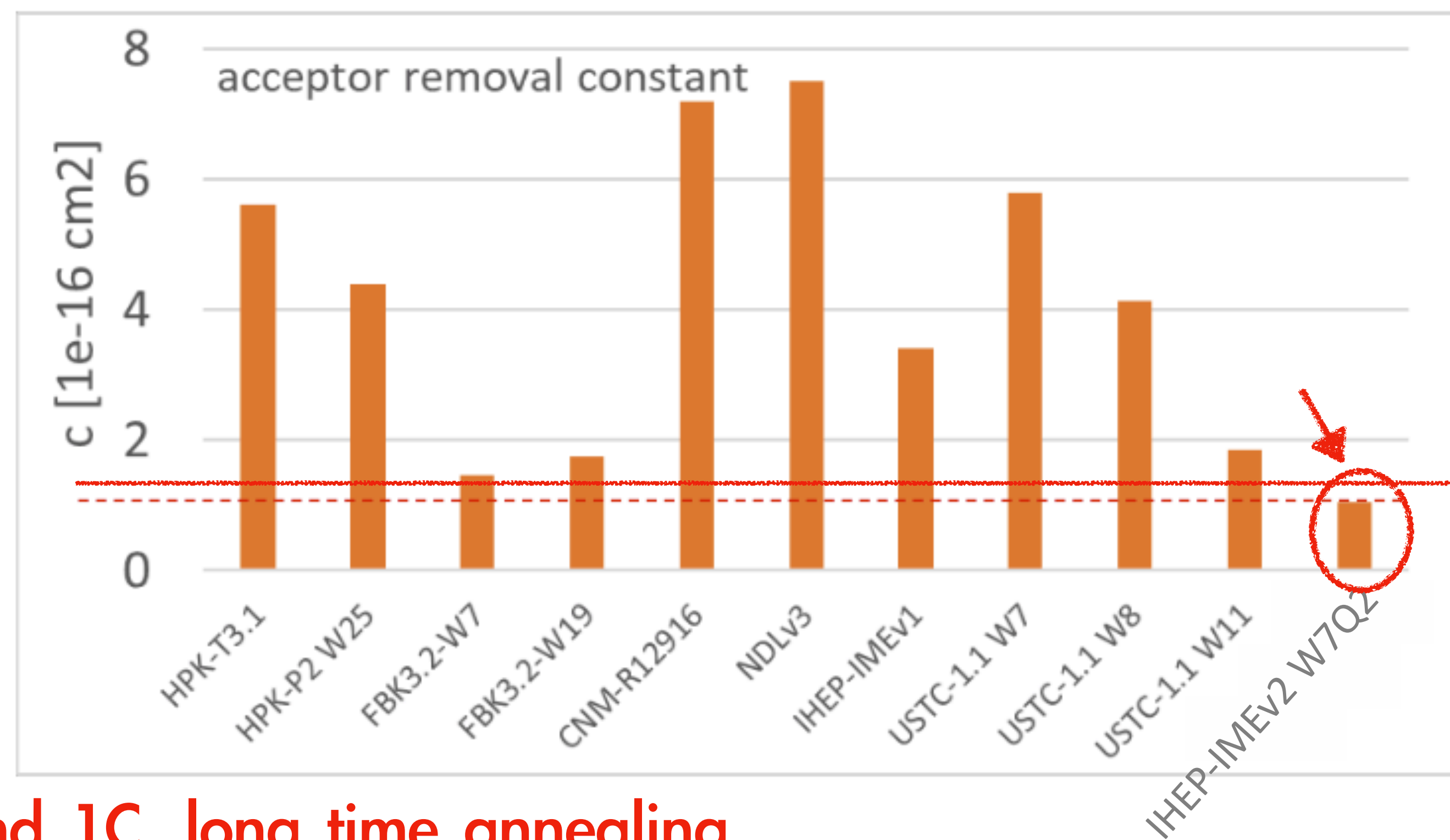
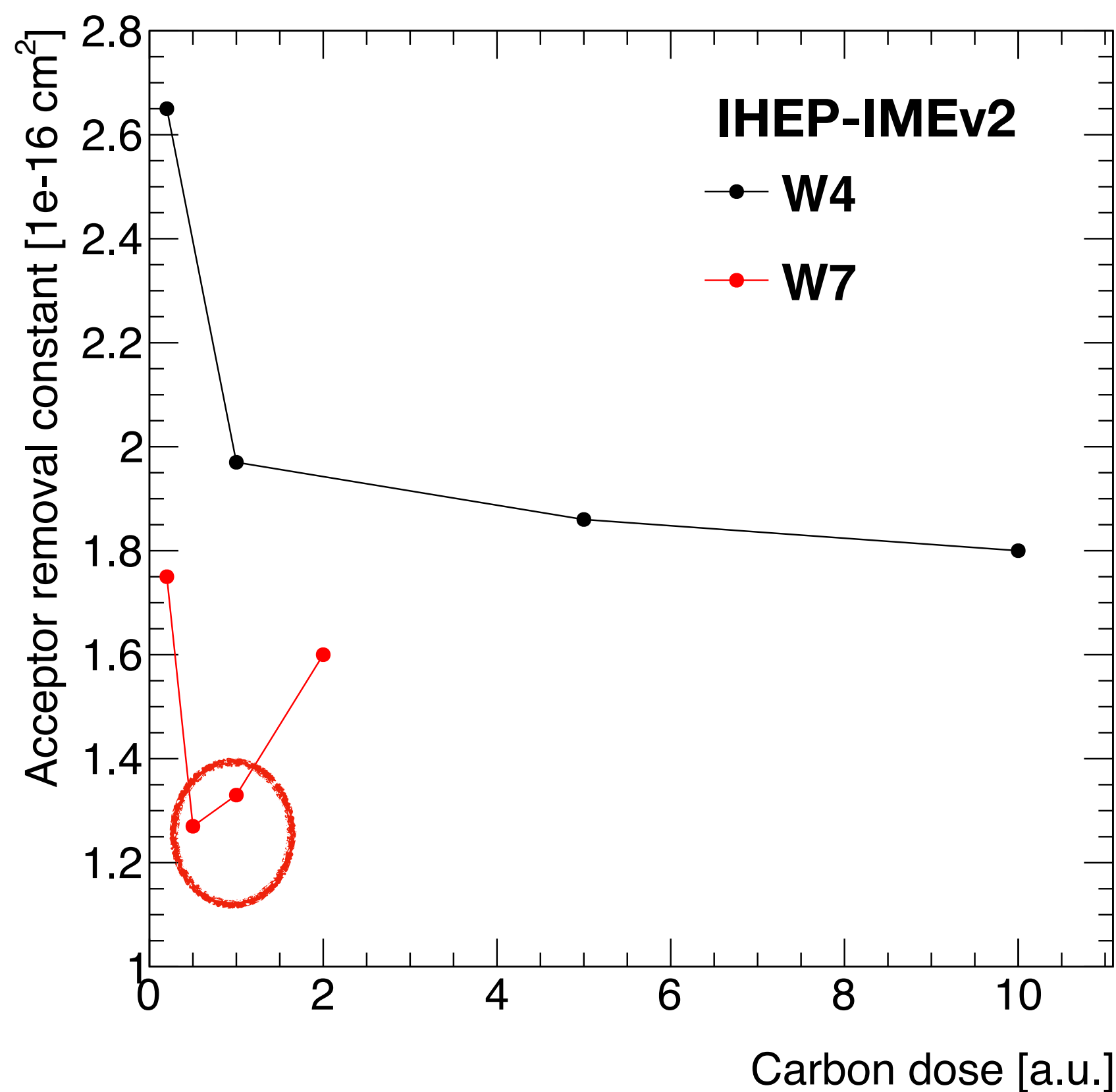
After irradiation:

- The leakage current increase nA- \rightarrow 100nA
- The acceptor concentration is reduced
 - V_{gl} decrease with the irradiation fluence (Acceptor removal constant)
- The sensor needs to be operated at higher voltage, higher power consumption ($I < 2 \mu A$)

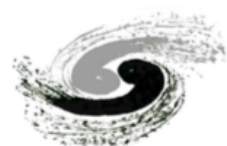
Carbonated sensor performance after irradiation

IHEP-IMEv2

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



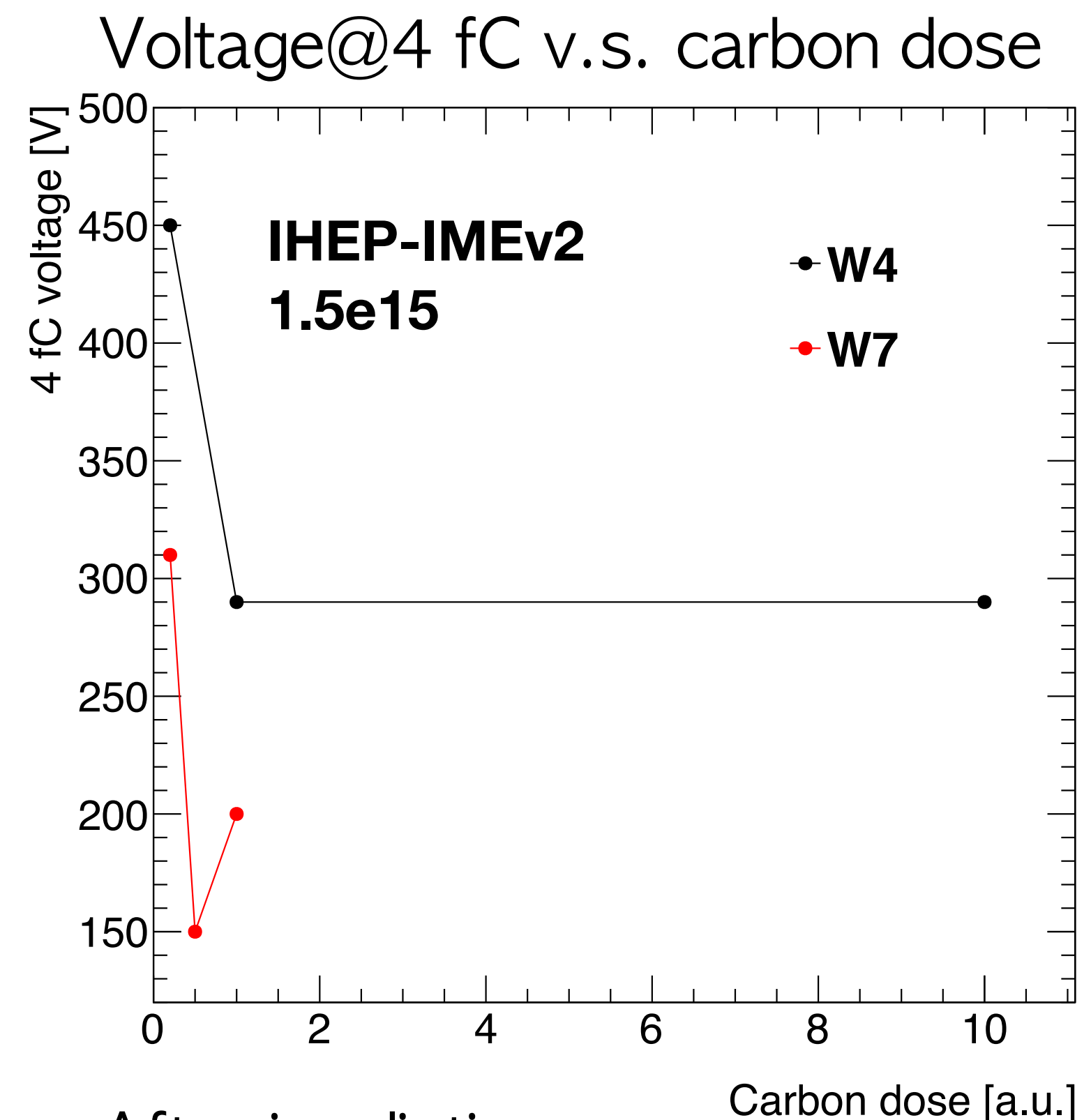
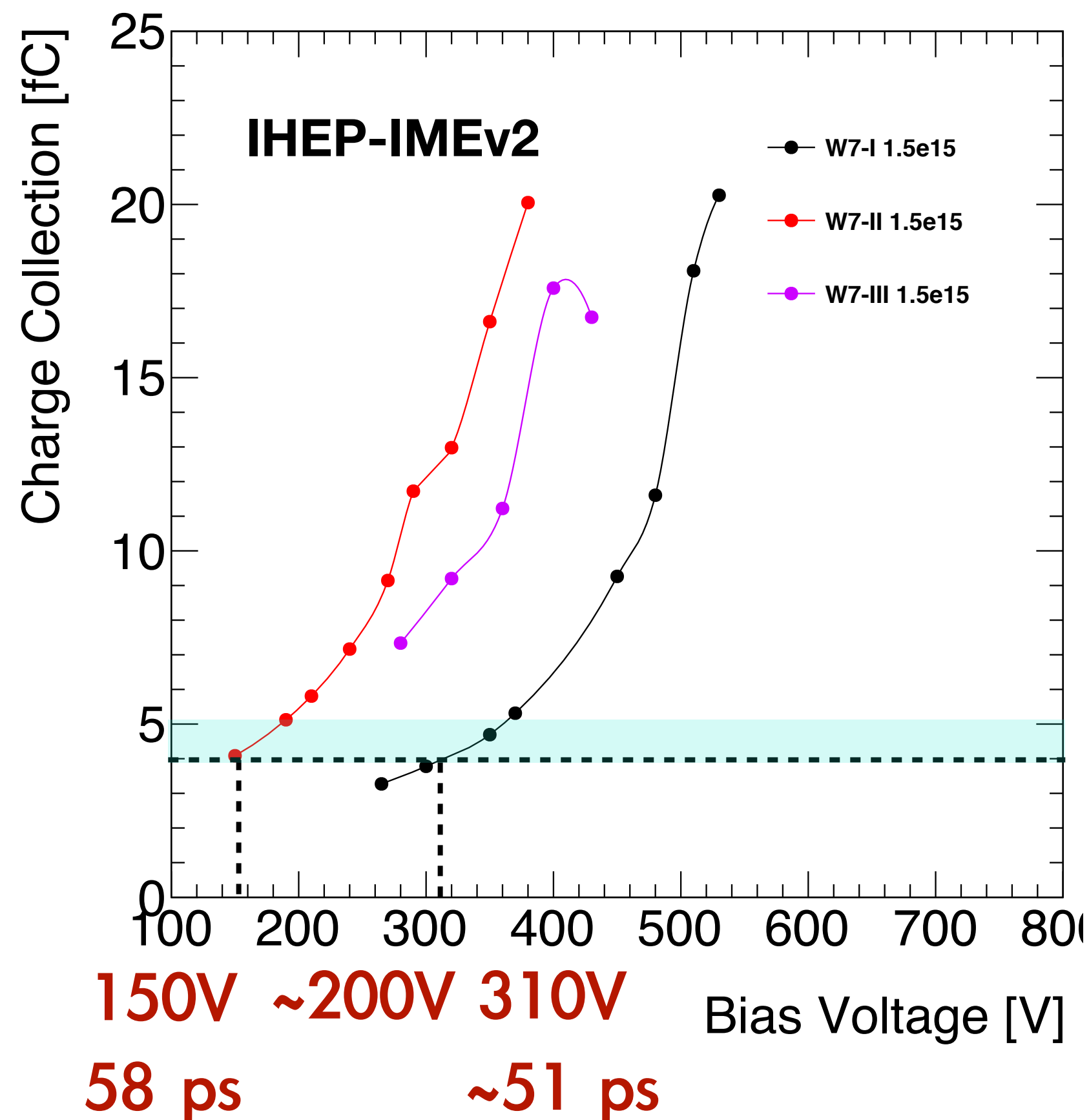
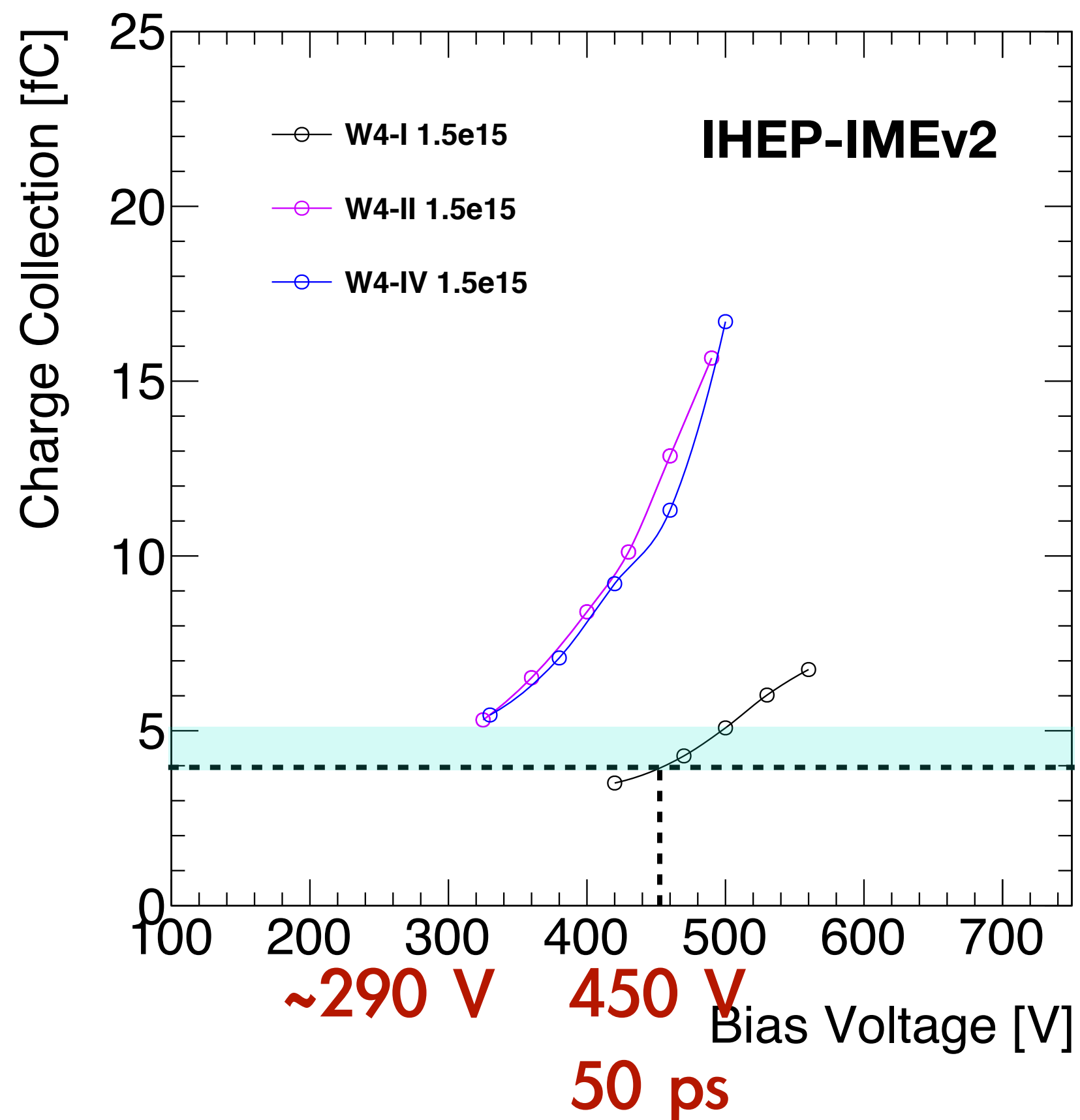
Between 0.2C and 1C, long time annealing seems to be the best recipe for irradiation hardness



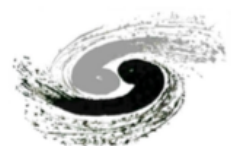
Carbonated sensor performance after irradiation

IHEP-IMEv2

After $1.5e15$ irradiation:



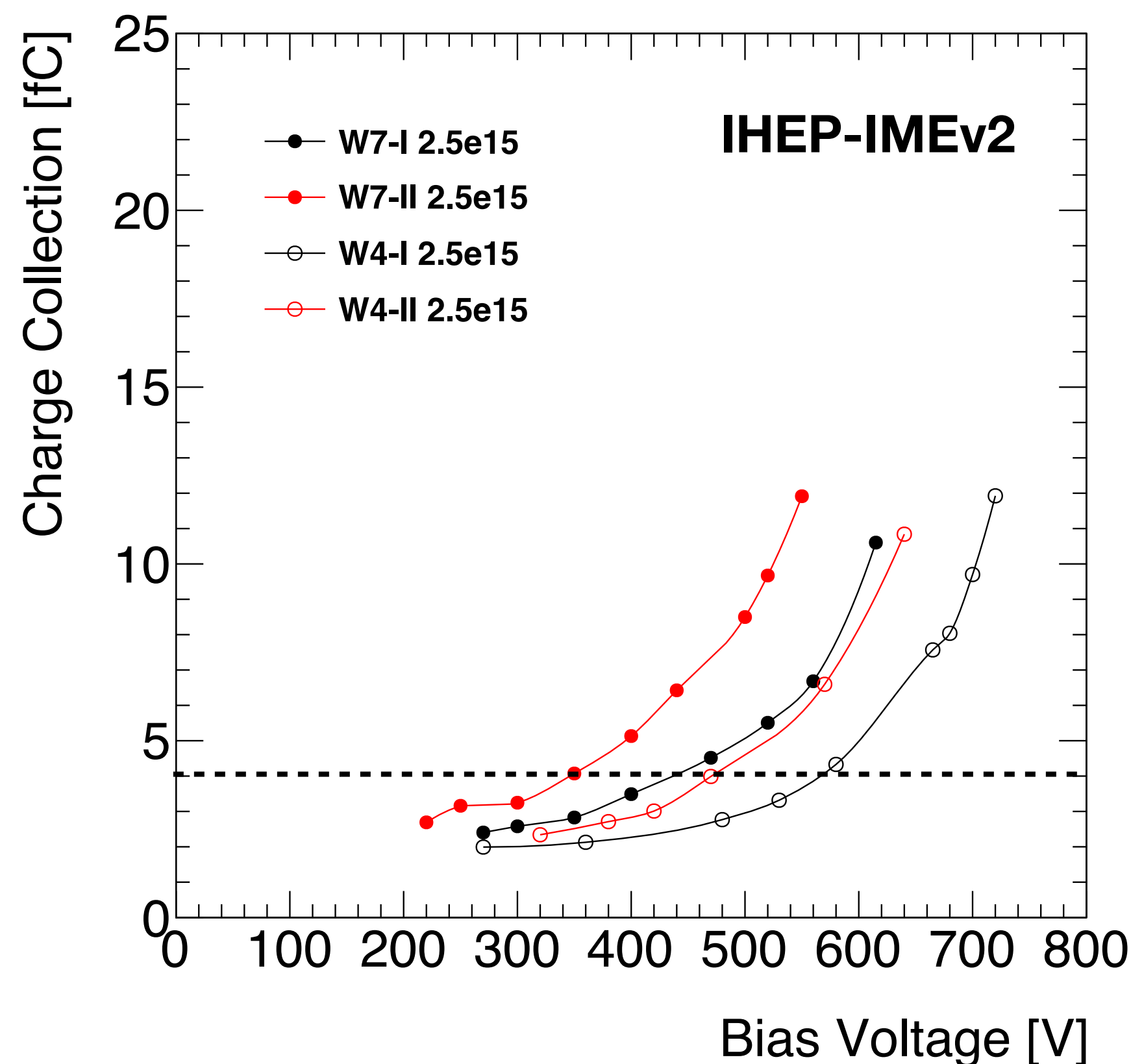
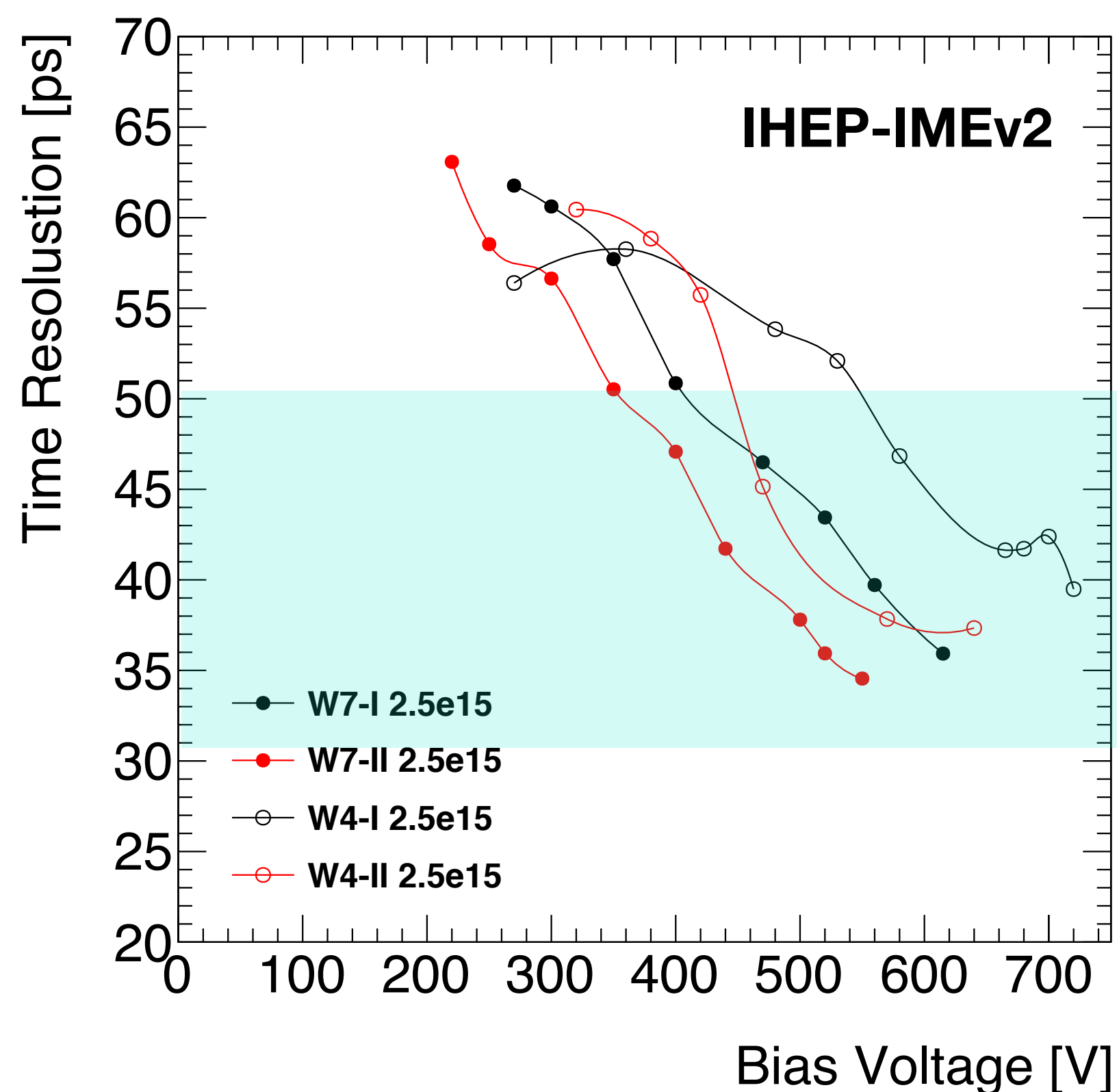
After irradiation
W7 performance better than W4



Carbonated sensor performance after irradiation

IHEP-IMEv2 time resolution and charge after $2.5e15$ irradiation:

- The best time resolution below 40 ps, charge larger than 10 fC
- W7 has better performance (long annealing)



4 fC at:

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

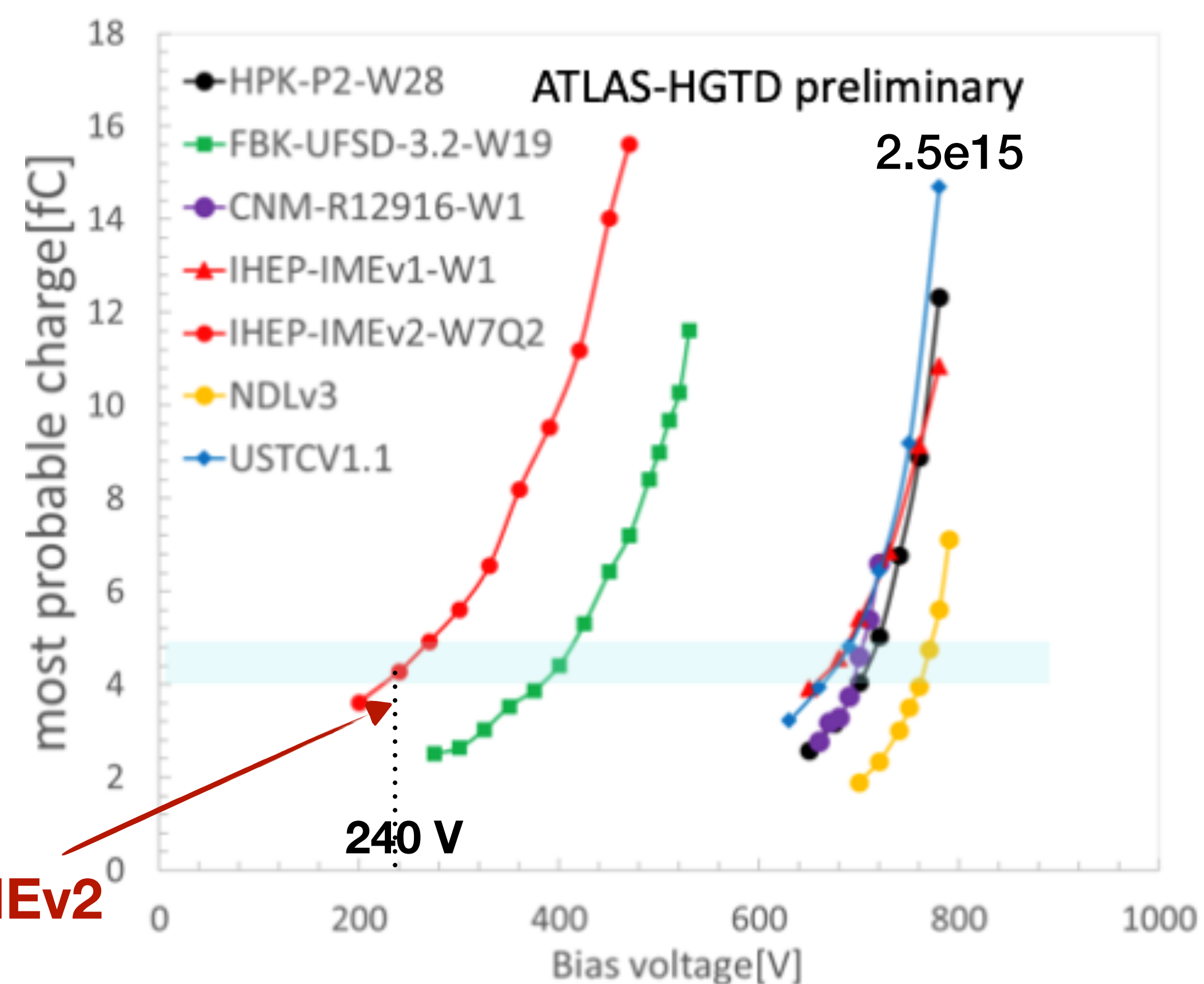
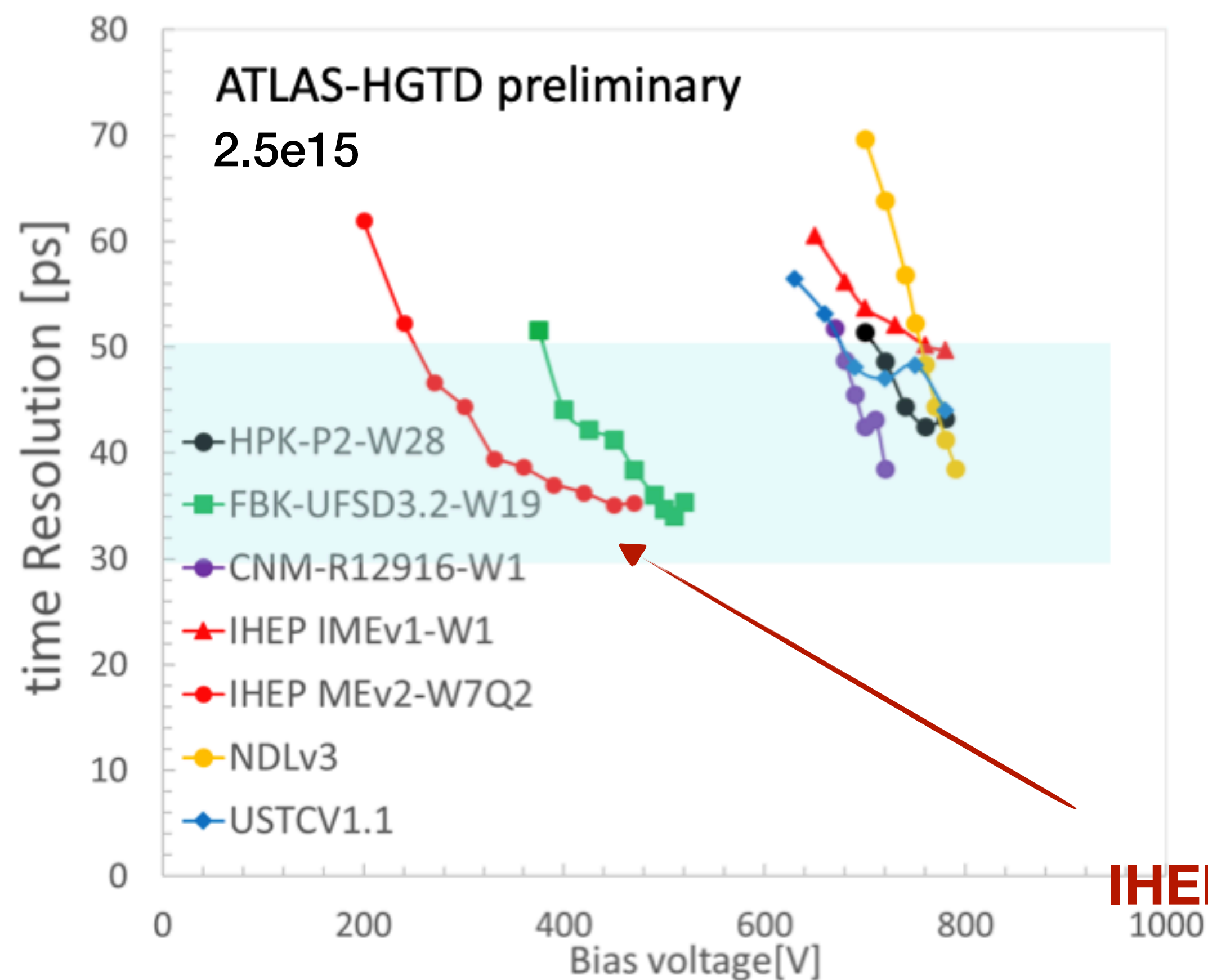
W7-I(0.2C): 440 V 48 ps

W4-II(1C): 470 V 45.1 ps

W4-I(0.2C): 560 V 49 ps

Carbonated sensor performance after irradiation

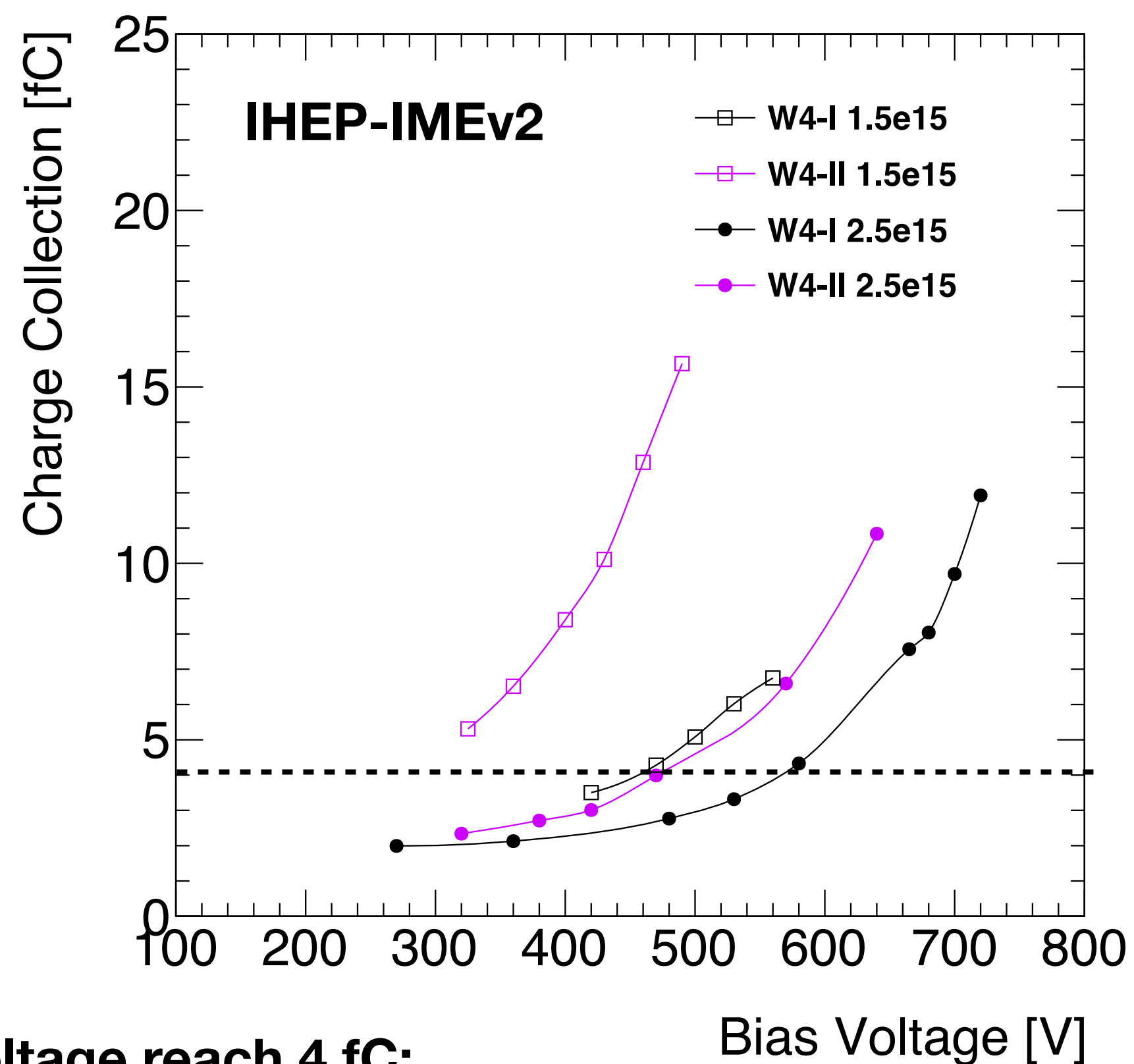
After $2.5e15$ irradiation:



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

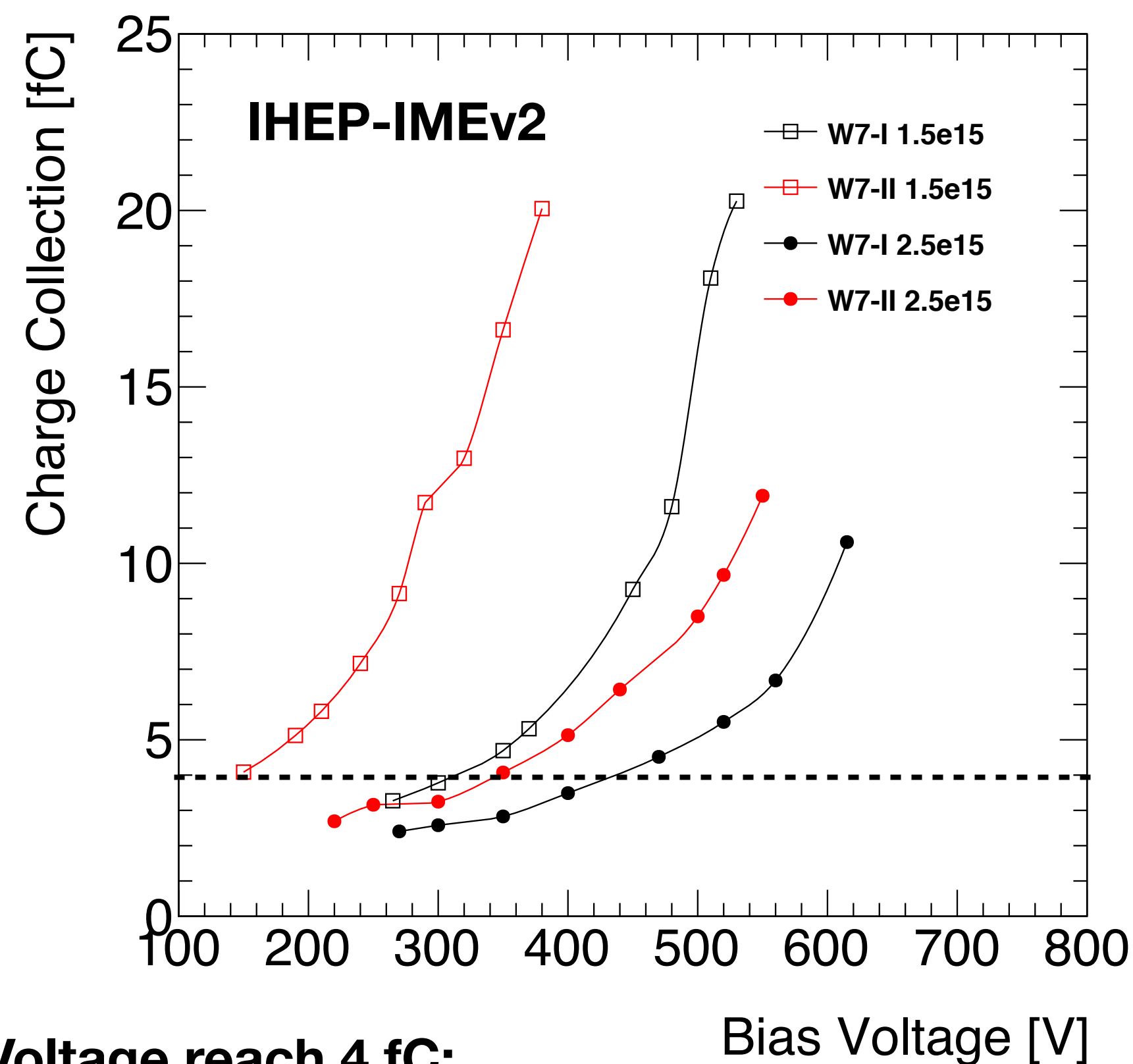
Carbonated sensor performance after irradiation

IHEP-IMEv2 1.5e15 and 2.5e15 comparison



Voltage reach 4 fC:

- W4-I(0.2C):
from 450 V(1.5e15) to 560 V(2.5e15), +90 V
- W4-II(1C):
from 290 V(1.5e15) to 470 V(2.5e15), +180 V



Voltage reach 4 fC:

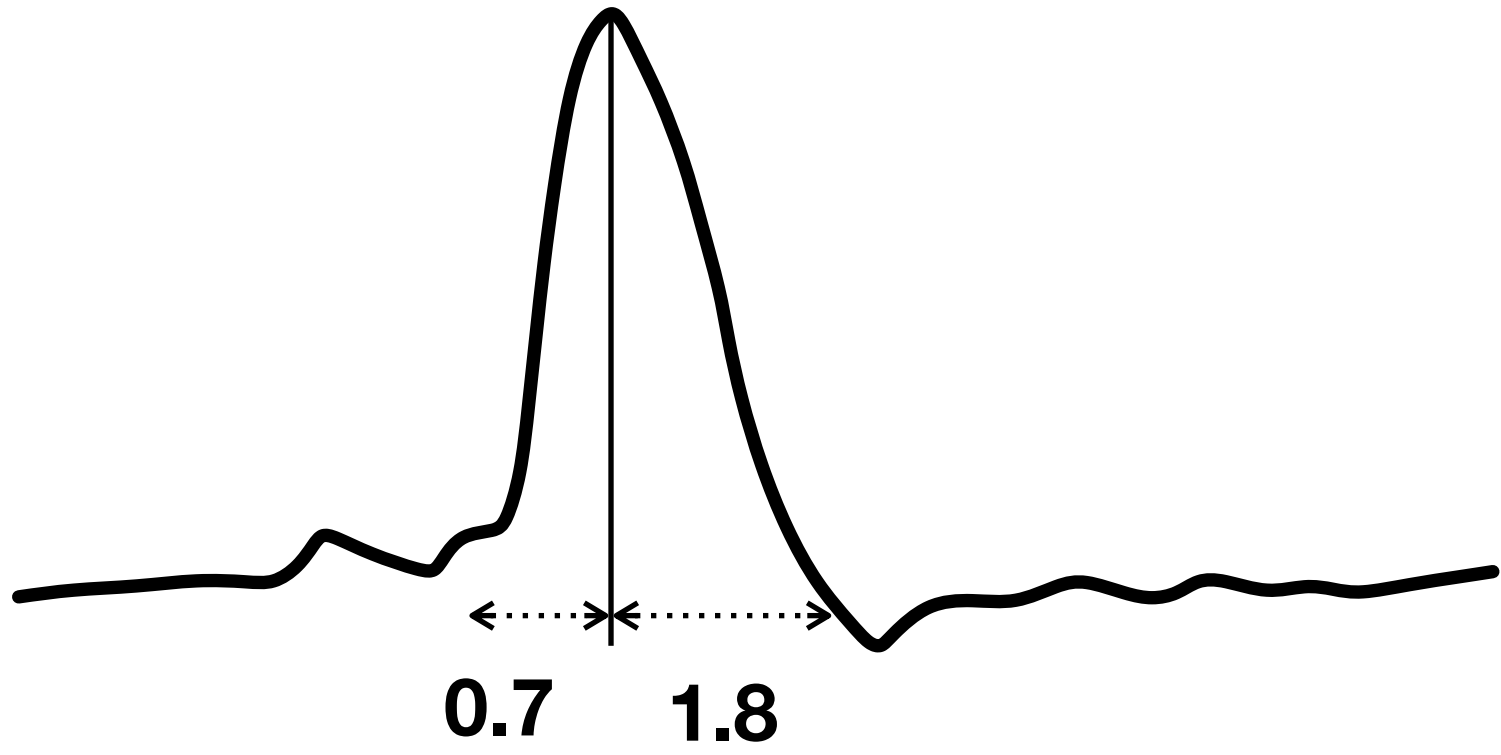
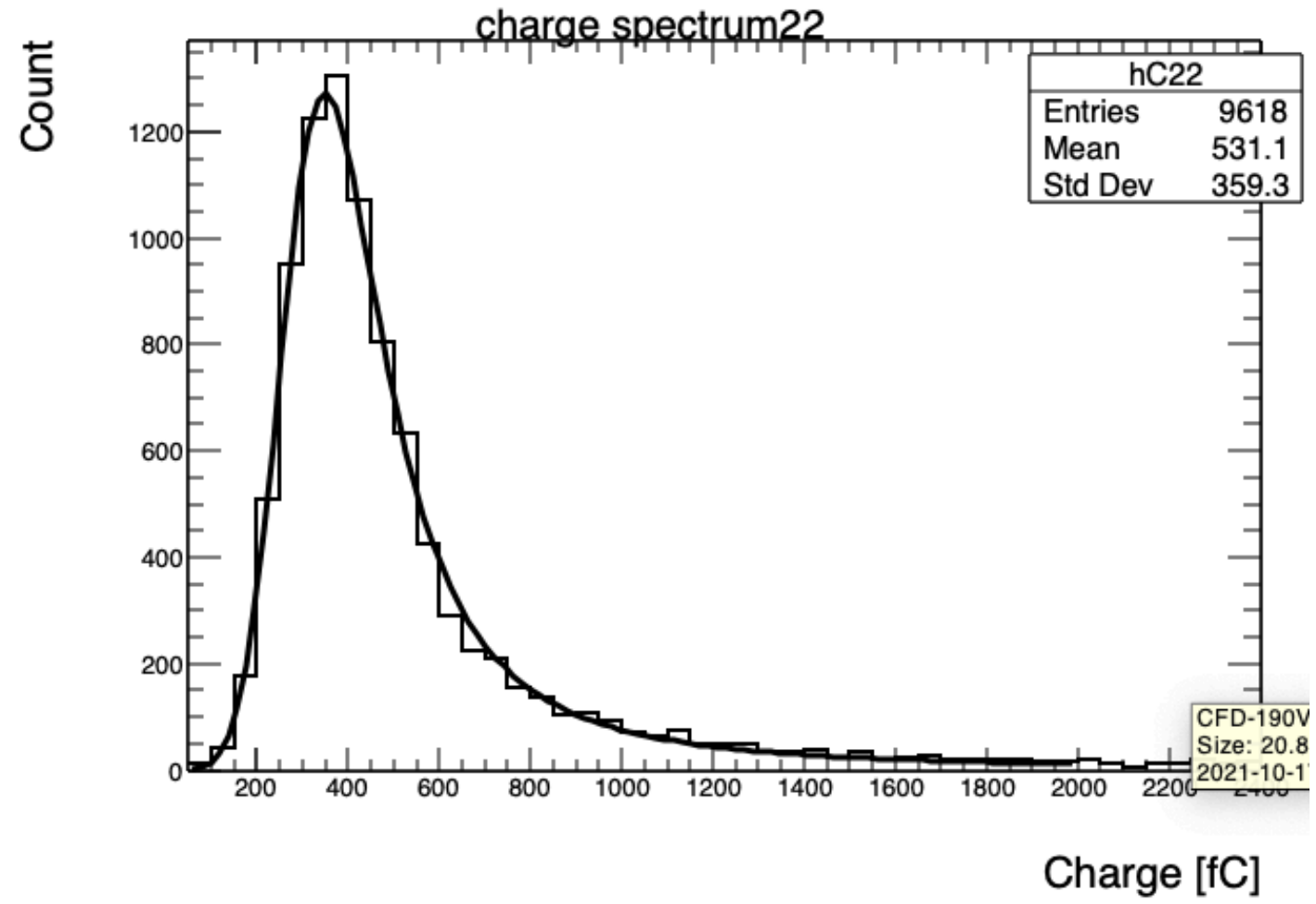
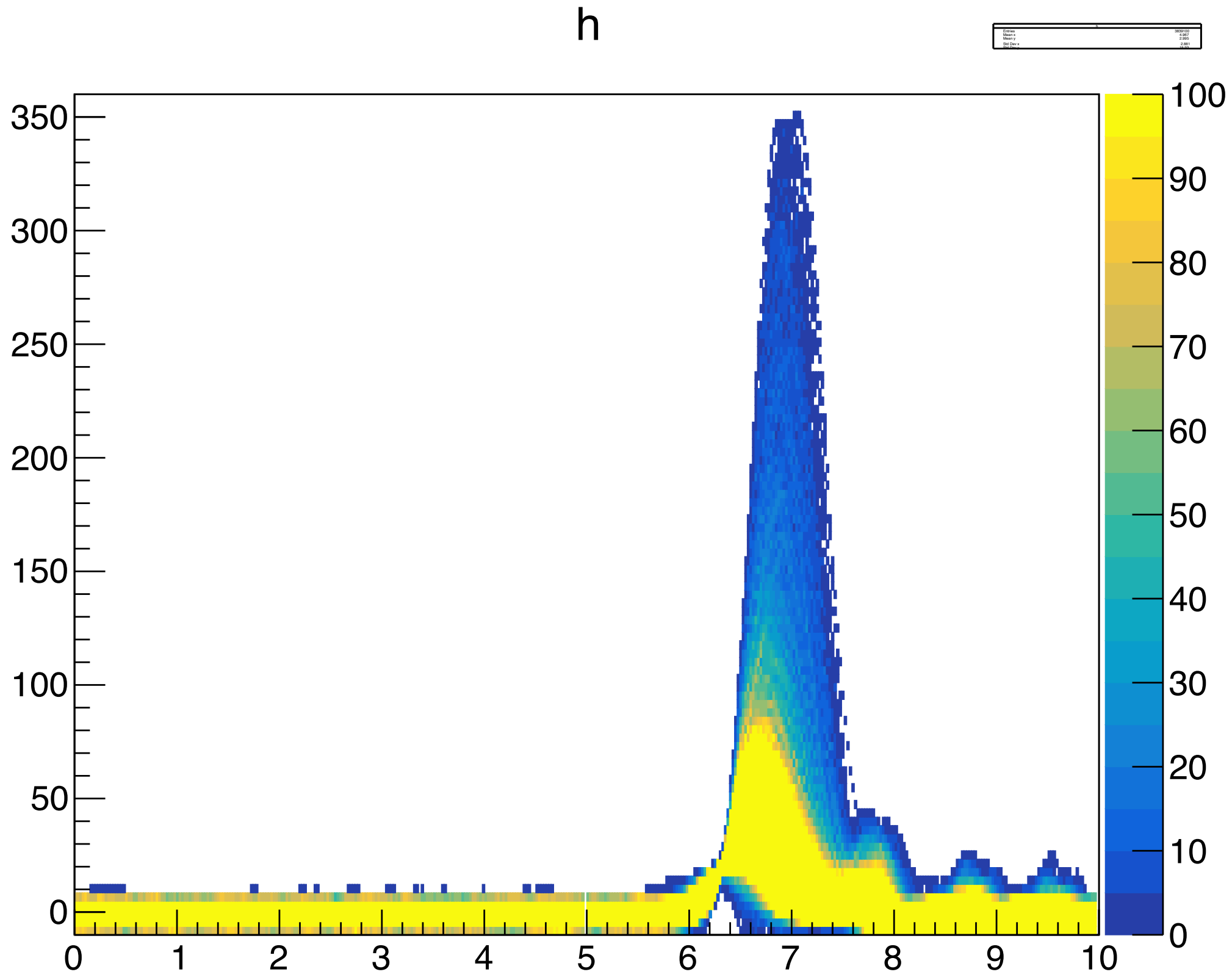
- W7-I(0.2C):
from 310 V(1.5e15) to 440 V(2.5e15), +130 V
- W7-II(0.5C):
from 150 V(1.5e15) to 350 V(2.5e15), +200 V

Summary

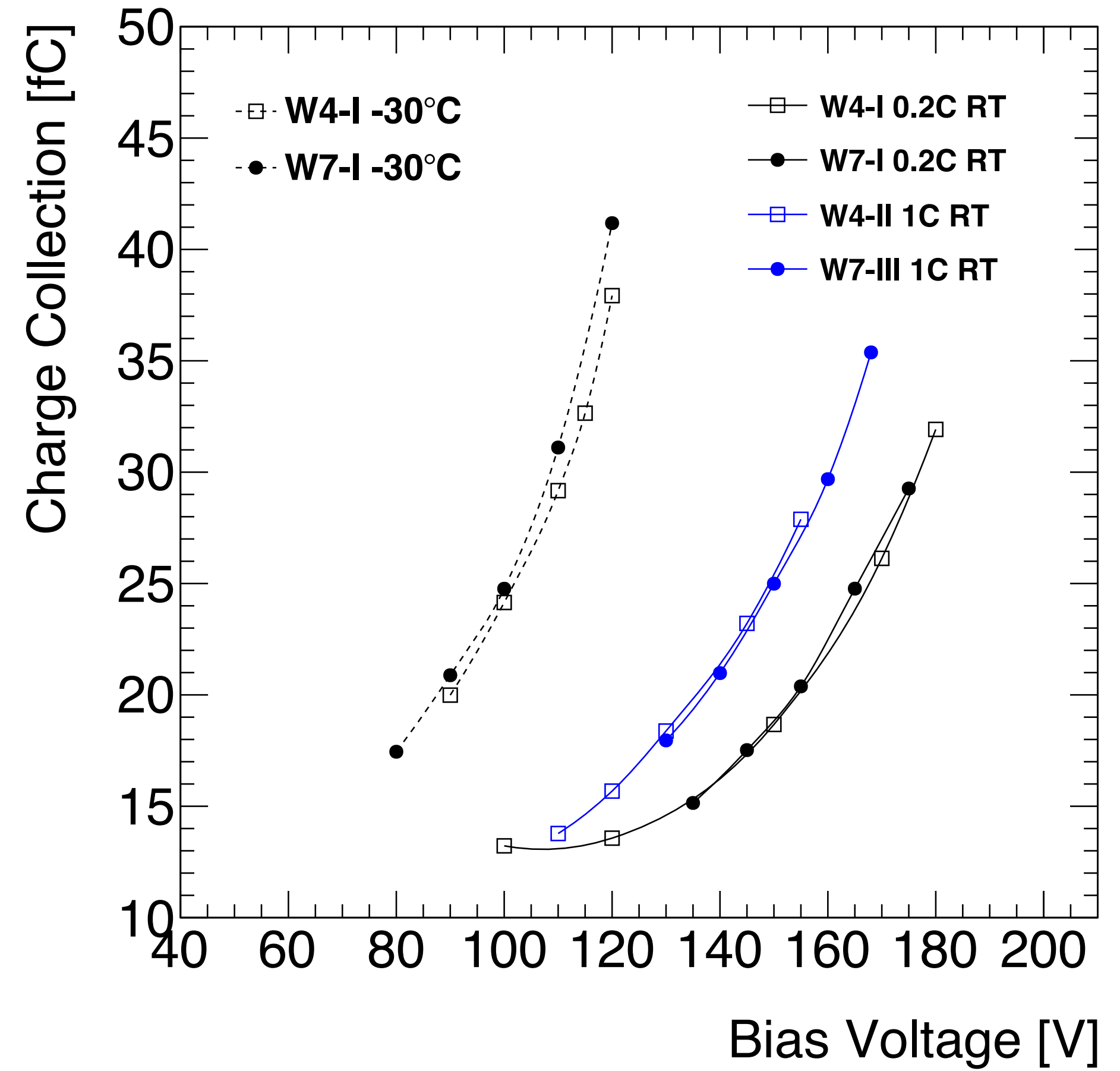
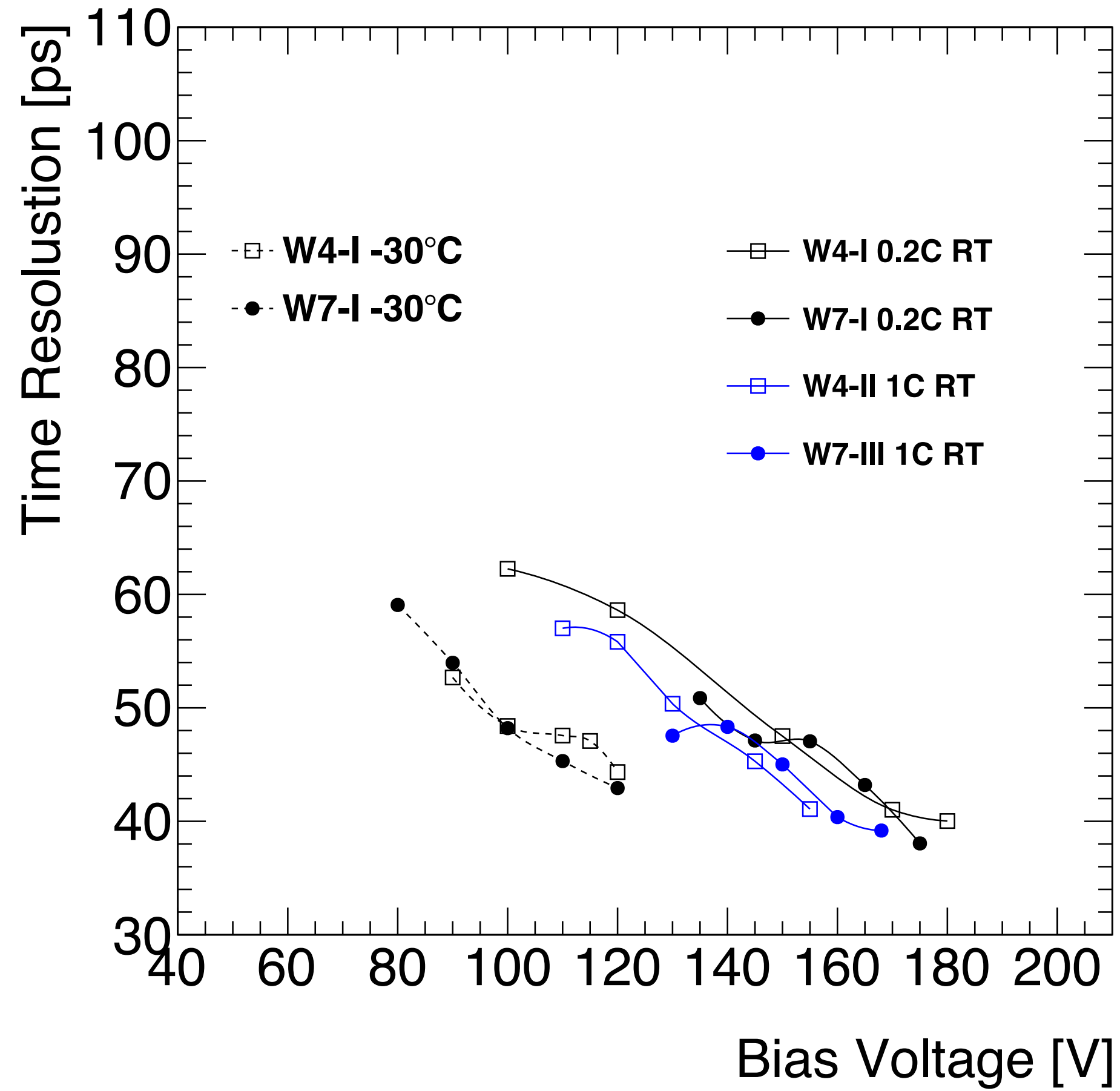
- IHEP-IME LGAD sensors showed promising results for the ATLAS HGTD project before and after irradiation.
Carbon implantation for the irradiation hardness was optimized.
- Before irradiation:
 - When carbon dose increase: $\left\{ \begin{array}{l} \text{the leakage current increase} \\ \text{the breakdown voltage decrease} \\ \text{the } V_{gl} \text{ increase} \\ \text{less uniformed} \end{array} \right.$
 - Best time resolution ~ 40 ps, charge collection > 35 fC
 - At low carbon dose, the gain at the voltage increase with the carbon dose.
 - Thermal treatment of carbon effect on the timing/charge is not significant at low carbon dose.
- After irradiation:
 - Sensors were tested at TB and there are positive outcomes for HGTD. The results will be released soon.
 - **IHEP-IMEv2 W7-II has the best performance** $\left\{ \begin{array}{l} \text{- with acceptor removal 1.2.} \\ \text{- } 4 \text{ fC@}350\text{V}(2.5\text{e}15)/150\text{V}(1.5 \text{ e}15), \text{ both } \sim 50 \text{ ps.} \\ \text{- Satisfied all the requirements for HGTD including the SEB one, within safety margin} \end{array} \right.$
 - After $2.5\text{e}15$ IHEP-IMEv2 W7-I,II have ≥ 4 fC below 450 V, W7-III also expected to be below.
 - Long annealing overall more irradiation hard than fast annealing though before irradiation they are close.

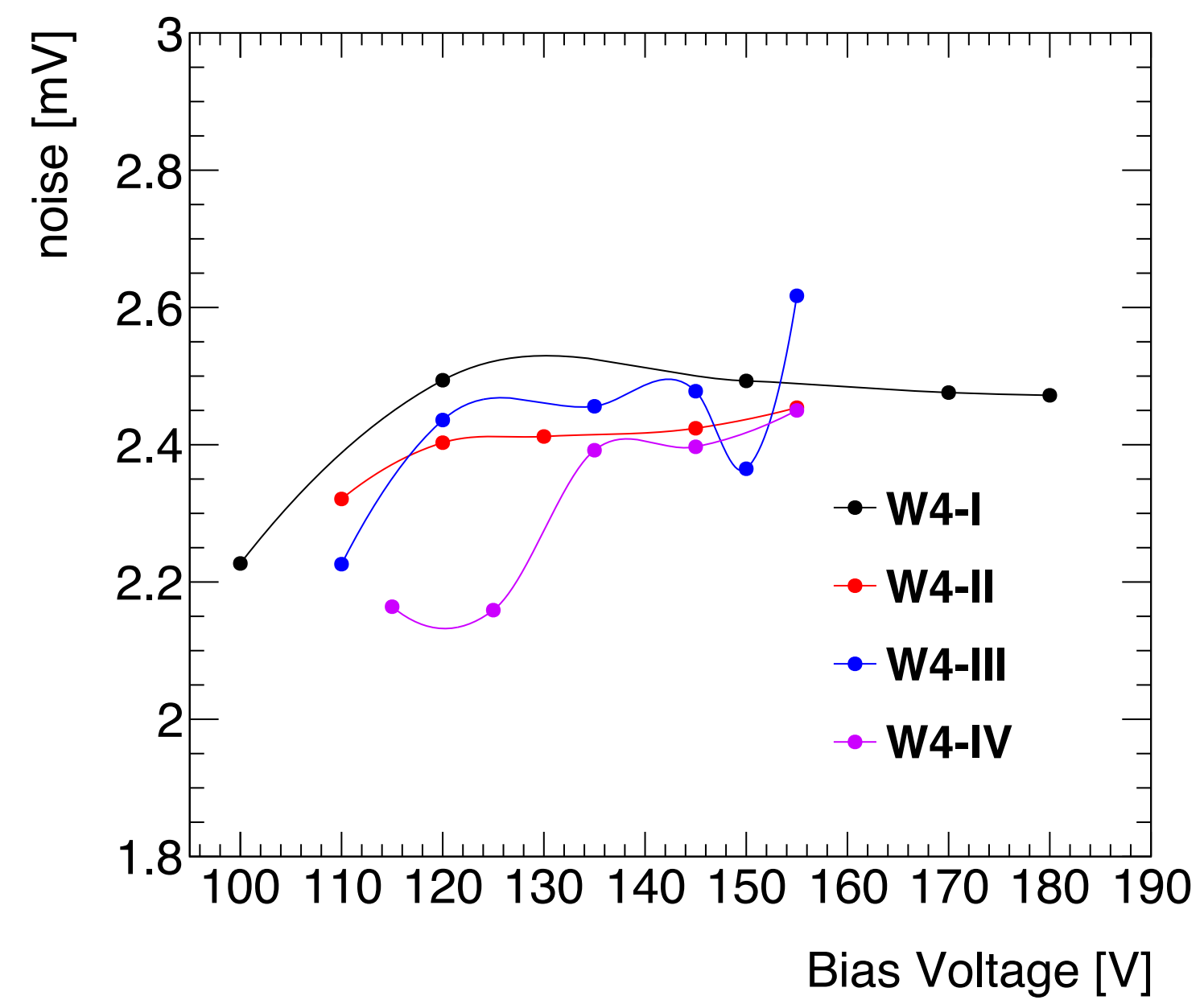
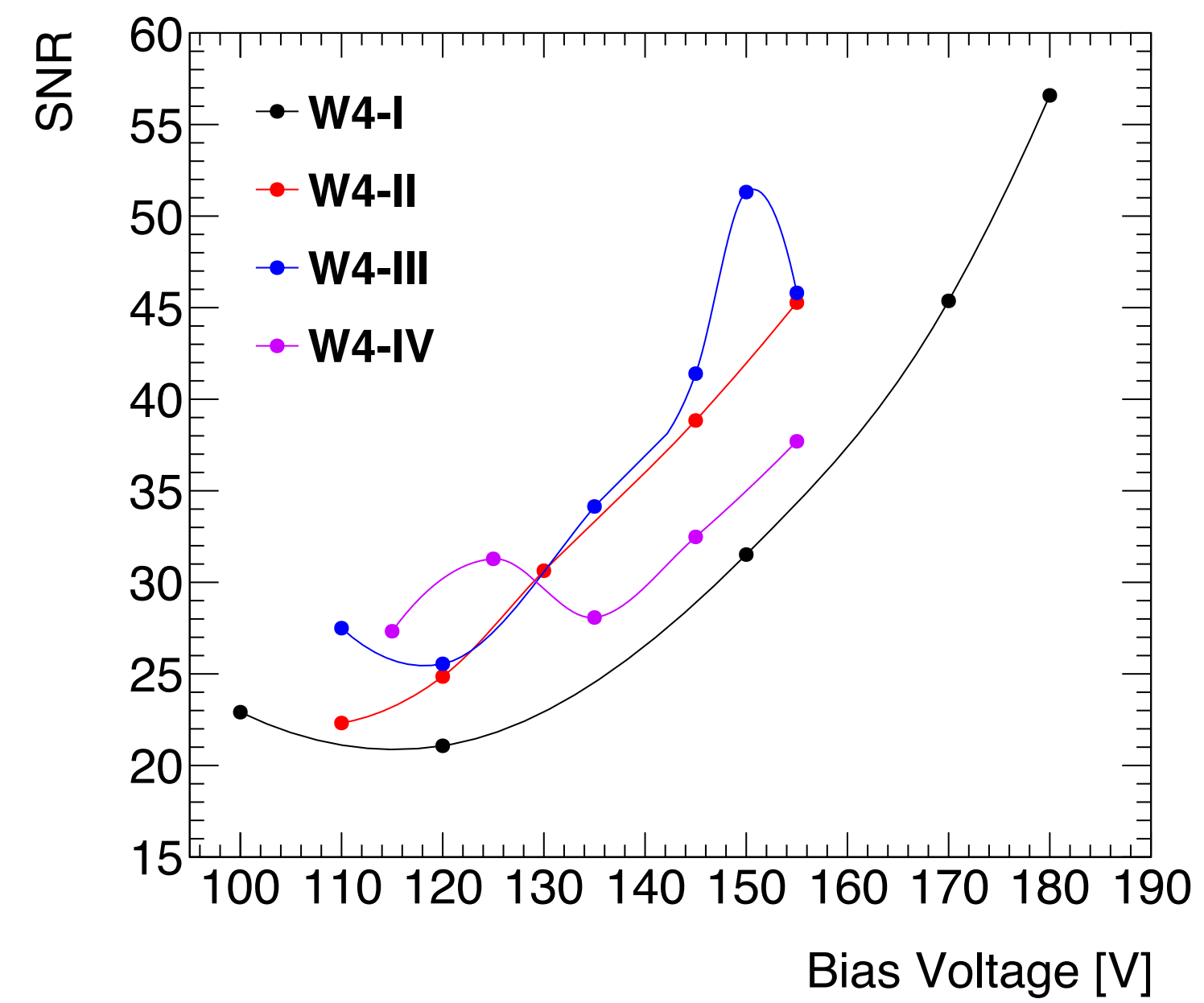
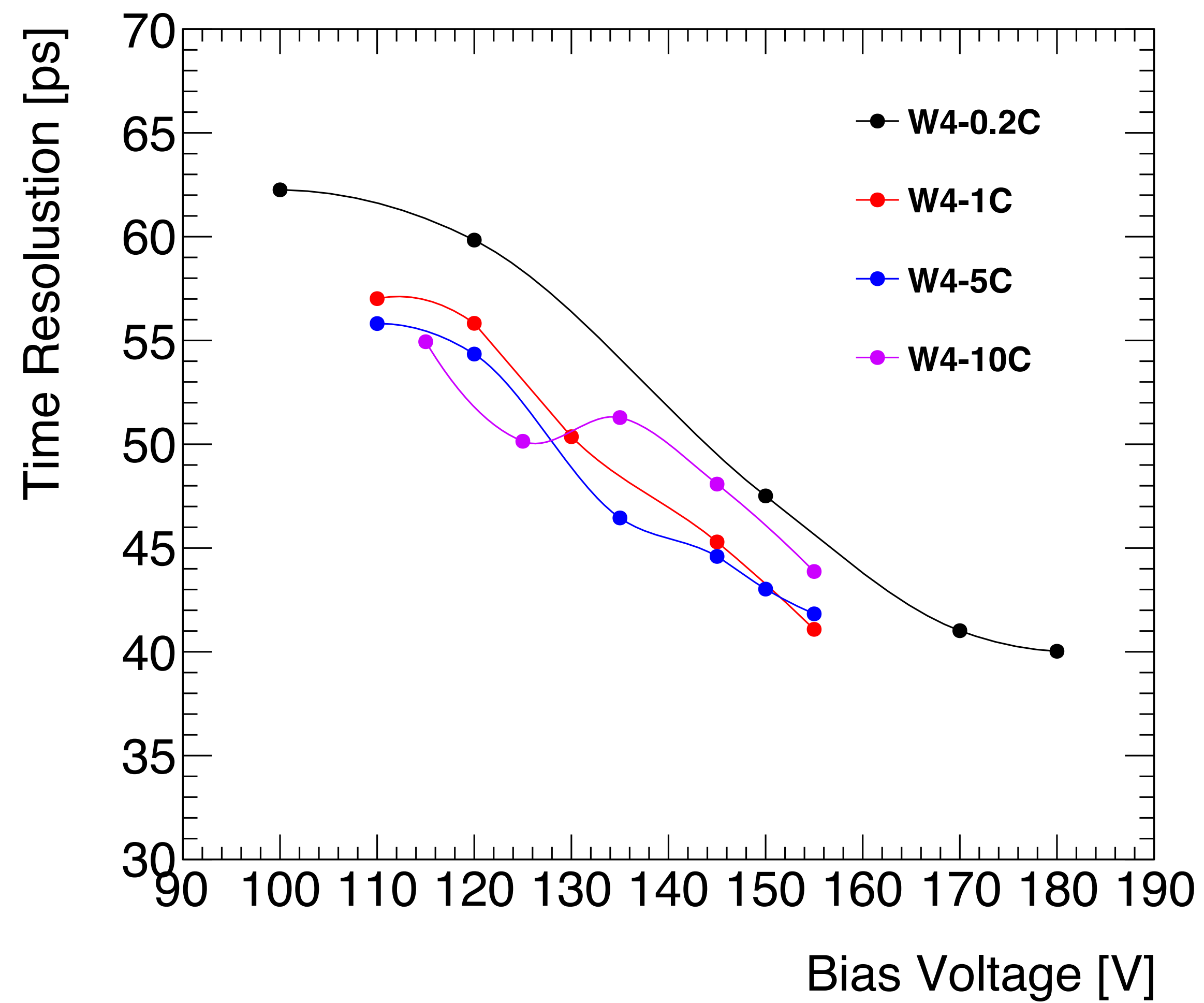
Back-up

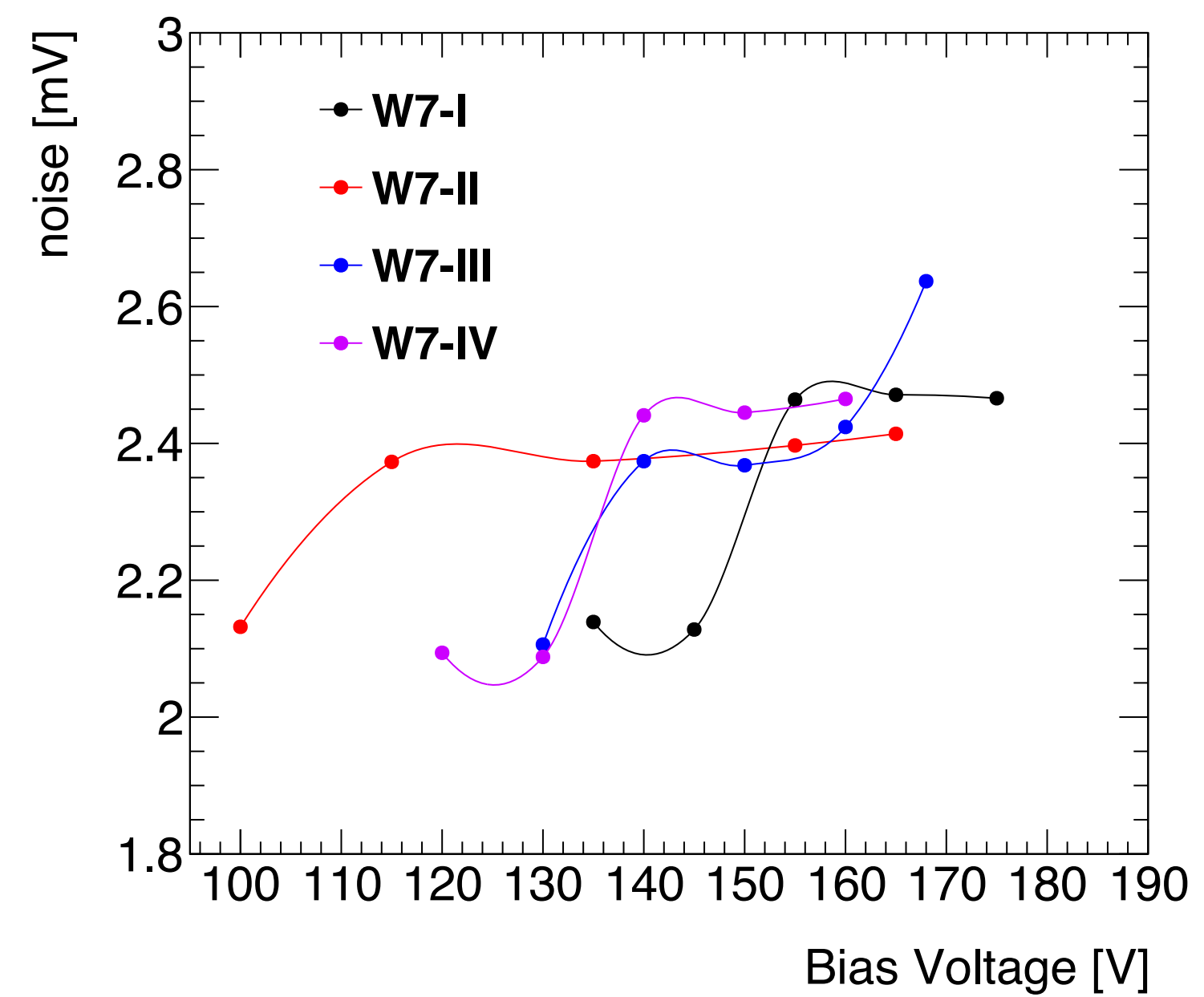
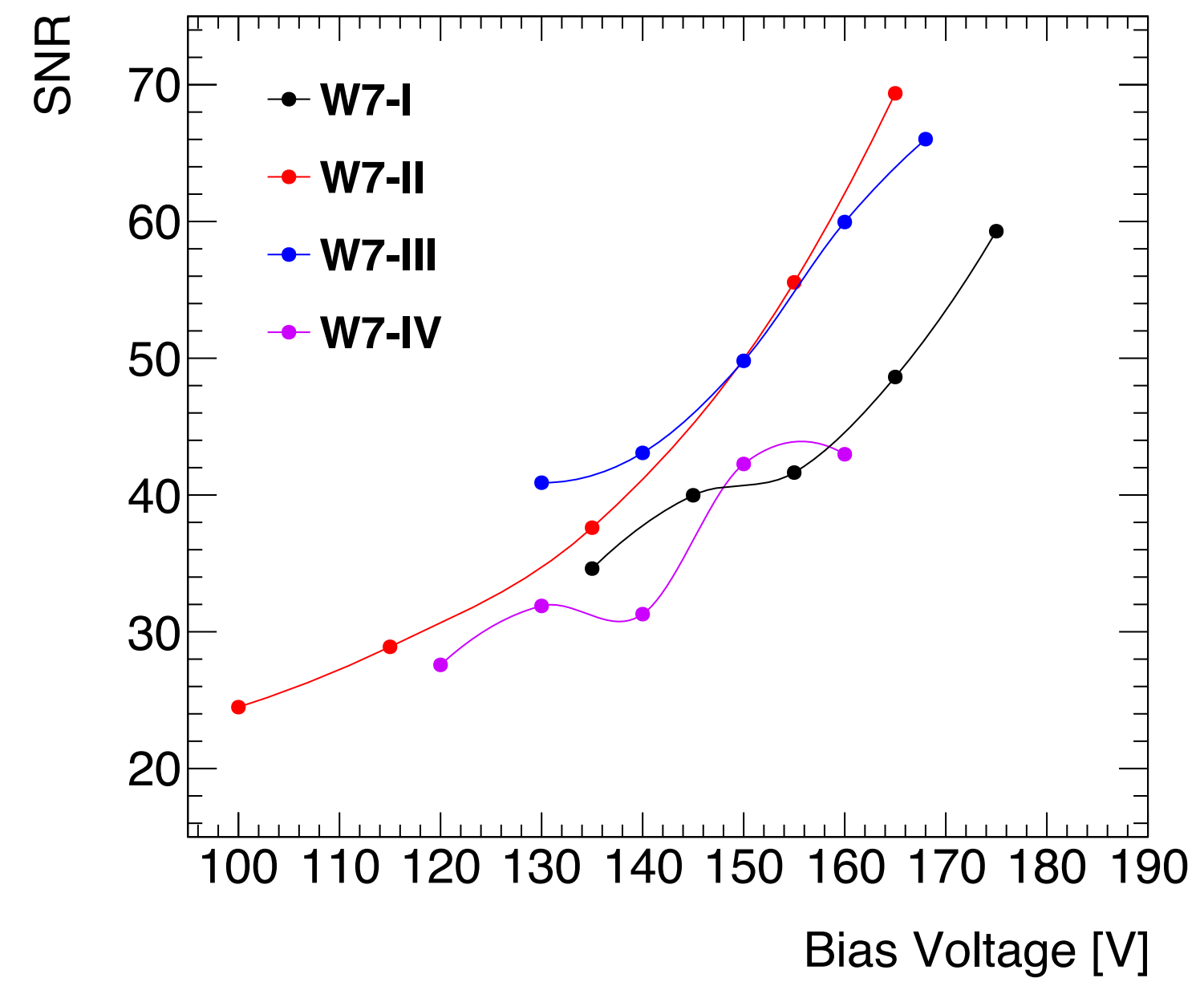
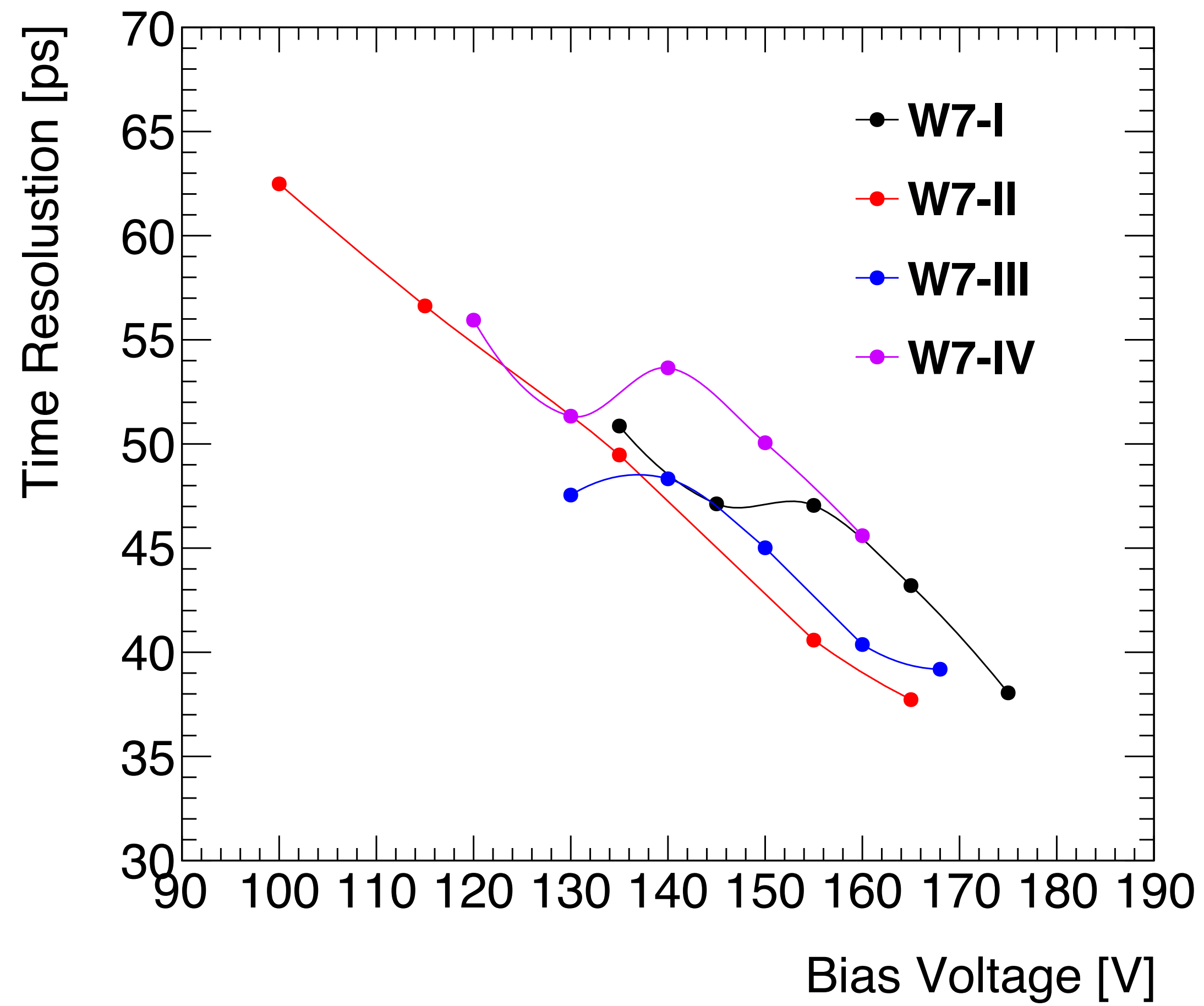
Charge



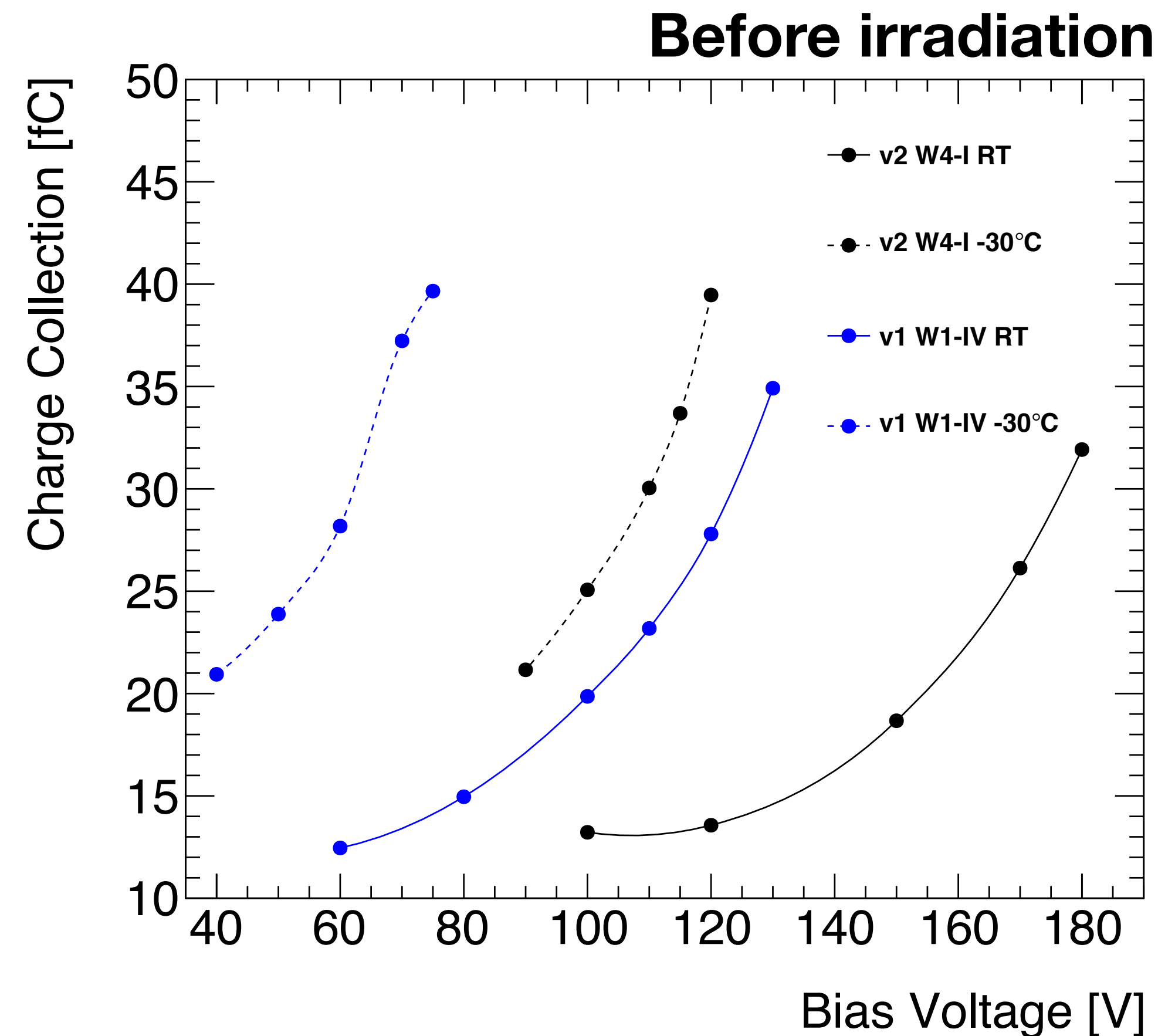
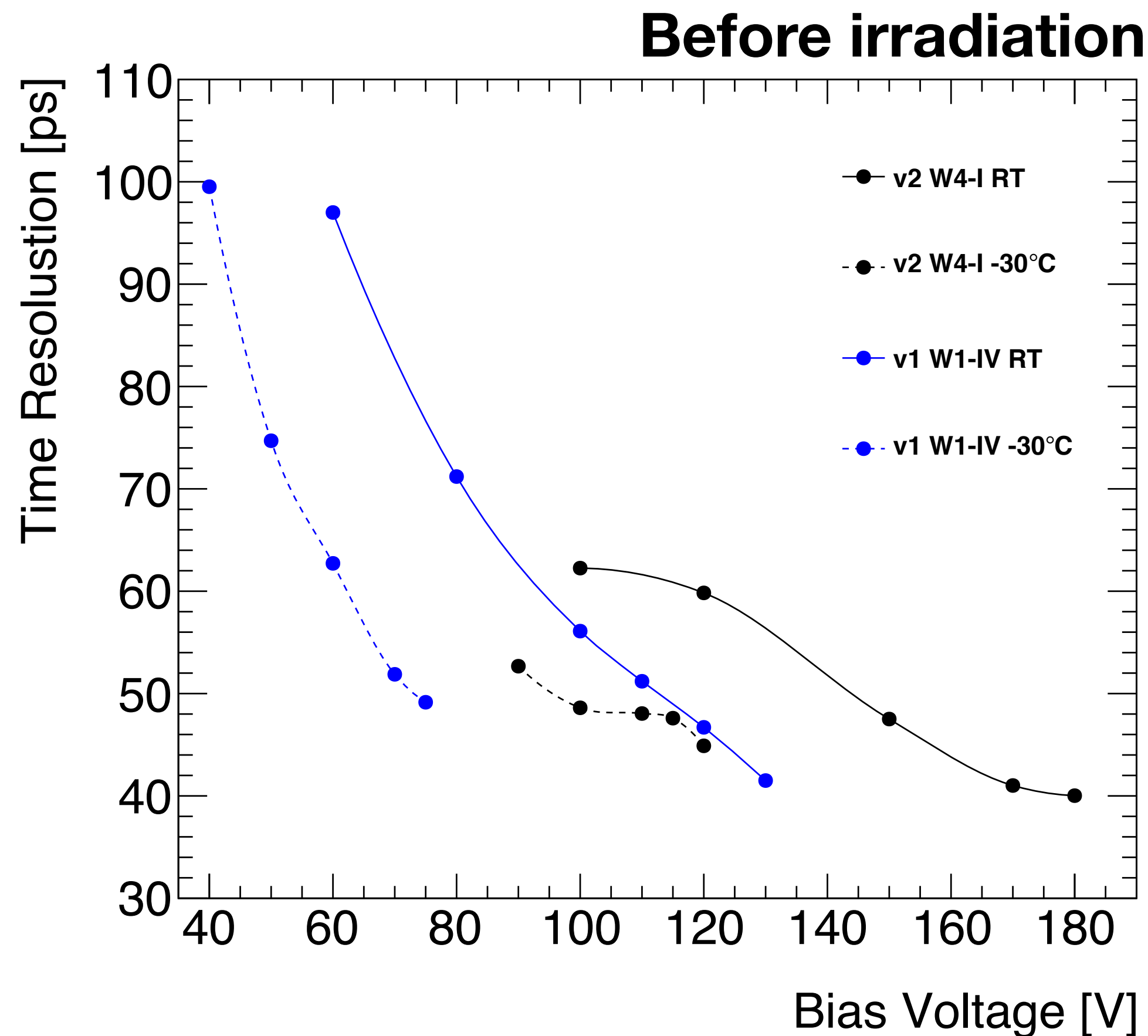
Performance before irradiation







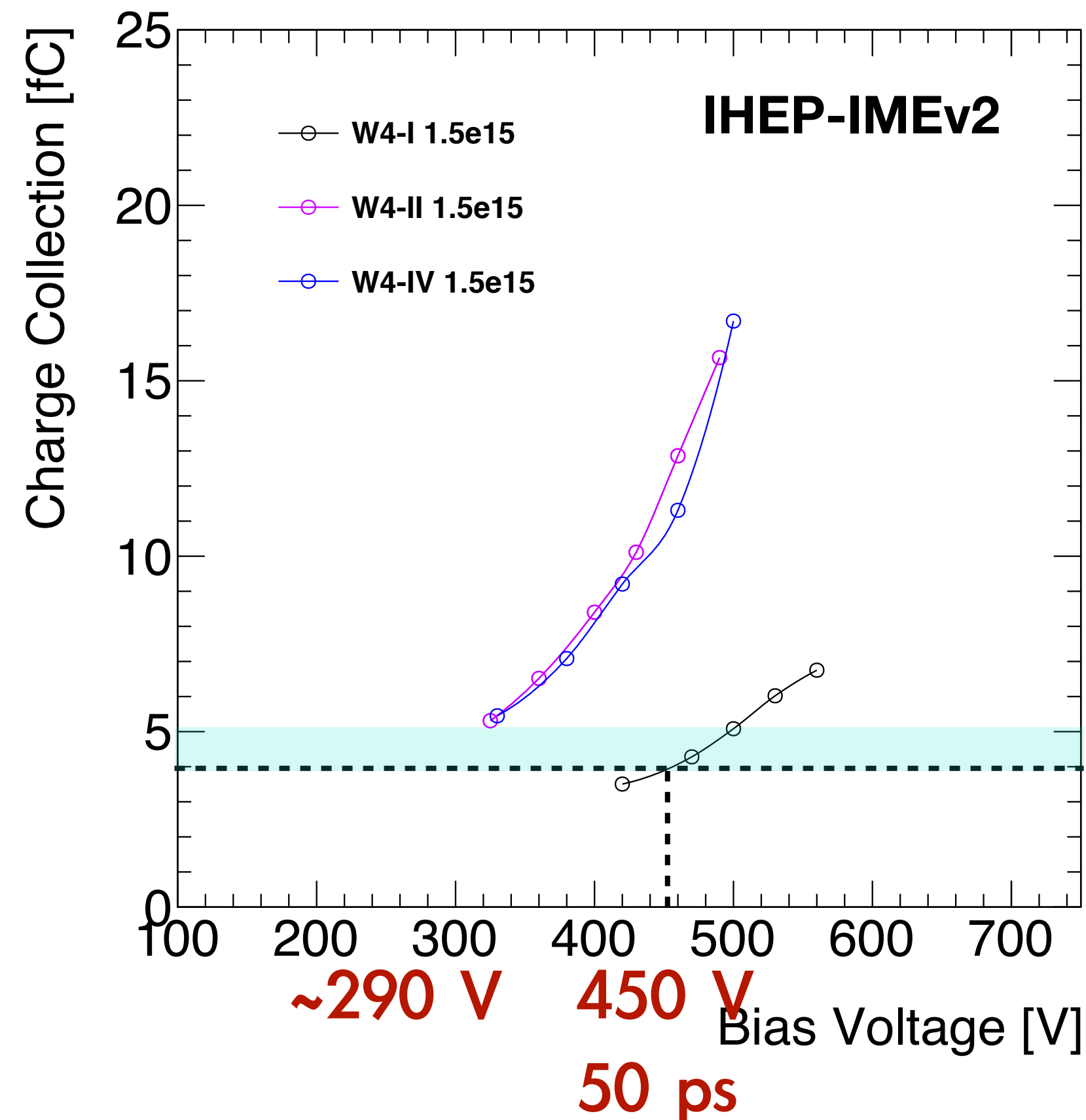
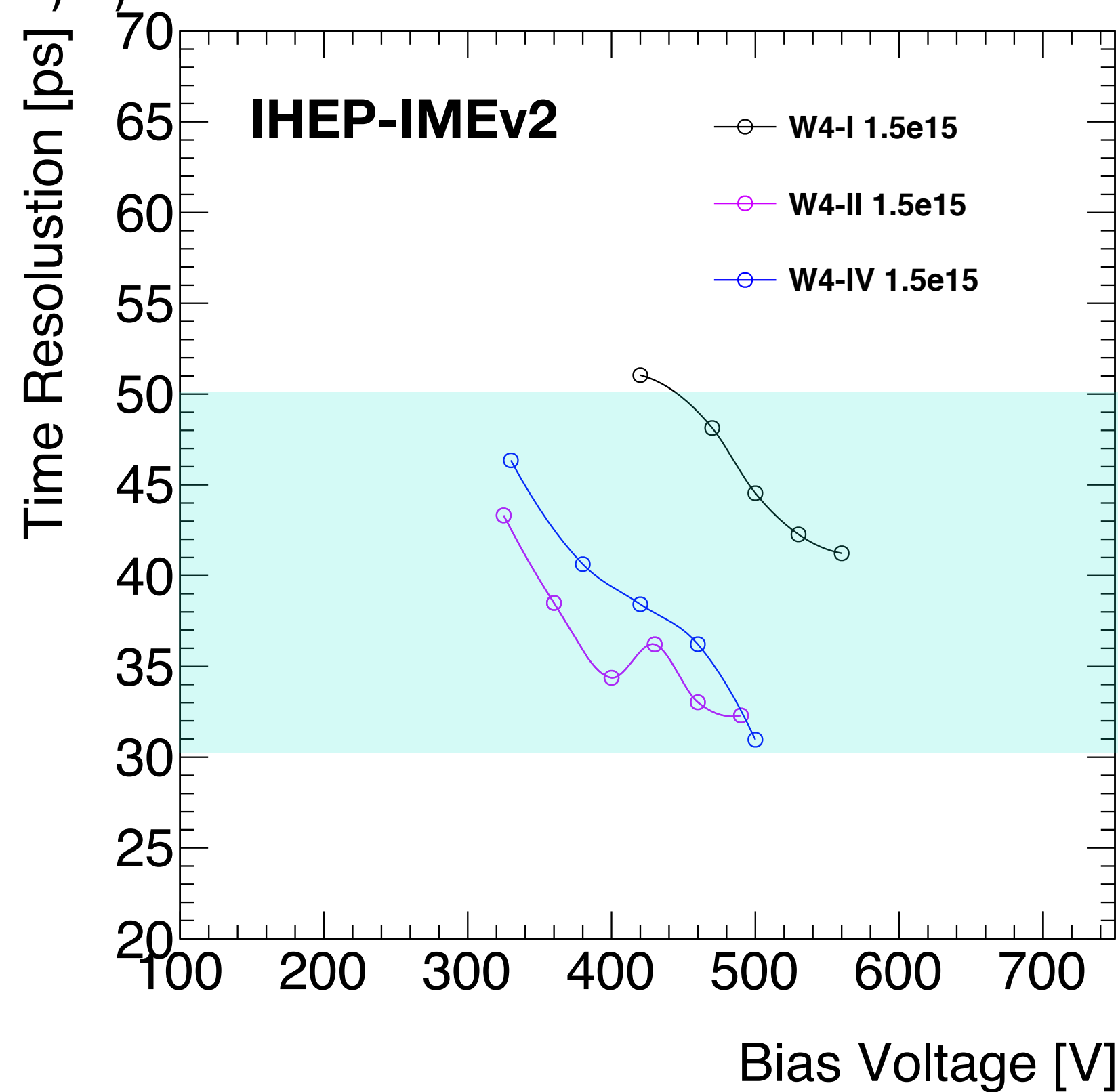
IHEP-IME v1 and v2 comparison at RT and -30°C



- **V2** have higher breakdown voltage than **V1**.
- Both have lower BV at -30°C (dashed), and collected more charge at -30°C.
- Best time resolution (~40 ps) are similar for **V1** and **V2**
- Best charge collection are also similar ~35 (40) fC at RT (-30°C).

Carbonated sensor performance after irradiation

W4-I,II,IV after $1.5e15$ irradiation



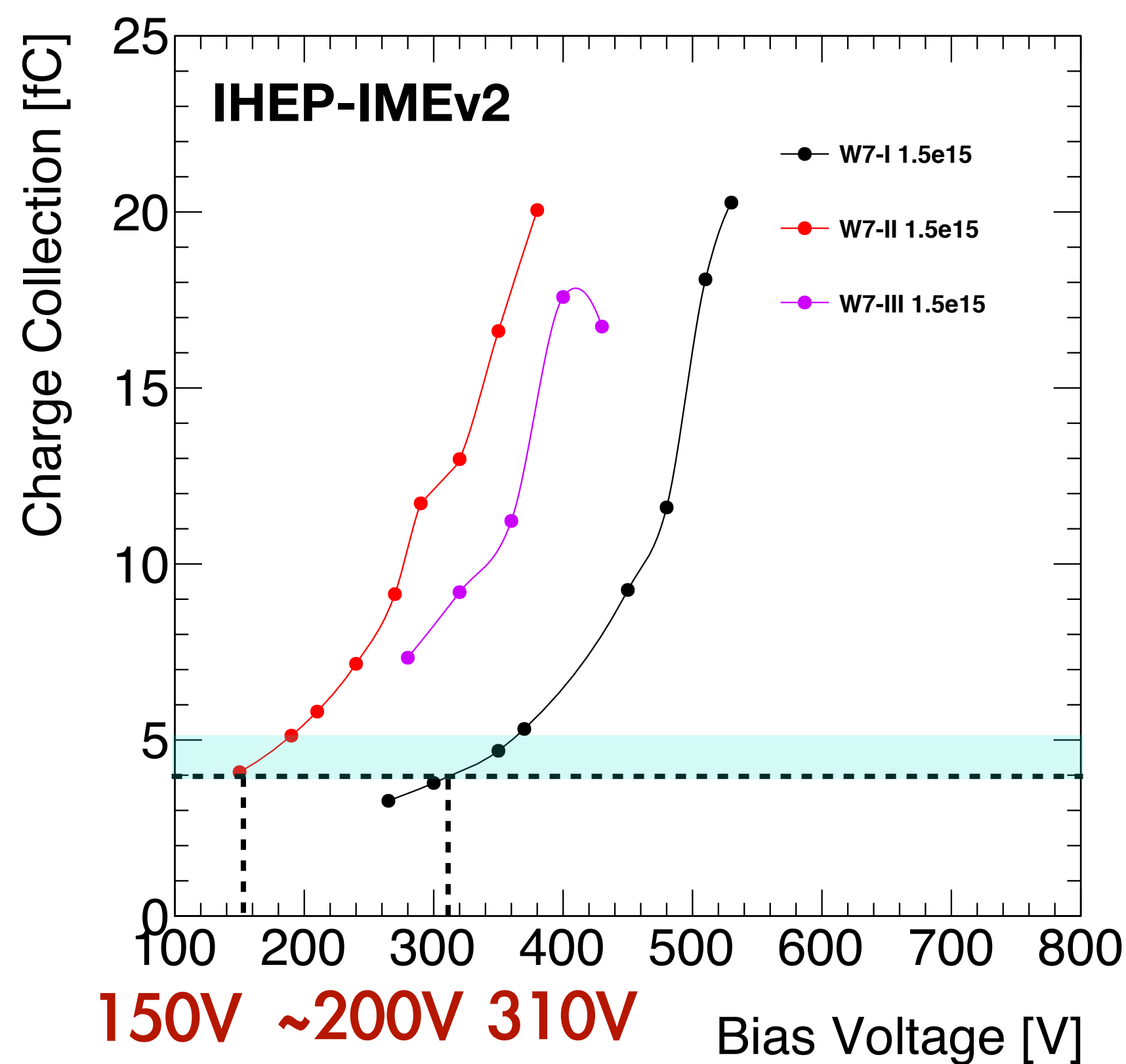
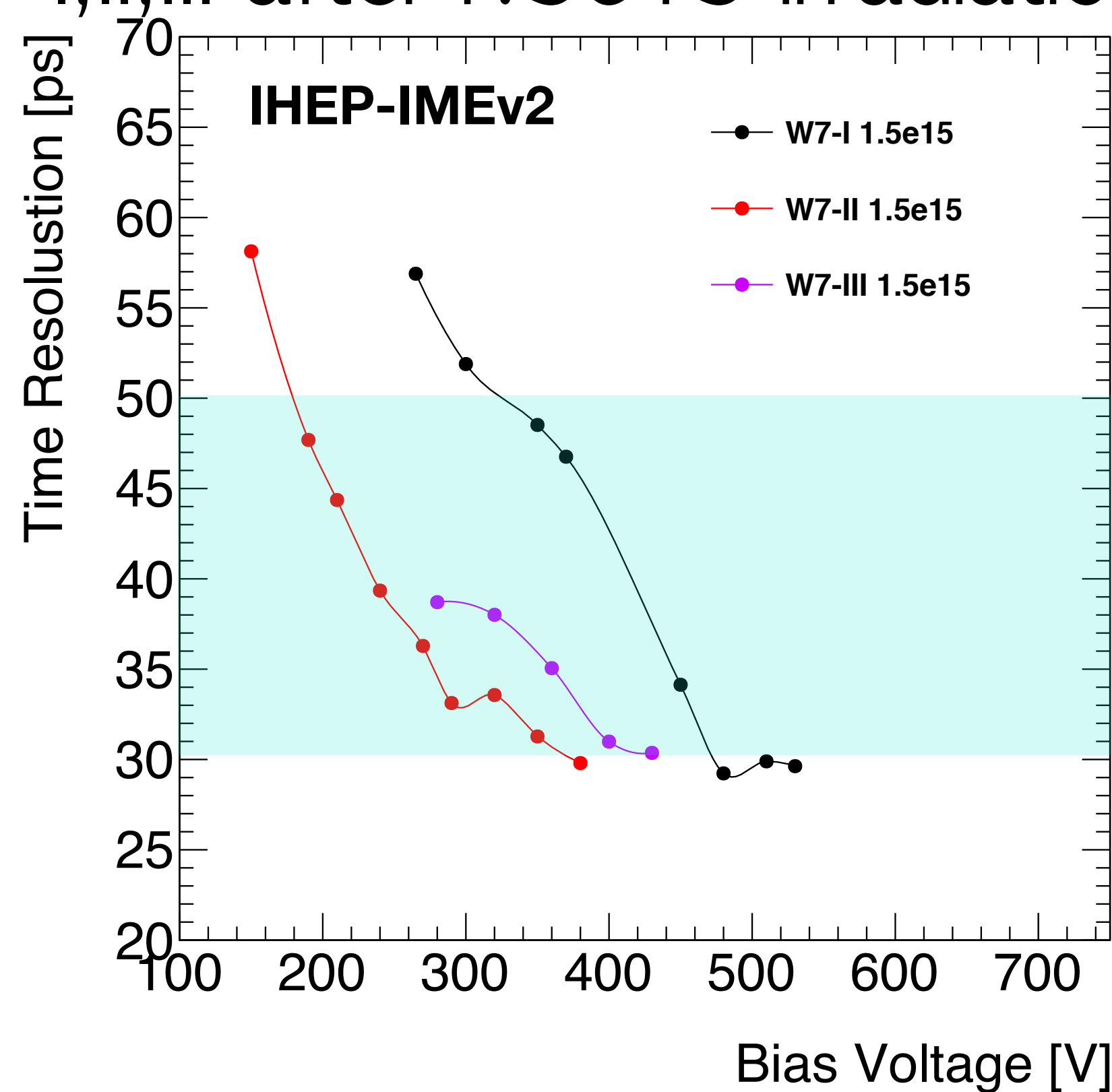
Voltage reaches 4 fC:

W4-II(1C), W4-IV(10C) 290 V < W4-I(0.2C) 450 V

W4-II and IV have similar characteristics, and better than W4-I

Carbonated sensor performance after irradiation

W7-I,II,III after 1.5×10^{15} irradiation



150V ~200V 310V
58 ps ~51 ps

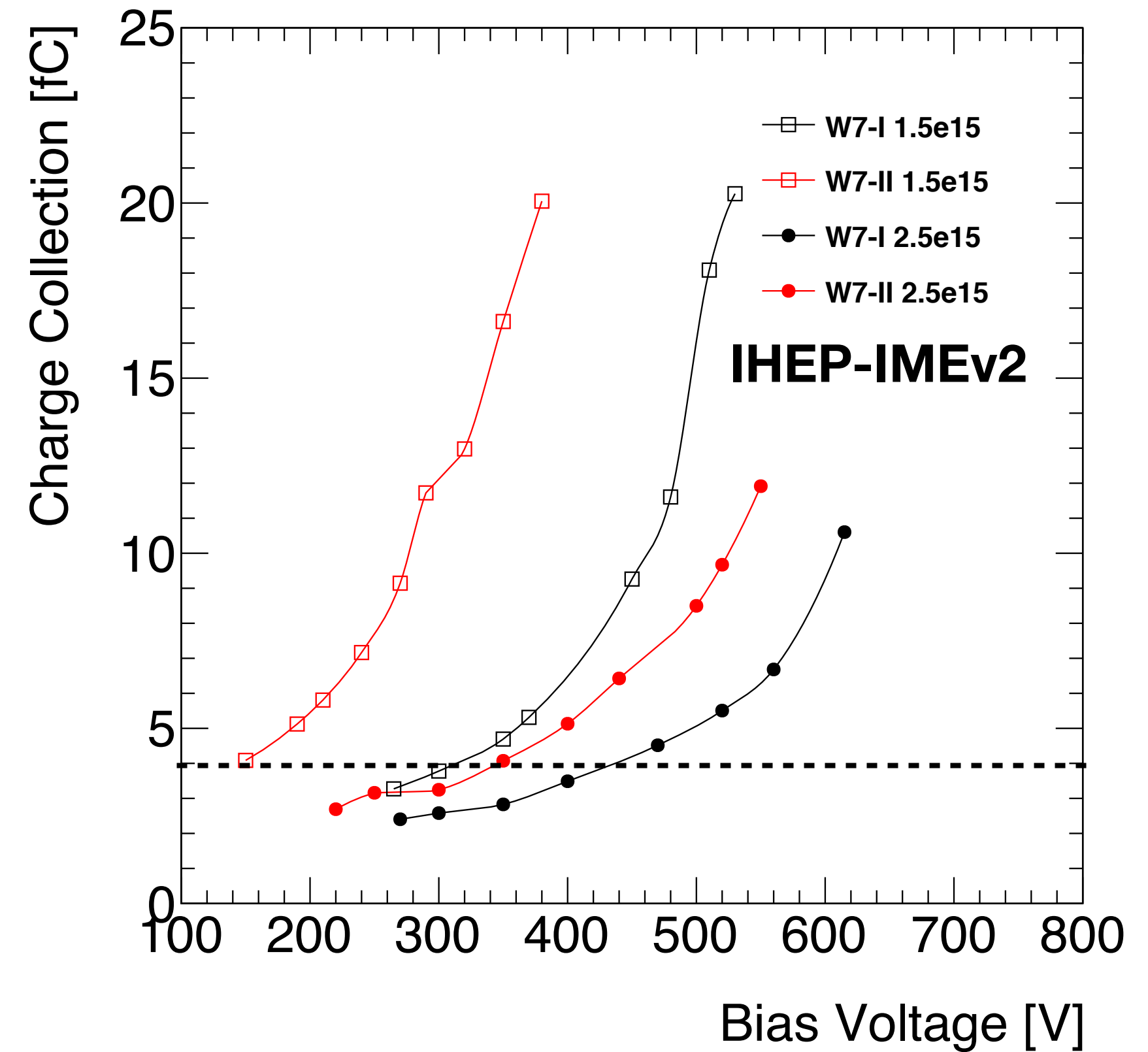
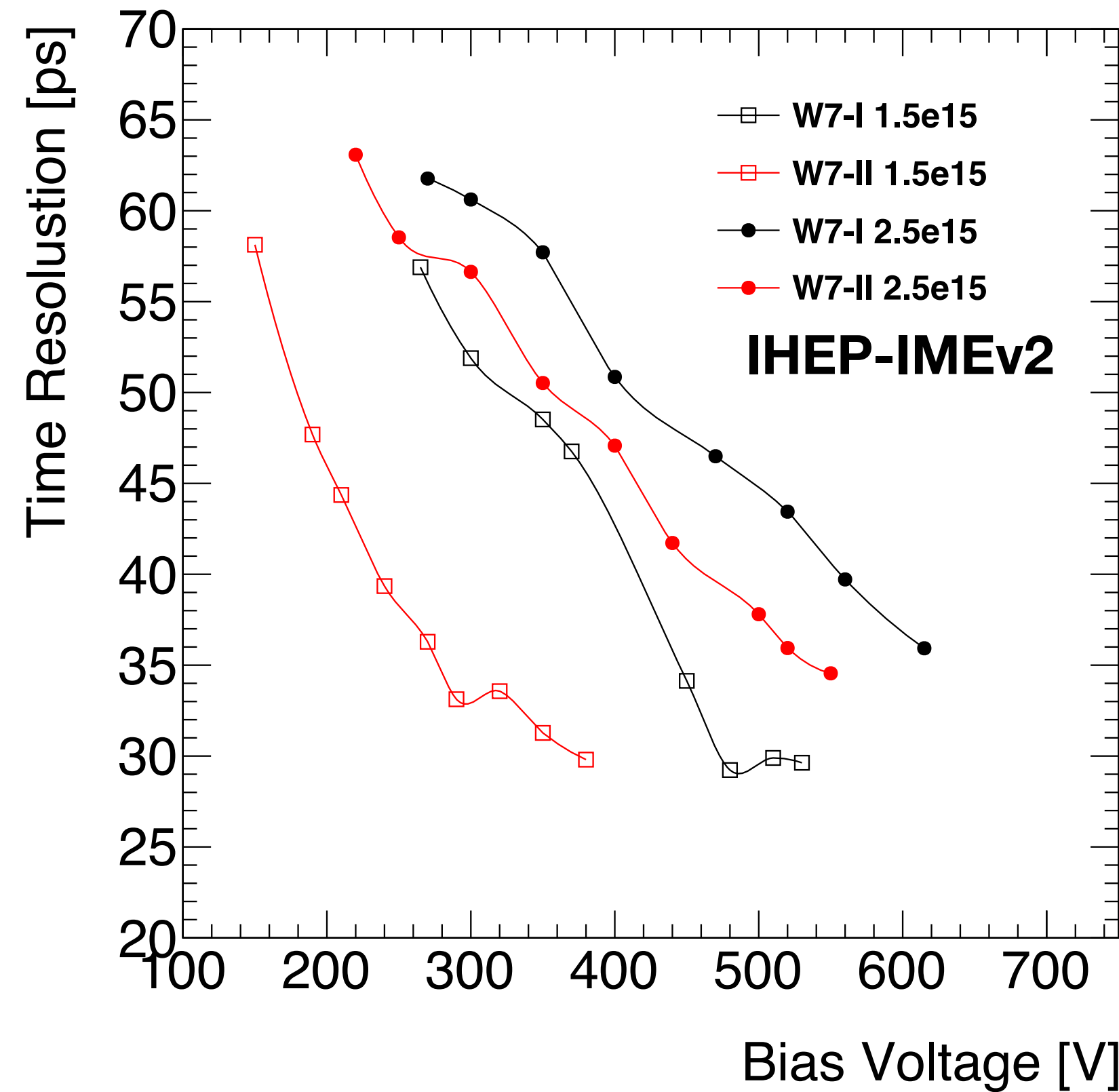
Voltage reaches 4 fC:

W7-II(0.5C) 150V < W7-III(1C) 200 V < W7-I(0.2C) 310 V

W7-II have the best performance

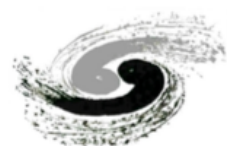
Carbonated sensor performance after irradiation

IHEP-IMEv2 W7-1.5e15 and 2.5e15 comparison



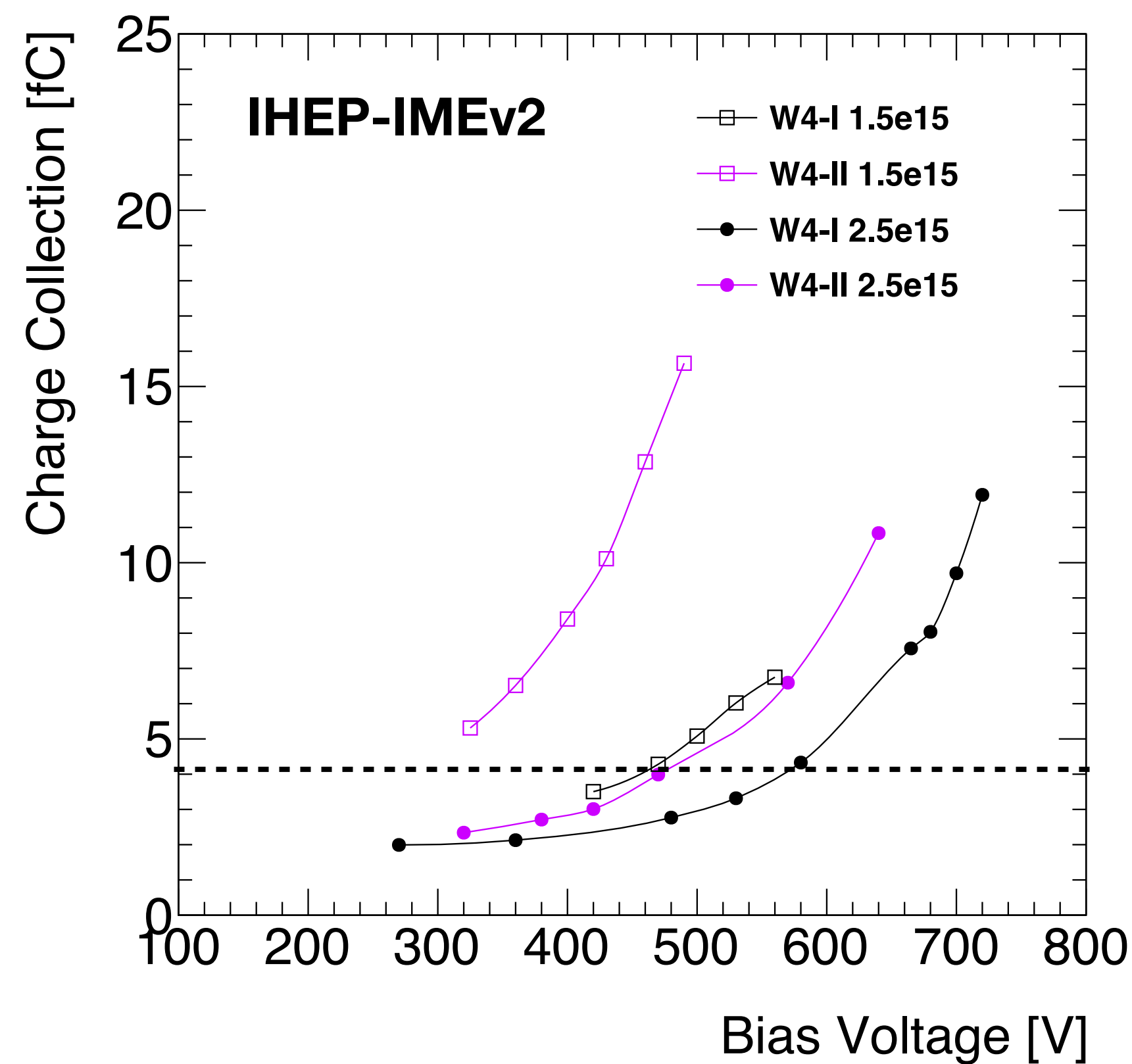
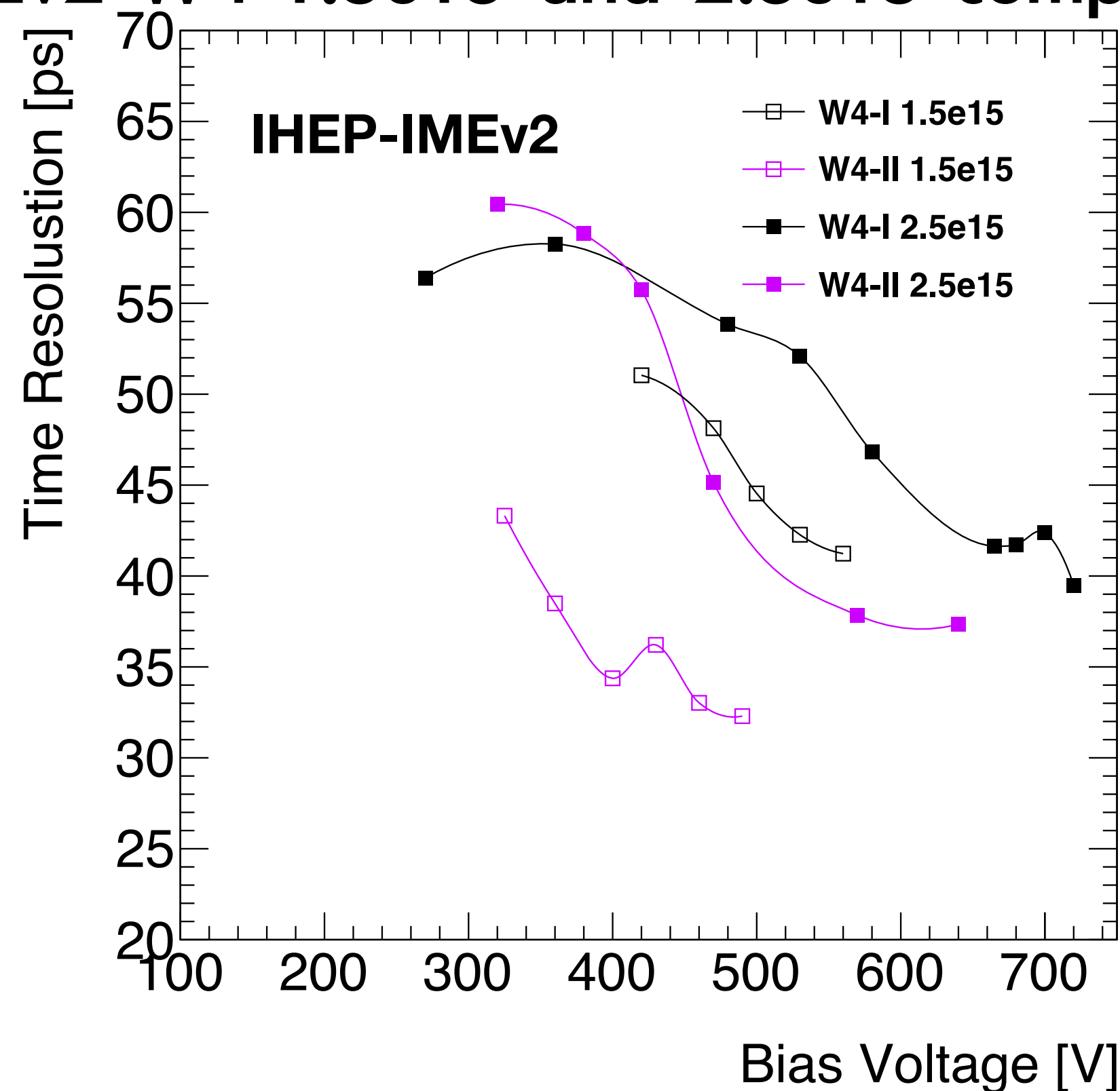
Voltage reached 4 fC:

- W7-I: from 310 V to 440 V, +130 V
- W7-II: from 150 V to 350 V, +200 V



Carbonated sensor performance after irradiation

IHEP-IMEv2 W4-1.5e15 and 2.5e15 comparison



Voltage reach 4 fC:

- W4-I: from 450 V to 560 V, +90 V, smaller but at higher voltage
- W4-II: from 290 V to 470 V, +180 V