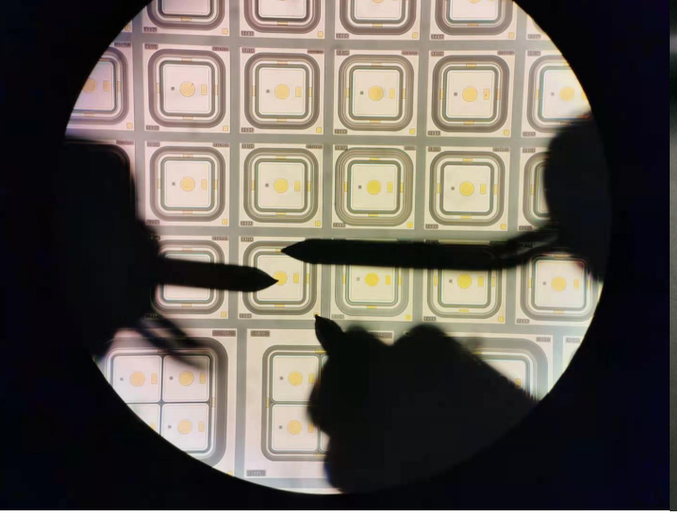
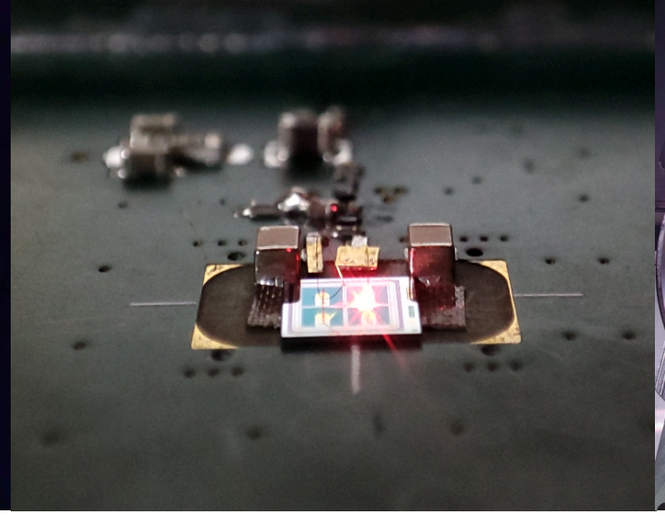
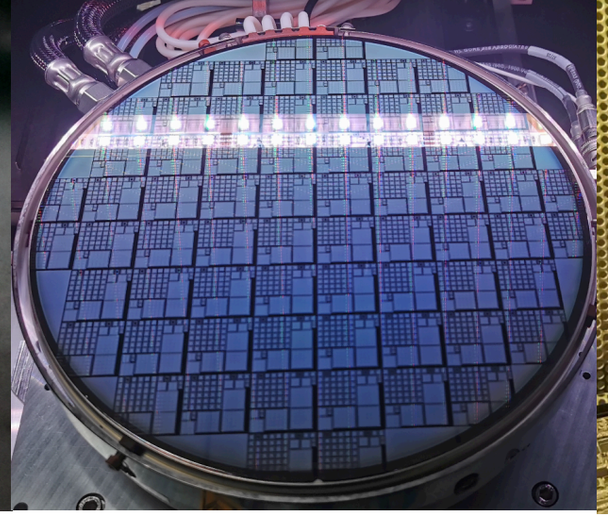
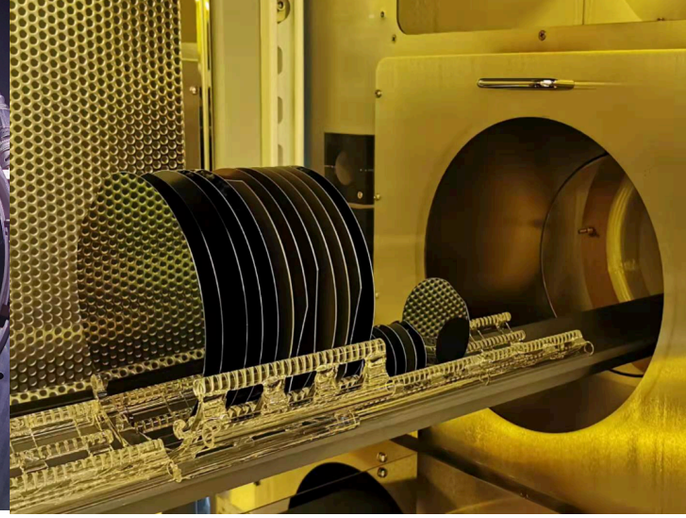





Performance of USTC LGADs for the ATLAS HGTD Upgrade

Xiao Yang
On behalf of the USTC HGTD sensor group

Overview

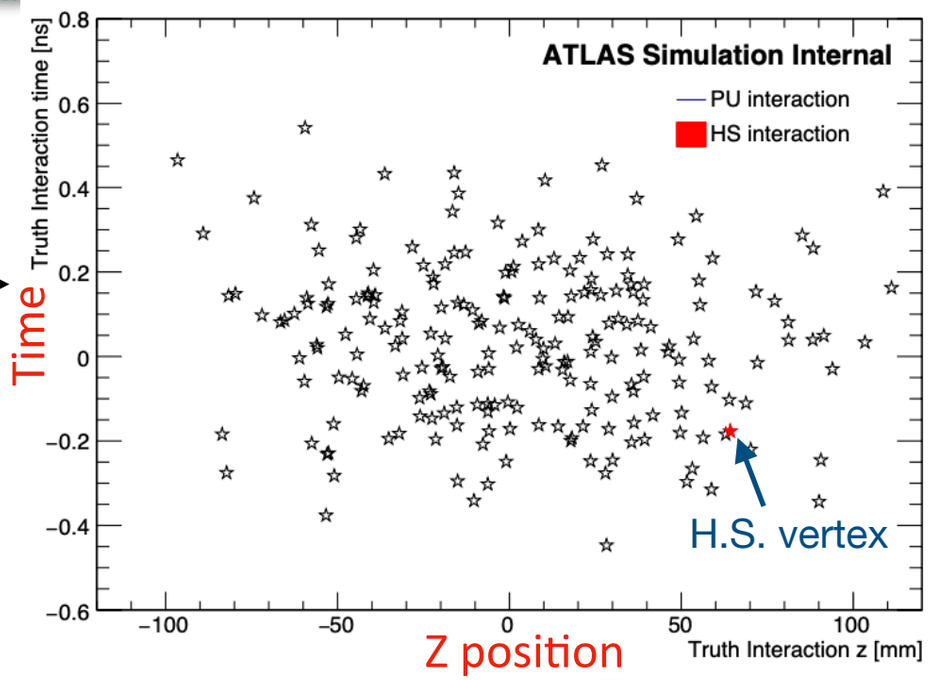
- ATLAS **HGTD** Upgrade and **LGAD** technology
- **Challenges** and **USTC efforts** on LGAD R&D
- **Radiation hardness** evaluation
- **Charge** collection and **timing** resolution
- **Large array** uniformity of USTC-IME batch2 LGADs
- Summary

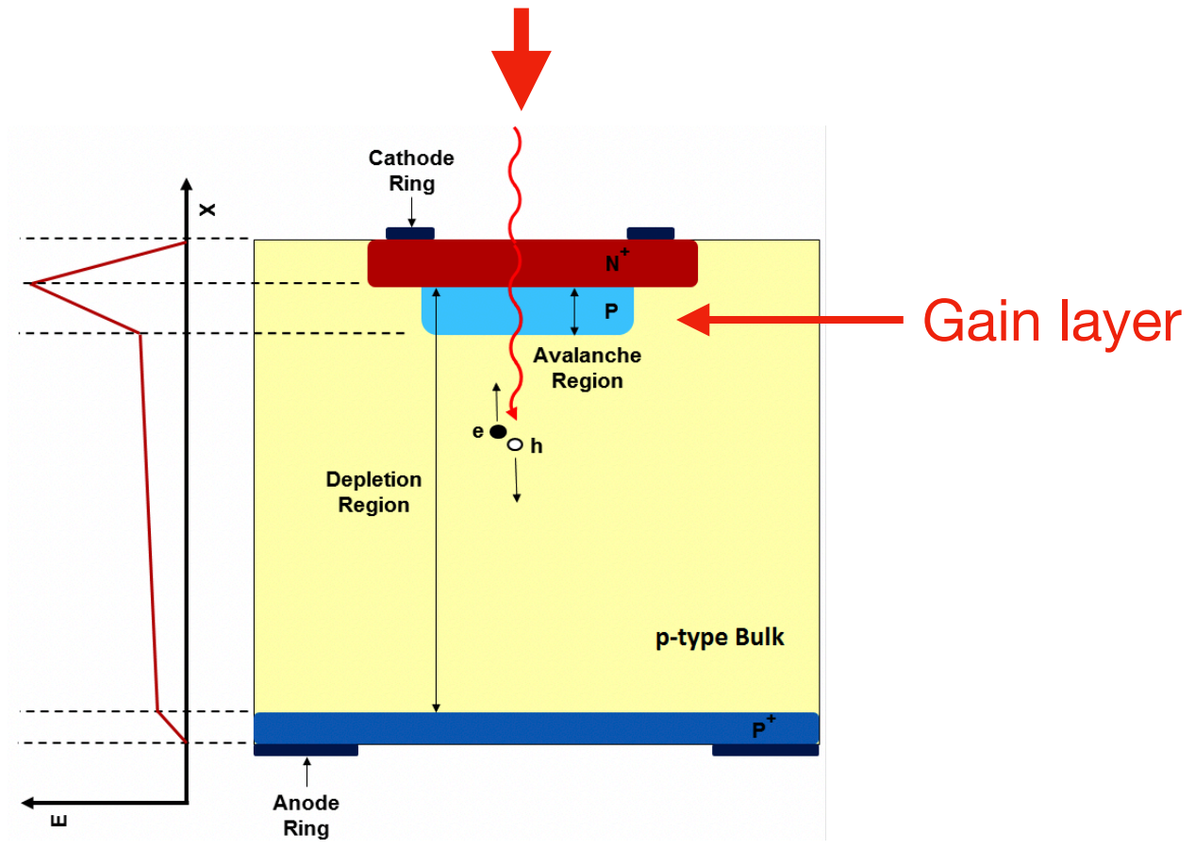
The High-Granularity Timing Detector(HGTD) for the ATLAS Phrase-II Upgrade

- In the HL-LHC, Pile-up density would get so high that track to vertex association would be very hard, especially in the forward region

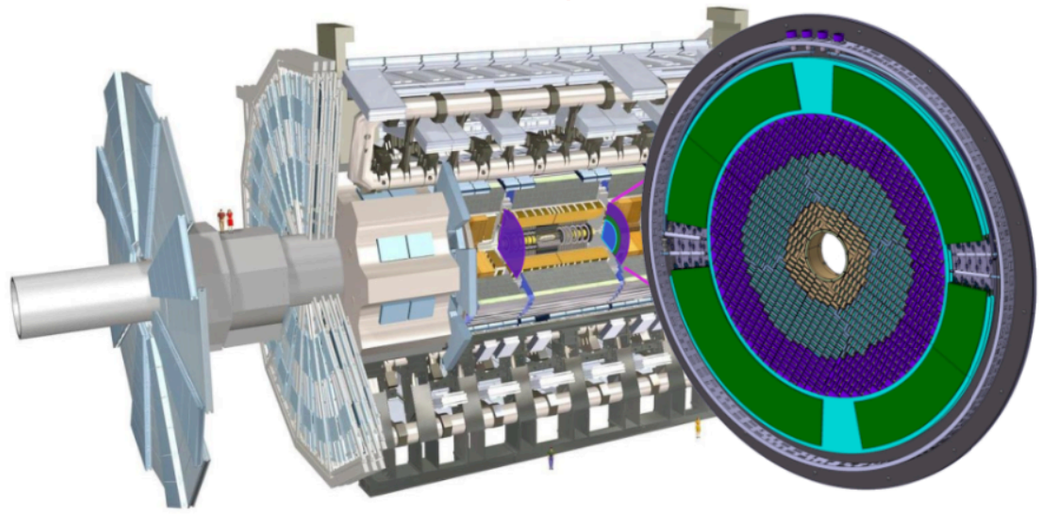
- Having a timing detector in forward region would allow us make the matching in "4-D" space. => **HGTD**

- A novel technology: LGAD (**Low-Gain Avalanche Detector**), which achieves promising S/N and σ_t by inducing an internal gain layer.





Gain layer



- σ_t ~30 ps per track

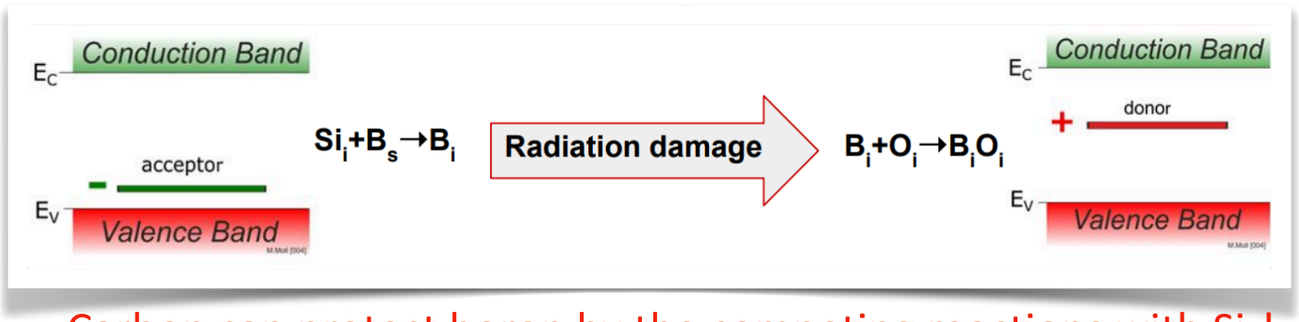
larger gain
↓
faster rising time and larger S/N
↓
better time resolution

LGAD Sensor R&D

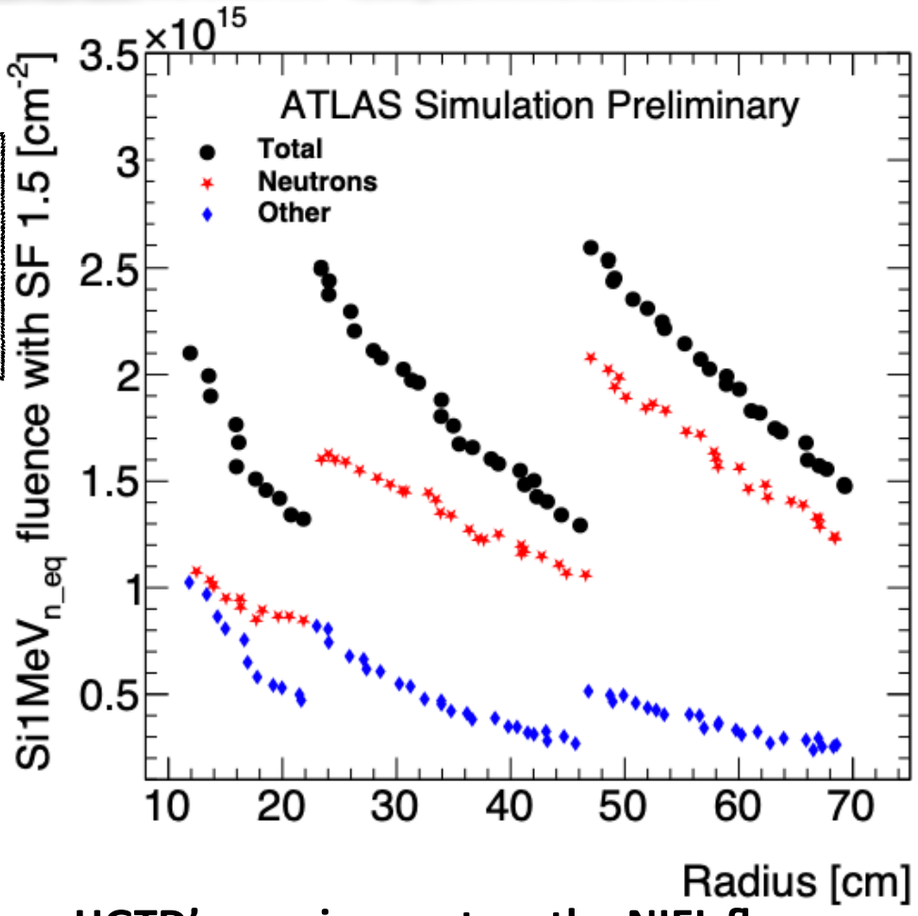
Challenges on LGAD Design

- **Radiation Hardness**:
  - Acceptor removal
    - **Solutions:**
      - Narrow and deep implantation of boron
      - Carbon diffusion

HGTD Requirement:
After 2.5E15/cm² 1MeV neq fluence:
Collected charge: > 4fC
Timing resolution: < 70 ps



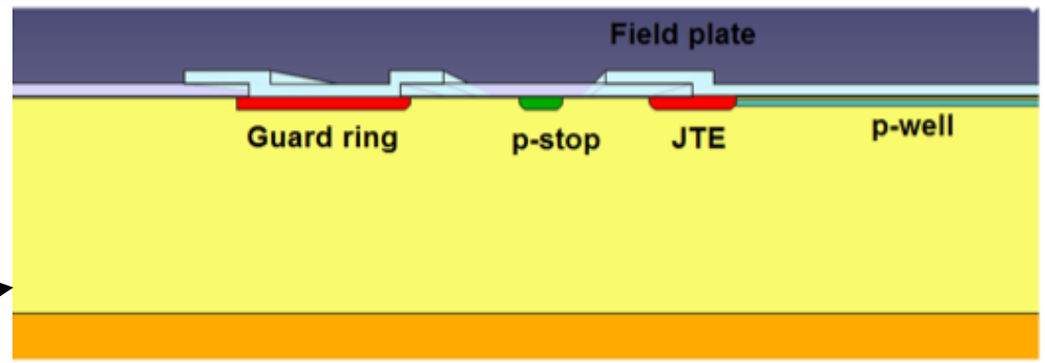
Carbon can protect boron by the competing reactions with Si_i !



HGTD's requirement on the NIEL fluence

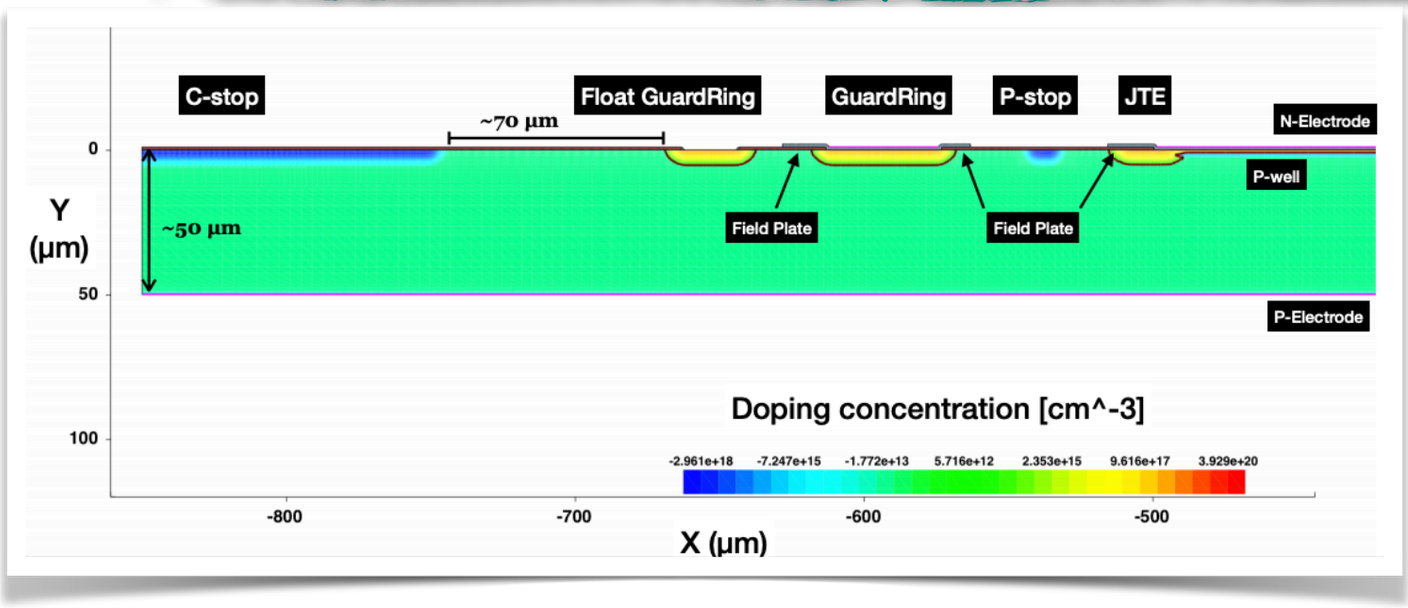
- **Premature breakdown**:
  - Optimization of the peripheral region to prevent premature breakdown
  - Implementation of the structures commonly used in ***power semiconductor device***:

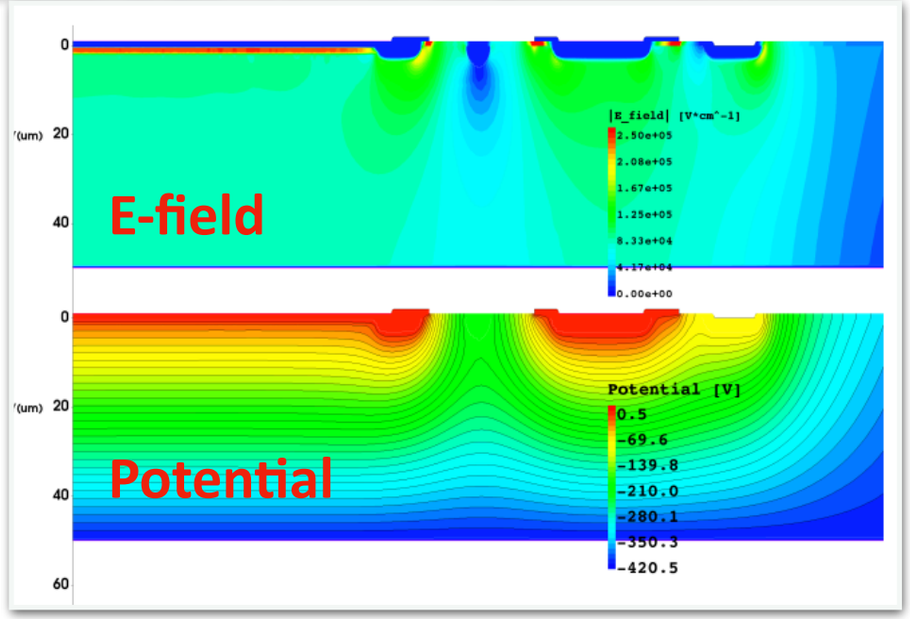
Guard ring, JTE, Field plate



Structures to avoid premature breakdown

USTC-LGAD Design with TCAD





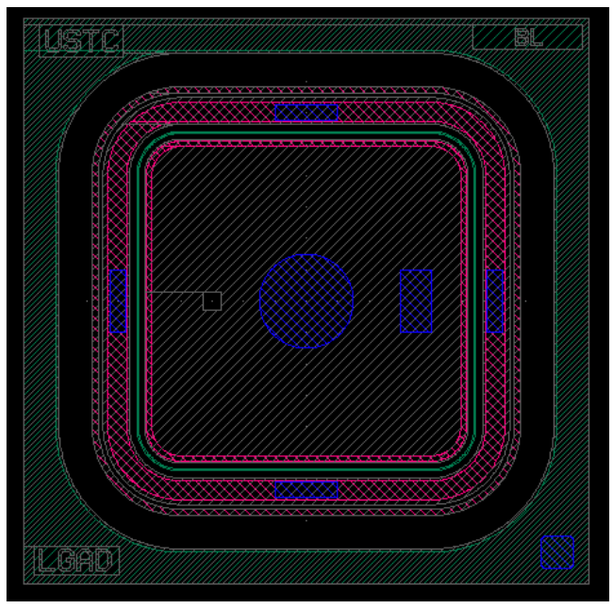
- TCAD structure based on the process simulation
  - The geometry and process are thoroughly optimized
  - Major radiation damage model included

- **Schedule**:
  - April 2019: Simulation work done
  - May 2019: Submitted the first strategy to factory with IHEP
  - Aug 2019: Ordered high resist. wafer (Shanghai)
  - Sep-Oct 2019: Design a full size mask layout and serval discussions with **IME** to improve the process for USTC own production
  - Dec 2019: Final process and layout fixed
  - Feb 2020: Photolithography produced
  - March 2020: Wafer process initiated
  - April 2020: High energy implantation finished
  - **July 2020: Delivery**

➡**Recommendation:**

- High resist. substrate: > 1kOhm*cm
- High energy boron implantation: at least ~1MeV
- Carbon diffusion on one wafer

Simulation ➡ Layout Mask / Fab. Process ➡ **Functional USTC LGADs**



Designed mask

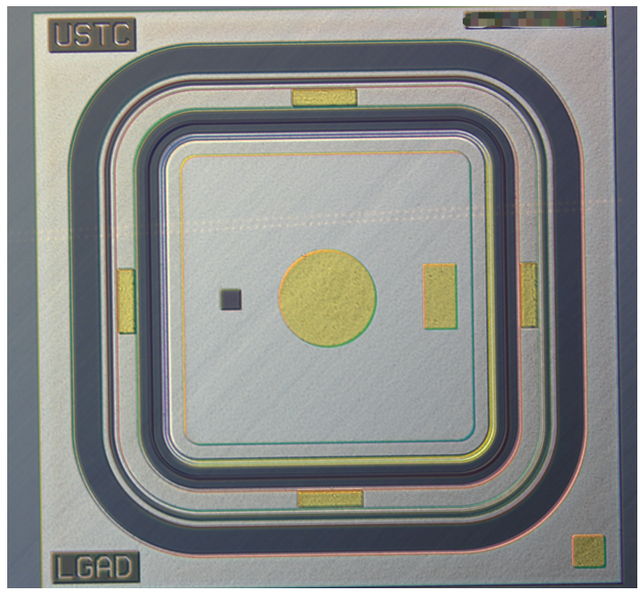


Photo of the device produced

USTC LGAD Fabriaction

中国科学院微电子研究所
INSTITUTE OF MICROELECTRONICS OF THE CHINESE ACADEMY OF SCIENCES

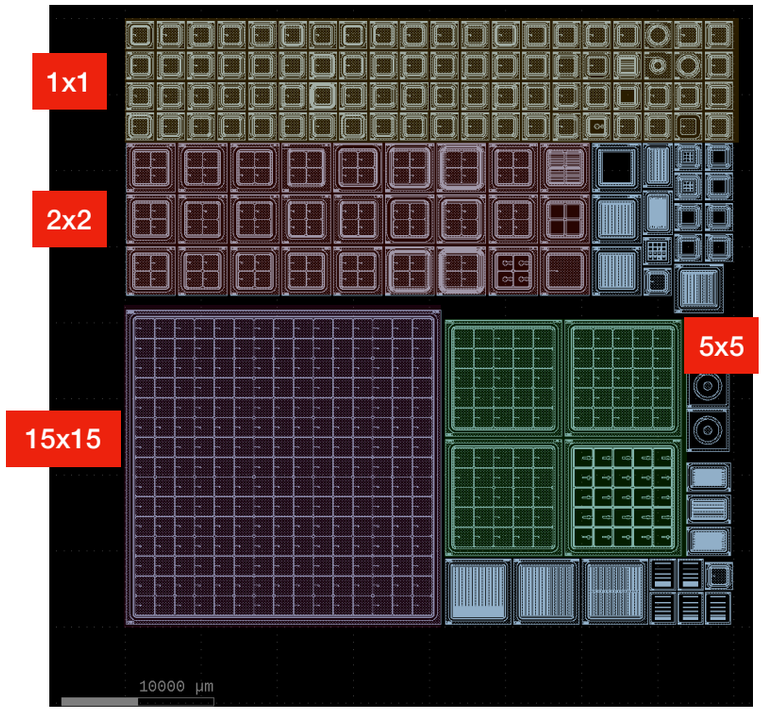
- USTC-**IME**:
  Institute of Microelectronics of the Chinese Academy of Sciences (IME,CAS)
  High standard **8-inch** line, **good quality control and yield.** mainly for large scale production.
  - Wafers: 1st batch:W7-W11, 2nd batch:W12-W21

NANO · USTC
中国科学技术大学微纳研究与制造中心
USTC Center for Micro- and Nanoscale Research and Fabrication

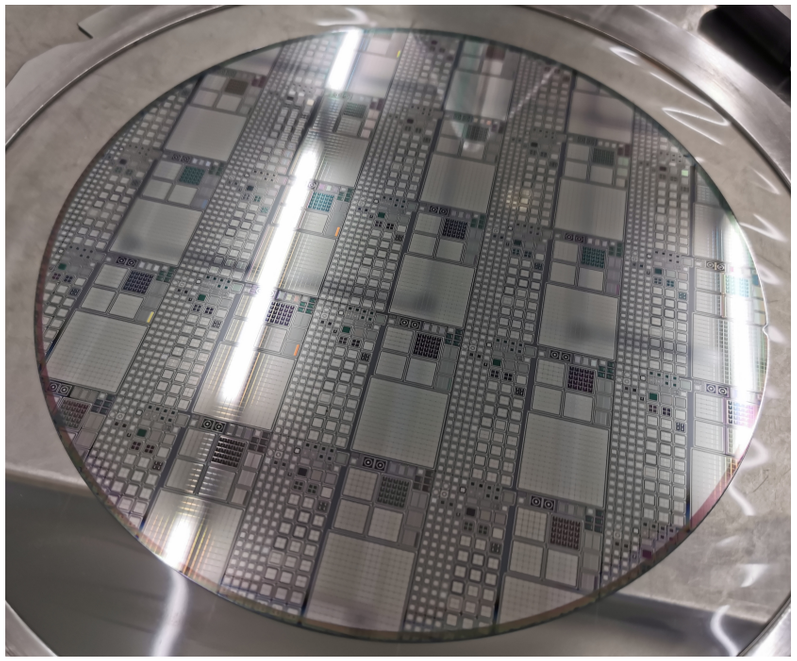
- USTC-**NRFC**:
  USTC Nanoscale Research and Fabrication Center
  The USTC own **6-inch** experimental fabrication line.

- **Goal:** Iteration the design on gain layer and geometry quickly, parameters will be share with IME
  - **Wafers: 1st batch:W3,W4, 2nd batch:W1,W2,W5,W6**

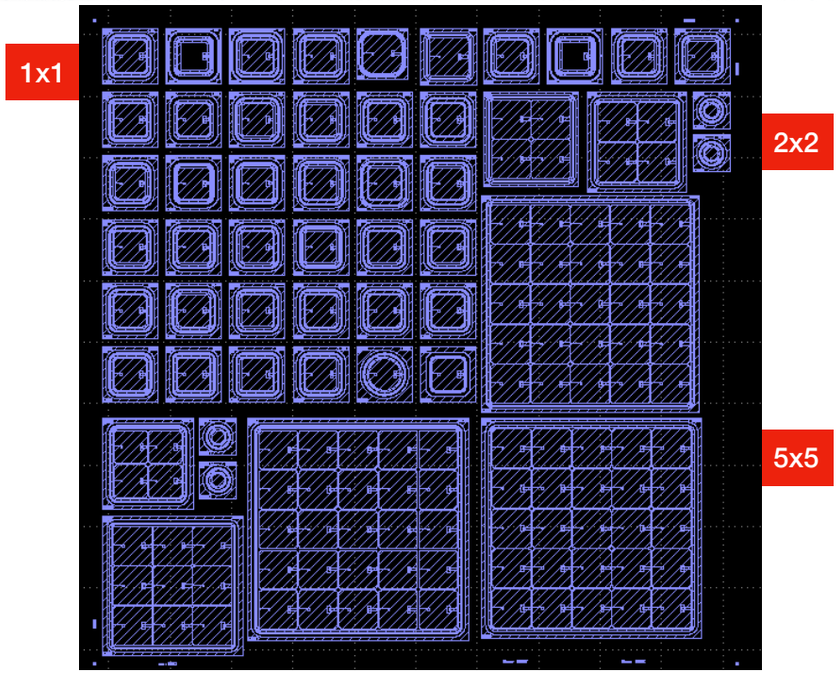
USTC-IME 1st Batch LGAD Wafers



Stepper size: 40 mm x 40 mm,



USTC-1.1

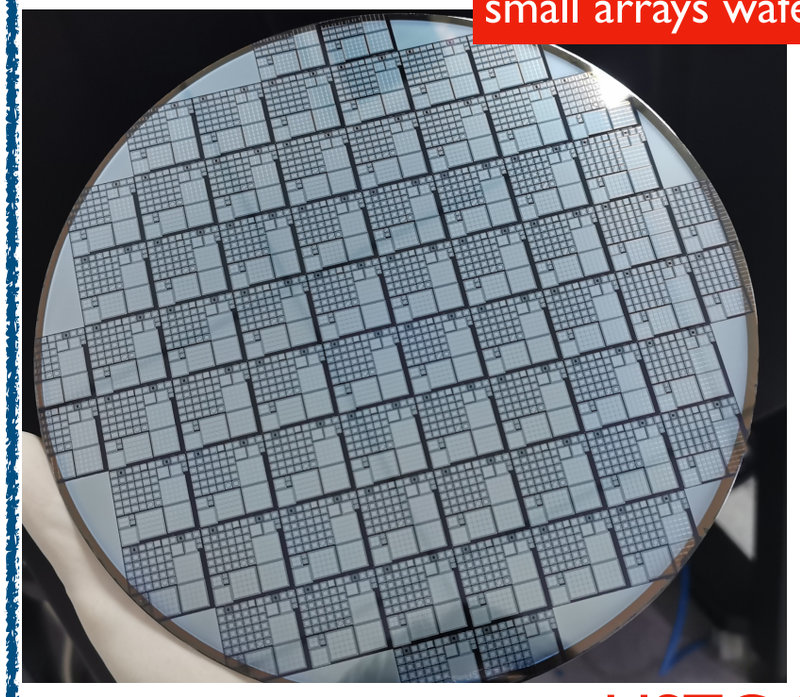


Stepper size: 21 mm x 21 mm,

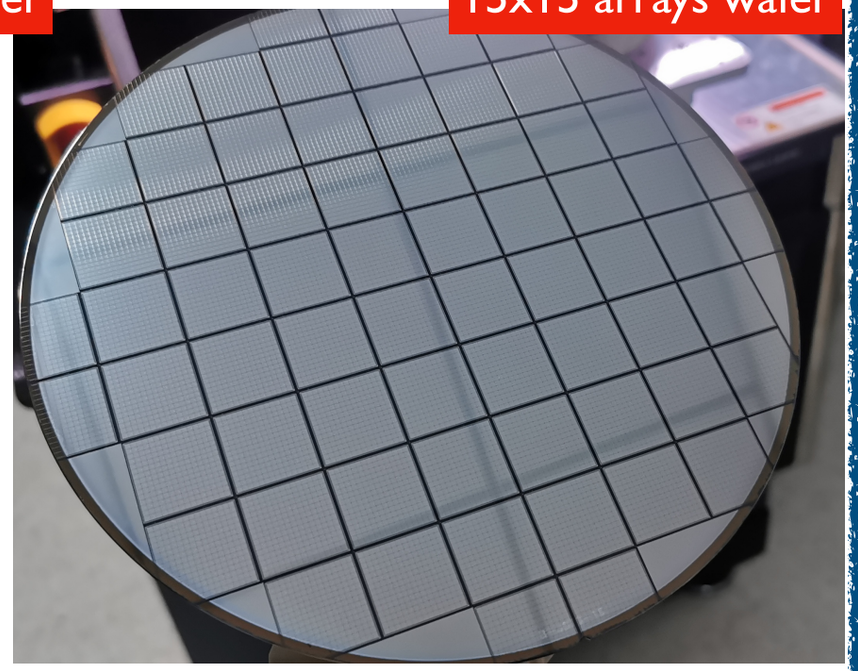
- Joint force:
  USTC(Design) + IME,CAS (Fab.)
- Deep gain layer
- Carbon diffusion

8 inch wafer, with 50 µm Epi. layer.

small arrays wafer



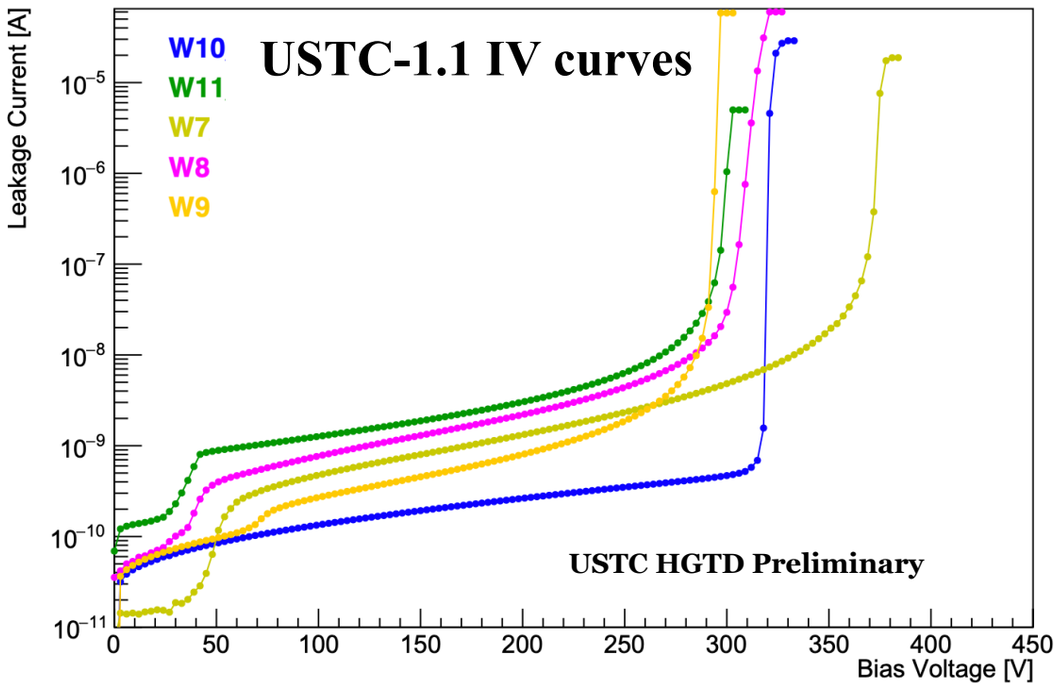
15x15 arrays wafer

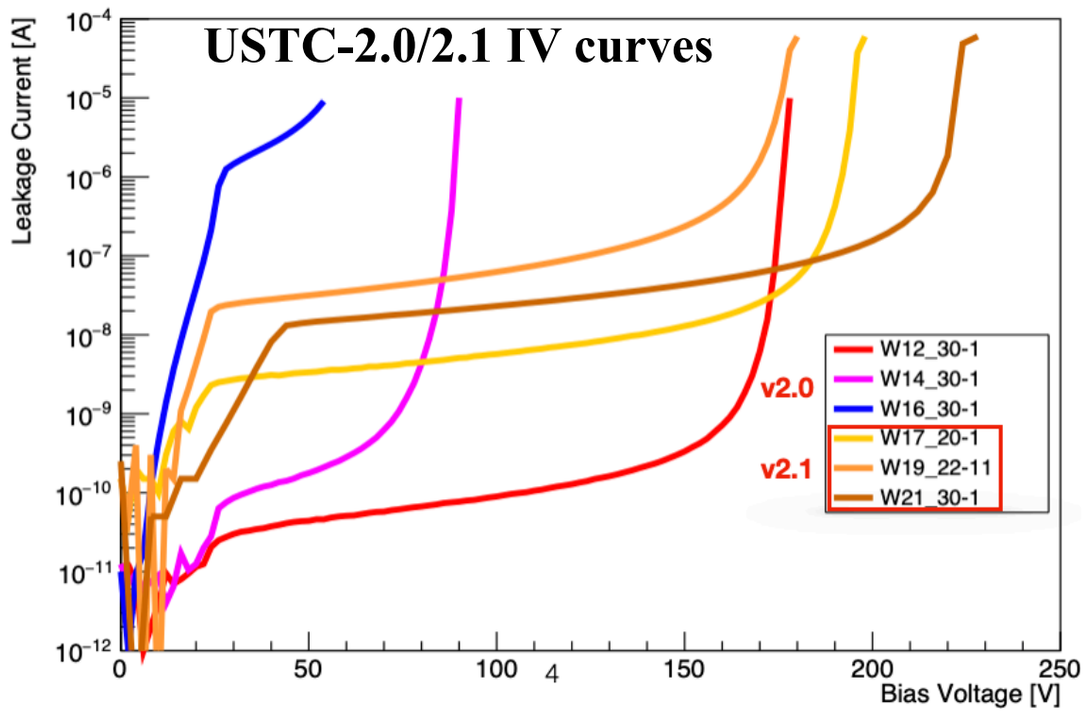


USTC-2.0/2.1

- **First** full 15x15 wafer produced!

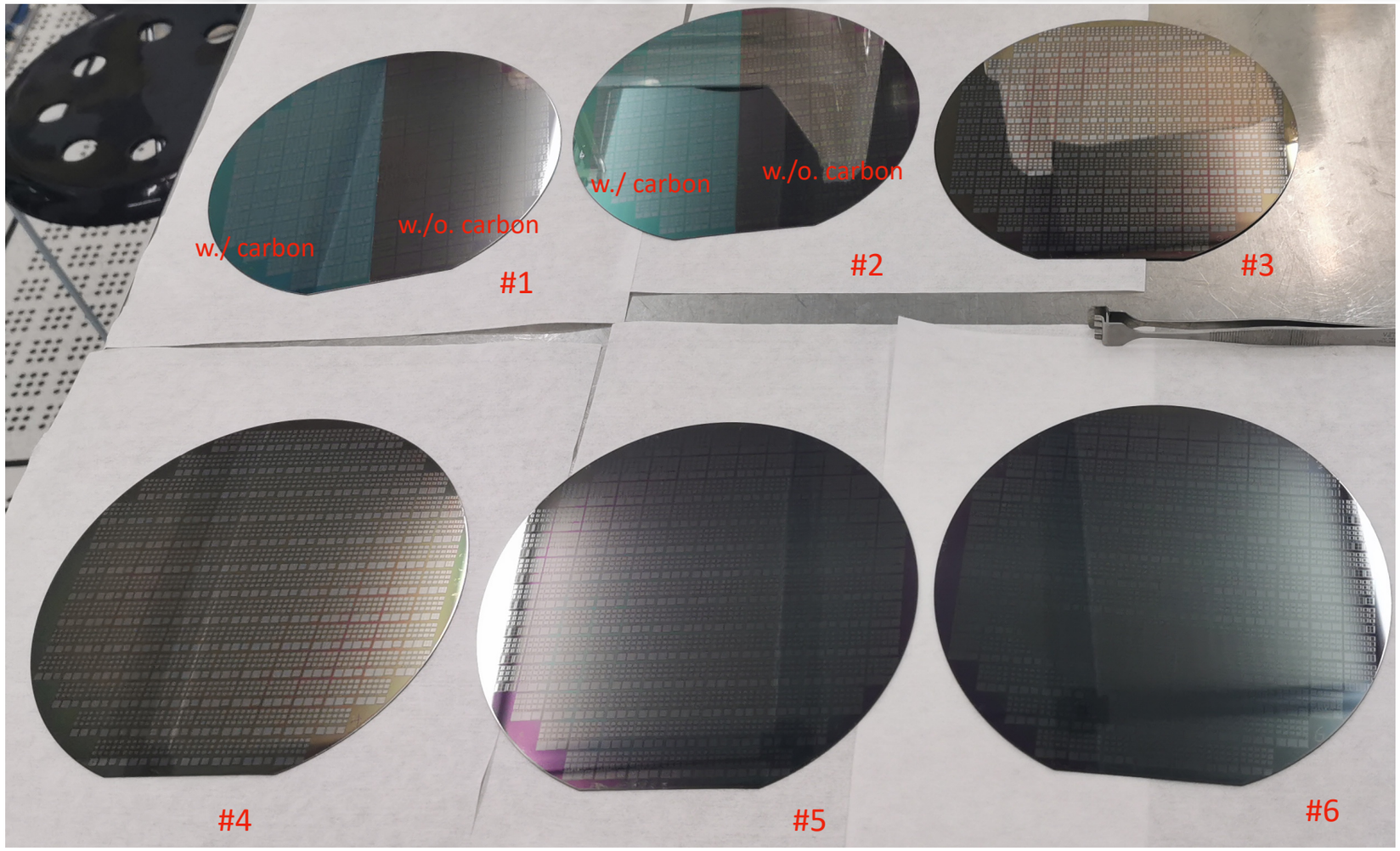
USTC-IME LGADs Overview

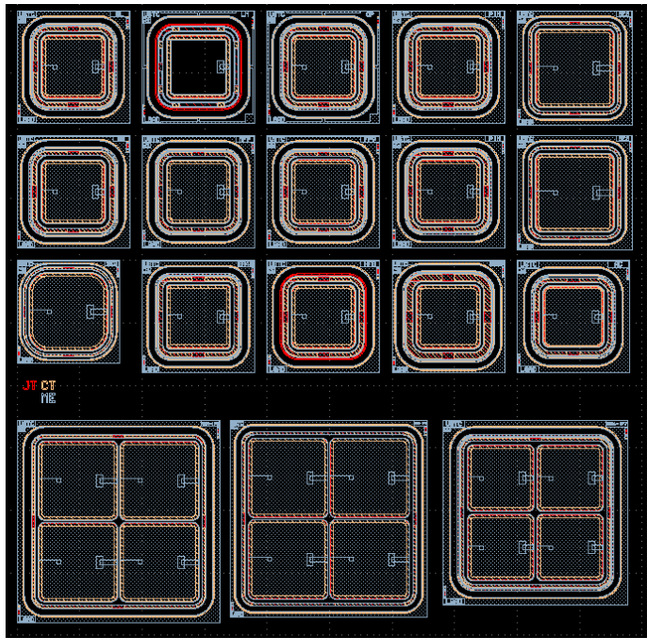




Production version	Wafer No.	GL.Dose	Implantation	Layout arrays	VBD_medium	UBMed	Diced	c-factor
USTC-1.1	W7	Low	B	Mixed	~370	No	✅	5.79
	W8	Medium	B	Mixed	~295	✅	✅	4.12
	W9	Medium	B	Mixed	~295	✅	✅	7.25
	W10	Medium	B	Mixed	~320	✅	✅	5.72
	W11	Medium	B+C	Mixed	~300	✅	✅	1.85
USTC-2.0	W12	Low	B	Small	~174	✅	✅	~3.66
	W13	Low	B	15x15	~172	✅		
	W14	High	B	Small	~84	✅	✅	~3.38
	W15	High	B	15x15	~100	✅		
	W16	High	B+10C	Small	~50	✅	✅	~1.36 -1.49
USTC-2.1	W17	Medimum	B+1C	Small	~190	✅	✅	
	W18	Medimum	B	15x15	~190			
	W19	Medimum	B+2C	Small	~165	✅	✅	
	W20	Medium	B+C	15x15	~220			
	W21	Medium	B+C	Small	~215	✅	✅	

USTC-NRFC LGAD

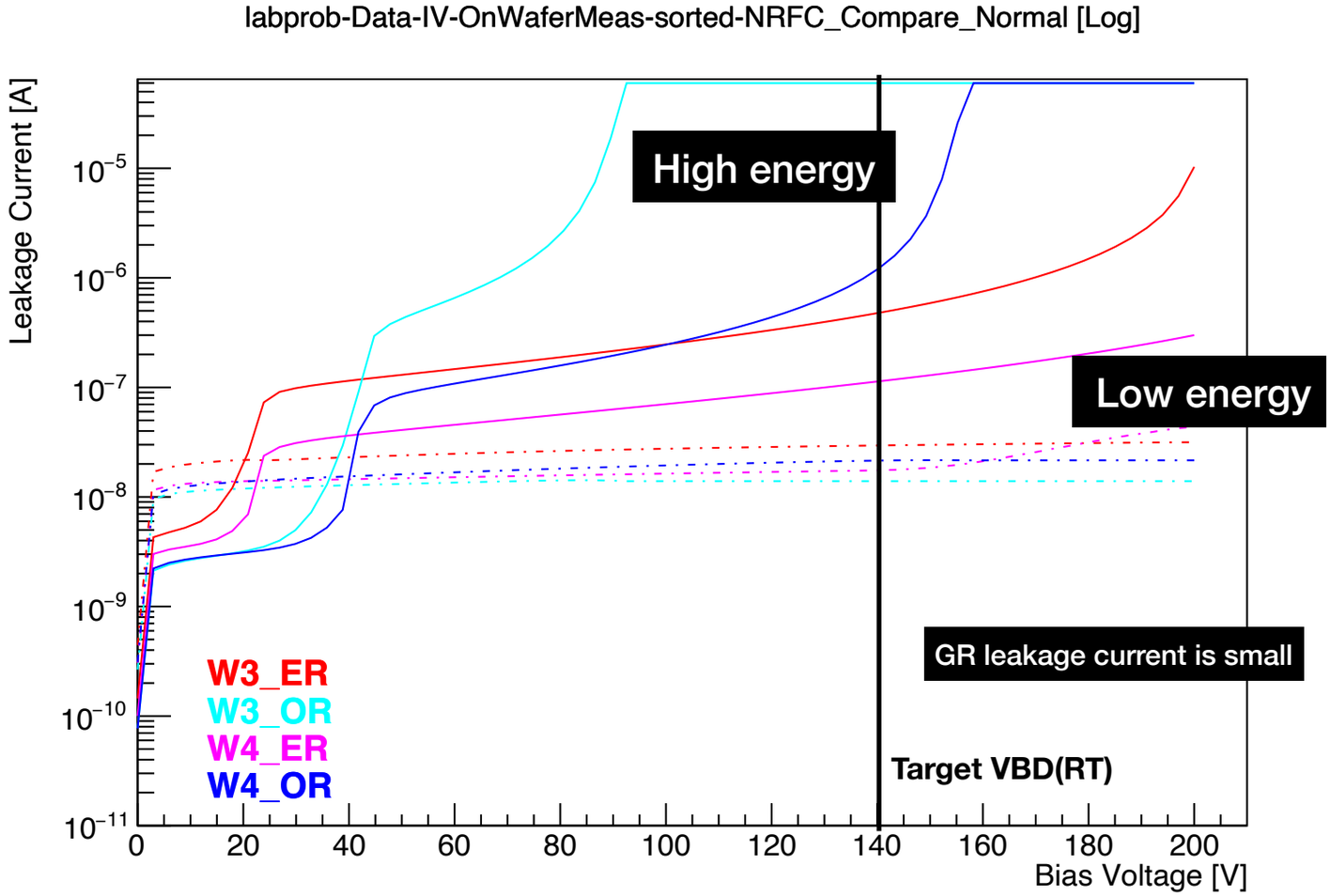




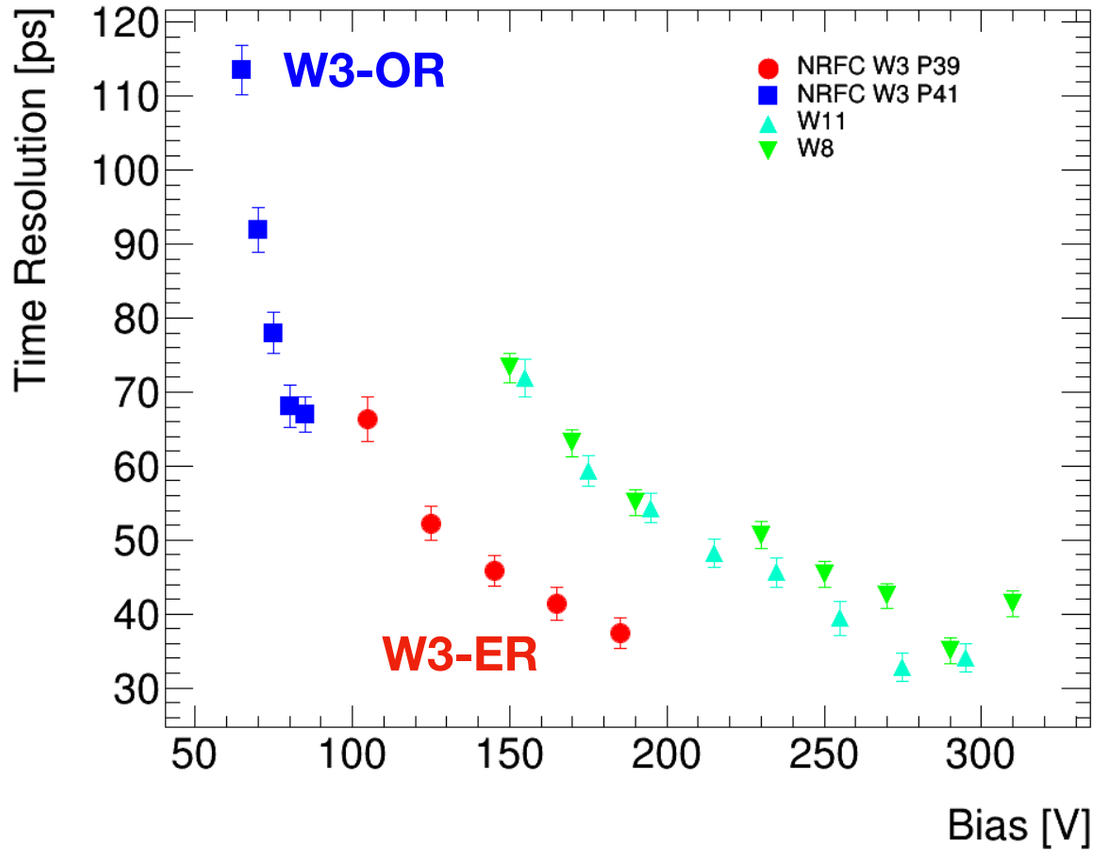
- LGAD Design&Fabricated at USTC

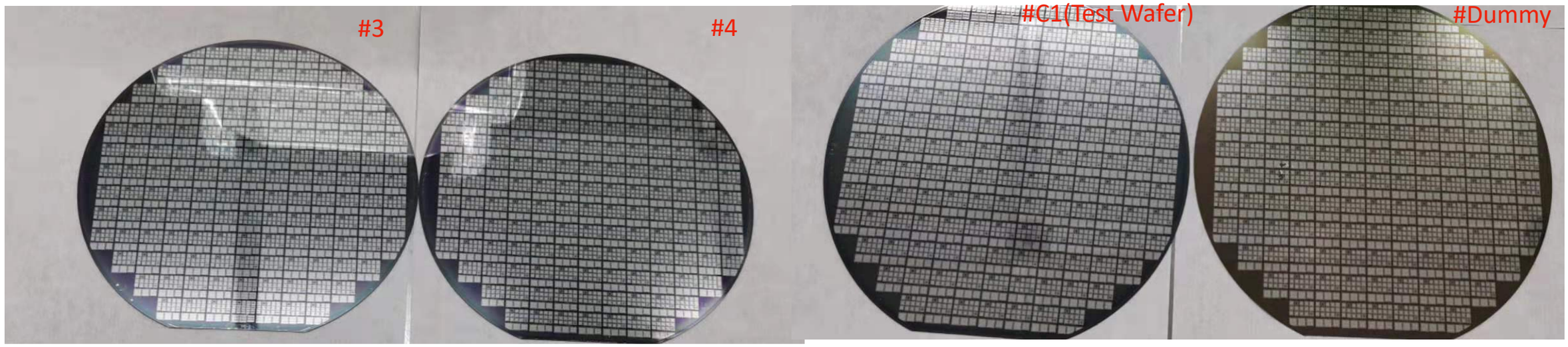
Splits	Wafer	Rows	GL.Energy	GL.Dose	Measured VBD[V]	Comment
1	W3	Odd	High	High	85	GL. Energy same as IME batch 1 W10/W11
2	W4	Odd	High	Low	150	
3	W3	Even	Low	High	200	GL. Energy same as batch 2
4	W4	Even	Low	Low	>200	

USTC-NRFC Preliminary Results



Measured at R.T.



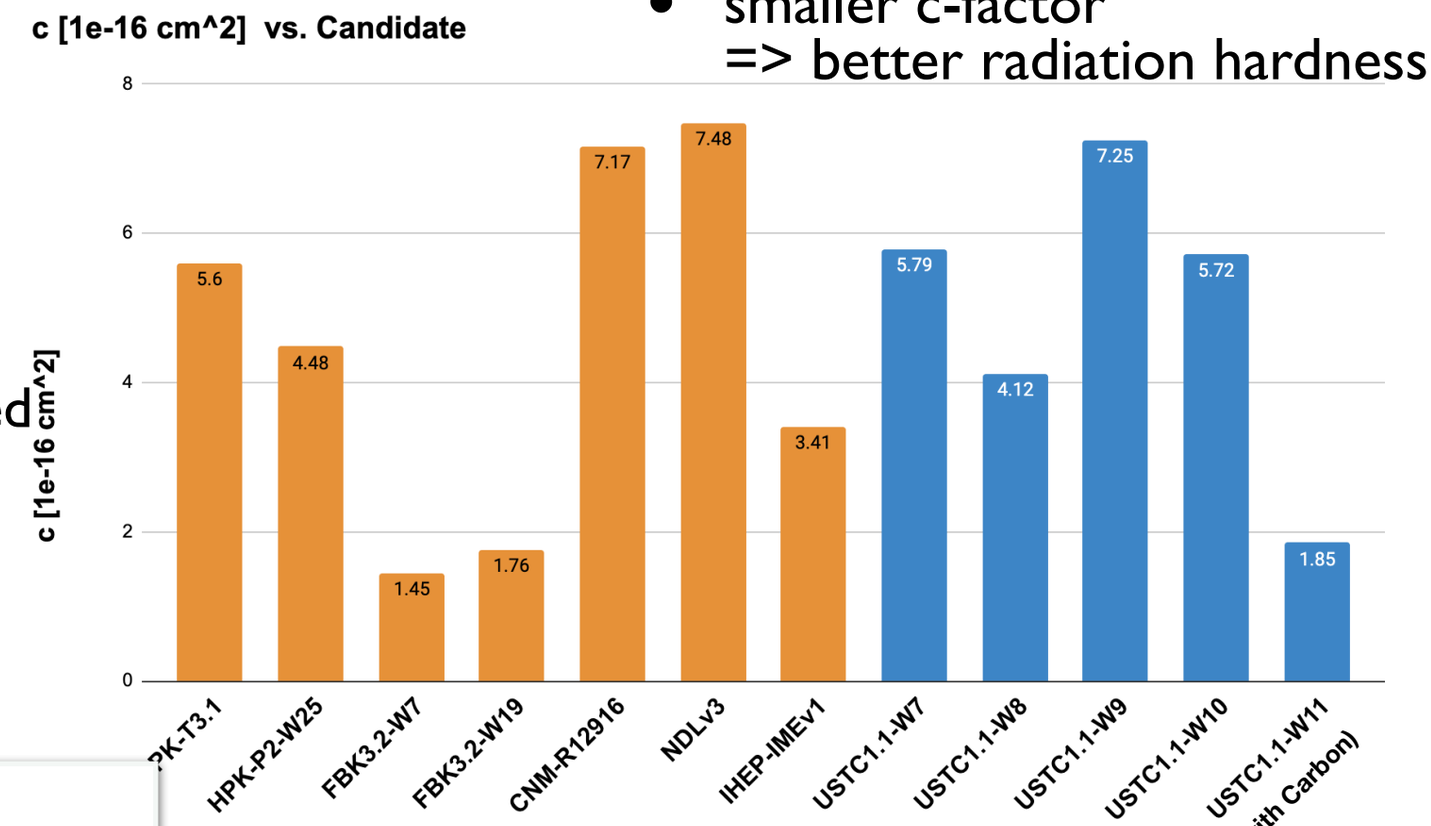


Radiation hardness performance

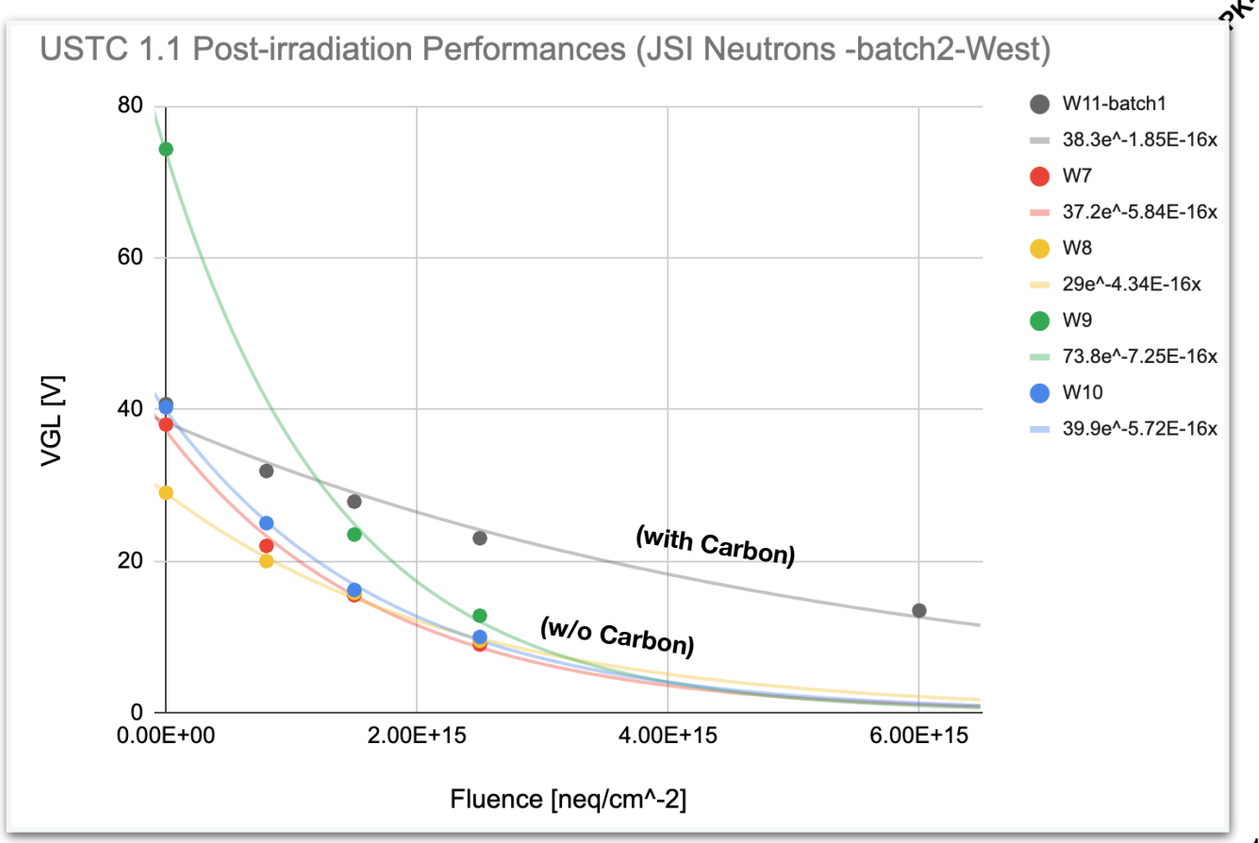
$$\rho_A(\phi) = g_{eff}\phi + \rho_A(0)e^{-c\phi}$$

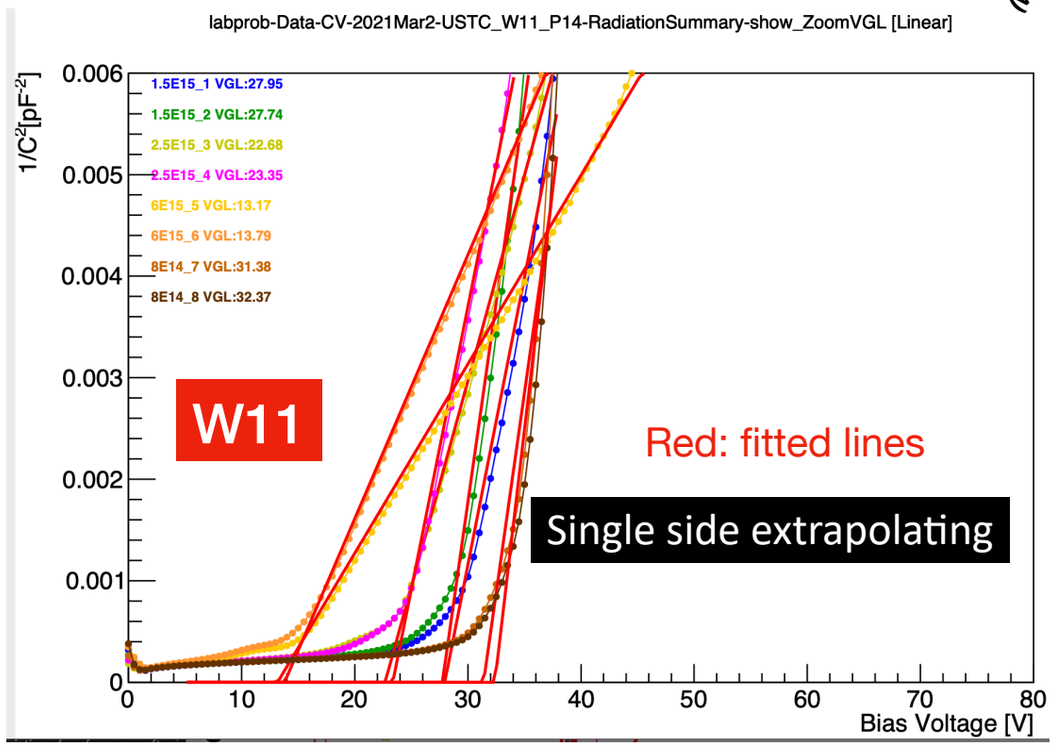
Acceptor density with NIEL fluence

- Gain-layer depletion volage(VGL) extracted from CV is proportional to $\rho_A(\phi)$
- LGAD samples are irradiated with neutrons at JSI (Slovenia) reactor and I-V/ C-V measured at USTC at -30°C.



- smaller c-factor
  => better radiation hardness



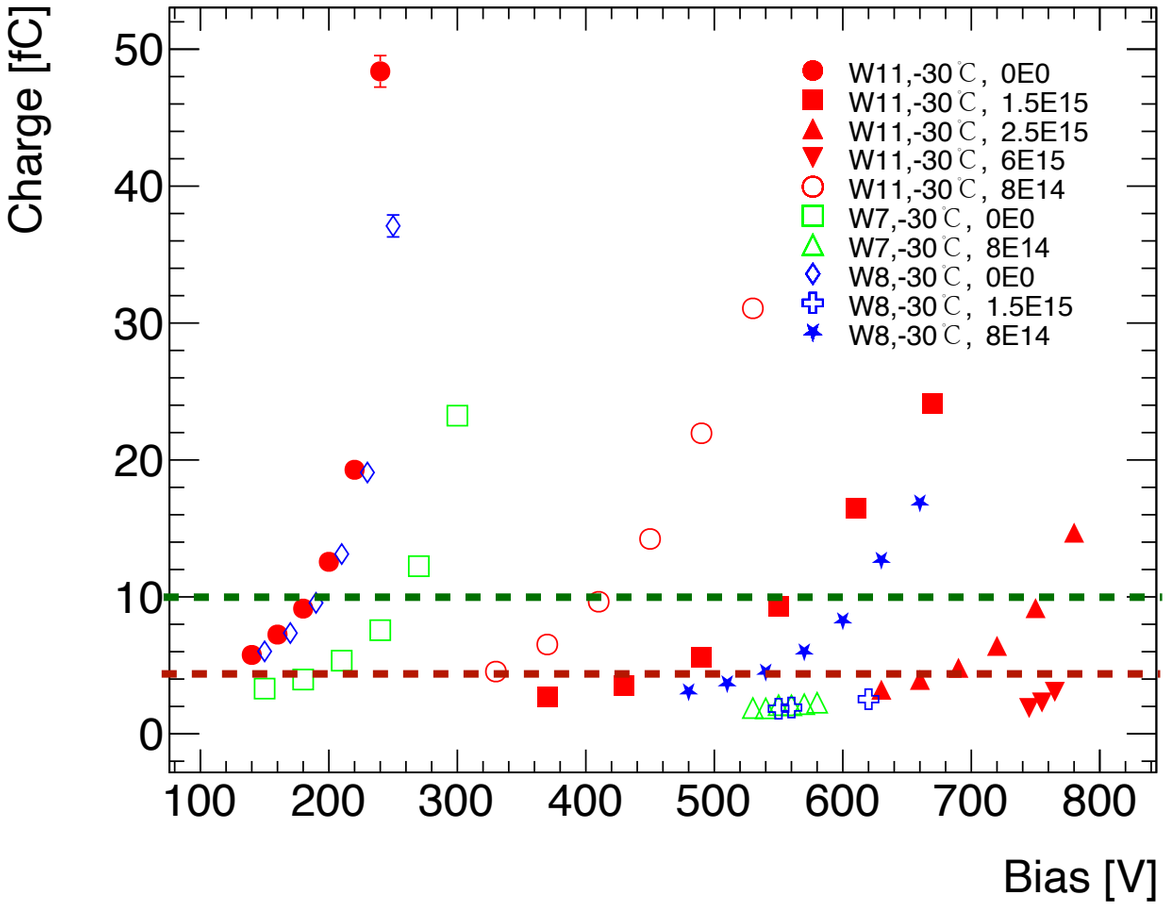


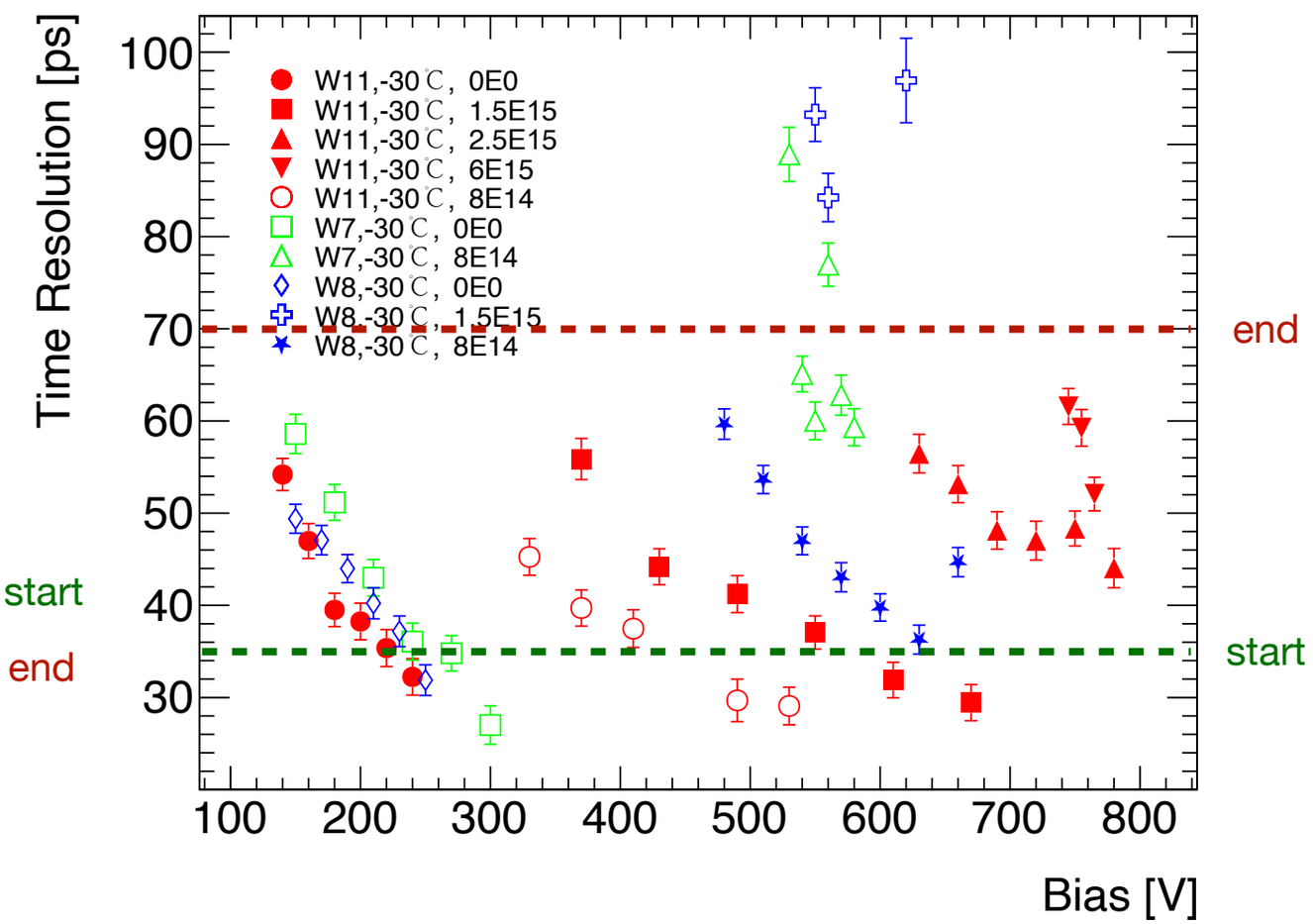
Charge collection and timing resolution

W11 (carbon diffused), most promising for v

*Measured at -30°C with Sr90 source

* Dashed lines indicated the specification of HGTD sensors, at the start/end of the operation

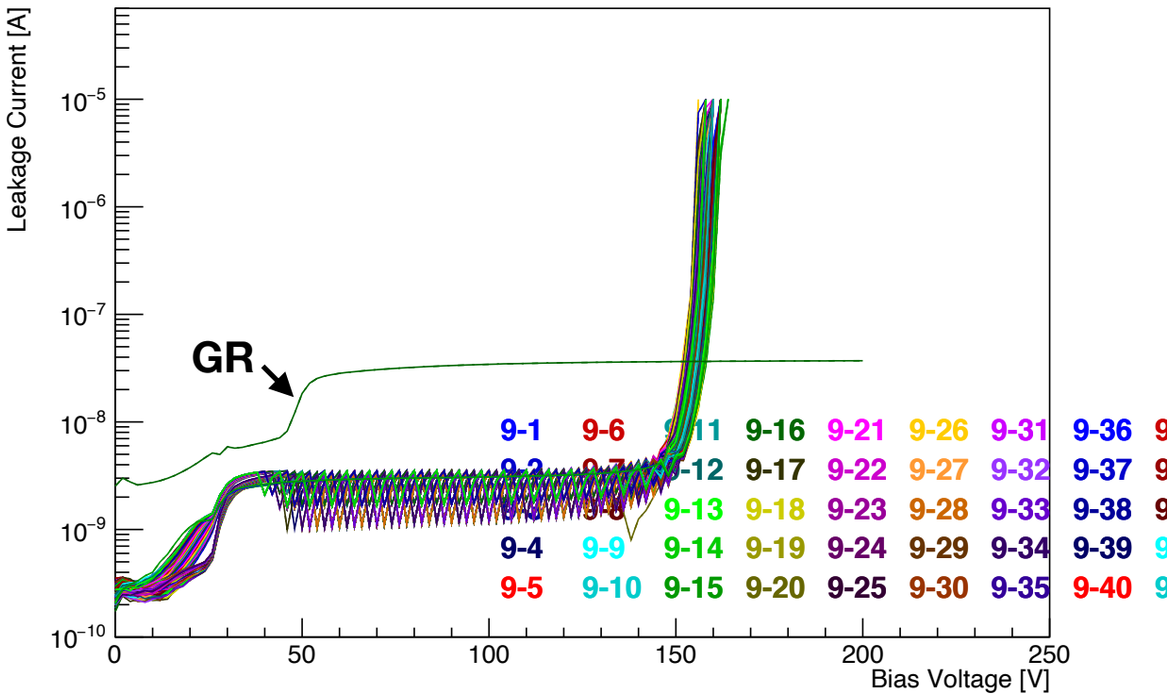




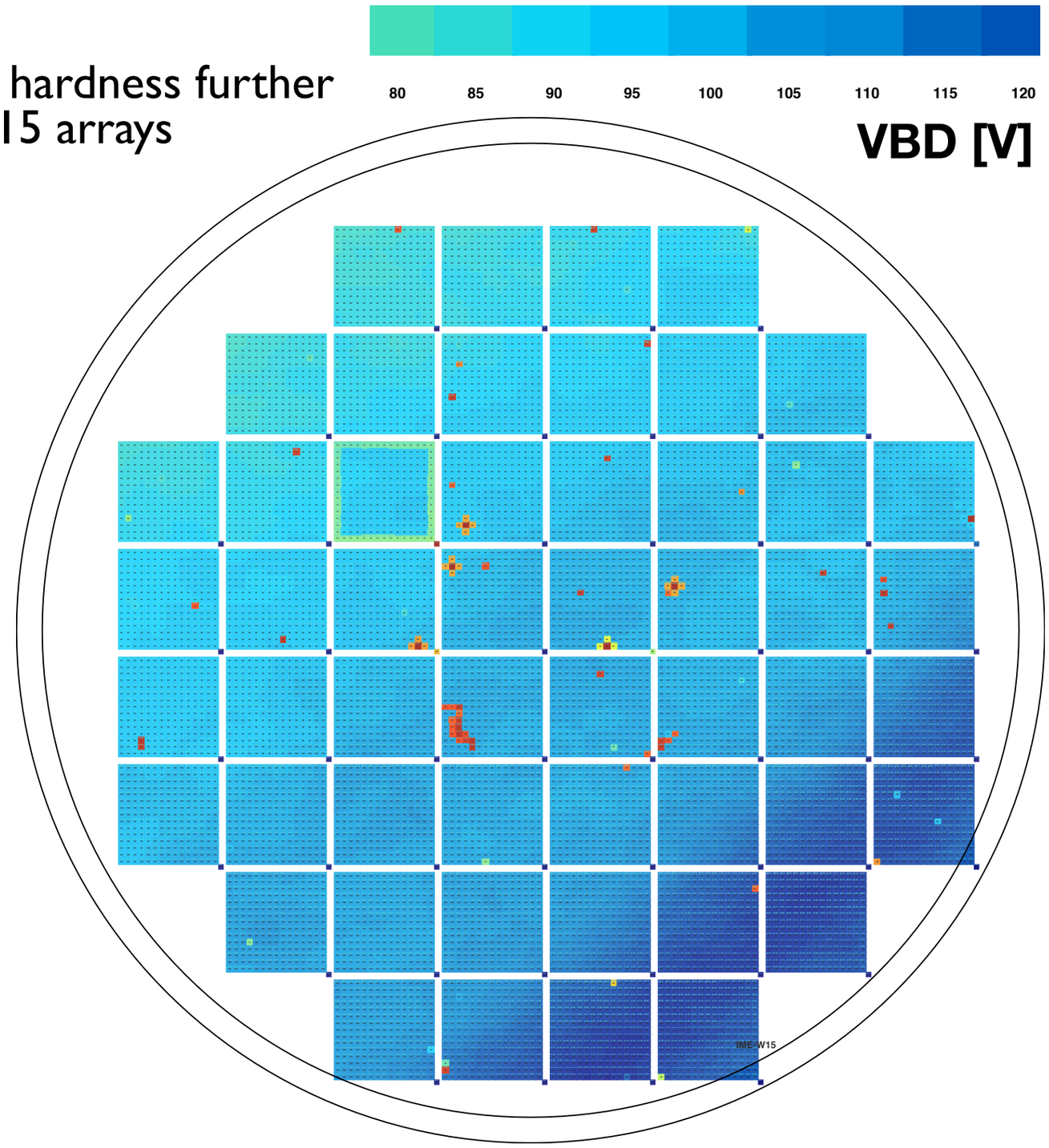
- The USTC W11 LGADs have fulfilled the radiation hardness requirement of HGTD. The σ_t can reach 50 ps within 700V bias after 2.5E15 fluence, two W11 sensors tested in DESY Testbeam.
- Even after 6E15 fluence, the detector can still provided σ_t below 70 ps with higher bias.
- Again we proved the USTC carbon works nicely compare to W7, W8 besides the CV data.
- If we can modify the VBD even lower, the detector can perform even better. => USTC IME batch 2 => v2.0/2.1

USTC-IME 2nd batch uniformity

- USTC-2.x are dedicated to
  1) lower the VBD to enhance the irradiation hardness further
  2) improve and evaluate the yield of the 15x15 arrays



Breakdown voltage RMS% = 1.91%
(HGTD requirement 5%)



Breakdown voltage distribution
of USTC W15 15*15 arrays
Current Yield ~ 35%

Summary

- The USTC group is **deeply involved** in the LGADs R&D for the ATLAS HGTD upgrade (Design, Fabrication, Characterization)

- The USTC group focus on the radiation hard LGAD development, **deep gain layer and carbon diffusion** have been realized at both IME and NRFC.

- **Carbon** diffused LGAD USTC W11/W16 show impressive radiation hardness(**14fC** @ 2.5E15 neq/cm^2), it meets the HGTD requirement, c-factor: **1.85E-16** cm^2 is quite close to the most promising one from FBK (1.45E-16 cm^2) currently.

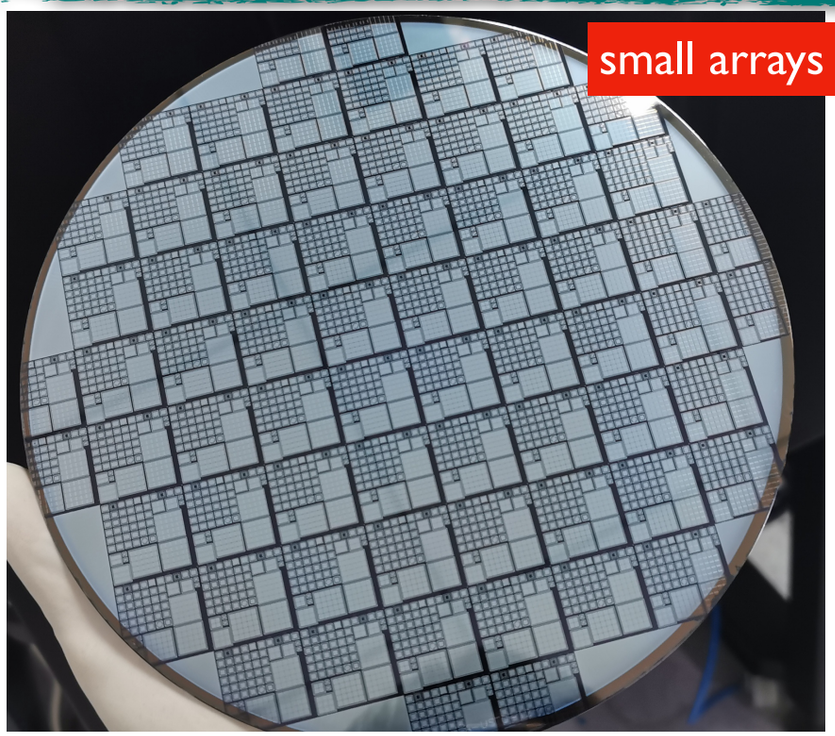
- Charge collection and timing resolution have been measured with beta source and DESY electron beam, **46 ps** @ 2.5E15 neq/cm^2 obtained, meet the requirements.

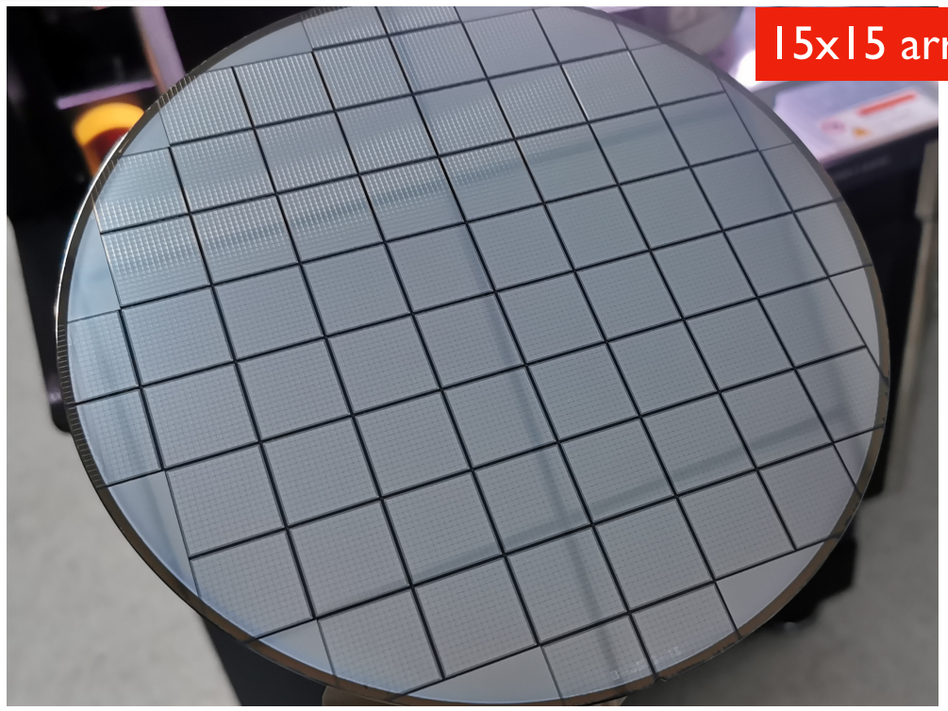
- USTC-IME batch2 show good uniformity(<**1-3% VBD** variation) and yield (**35%**) for 15x15 array, further optimization are ongoing. Irradiation hardness evaluation ongoing

Thanks for your attention!

Backup

USTC-IME 2nd Batch LGADs





Production Batch	Wafer No.	GL.Dose	Implantation	Layout arrays	VBD_low	VBD_high	VBD_medium
USTC-2.0	**W12**	Low	B	Small	166	184	**~174**
	W13	Low	B	15x15	154	190	**~172**
	W14	High	B	Small	70	122	**~84**
	W15	High	B	15x15	84	134	**~100**
	W16	High	B+C	Small	32	80	**~50**

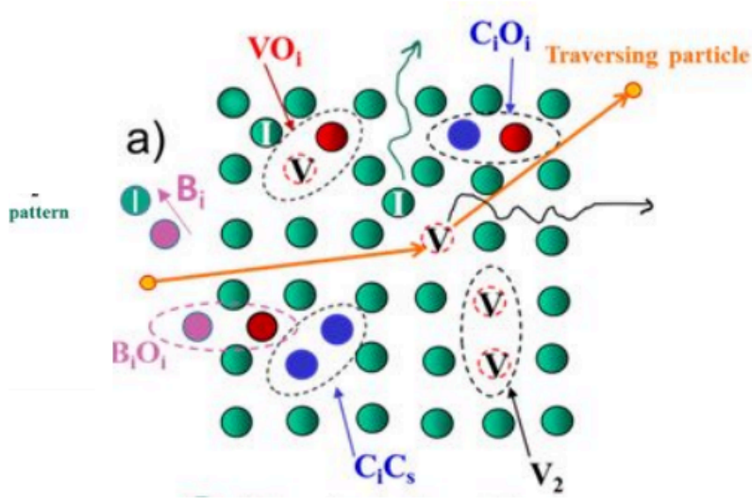
- Five 8-inch wafers delivered to the beginning of July and on wafer test performed quickly at USTC, after UBM, the sensor will be diced for further test

- Dedicated to
  1) lower the VBD to enhance the irradiation hardness further
  2) improve and evaluate the yield of the 15x15 arrays

Full size array: 15x15 pads
Pad size: 1.3*1.3 mm²

- **First** full 15x15 wafer produced!

Acceptor removal effect in silicon



Competing reactions with Si$_i$ involving B, C and O

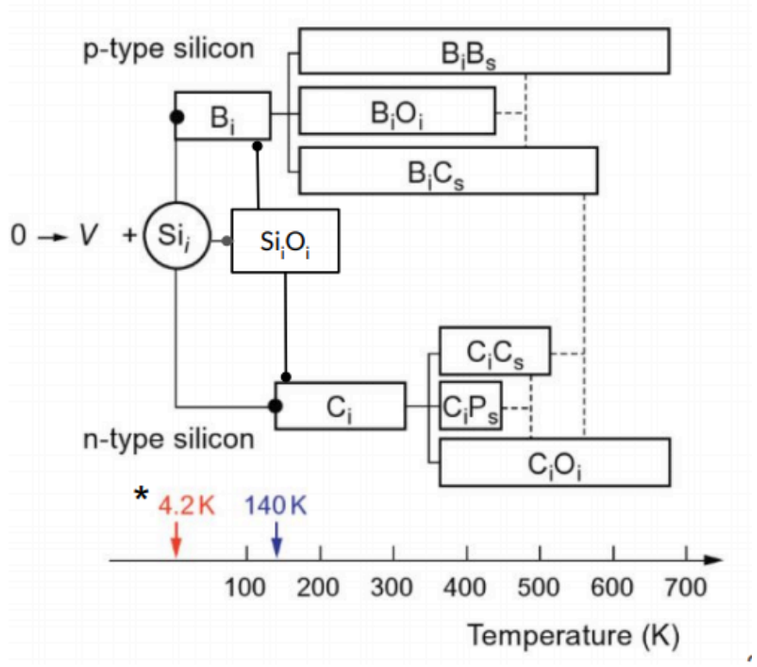


Photo of the five wafers received

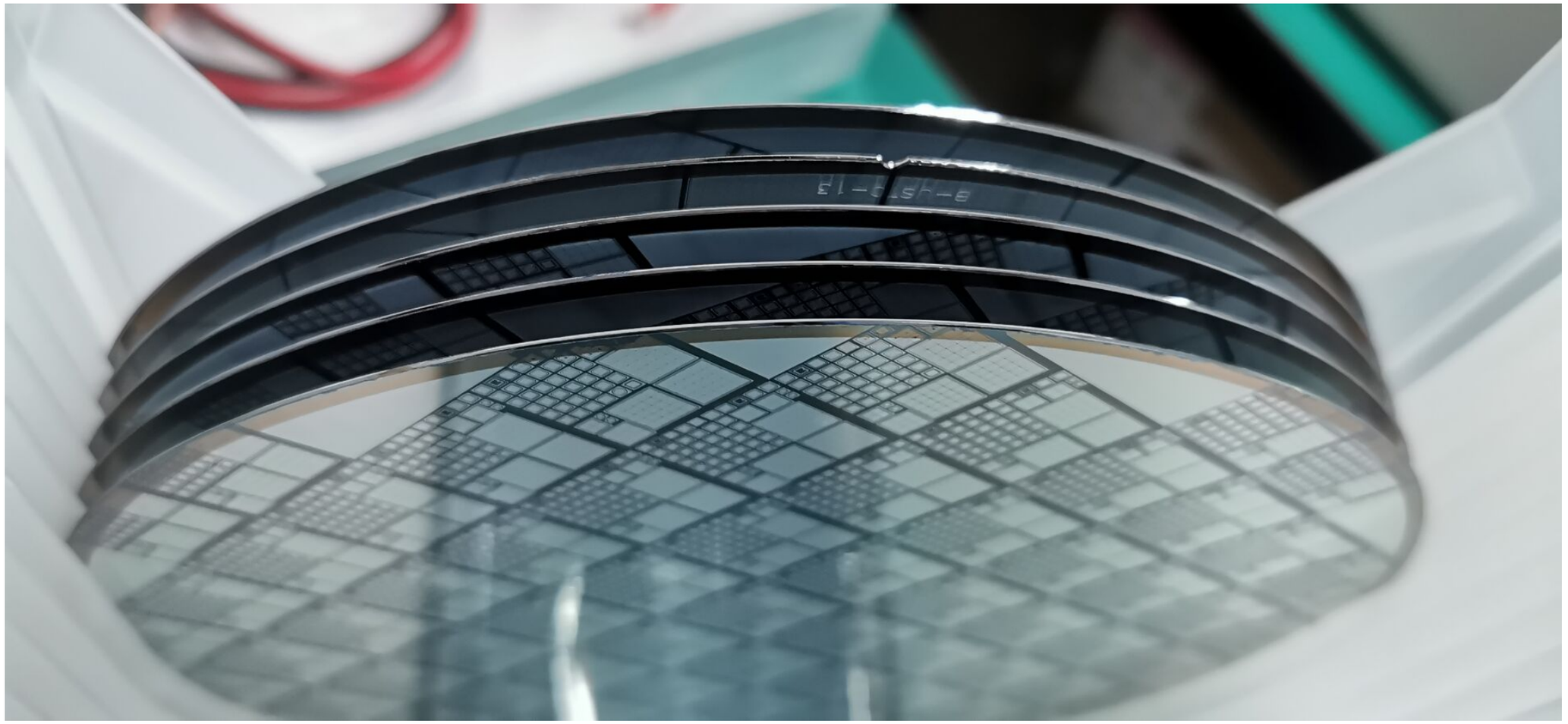
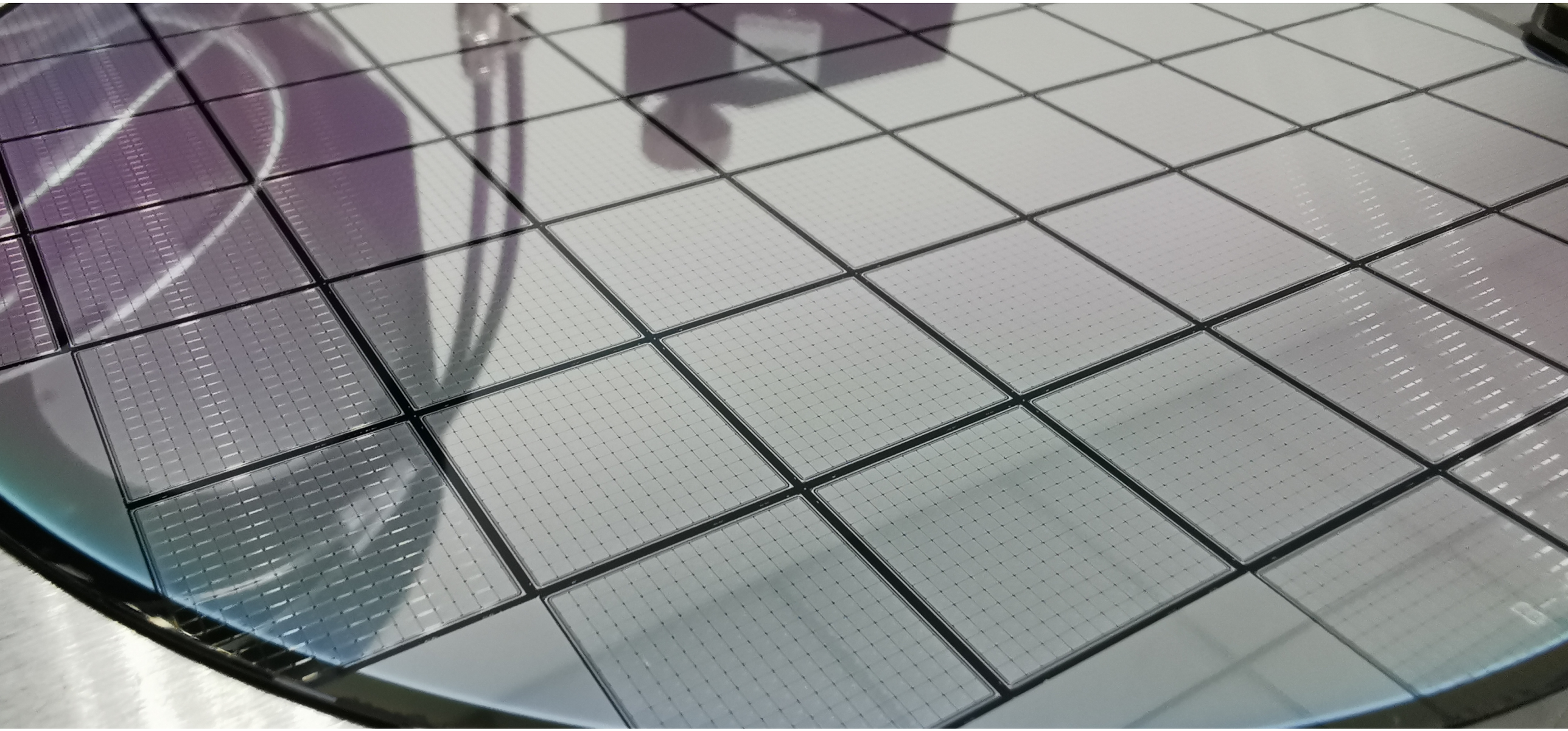
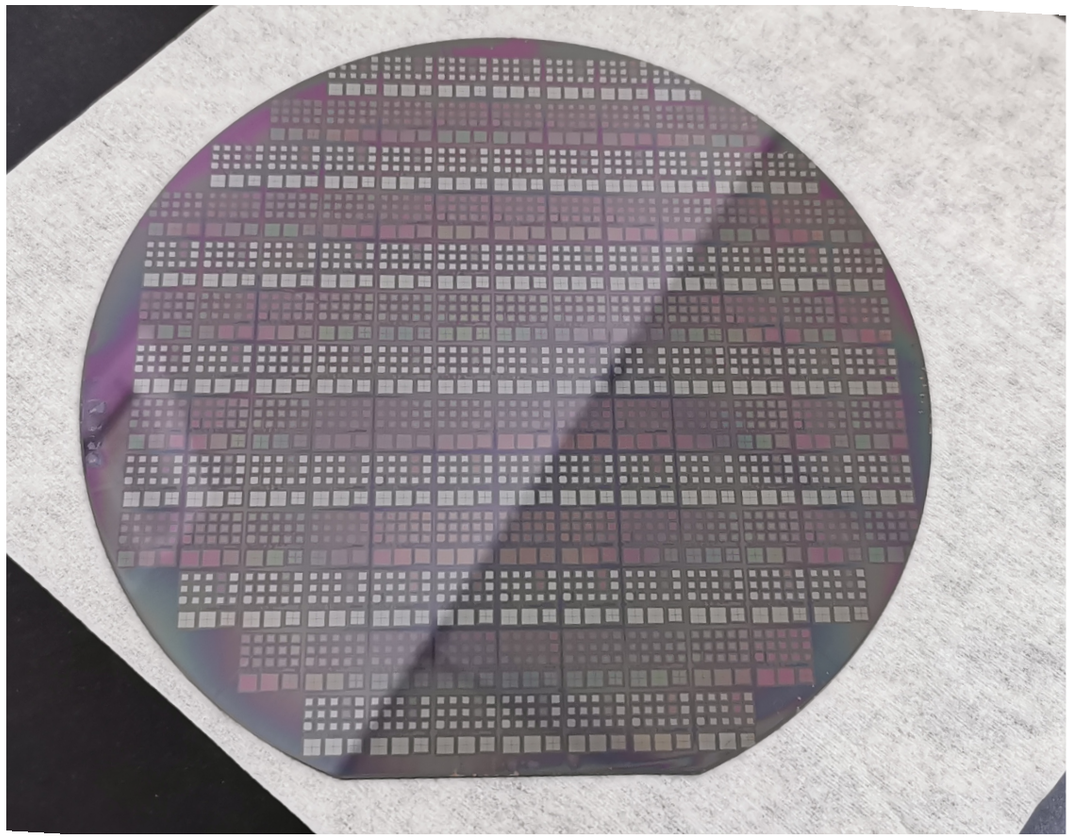
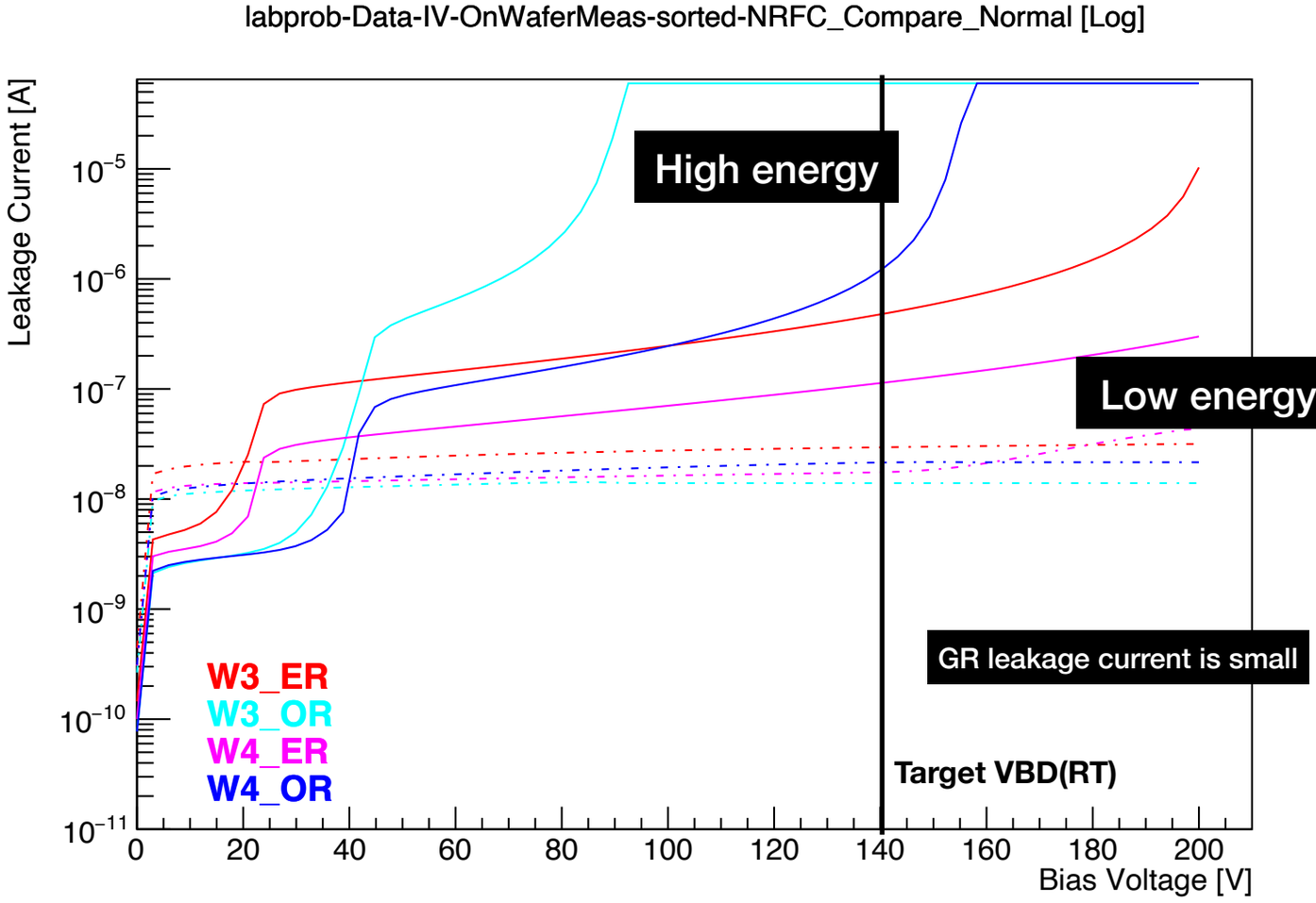


Photo of the full 15x15 LGAD wafer



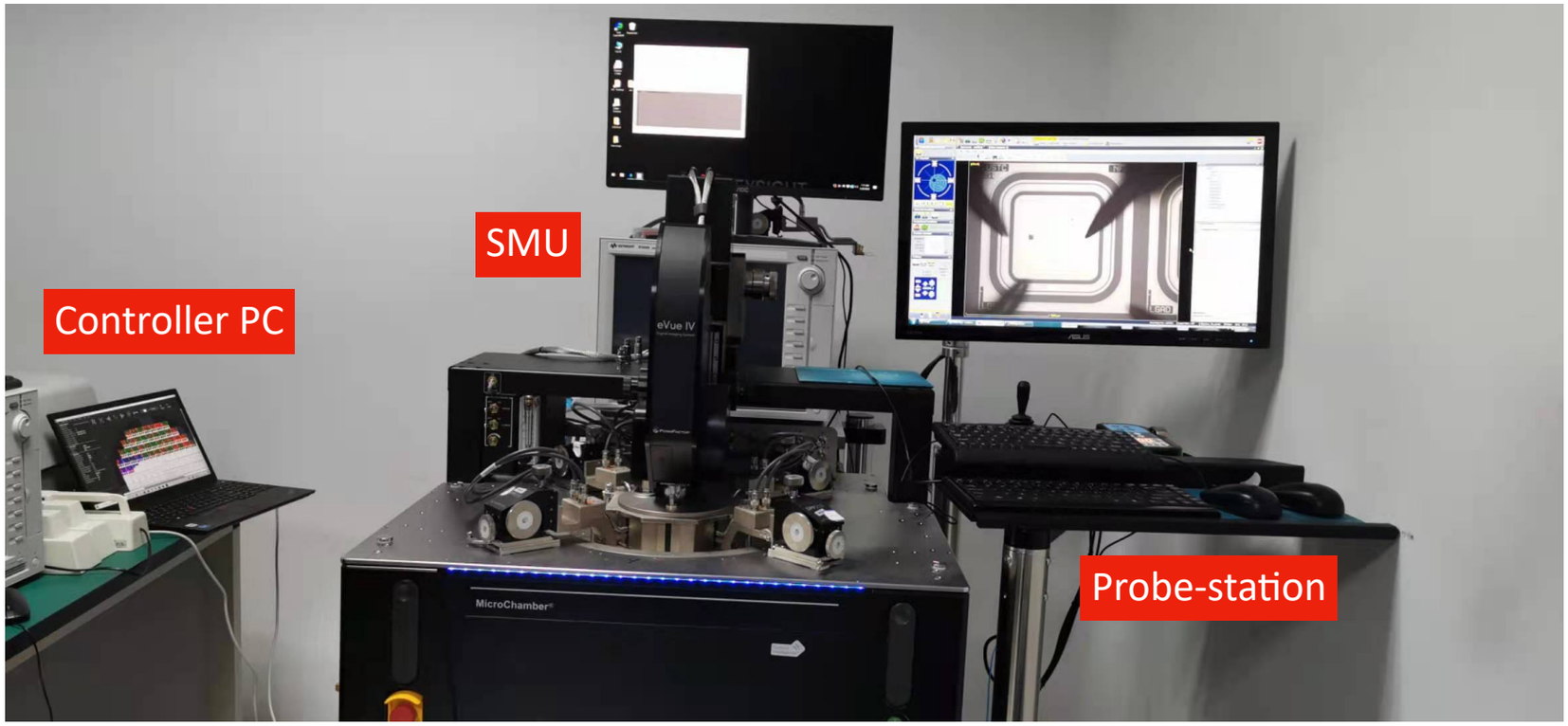
Preliminary IV data

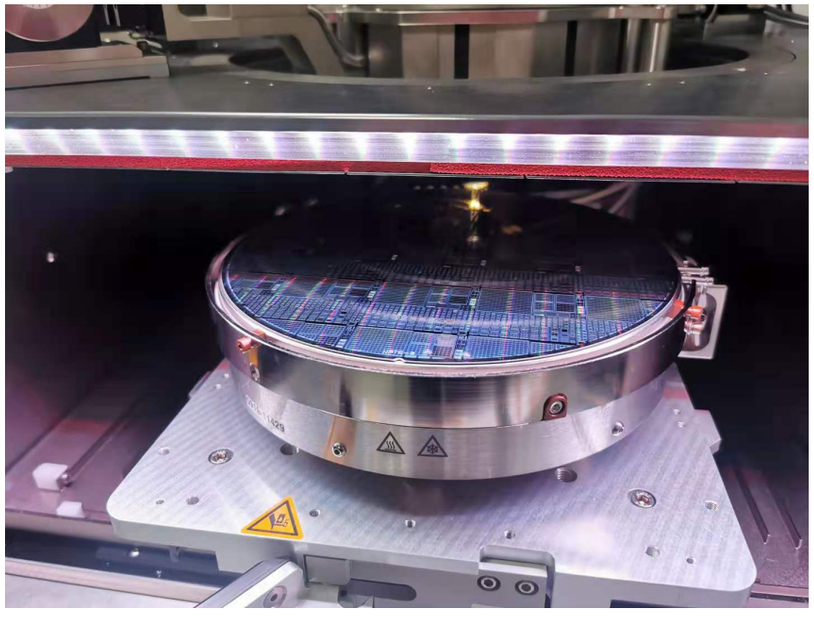


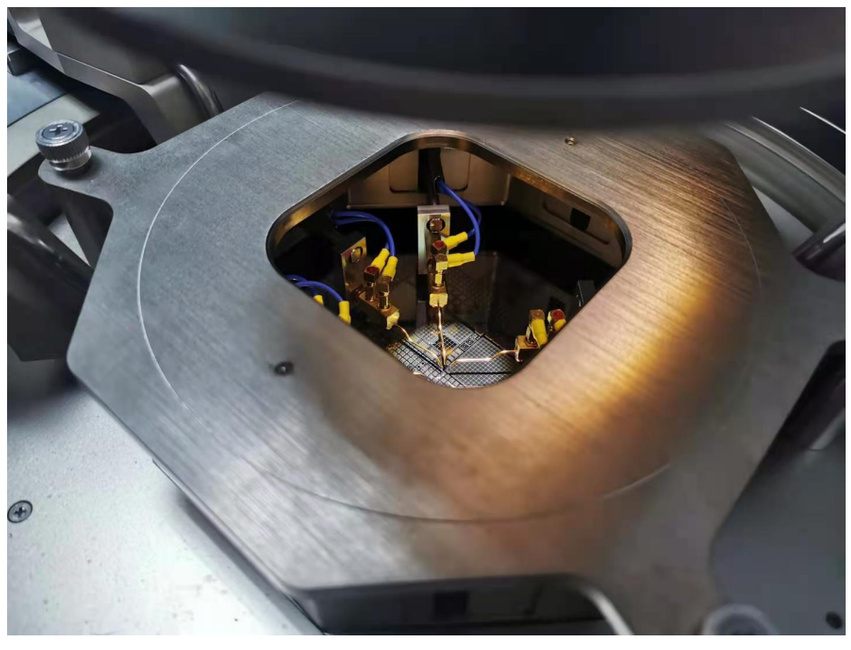


Splits	Wafer	Rows	GL.Energy	GL.Dose	Measured	Comment
1	W3	Odd	High	High	85	GL. Energy same as IME batch 1 W10/W11
2	W4	Odd	High	Low	150	
3	W3	Even	Low	High	200	GL. Energy same as batch 2
4	W4	Even	Low	Low	>200	

Wafer-level Measurement System Upgrade at USTC



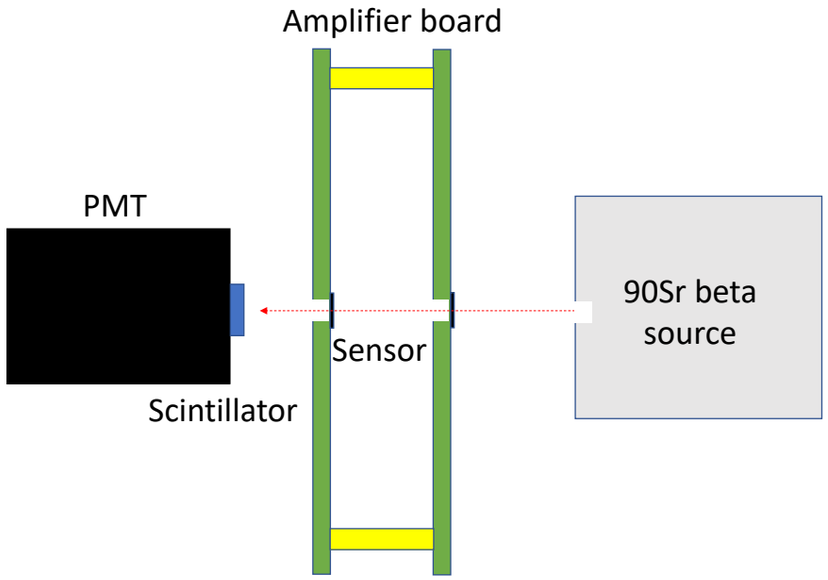


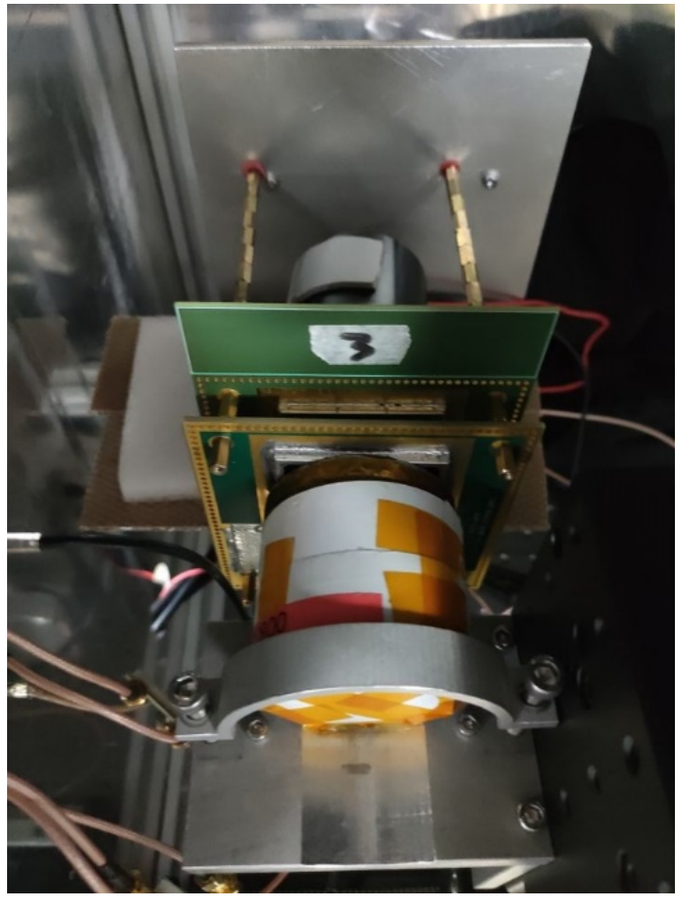


- Previously, we have semi-automatic probe station
- To test large wafers, we upgrade the control software which assemble the SMUs and Probe station together
- Now, The machine can test the whole wafer fully automatically, 5s/pad with 2V step, very fast.
- We tested USTC-NRFC 6-inch wafers. prepared for the IME 8-inch wafers coming soon

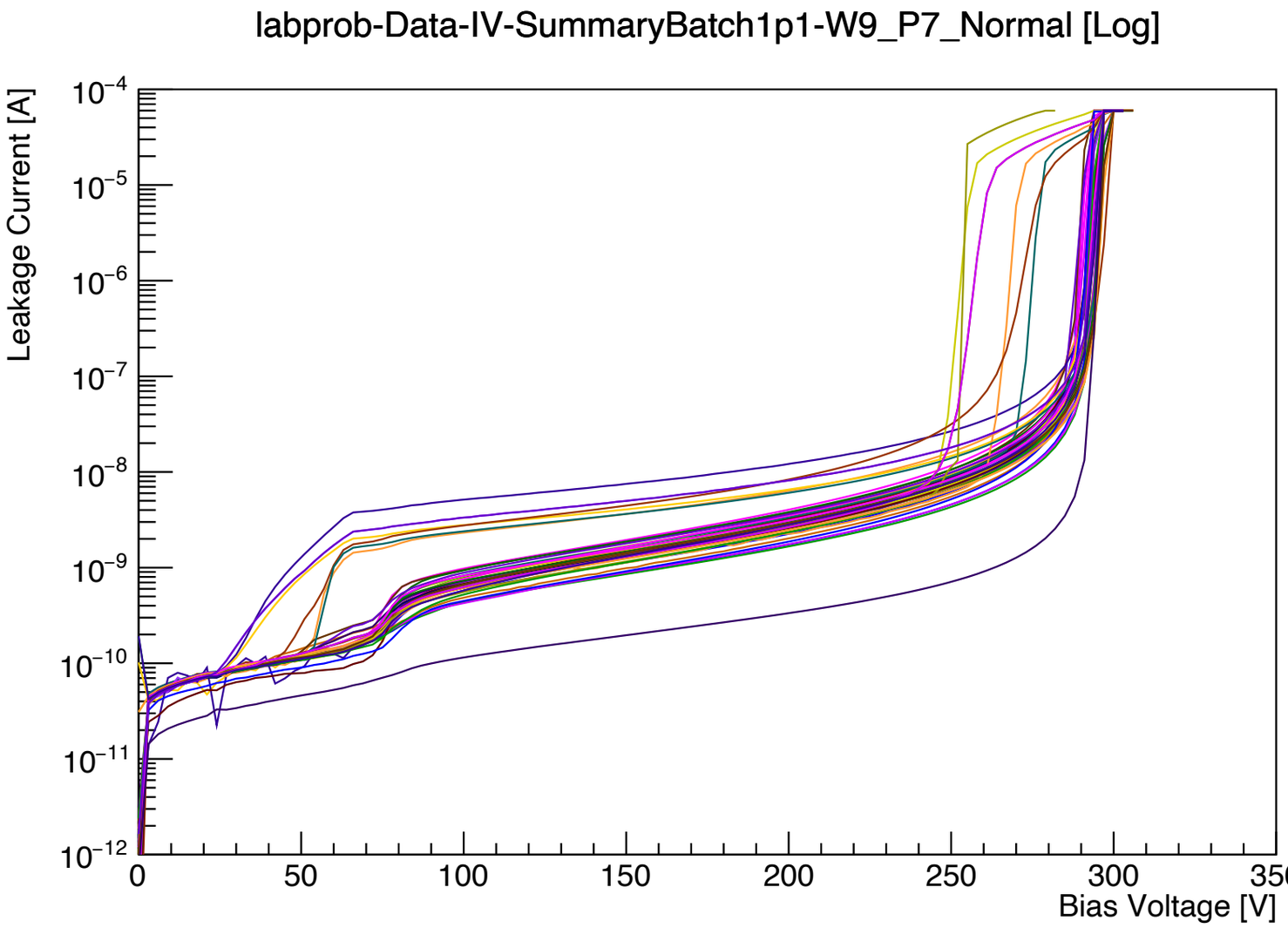
Setup of the USTC beta-TCT system

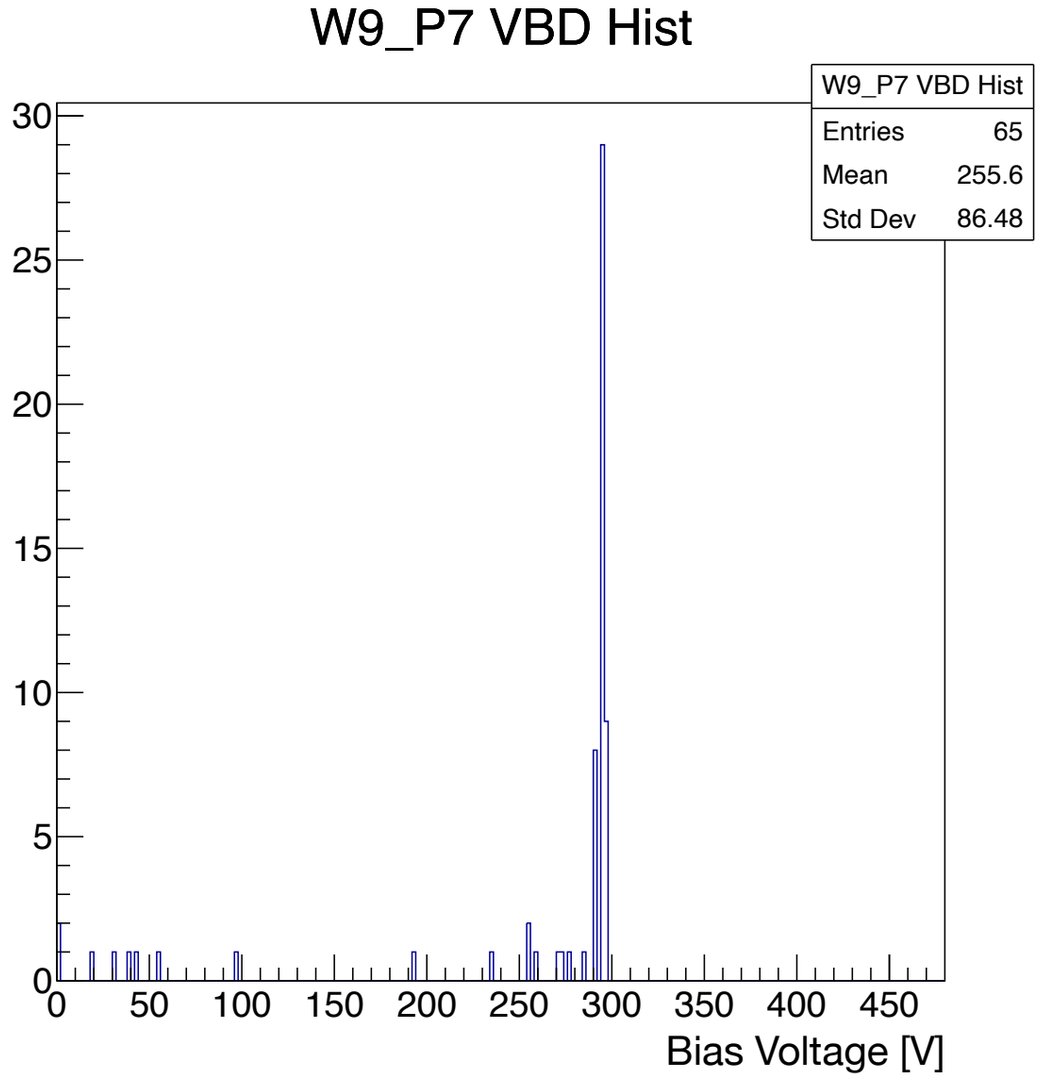
- Room temperature
- Reference
  - UCSC pre-amplifier & HPK Type 1.1 single, un-irradiated
  - With the 2nd stage amplifier
  - Bias: -210V
- DUT
  - UCSC pre-amplifier & USTC-1.1 single, un-irradiated
  - With the 2nd stage amplifier
- Trigger (Coincidence with reference)
  - R5924 PMT & EJ 232 Scintillator
  - With the attenuator
  - HV: +2000V
  - Threshold: 350 mV
- Oscilloscope
  - Sampling rate: 20 Gs/s
  - Bandwidth: 1 GHz





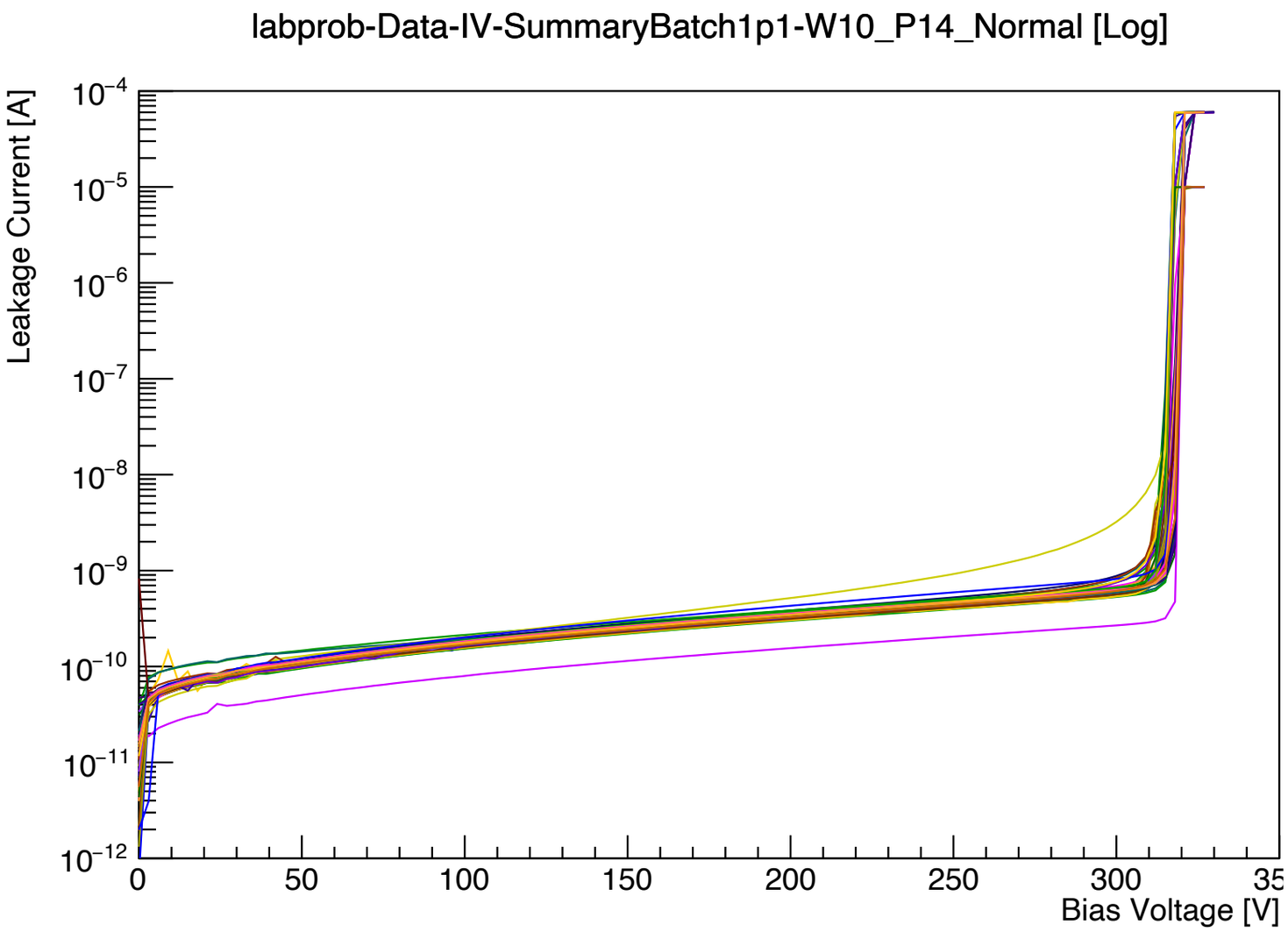
W9: Ultra-deep gain layer

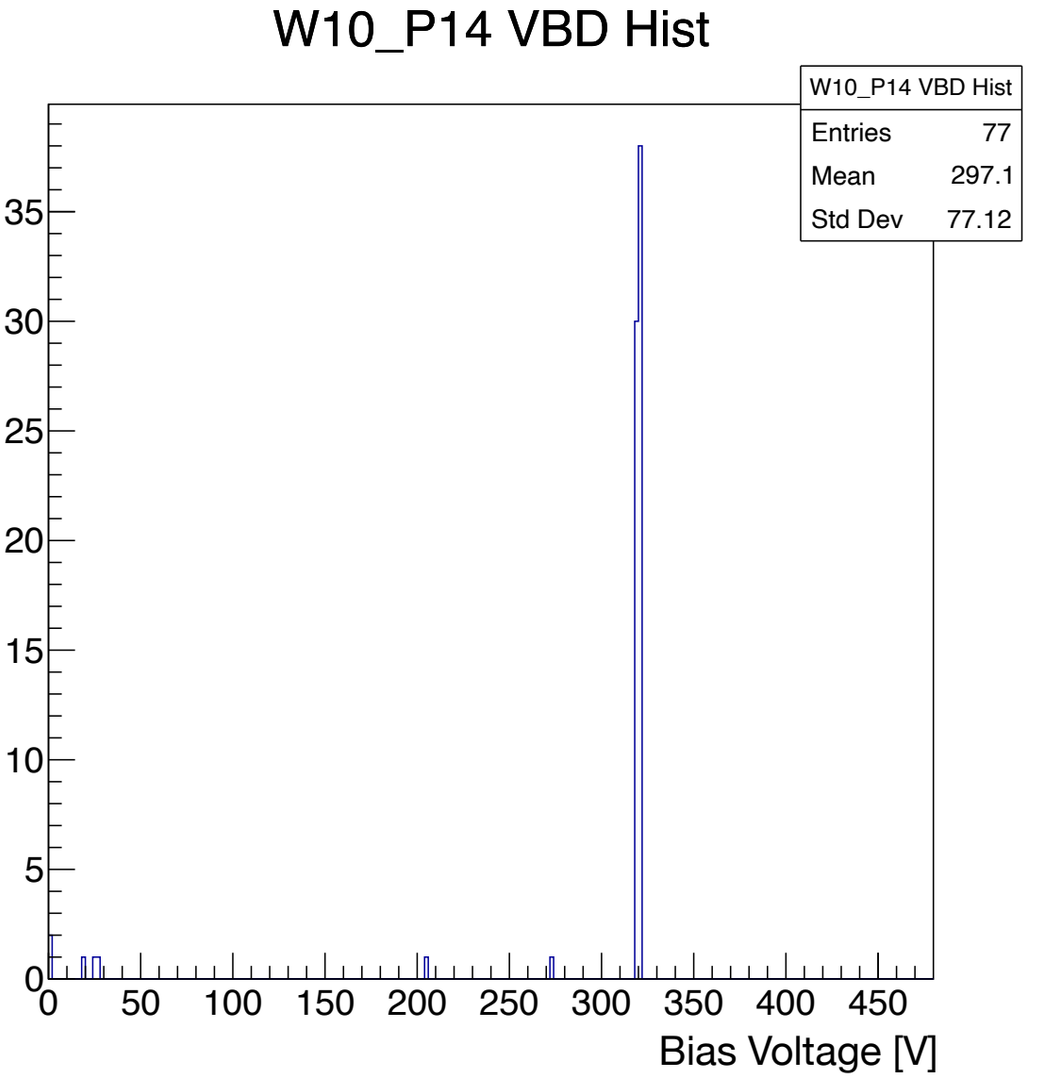




Non-uniform leakage current and VBD for some LGADs, further investigation ongoing.

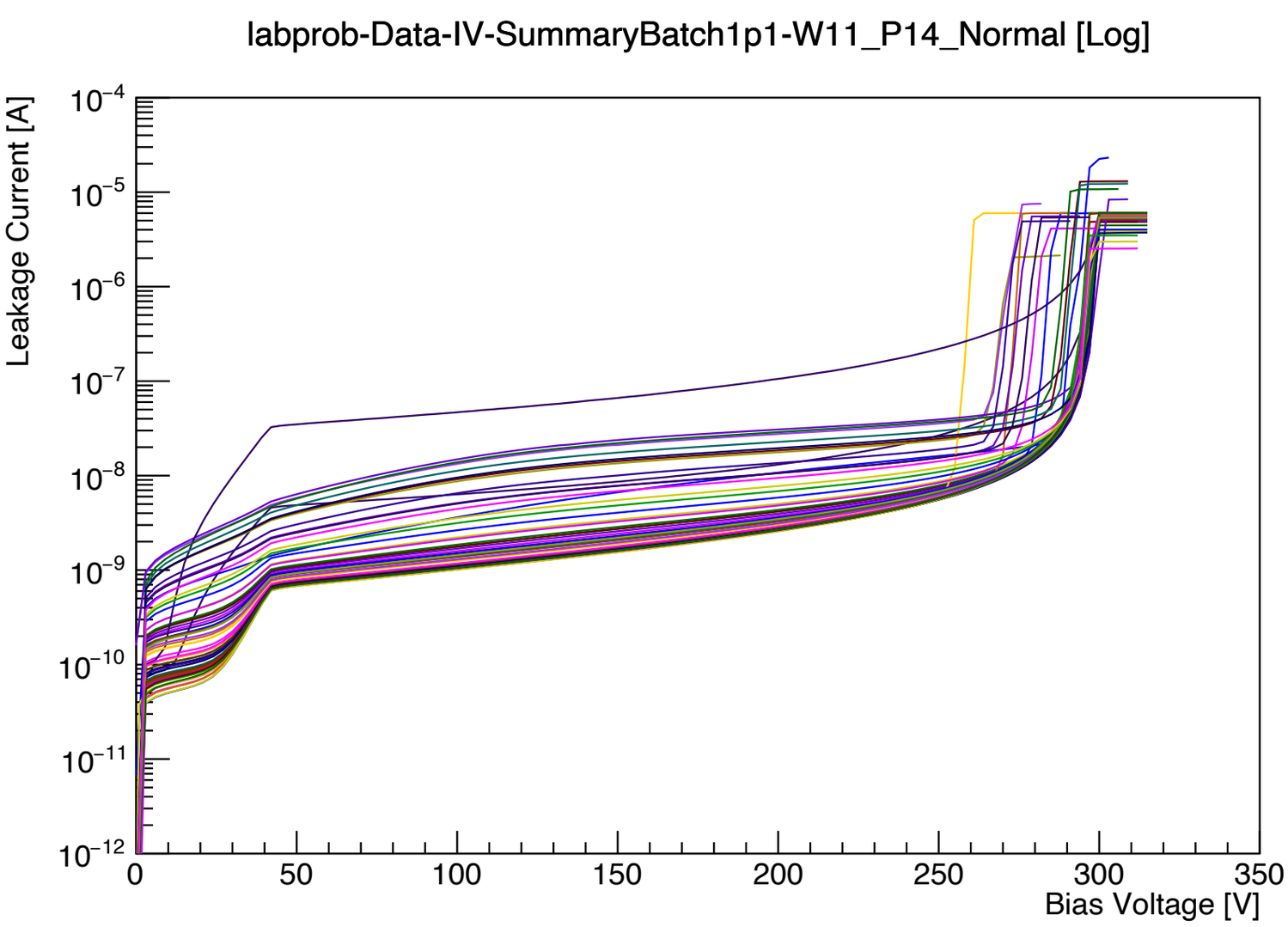
W10: Baseline gain layer (Mid. Energy&Dose)

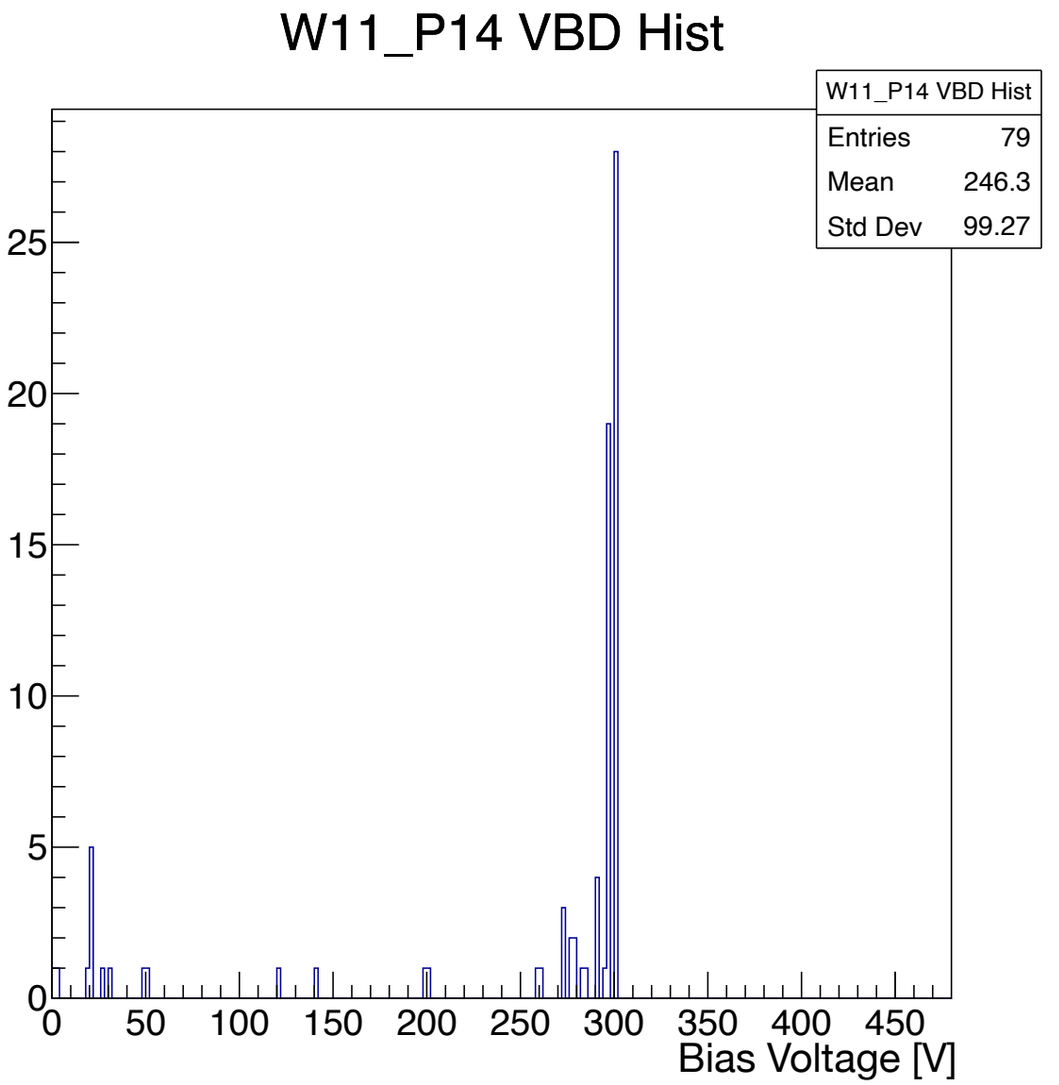




Good uniformity on both leakage current and VBD obtained.

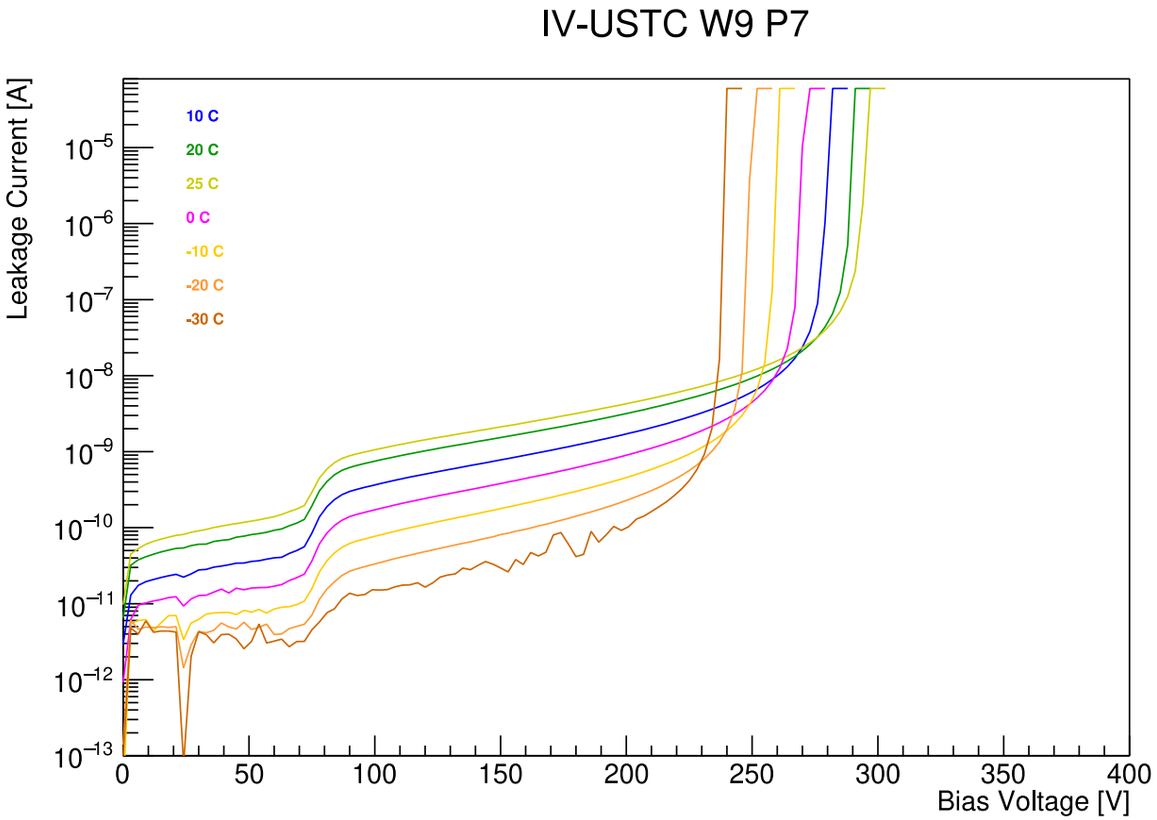
W11: Carbon diffused gain layer

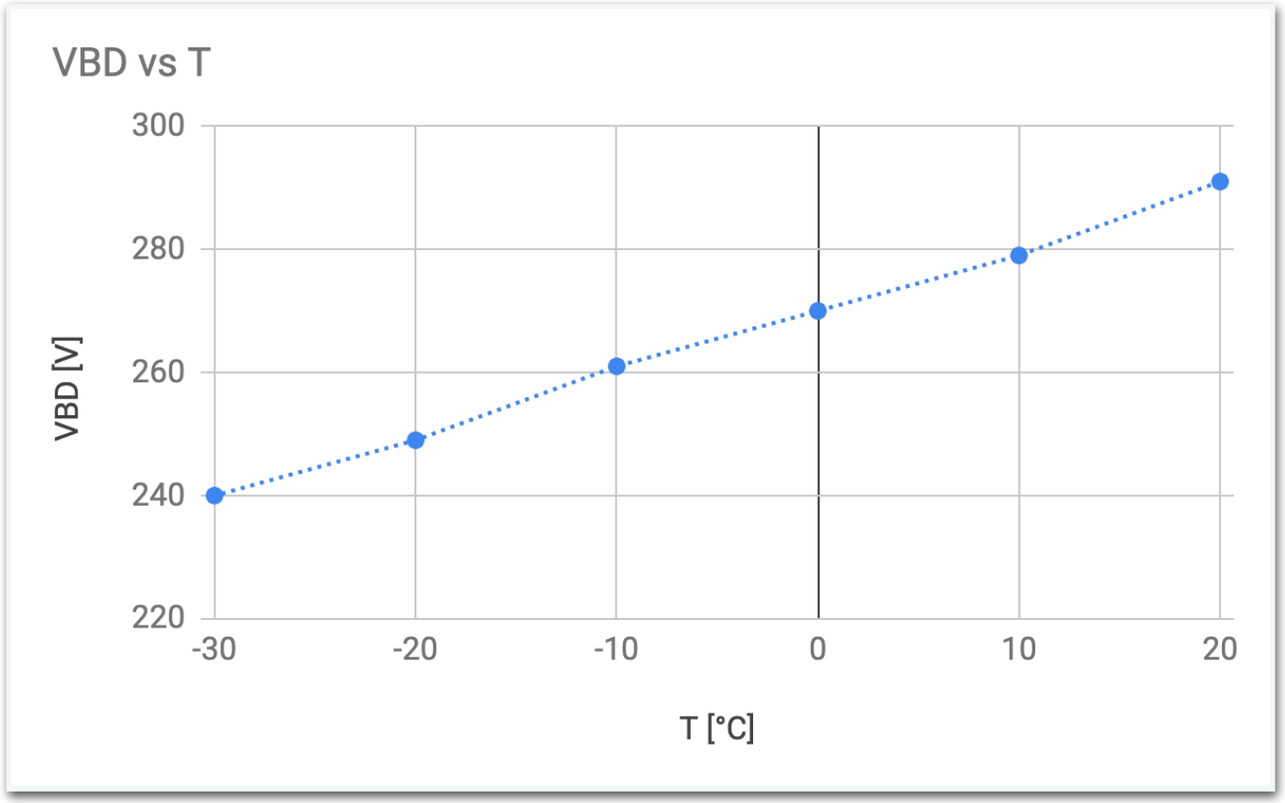




Non-uniform leakage current and VBD for some LGADs, further investigation ongoing.

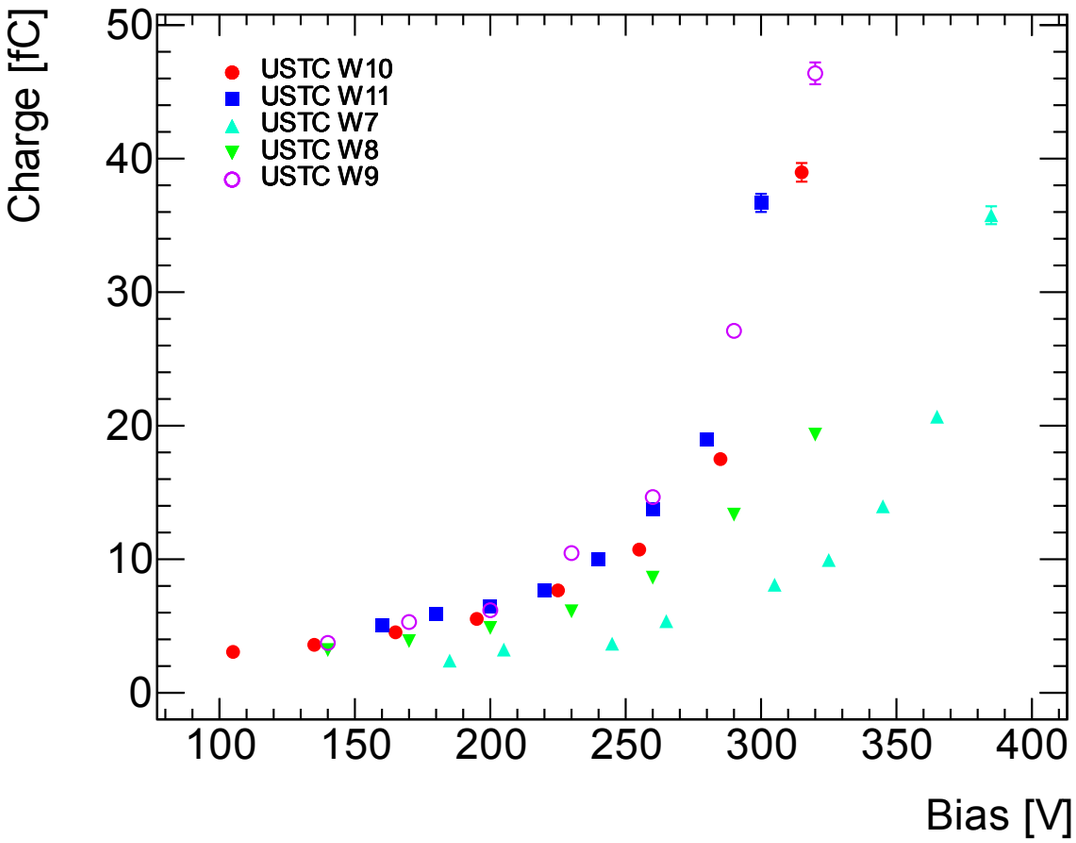
Temperature dependency of the I-V curve

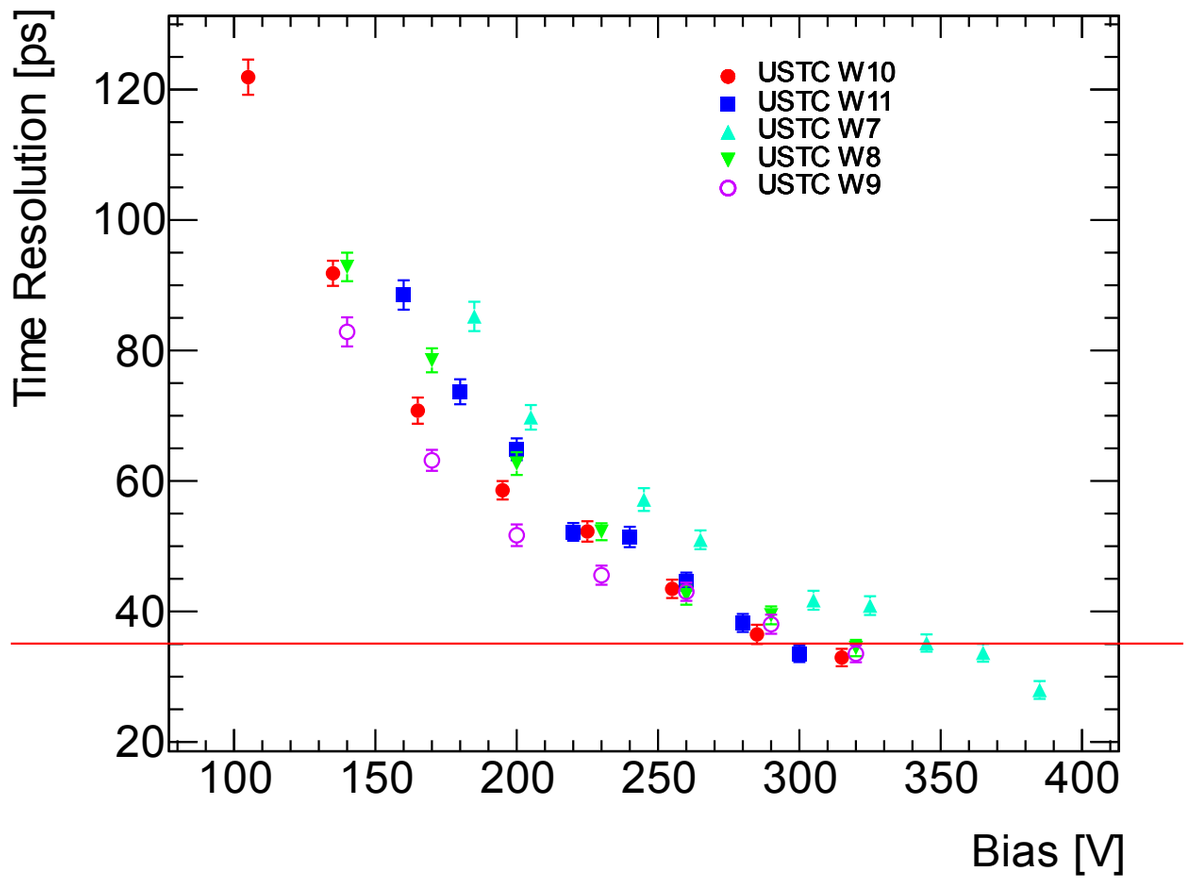




- Sufficient bias after full-depletion (~170V) to saturate the drift velocity at -30 °C
- Target VBD will be reduced by ~ 70V in next batch.

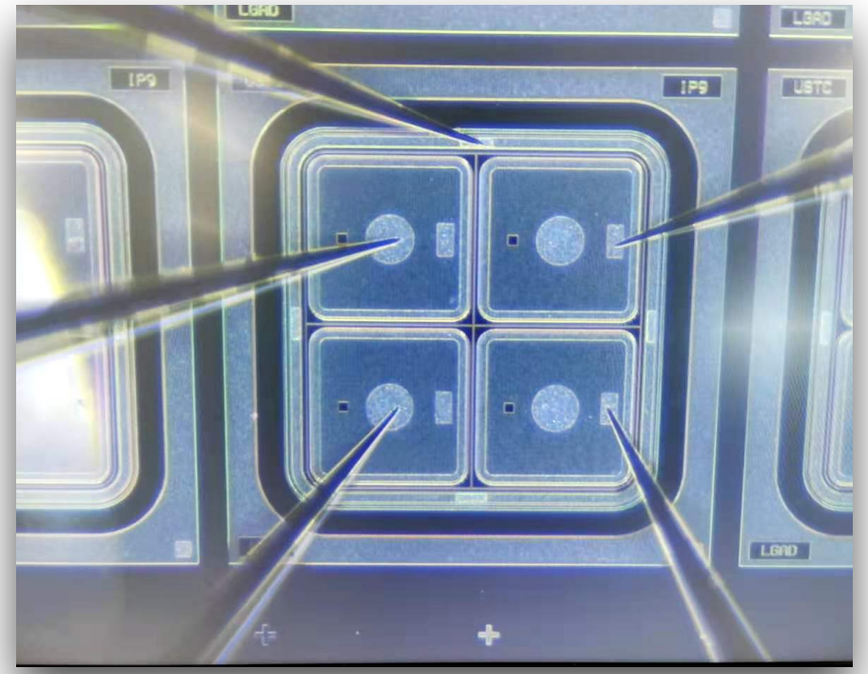
Pre-irradation TCT performance of USTC-1.1

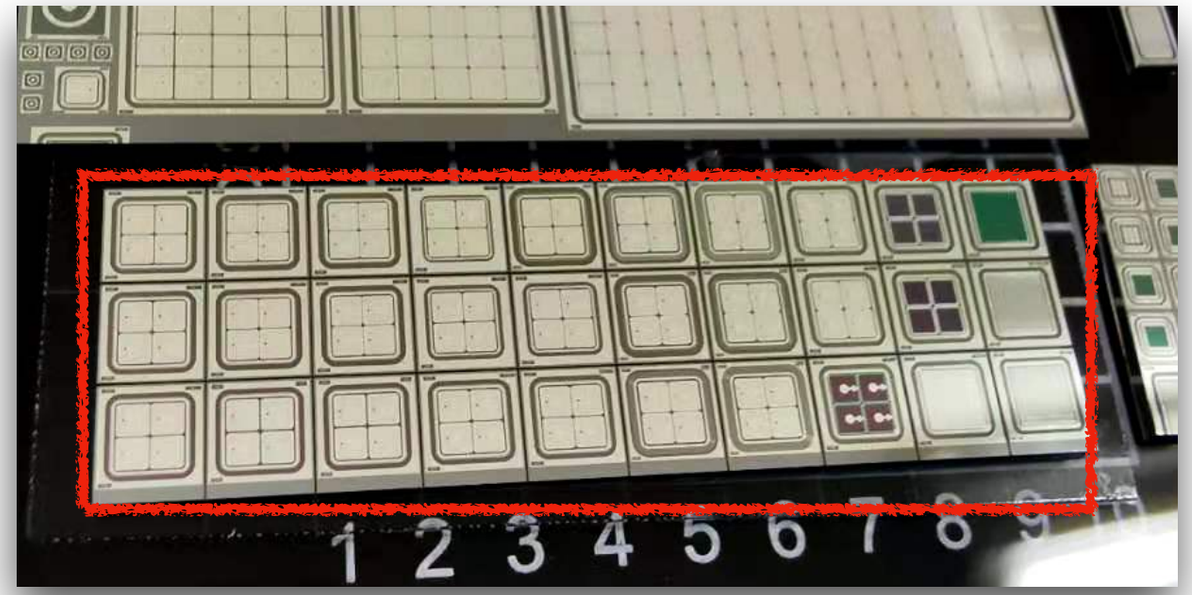


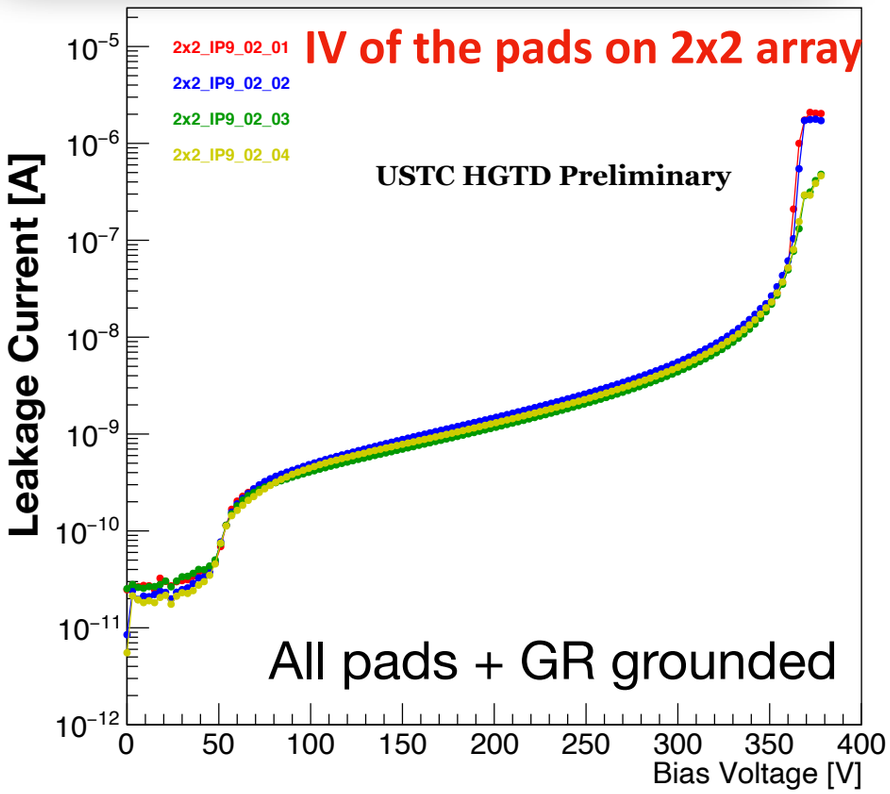


- All the 5 wafers can have time resolution of ~35 ps.
- Sensors with deep implantation(W9) and carbon diffusion(W11) can work normally as W10 before irradiation.

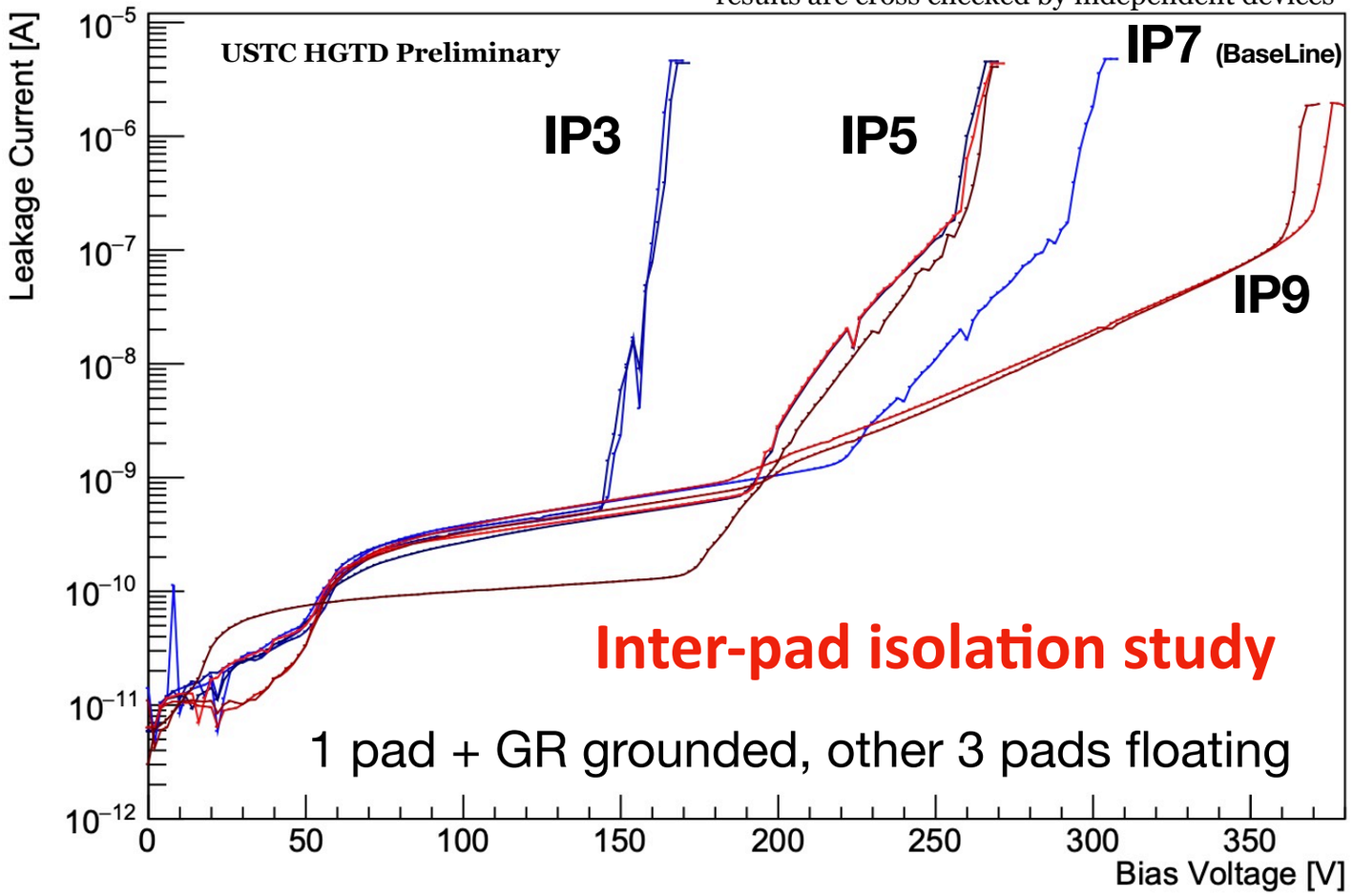
2x2 array test of USTC-1.1



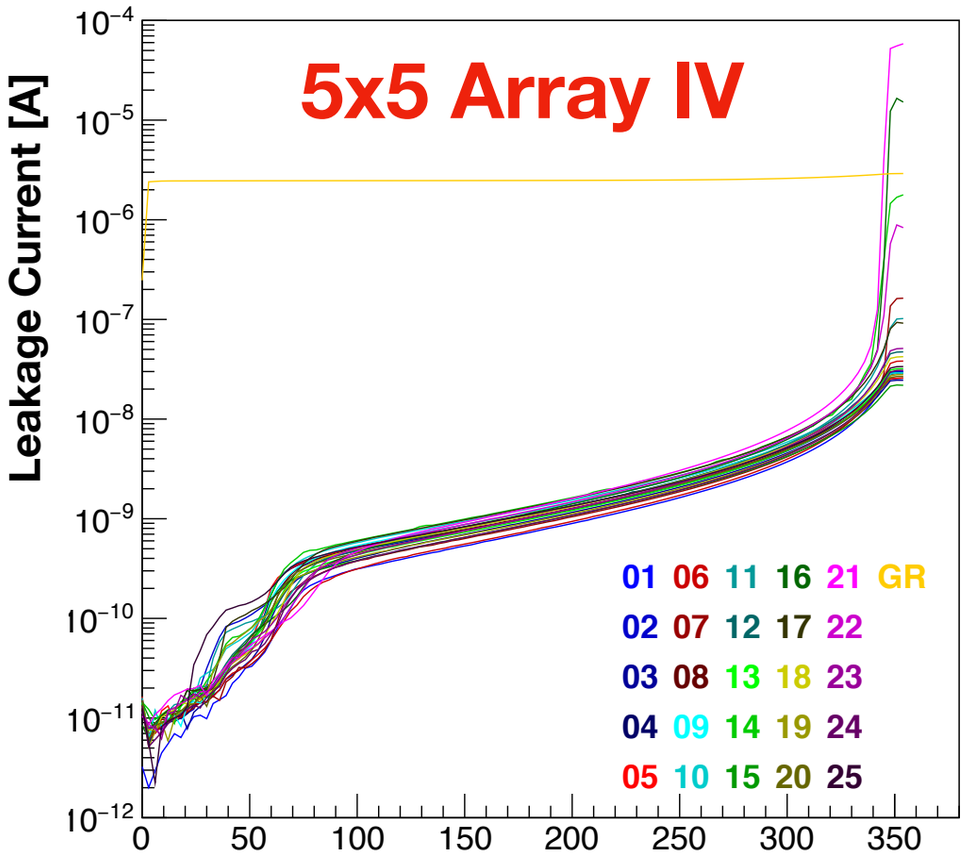


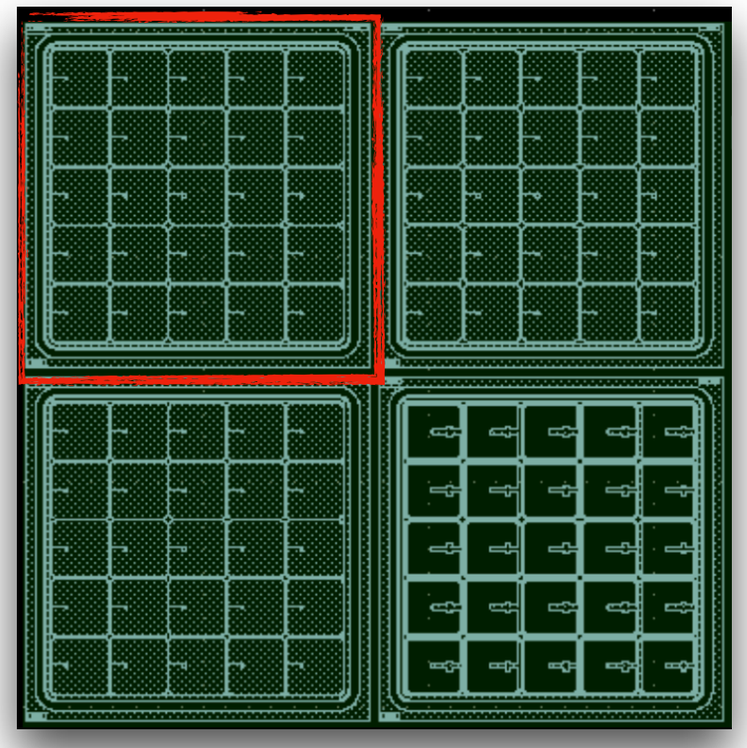


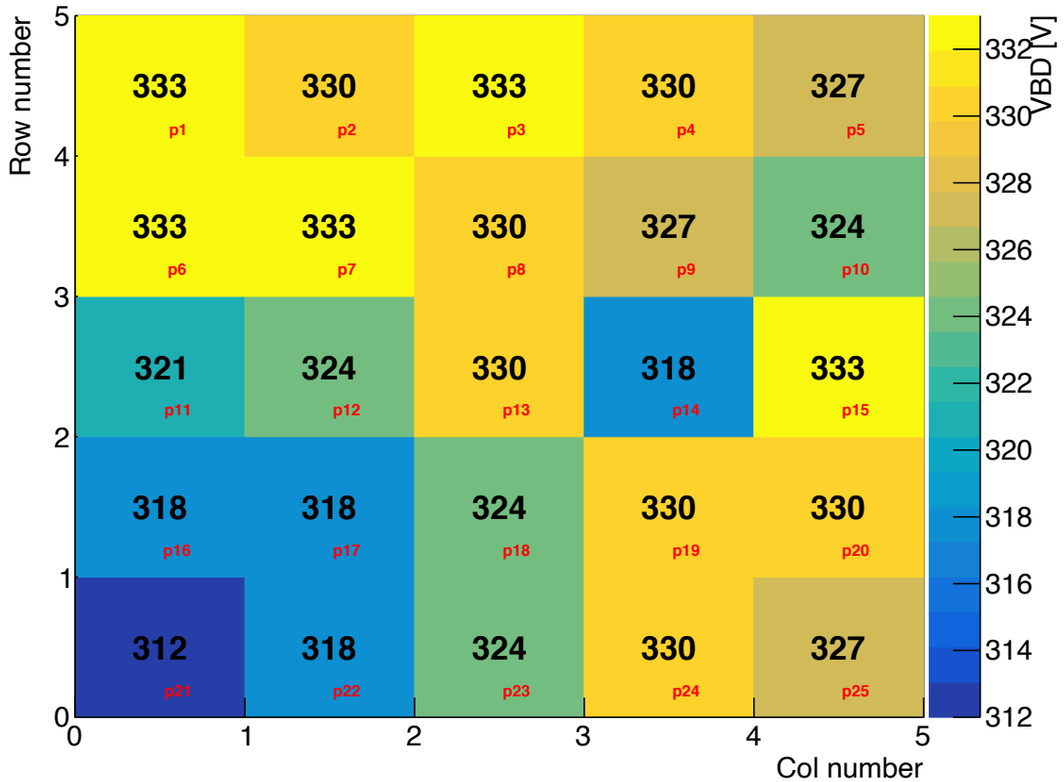
*results are cross checked by independent devices

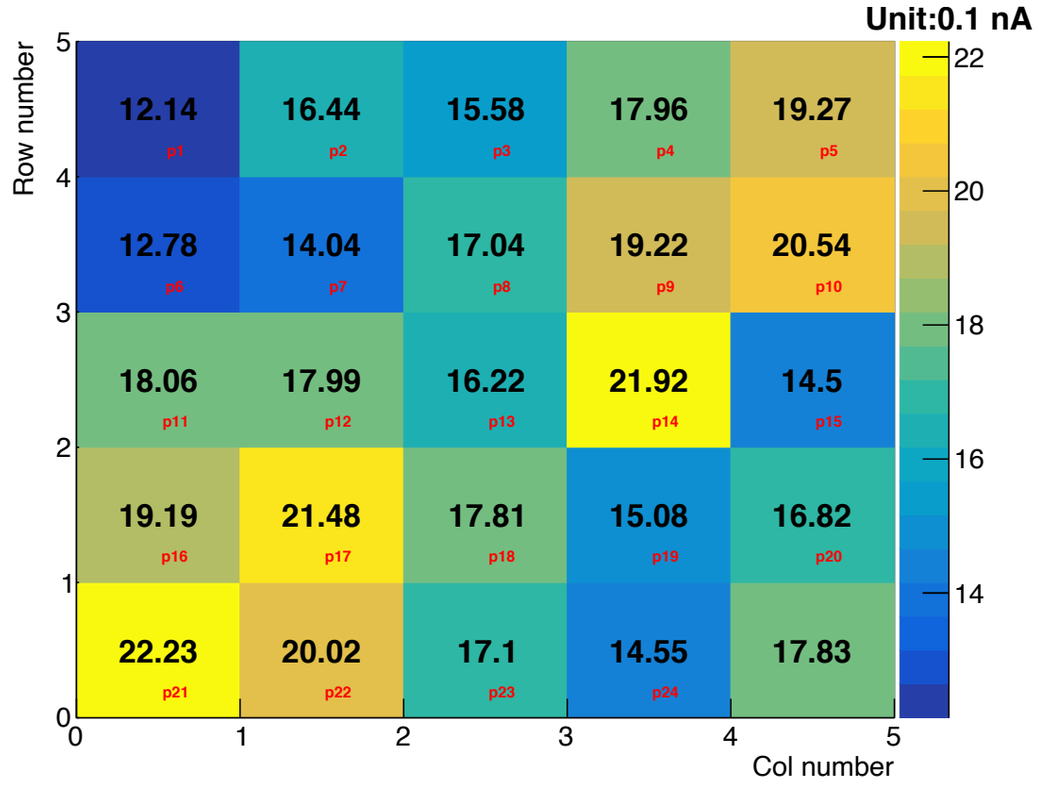


5x5 array test of USTC-1.1

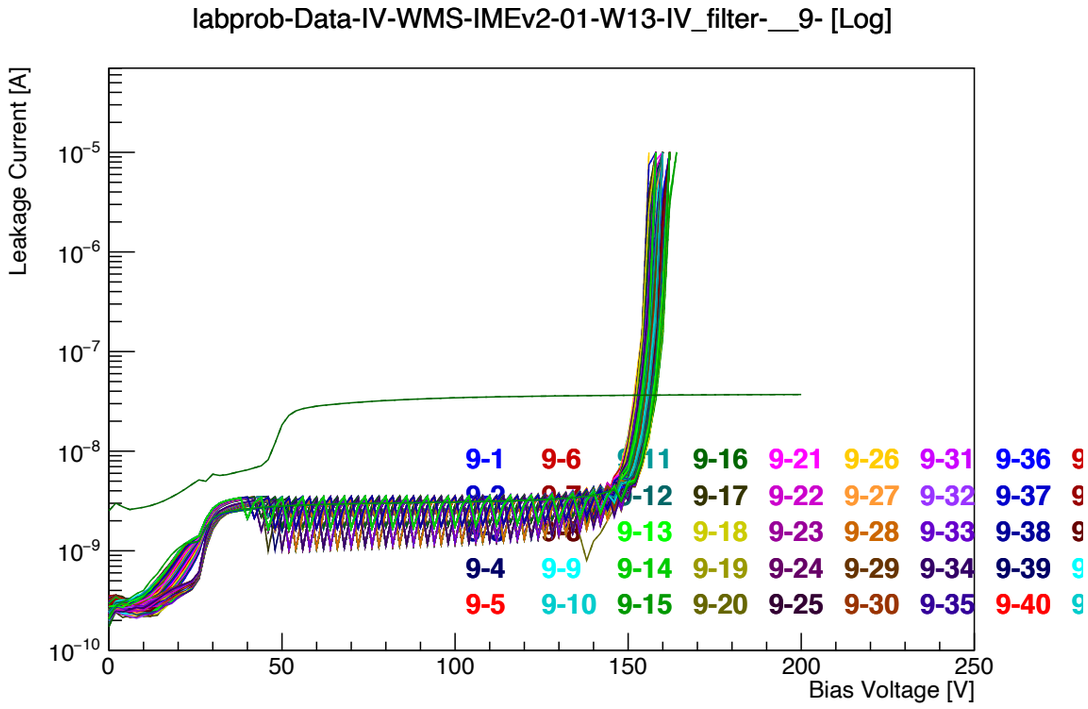


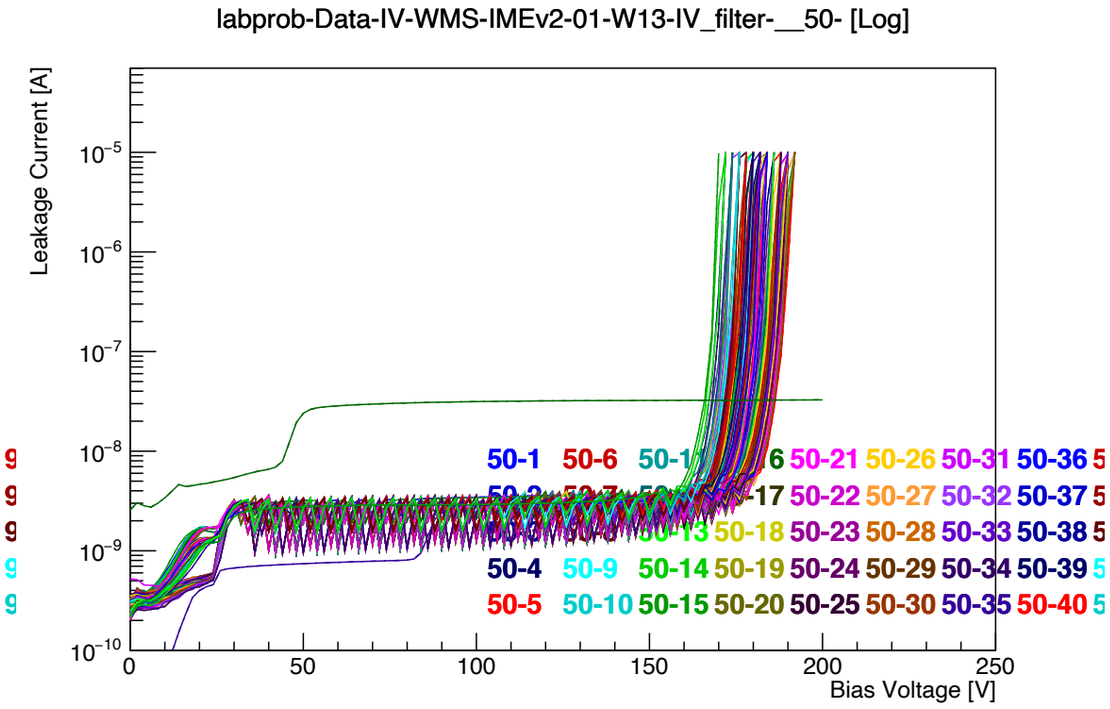


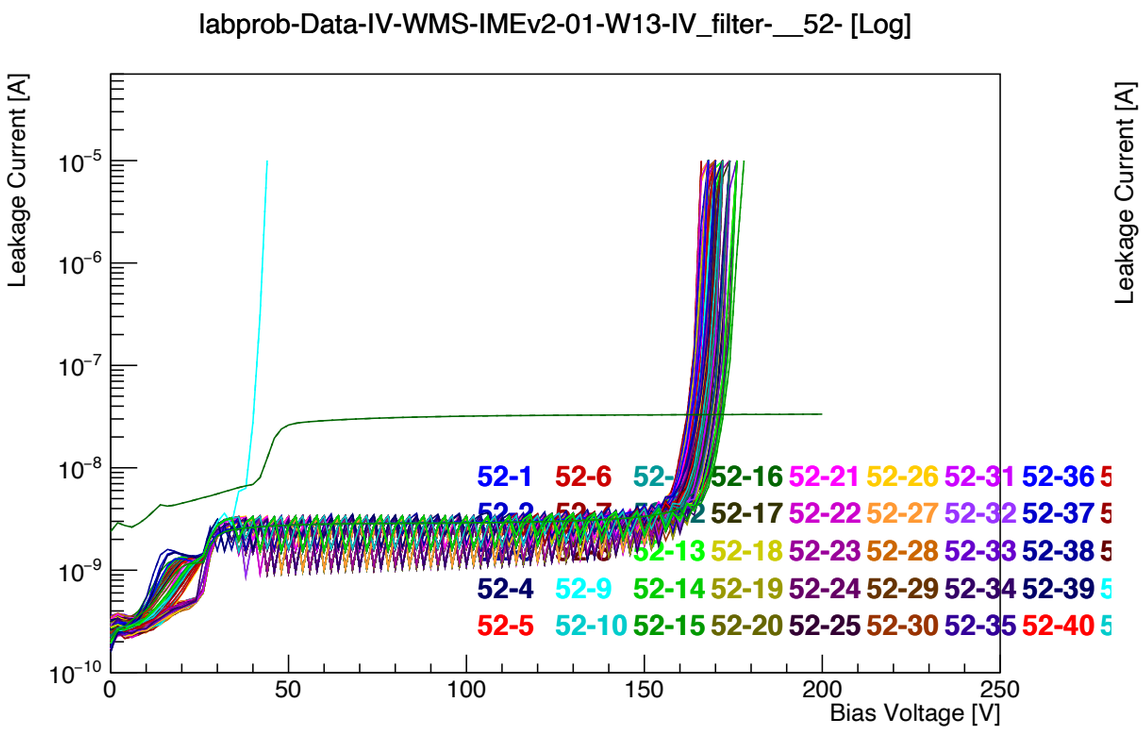


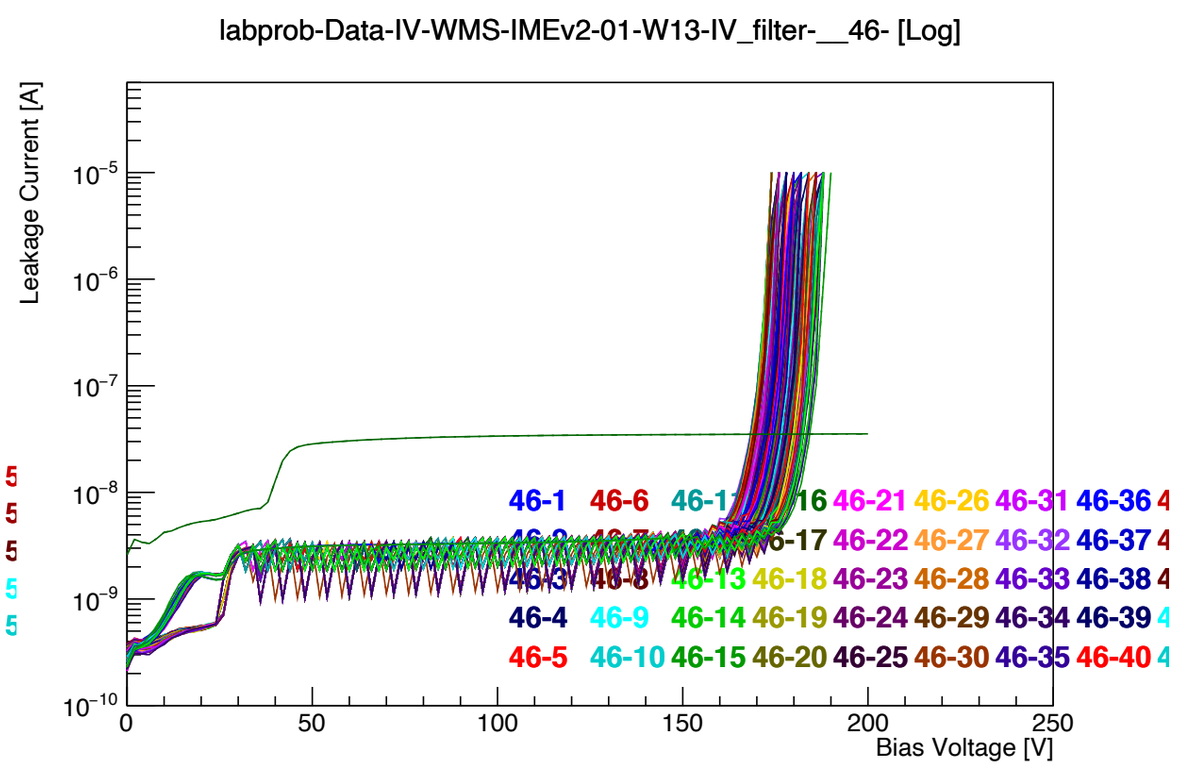


Eg. Of good arrays on W13







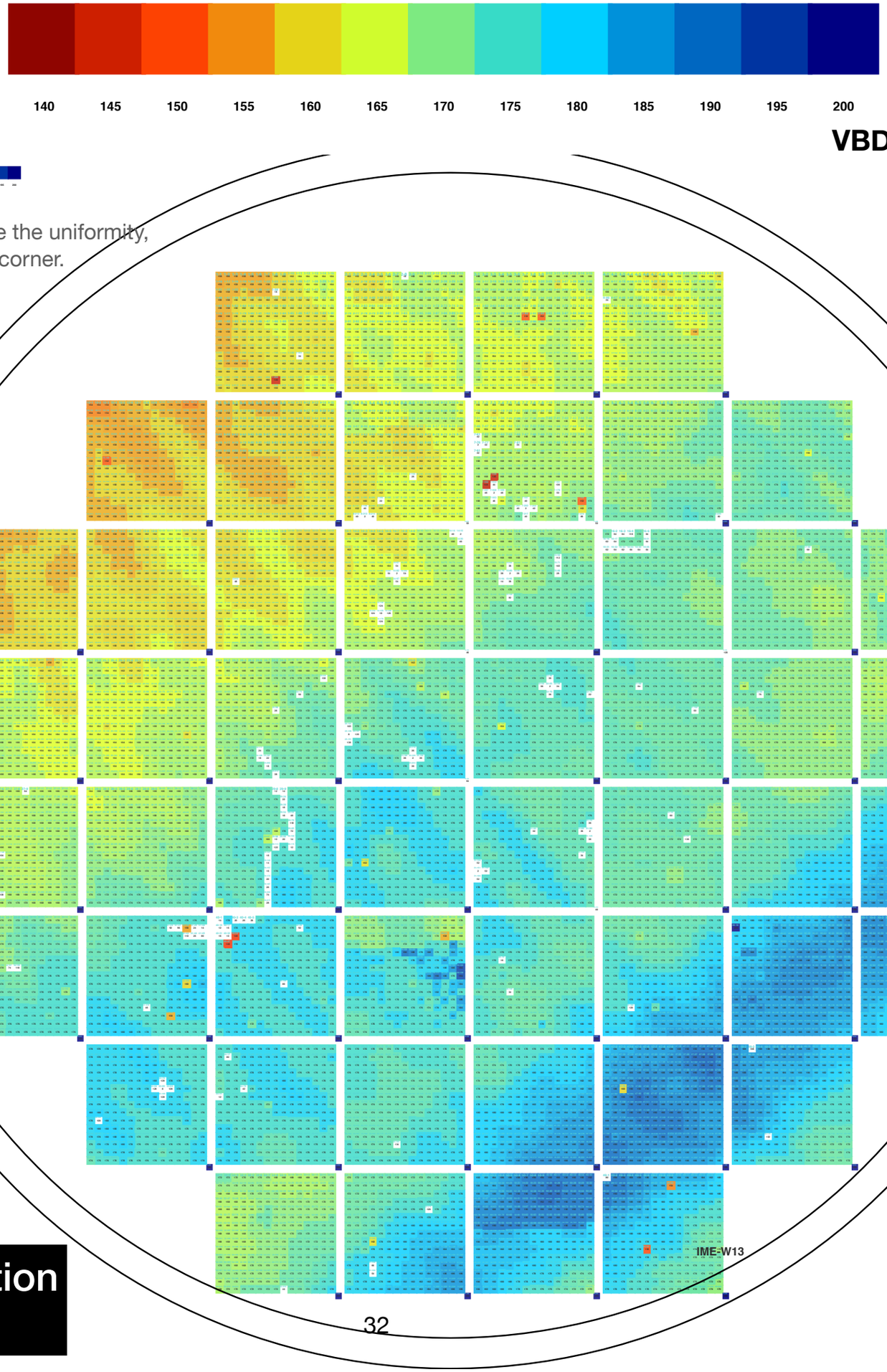


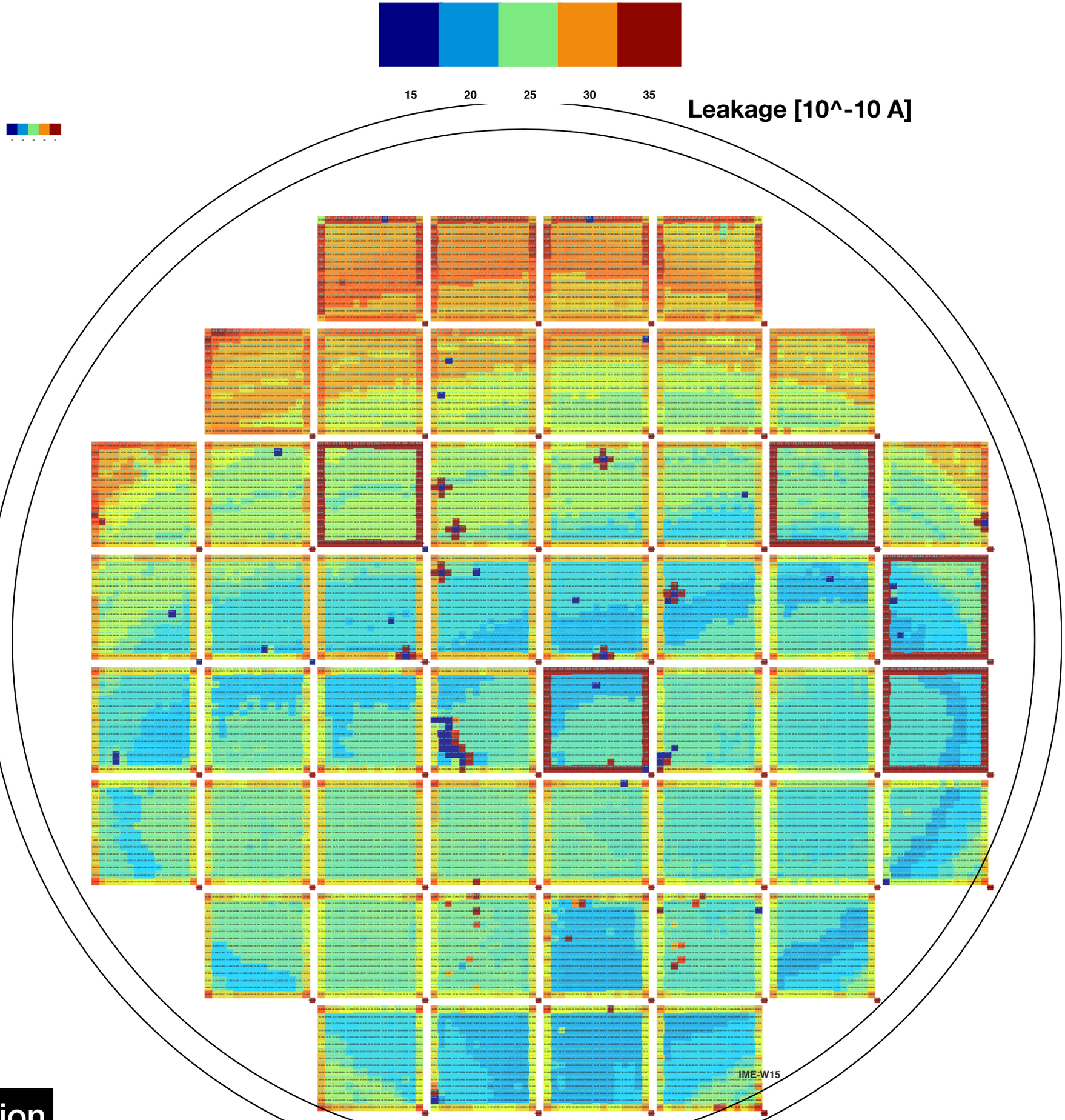
Breakdown voltage distribution (Zoomed)

If we zoom in the breakdown voltage color scale to see the uniformity, a clear **implantation valley** shown in the bottom right corner.

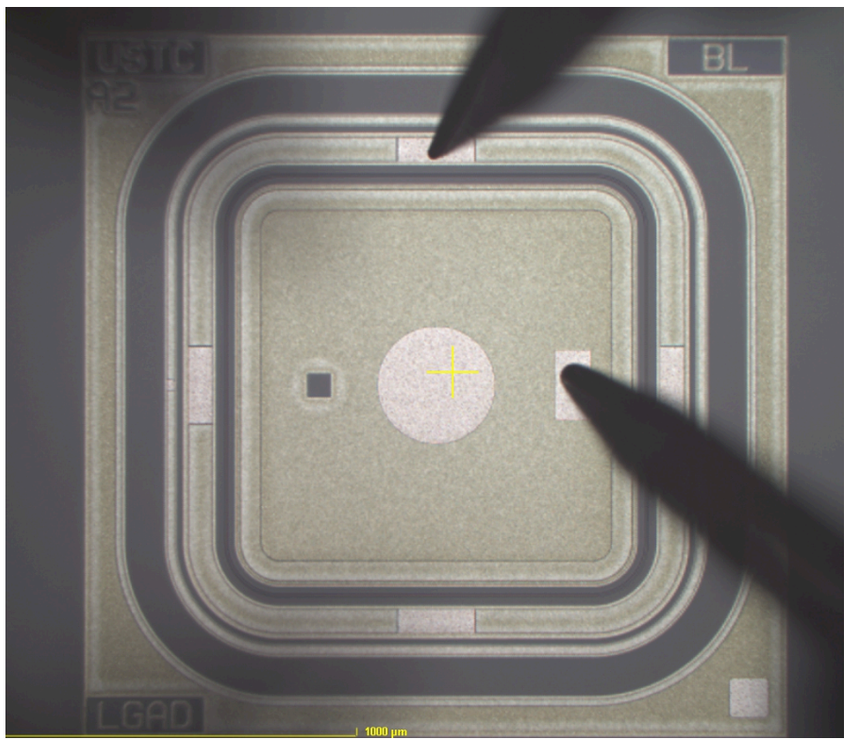
The VBD variation on the whole wafer is significant, although in single device it's generally tolerant

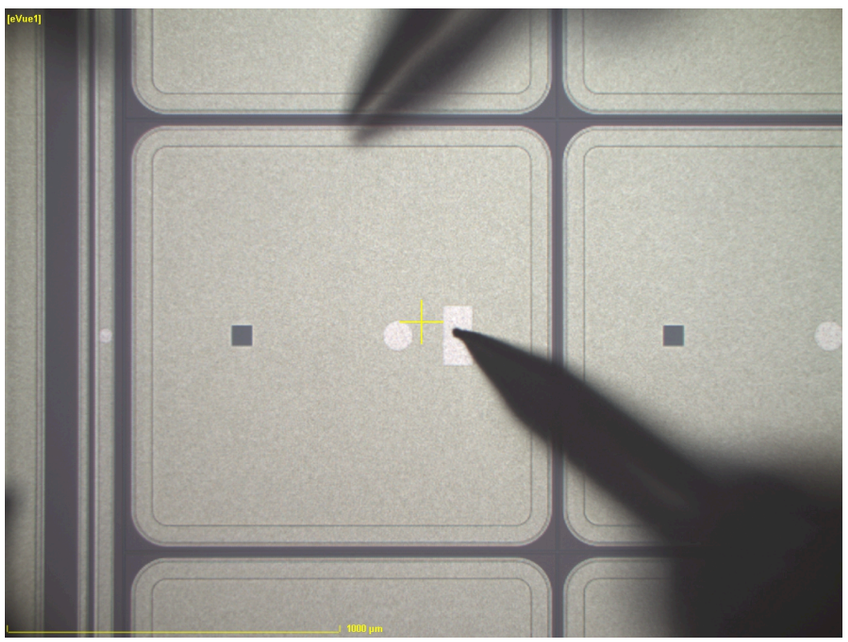
The same pattern shown up in all USTC IME version 2 wafers and seems also in IHEP wafers




15
20
25
30
35
Leakage [10^-10 A]
W15
35-50 V averaged
Leakage distribution
IME-W15

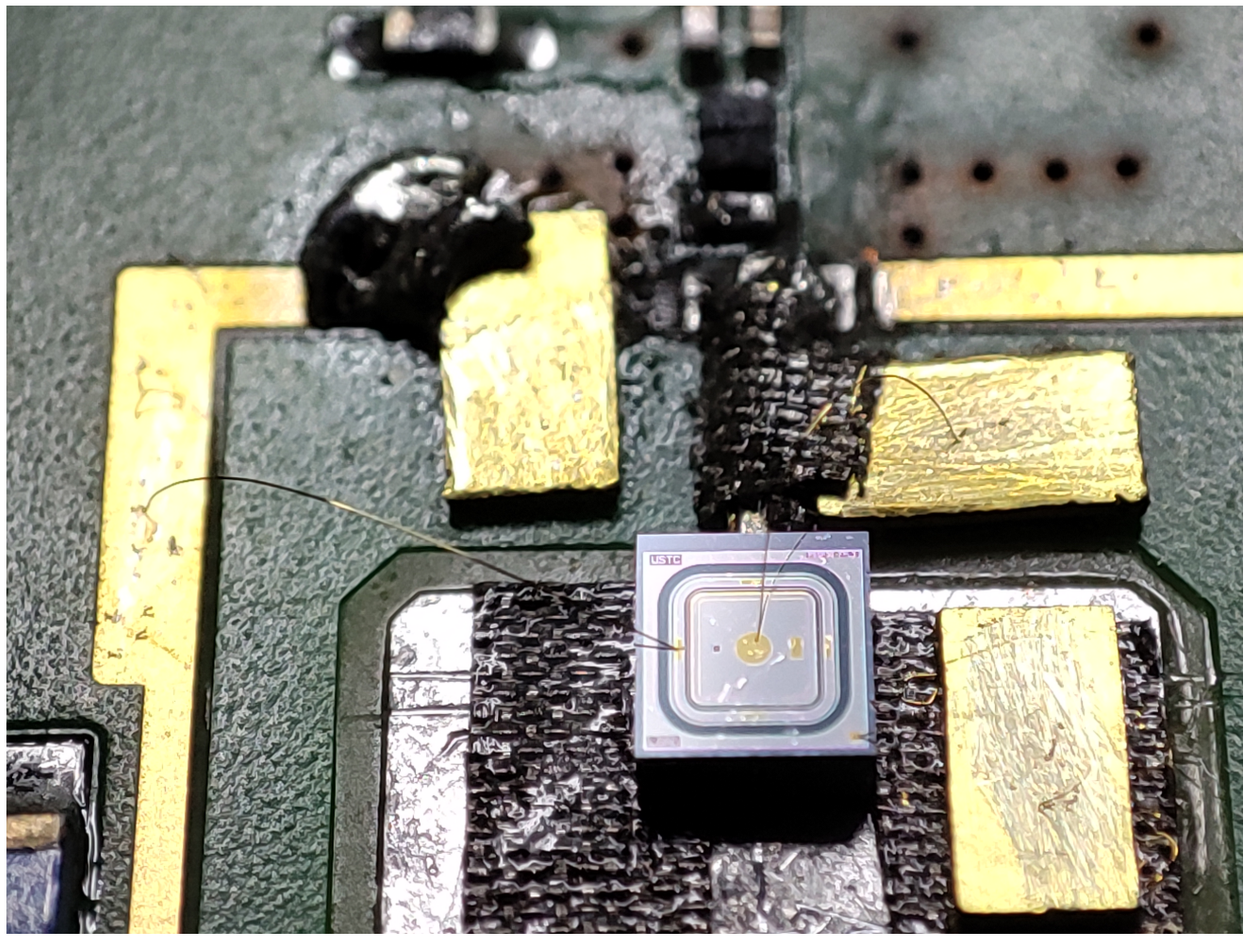
Test configuration



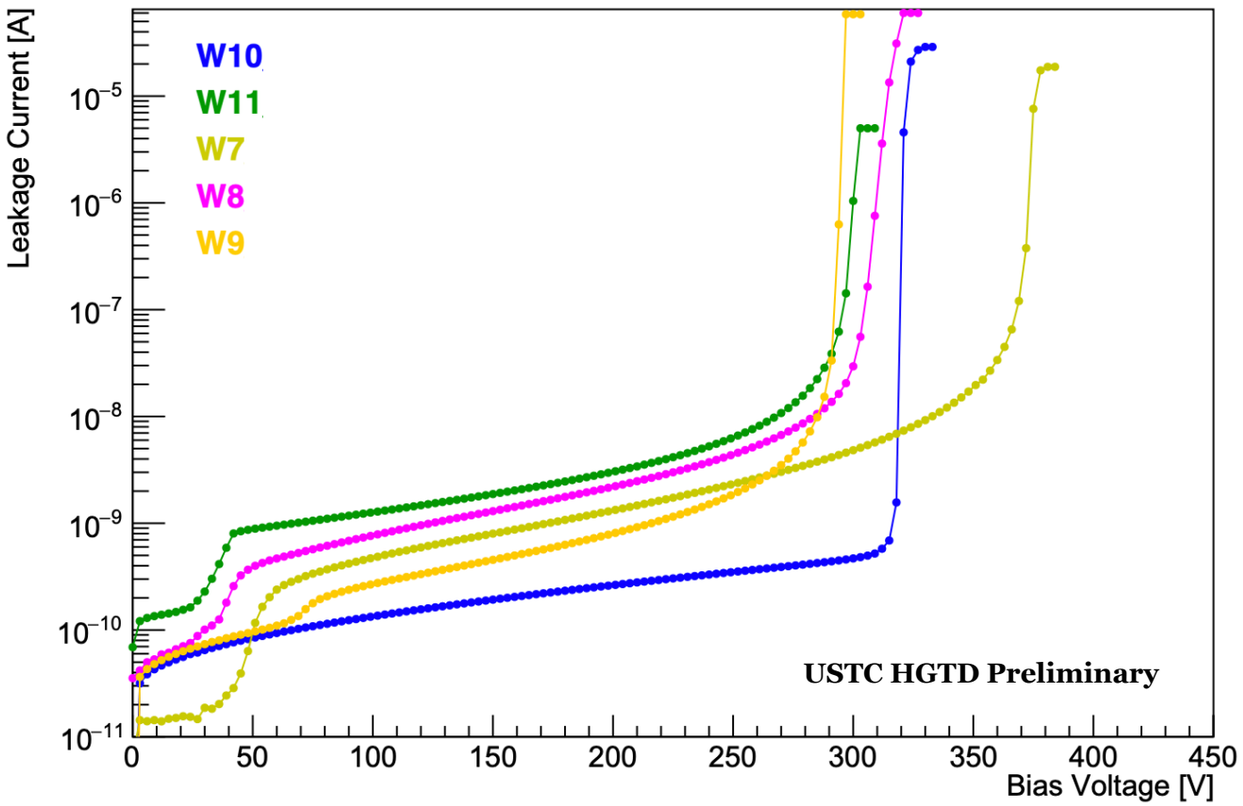


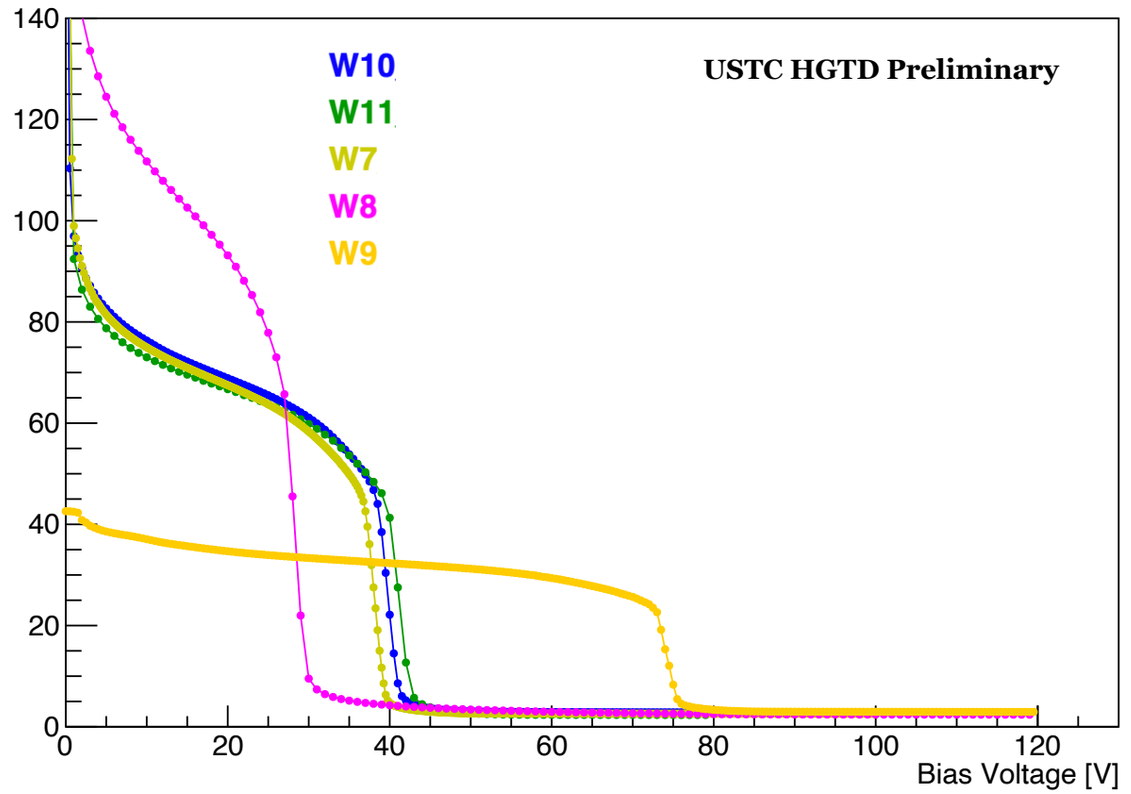
- For single pad LGADs the I-Vs are measured with guarding grounded
- For 2x2, 5x5, 15x15 arrays, the I-Vs are measured with other-pads and GR floating.
- 15x15 arrays' GR current are measured specially.
- Step: 2V
- The current are measured with 10uA compliance.

Sensor on board



USTC-IME 1st Batch LGADs Overview





Production Batch	Wafer No.	Target VBD [V]	GL.Energy	GL.Dose	Implantation	VBD [V]	VGL [V]	VFD [V]	Status
USTC-1	W1	165	Medium	Medium	B	154	45	65	Pre-production
	W2	165	Medium	Medium	B	150	46	54	
	W3	150	Low	High	B	110	34	>70	
	W4	180	High	Low	B	148	75	100	
	W5	265	Medium	Low	B	264	45	80	
	W6	165	Medium	Medium	B+C	84	48	>65	
USTC-1.1	W7	270	Medium	Low	B	370	38	55	Stable version
	W8	195	Low	High	B	295	29	40	
	W9	200	High	Low	B	295	70	85	
	W10	200	Medium	Medium	B	320	40	50	
	W11	200	Medium	Medium	B+C	300	41	52	