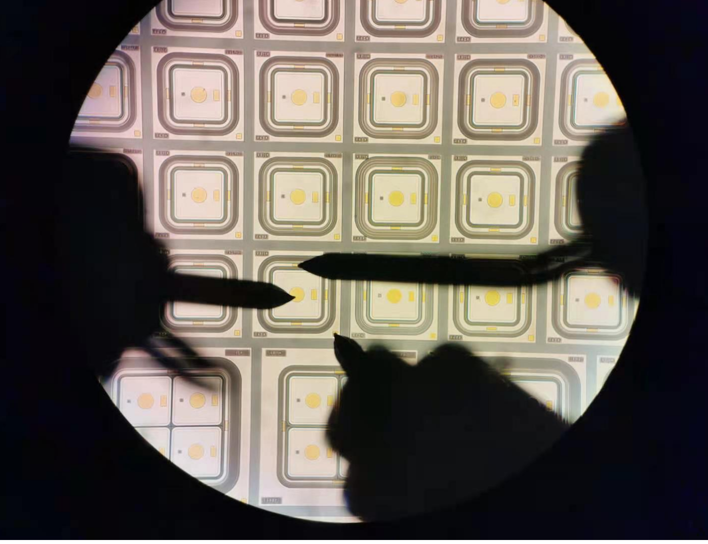
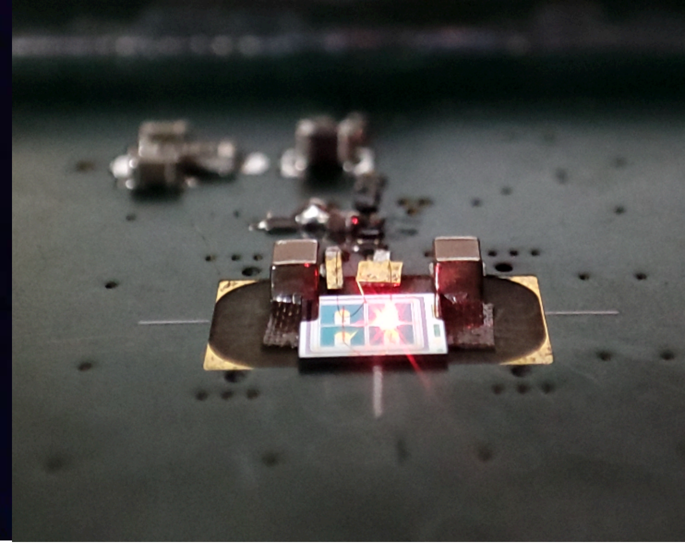
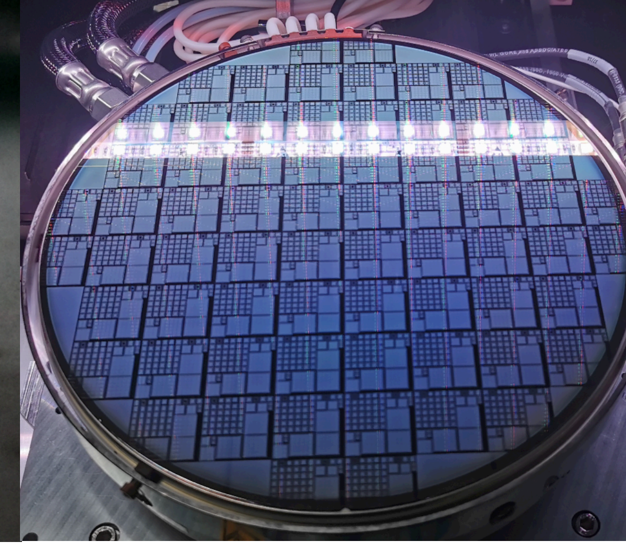
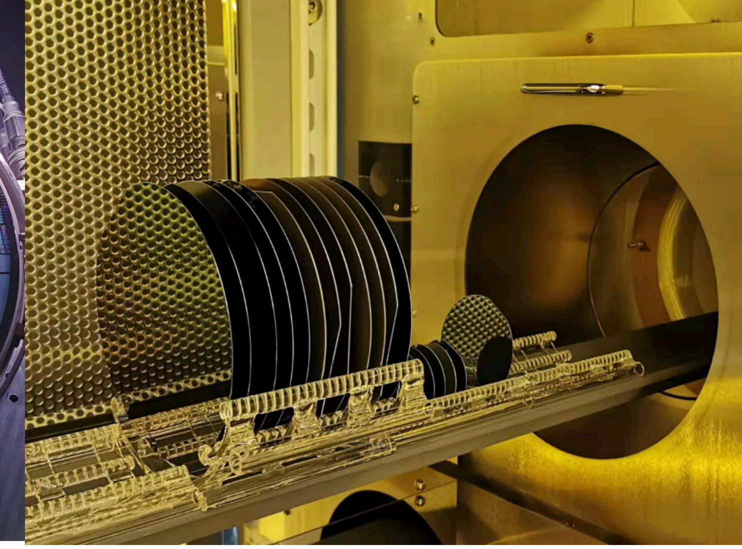





Recent results of the carbonated USTC-IME LGADs and fabrication of the AC-LGADs at USTC NRFC

*Jiajin Ge, Chihao Li, Yanwen Liu, Kuo Ma, Mario Sousa, Yongjie Sun, Aonan Wang, Tao Wang, Tian'ao Wang, Yusheng Wu, Lailin Xu, **Xiao Yang**, Yifan Yang, Yangfan Zhang, Xiangxuan Zheng*

University of Science and Technology of China

40th RD50 workshop, CERN

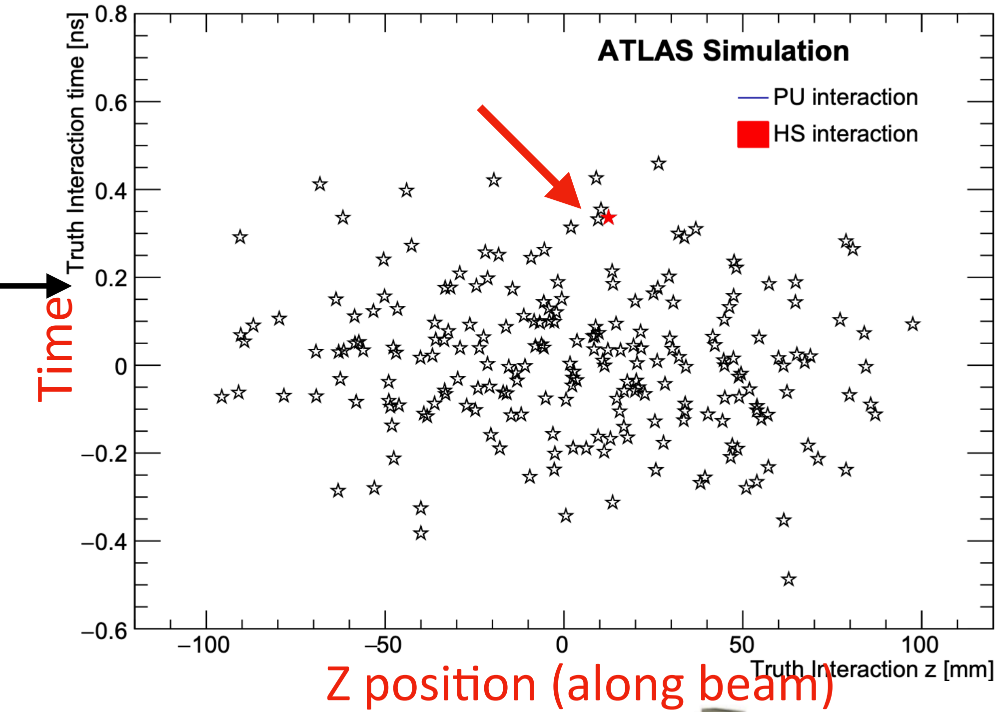
June 23rd, 2022

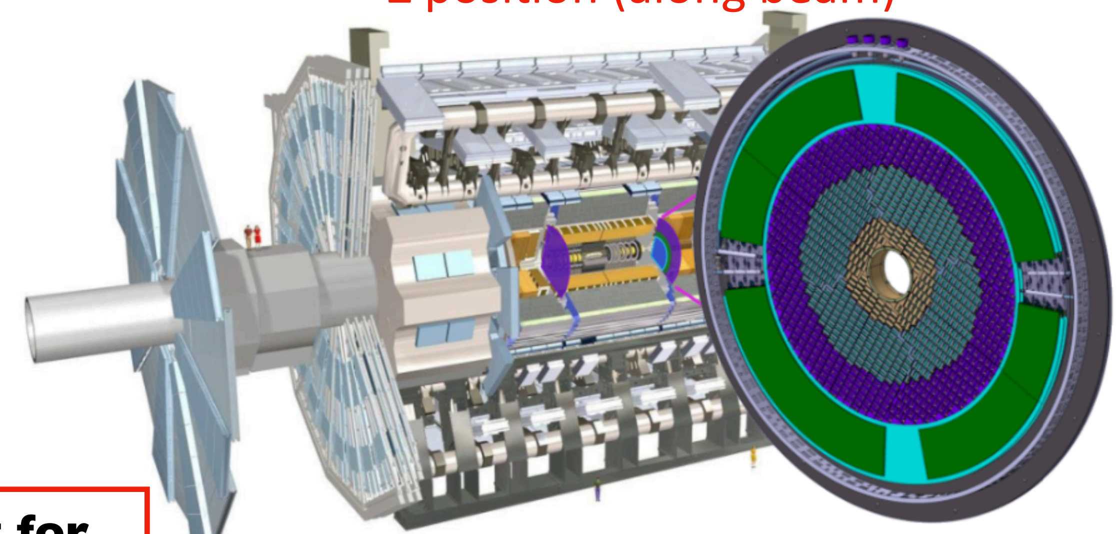
The High-Granularity Timing Detector(HGTD) for the ATLAS Phase-II Upgrade

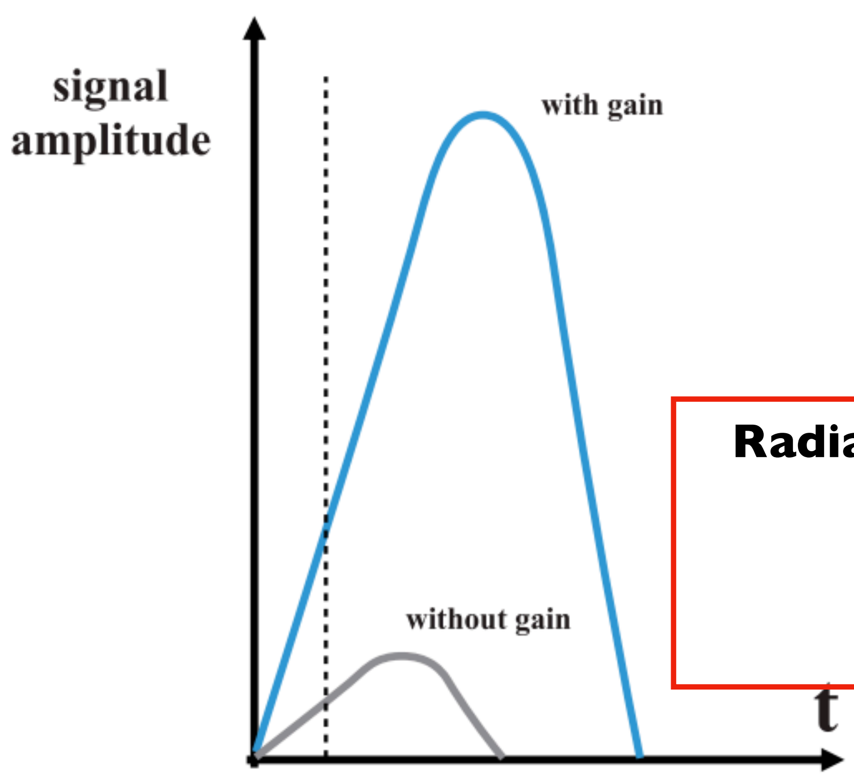
- In the HL-LHC, Pile-up density would get so high that track to vertex association would be very hard, especially in the forward region

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

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







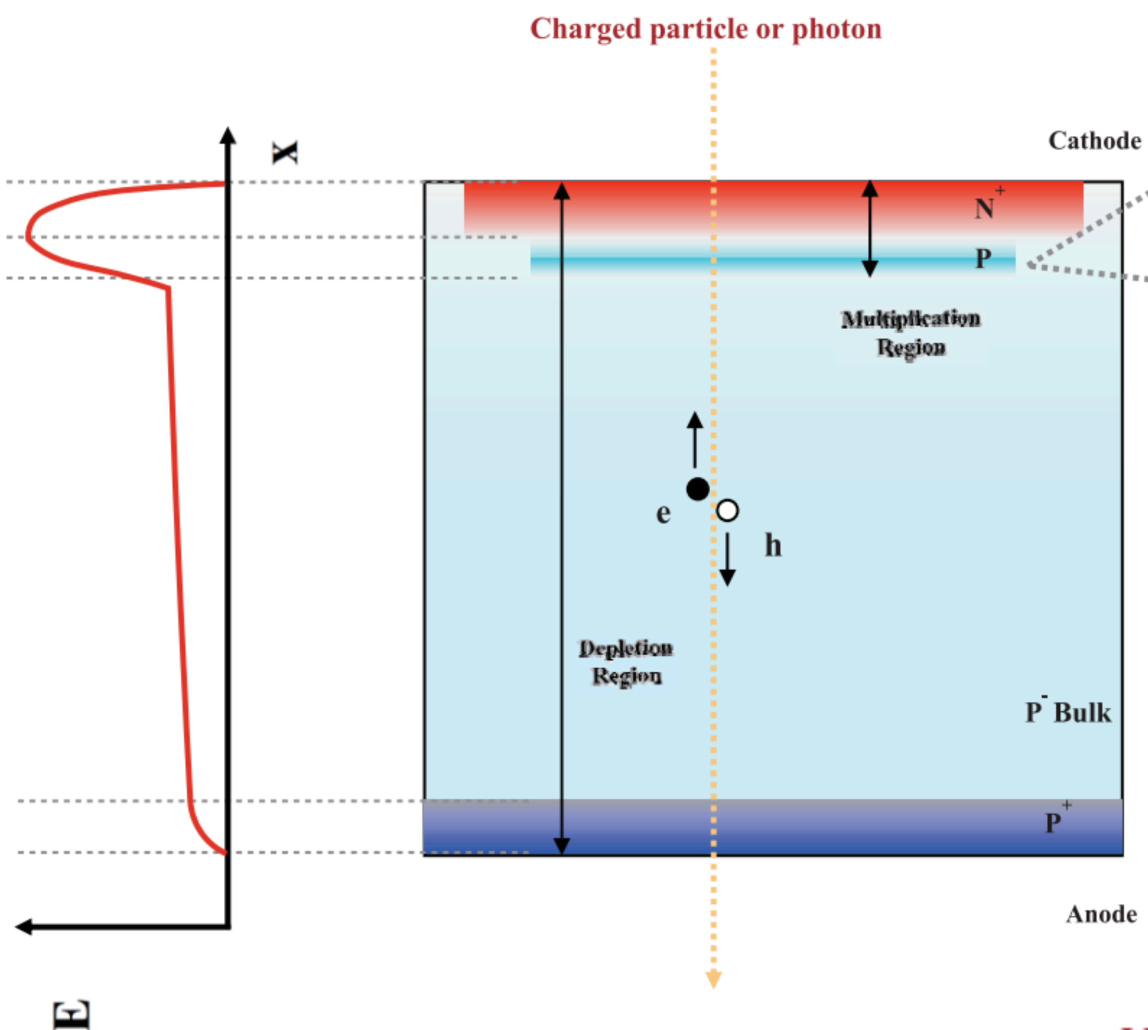
LGAD's internal gain provide signal with faster rising edge, leading to a better timing performance

Radiation hardness requirement for HGTD Sensor:
70 ps and 4fC
@ 2.5E15 neq/cm-2

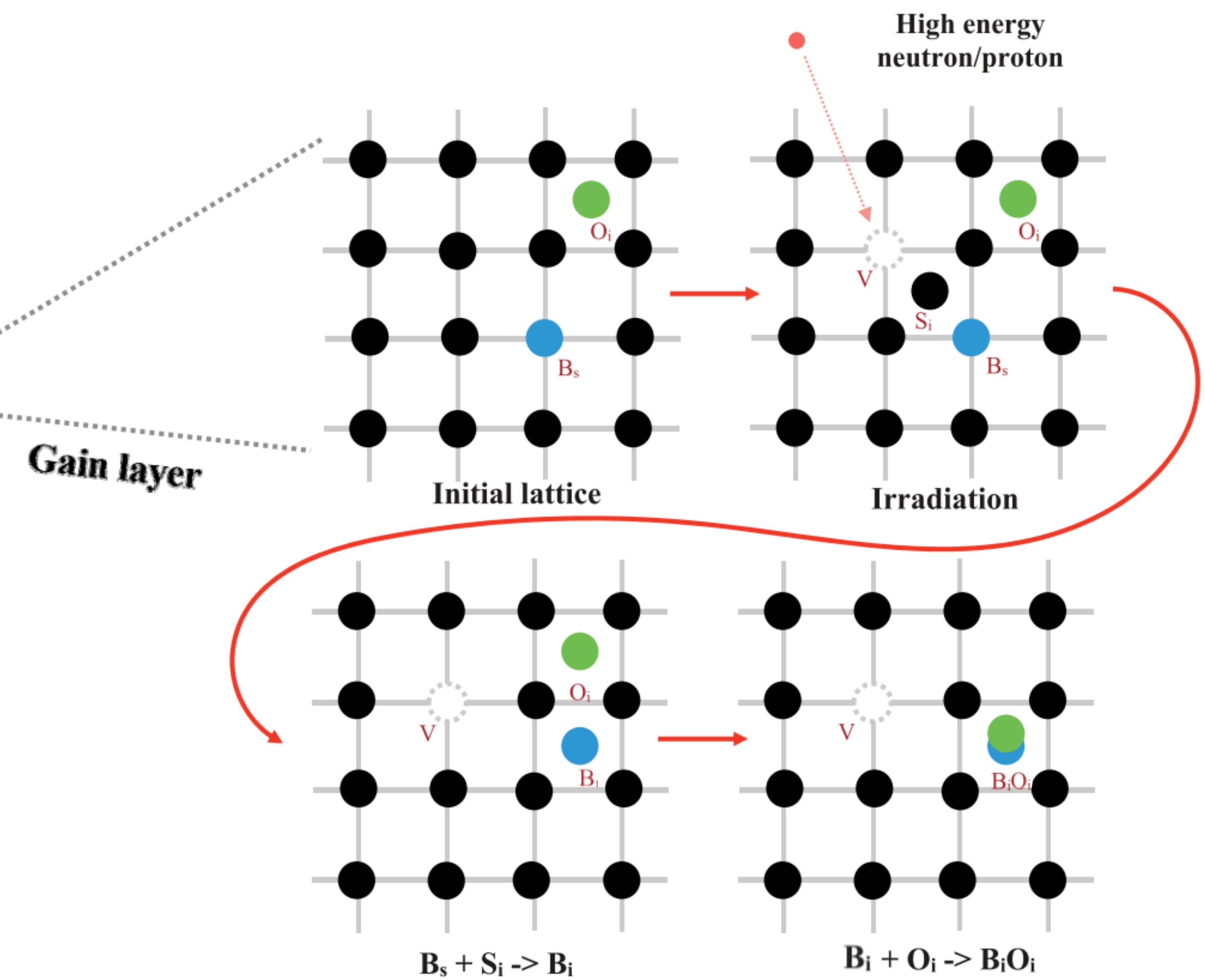
- σ_t ~30 ps per track

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

LGAD's radiation damage



The LGAD Structure



V : Vacancy
S_i: interstitial silicon
B_i: interstitial boron
O_i: interstitial oxygen
B_s: substitutional boron

Acceptor (B_s) removal in the gain layer after irradiation

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

Described by the exponential model

- The BiOi complexes are generated after neutron/proton irradiation, leading to the **reduction of the effective doping** concentration and detector's gain
- The $\mathbf{C_i + O_i \rightarrow C_iO_i}$ would compete with $\mathbf{B_i + O_i \rightarrow B_iO_i}$ => Borons are protected!

USTC LGAD Fabrication

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

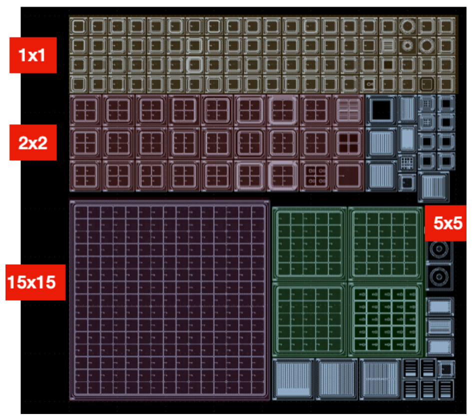
- USTC-**IME**:
  Institute of Microelectronics of the Chinese Academy of Sciences (IME,CAS)
  High standard **8-inch** line, **good quality control and yield.** Mainly for large scale production.
  - Wafers: 1st batch: W7-W11,
    2nd batch: W12-W16(v2.0), W17-W21(v2.1).

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

- USTC-**NRFC**:
  USTC **N**anoscale **R**esearch and **F**abrication **C**enter [link]
  The USTC own **6-inch** experimental fabrication line.

- Goal: **Iteration the design on gain layer and geometry quickly,** the optimized process parameters will be shared with IME immediately for large scale production.
  - Wafers: 1st batch: W3, W4
    2nd batch: W1, W2, W5, W6

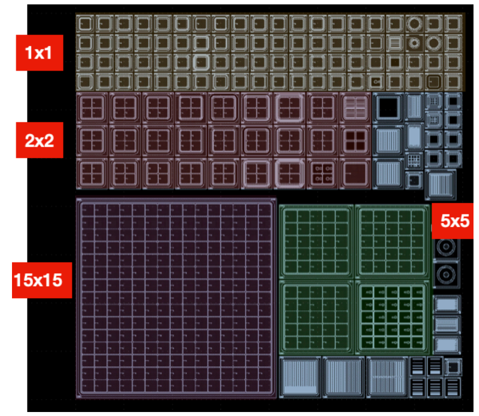
USTC's roadmap on LGAD R&D with IME



USTC-1.0

Deliver: 2020.7

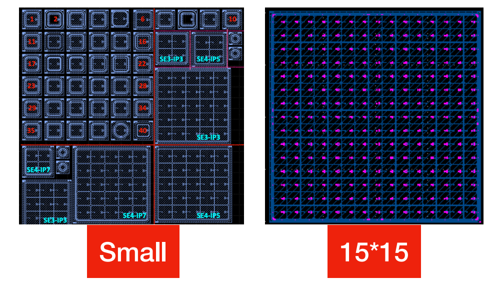
First attempt
8 inch, 6 wafers (1 carbonated)
Large lithographic used (40*40 mm^2),
Deep-Boron.15x15 included
Performance:
Almost all device have large current, VBD: <10V
Very few devices can work (<1% pad yield)
I-V/C-V agree with the simulation for good devices,
VBD ~ 250V, VGL: 40V



USTC-1.1

Deliver: 2020.10

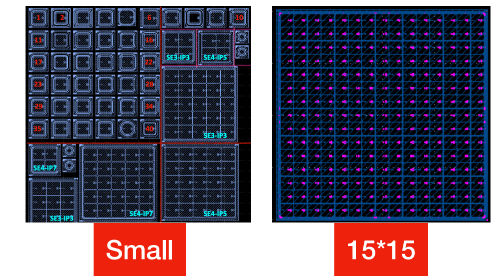
Improved attempt
8 inch, 5 wafers (1 carbonated)
Same layout as 1.0
Performance:
Larger number of sensors can work
(~30% pad yield) allowing
more tests (β-scope, n-rad., probe-card)
Almost all devices have large GR current,
I_GR position dependency observed
GR leakage not influence the function too much
In batch I-V/C-V agree with simulation,
VBD: ~300V



USTC-2.0

Deliver: 2021.4

8 inch, 5 wafers (1 carbonated)
New layout
Mainly for yield study and issues fix,
only shallow doping within Fab.
Performance:
Nearly all small sensors can work
(>99% pad yield)
~35% 15*15 array yield
GR leakage disappeared
VBD are lowered (~100V-170V)
Too low VBD for some wafers,
indicate B/C too much

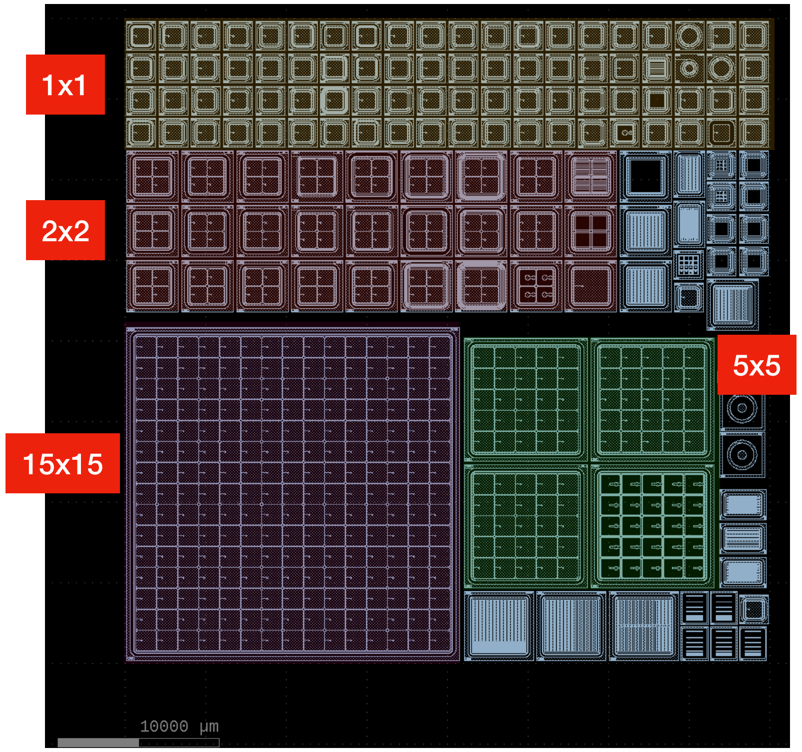


USTC-2.1

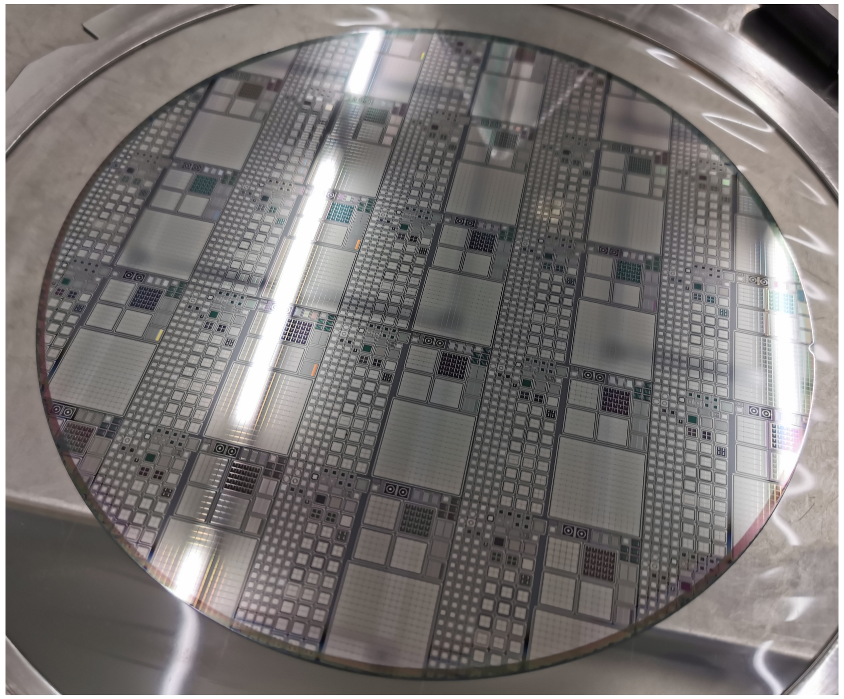
Deliver: 2021.10

8 inch, 5 wafers (4 carbonated)
Same layout as 2.0, fast iteration
Performance:
Nearly all small sensors can work
(>99% pad yield)
VBDs are in idea range (~150V-240V)
~35% 15*15 array yield
Better uniformity, GL variation source confirmed
Comparable performance with FBK,IHEP (1st team)
Performance verified in Beta/Laser/TB and individual institute (JSI)
Final design and proved to meet all HGTD Specification,
Positive MS feedback from the ATLAS Group

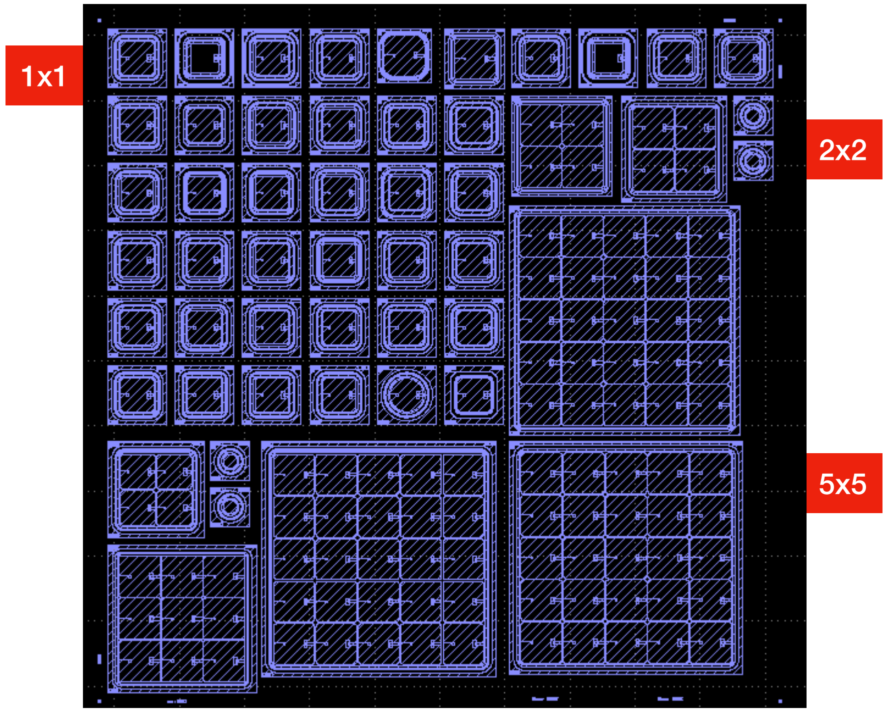
USTC-IME LGAD Wafers



Stepper size: 40 mm x 40 mm,



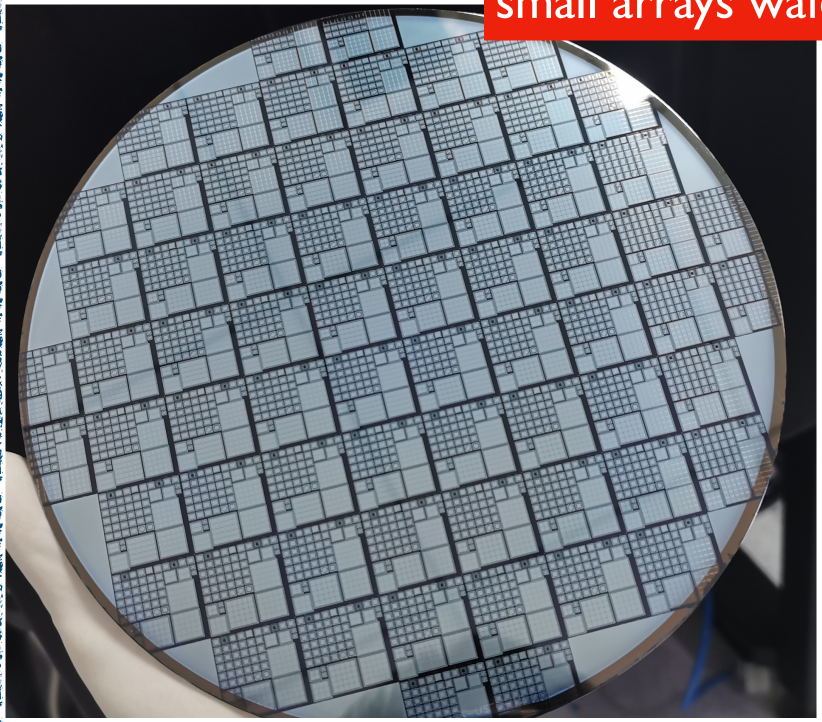
USTC-1.1



Stepper size: 21 mm x 21 mm,

- Joint force:
  USTC(Design) +
  <u>IME,CAS</u> (Fab.)
- Deep&Shallow gain layer
- Carbon diffusion
  8 inch wafer,
  with 50 µm Epi. layer.

small arrays wafer

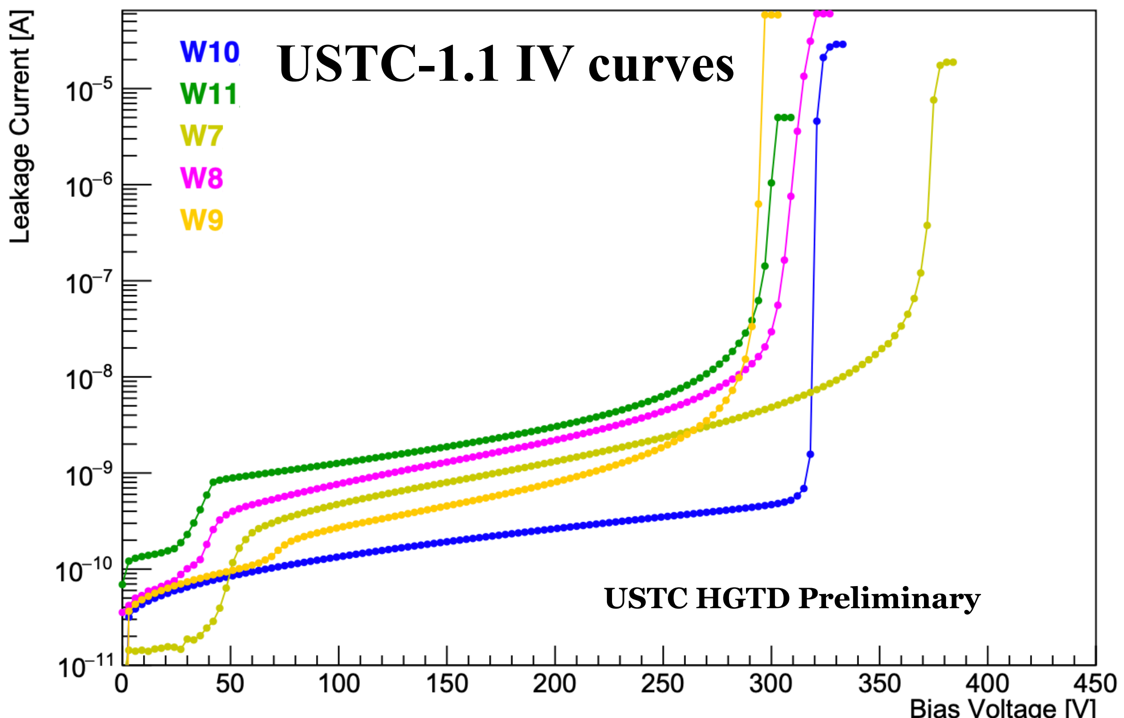


15x15 arrays wafer

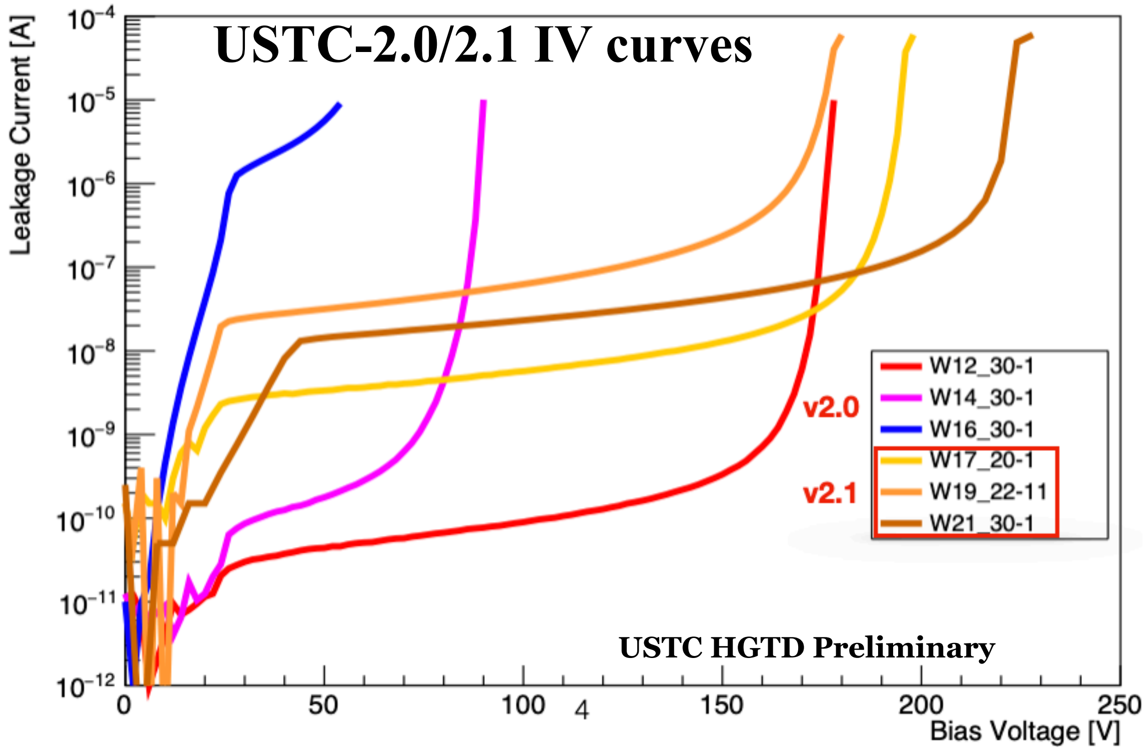
- **First full 15x15 wafer produced!**

USTC-2.0/2.1

USTC-IME LGADs Overview

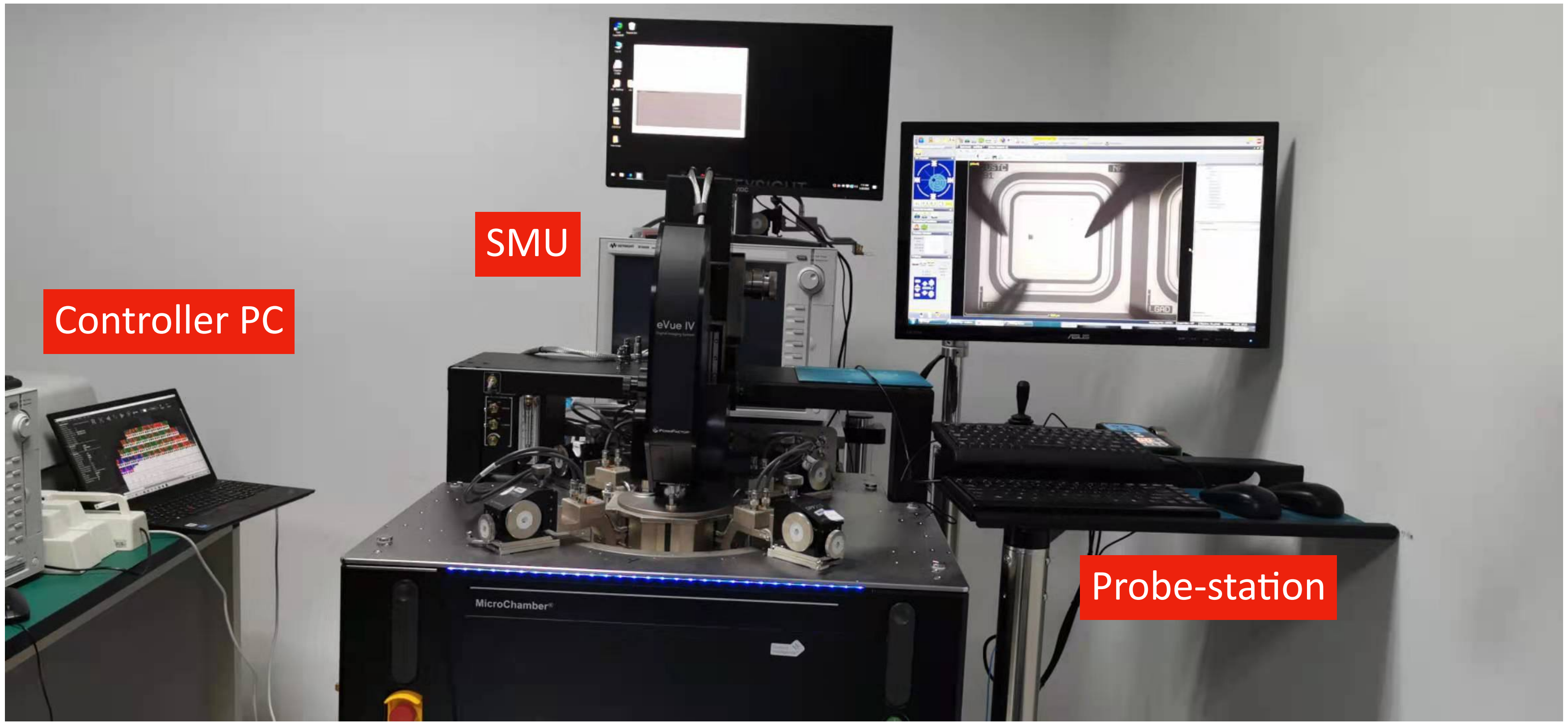


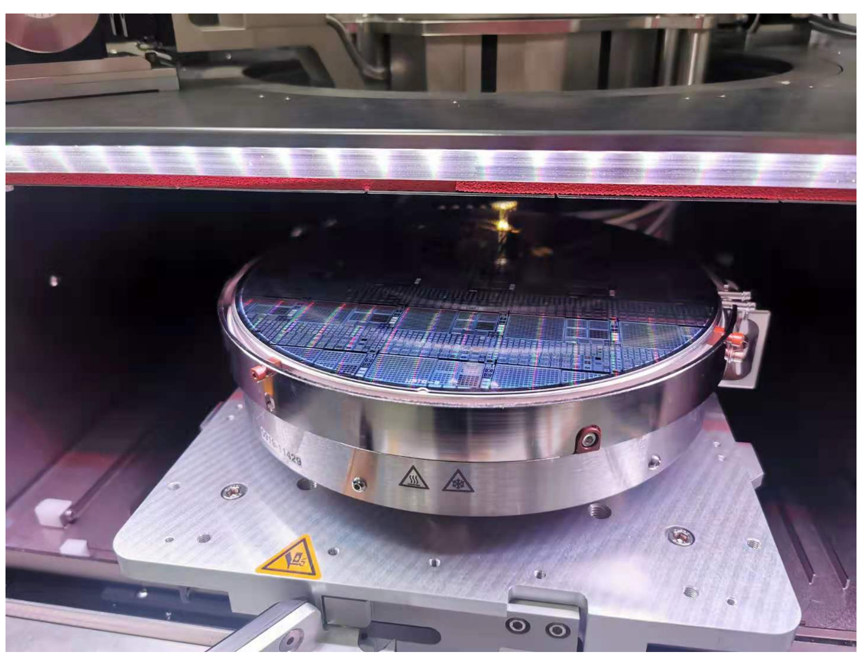
TCAD Designed VBD is 200V, possibly related to the issue introduced in Michael's talk

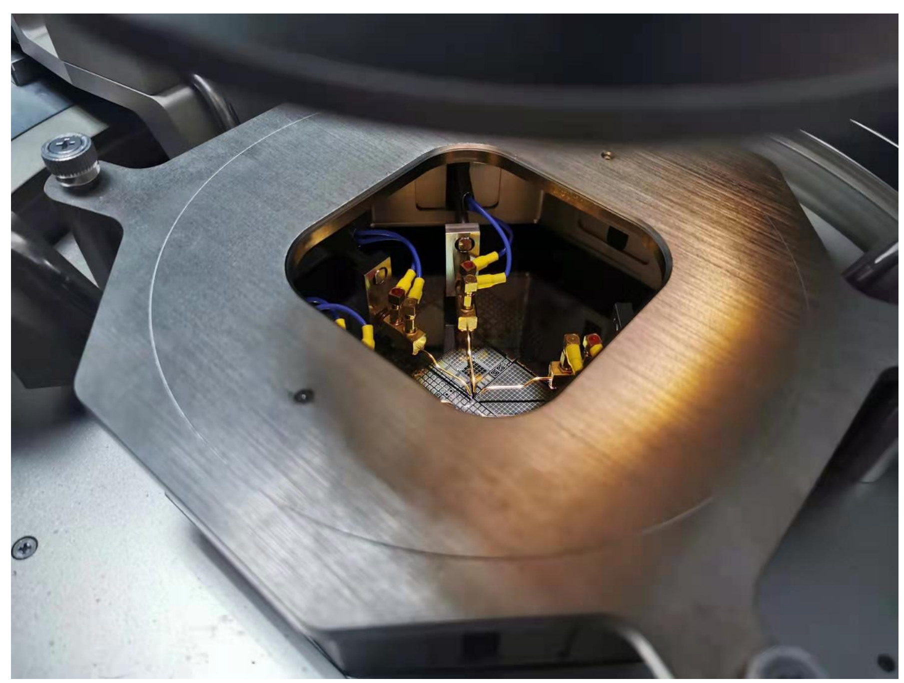


Production	Wafer No.	GL.Dose	GL.Energy	Implantation	Layout arrays	VBD_mediu	c-factor	Tested available (irrad.)
USTC-1.1	W7	Low	High	B	Mixed	~370	5,79	beta-USTC
	W8	Medium	Low	B	Mixed	~295	4,12	beta-USTC
	W9	Medium	Very High	B	Mixed	~295	7,25	beta-USTC
	W10	Medium	High	B	Mixed	~320	5,72	beta-USTC
	W11	Medium	High	B+C	Mixed	~300	1,85	beta-USTC/JSI, Beam-DESY
USTC-2.0	W12	Low	Low	B	Small	~174	~3.66	beta-USTC
	W13	Low	Low	B	15x15	~172		
	W14	High	Low	B	Small	~84	~3.38	beta-USTC
	W15	High	Low	B	15x15	~100		
	W16	High	Low	B+10C	Small	~50	~1.36 -1.49	beta-USTC/JSI, Beam-DESY
USTC-2.1	W17	Medium	Low	B+1C	Small	~190	~1.23	beta-USTC/JSI, Beam-DESY
	W18	Medium	Low	B	15x15	~190		
	W19	Medium	Low	B+2C	Small	~165	~1.29	beta-USTC/JSI, Beam-DESY
	W20	Medium	High	B+C	15x15	~220		
	W21	Medium	High	B+C	Small	~215	~2.07	beta-USTC/JSI, Beam-DESY

Wafer-level Measurement System at USTC





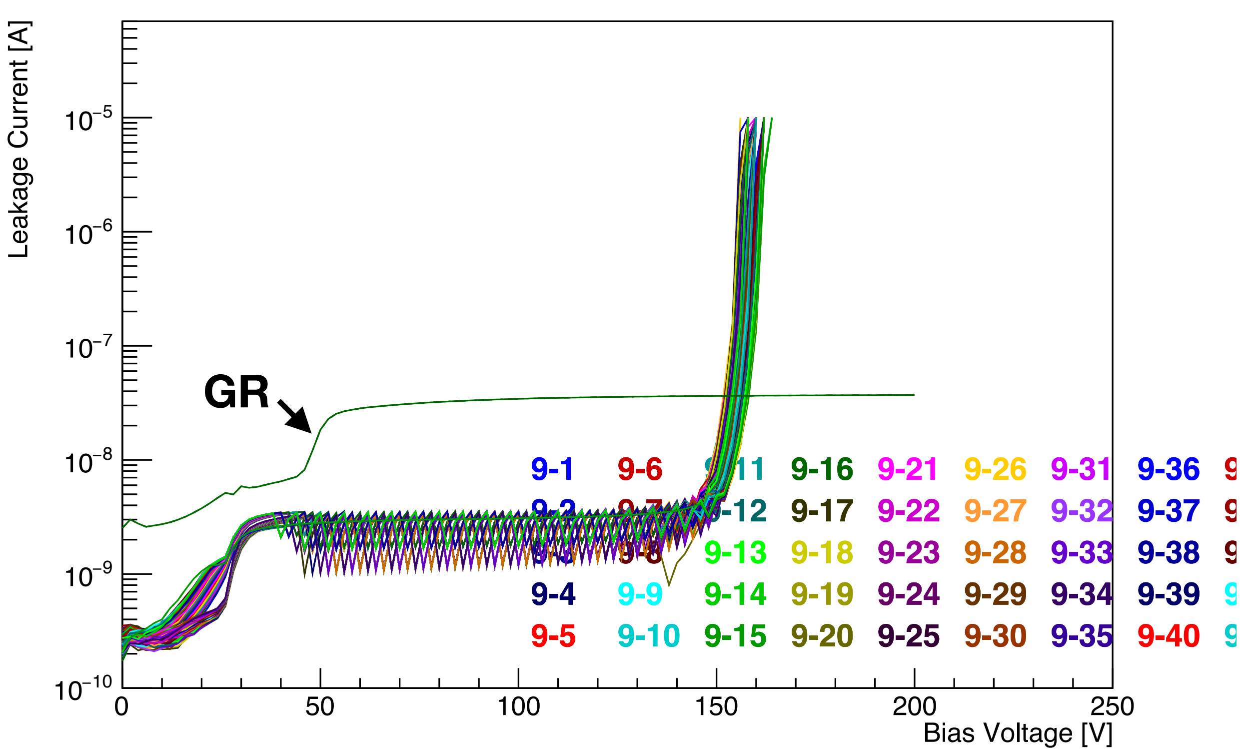


- Fully automatic probe station
- Dedicated DAQ software
- Speed: **5s/pad** with 2V step

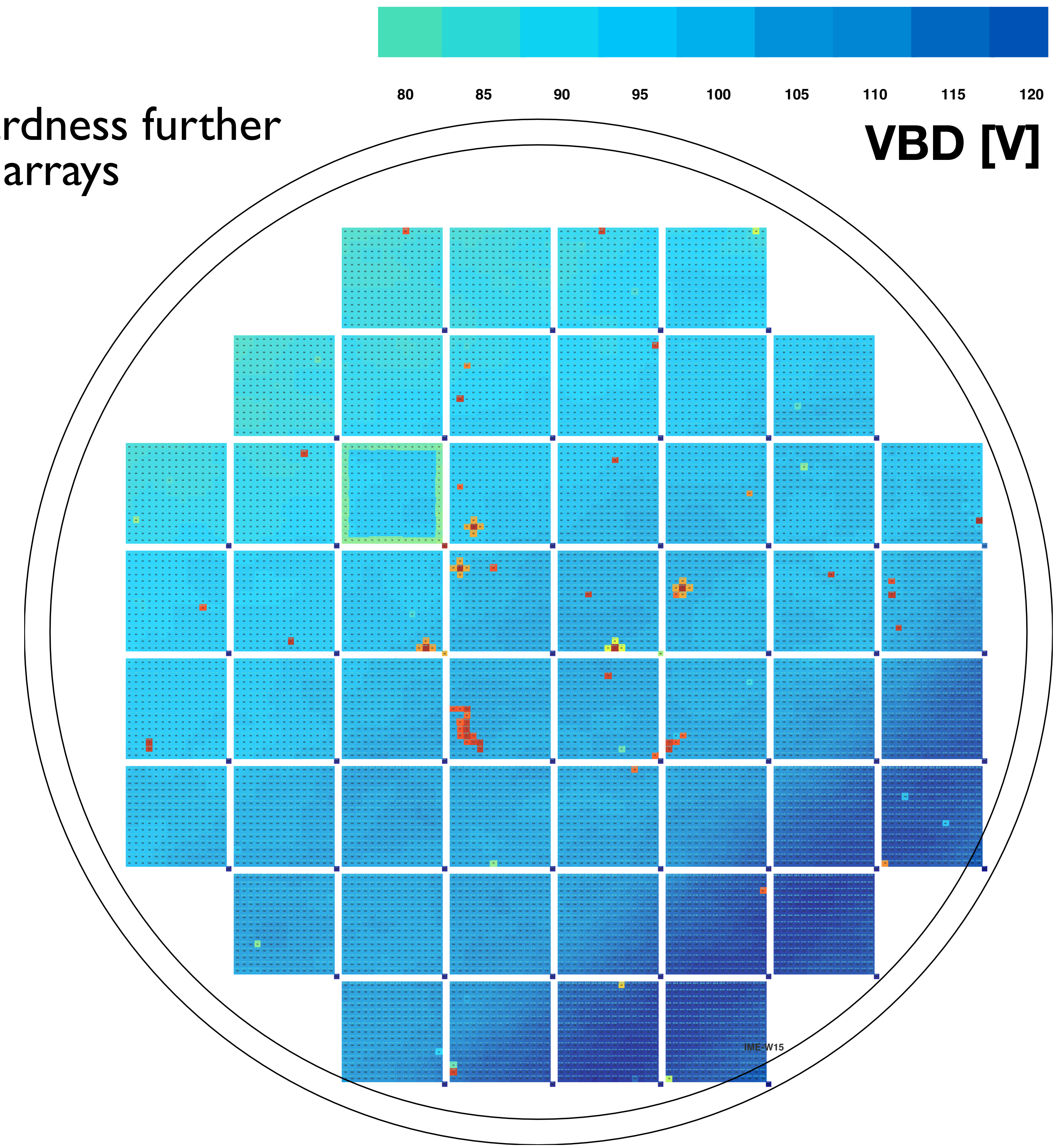
USTC-IME 2nd batch uniformity

- 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

USTC W13 15x15 array I-V curves

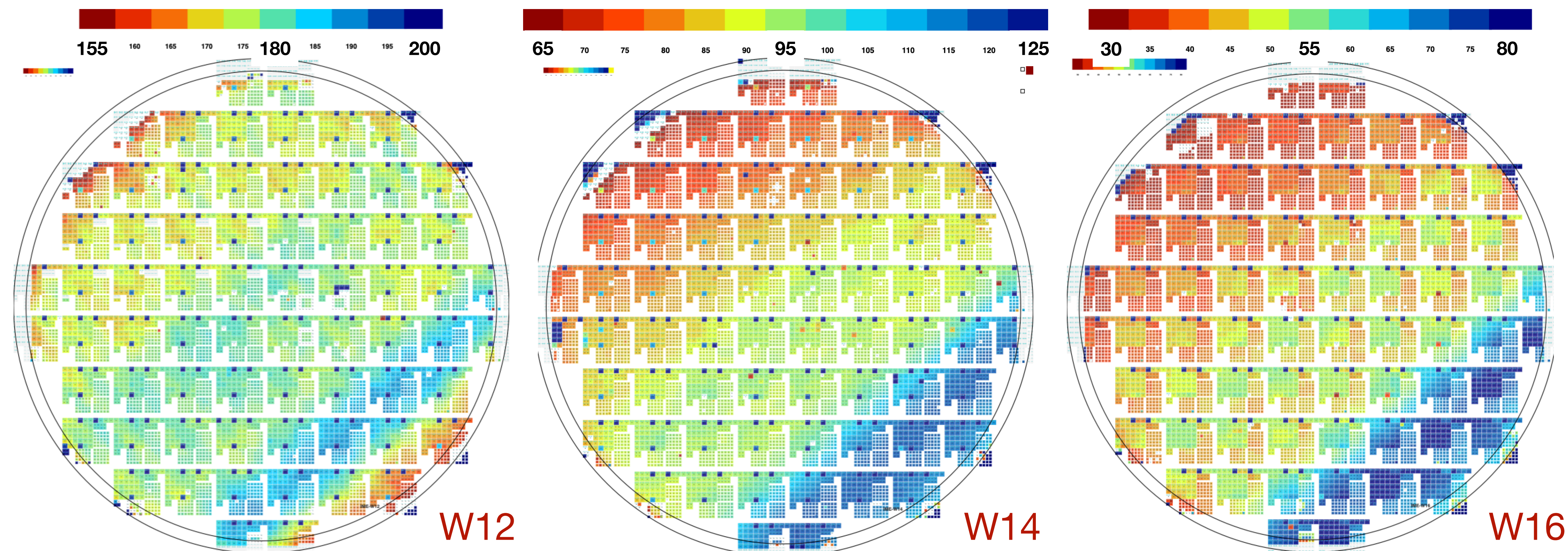


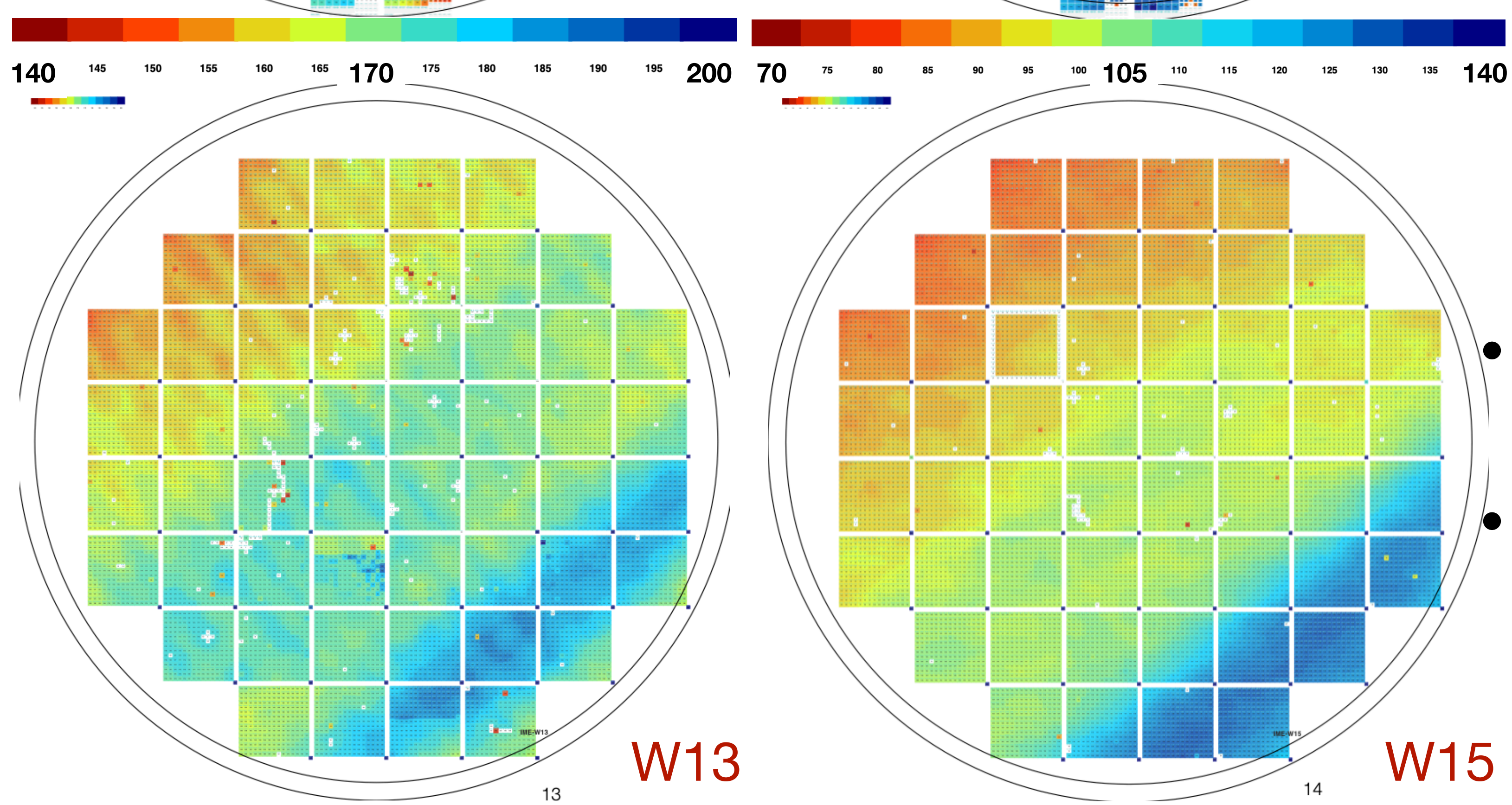
Breakdown voltage RMS% = 1.91%
(HGTD requirement: RMS% < 5%)



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

Uniformity comparison of the USTC-IMEv2.0 wafers

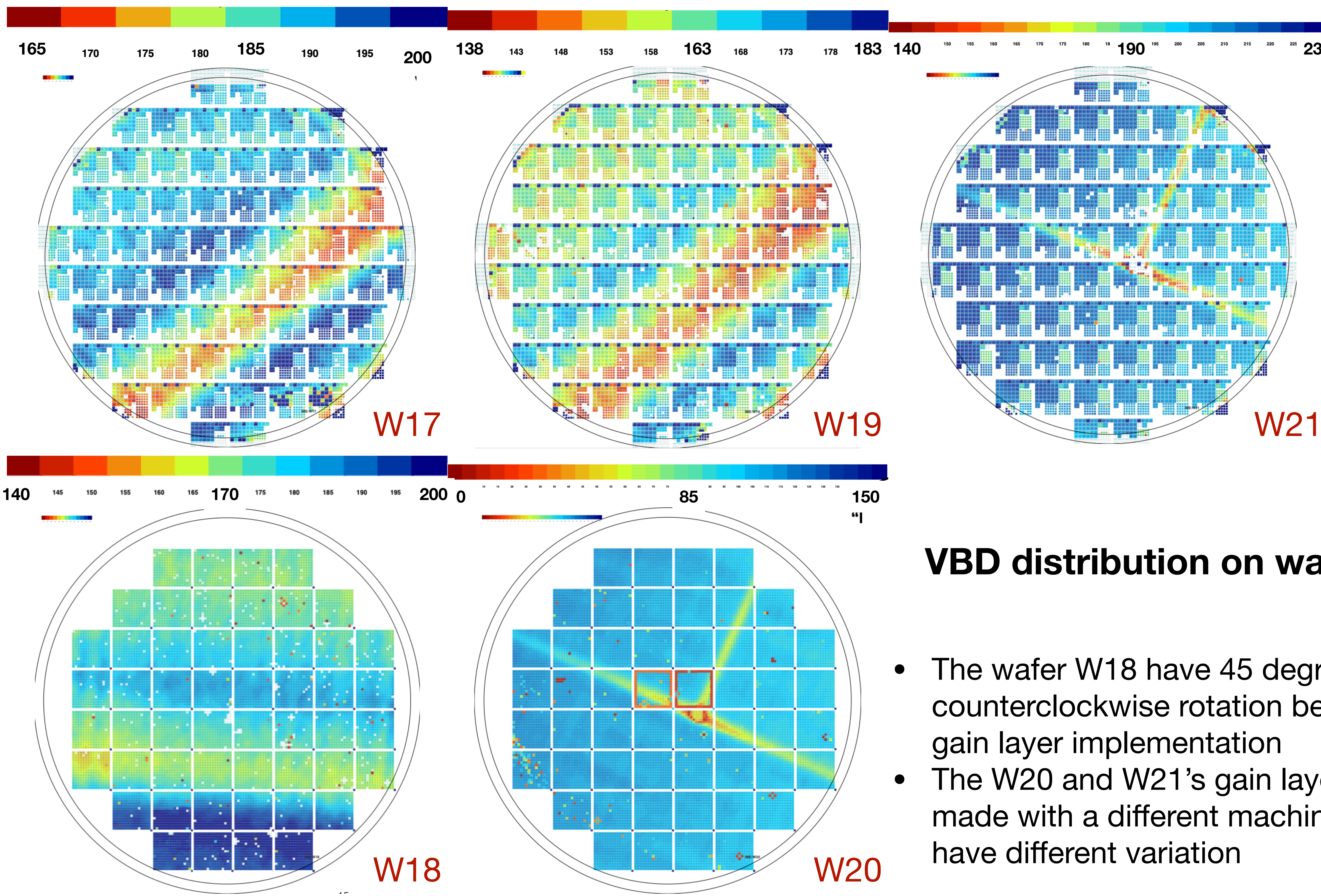




VBD distribution on wafer

- All wafer have similar patten of the VBD distribution, VBD trend to be higher at right bottom side
- => Gain layer concentration trend to be lower at right bottom side
  - **"Doping valley"**

Uniformity comparison of the USTC-IMEv2.1 wafers



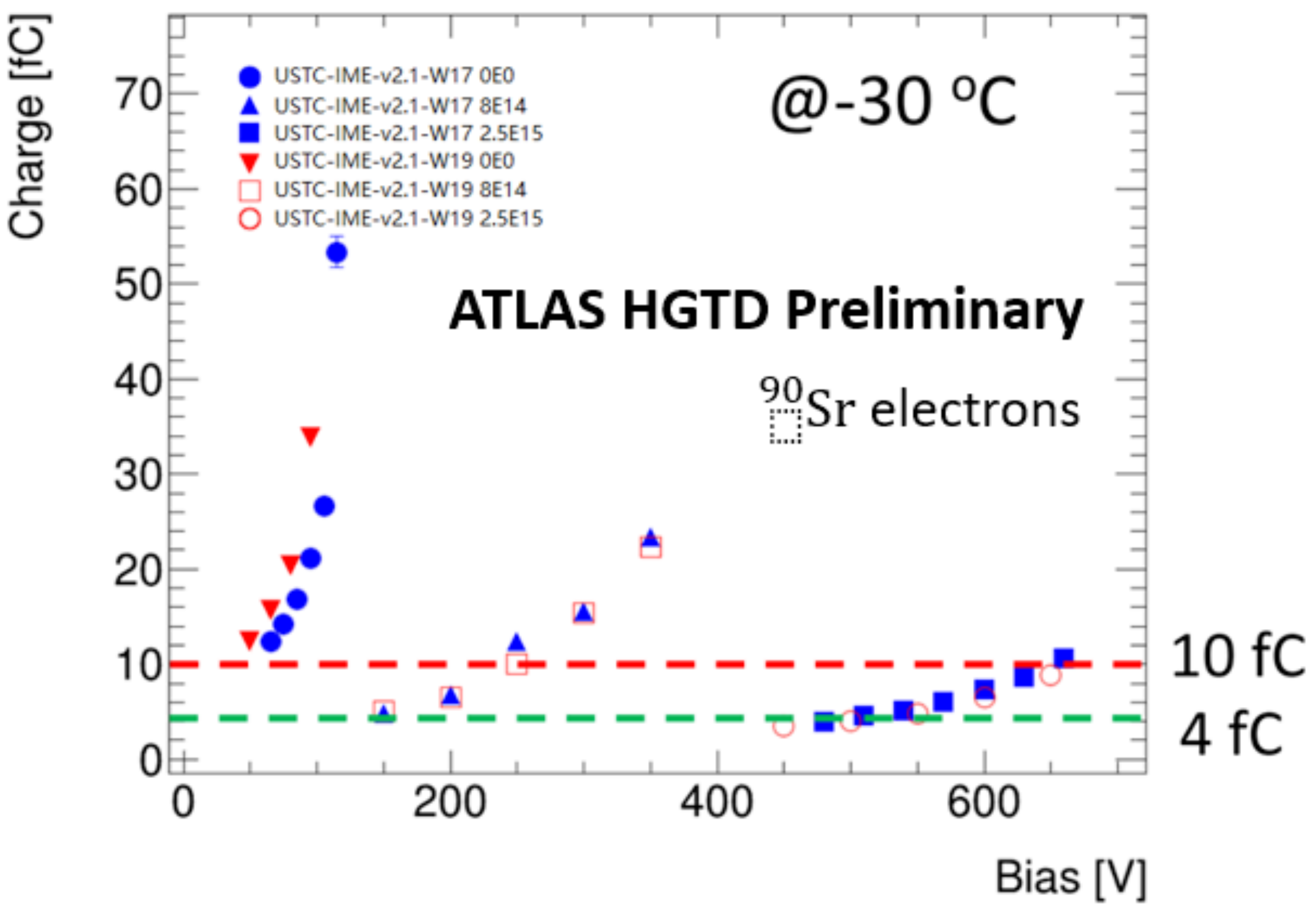
VBD distribution on wafer

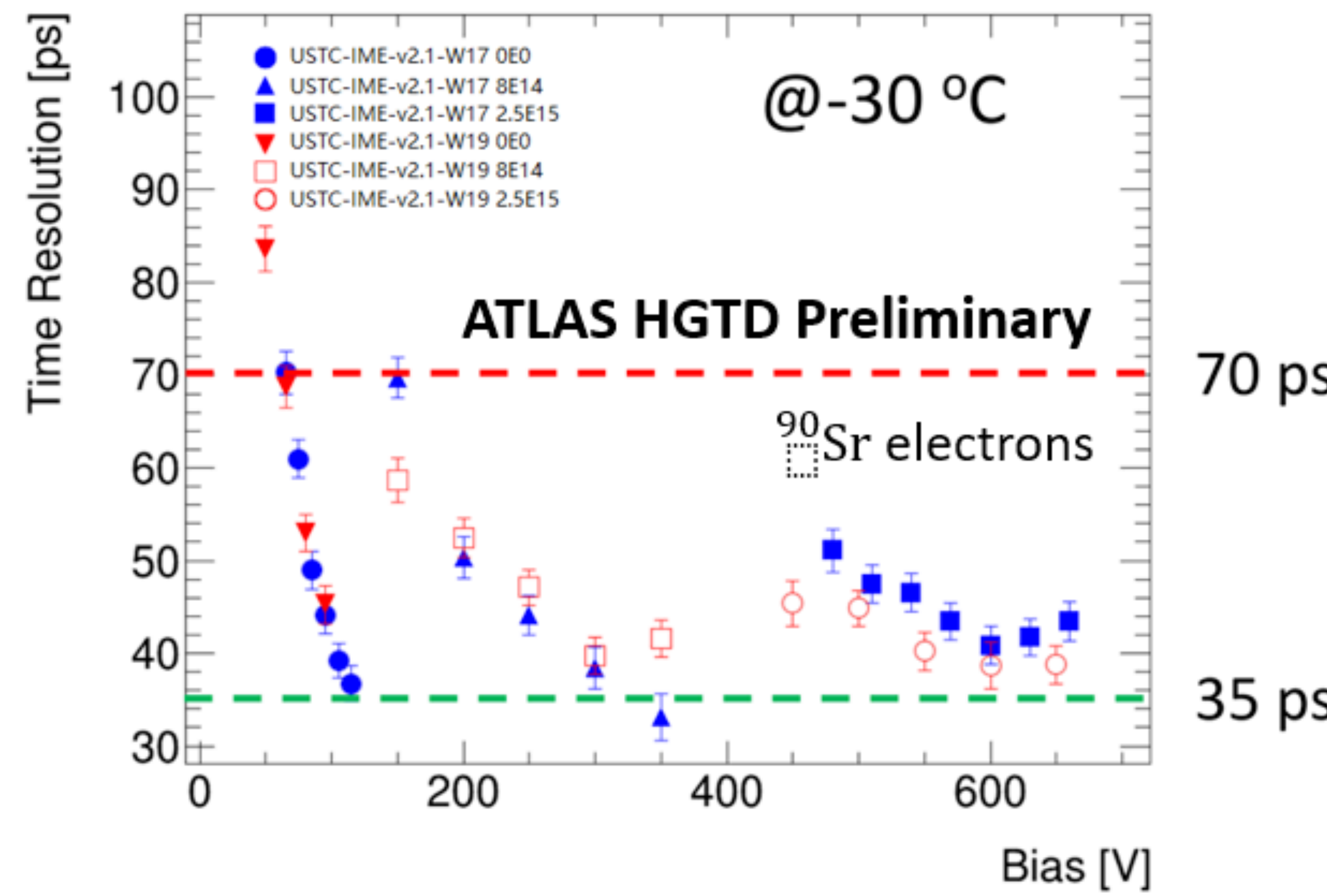
- The wafer W18 have 45 degree counterclockwise rotation before gain layer implementation
- The W20 and W21's gain layer are made with a different machine, thus have different variation

Charge collection and timing resolution (v2.1)

ATLAS HGTD Public Plots

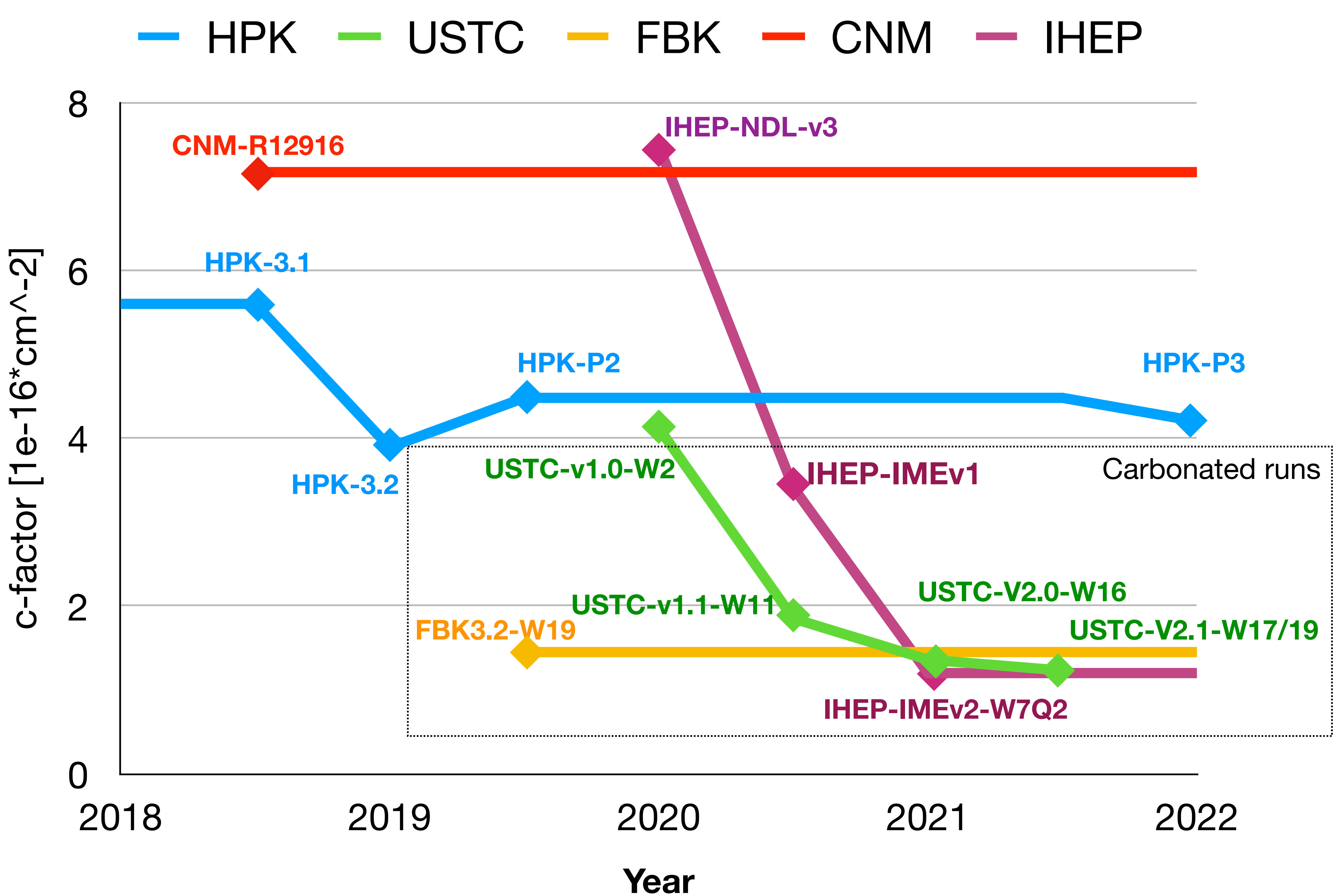
*Measured at -30°C with Sr90 source





- The carbonated USTC W17, W19 LGADs again fulfilled the radiation hardness requirement of HGTD, after the previous batch.

Evolution of the c-factor from different vendors



- c factor measured with CV method on the most promising wafer (rad. hard) for each vendors' run.

USTC **N**ano **R**esearch&**F**abrication **C**enter

Stepper lithography

Ion implanter (w/ carbon)

RIE

LPCVD

6-inch compatible

Wet etch/clean

RTA

PECVD

Sputter/Ebeam

USTC NRFC LGAD

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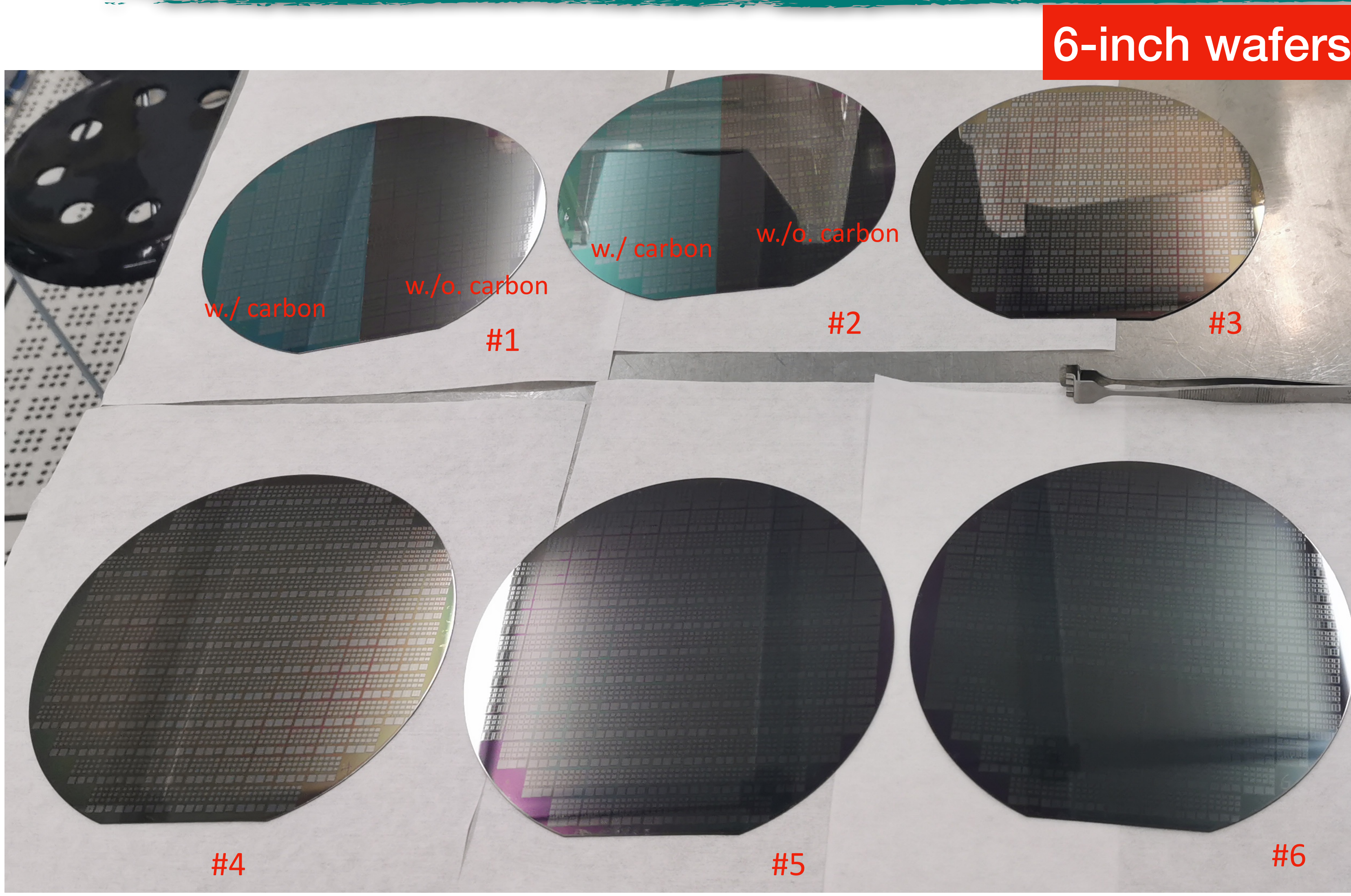
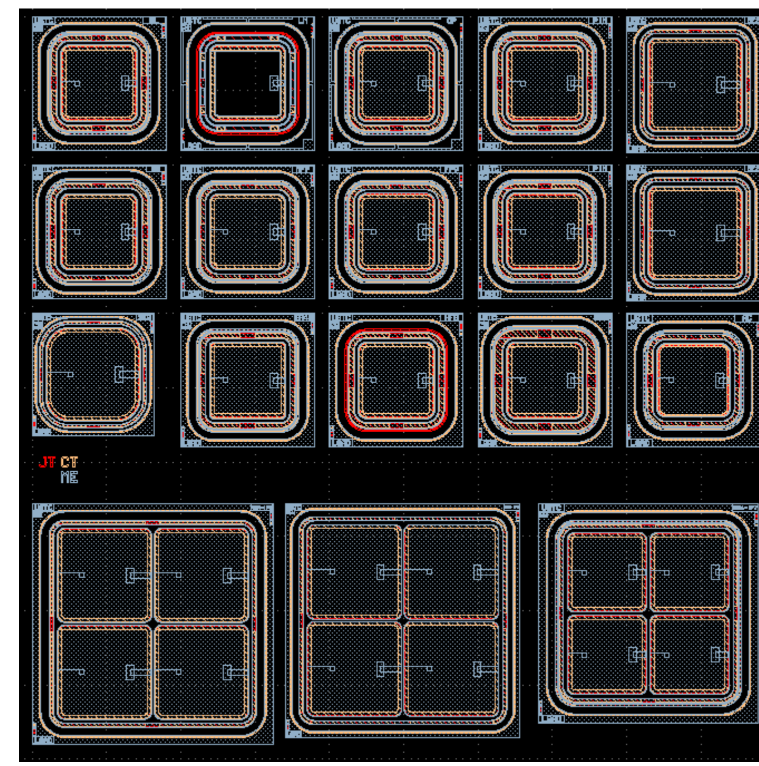


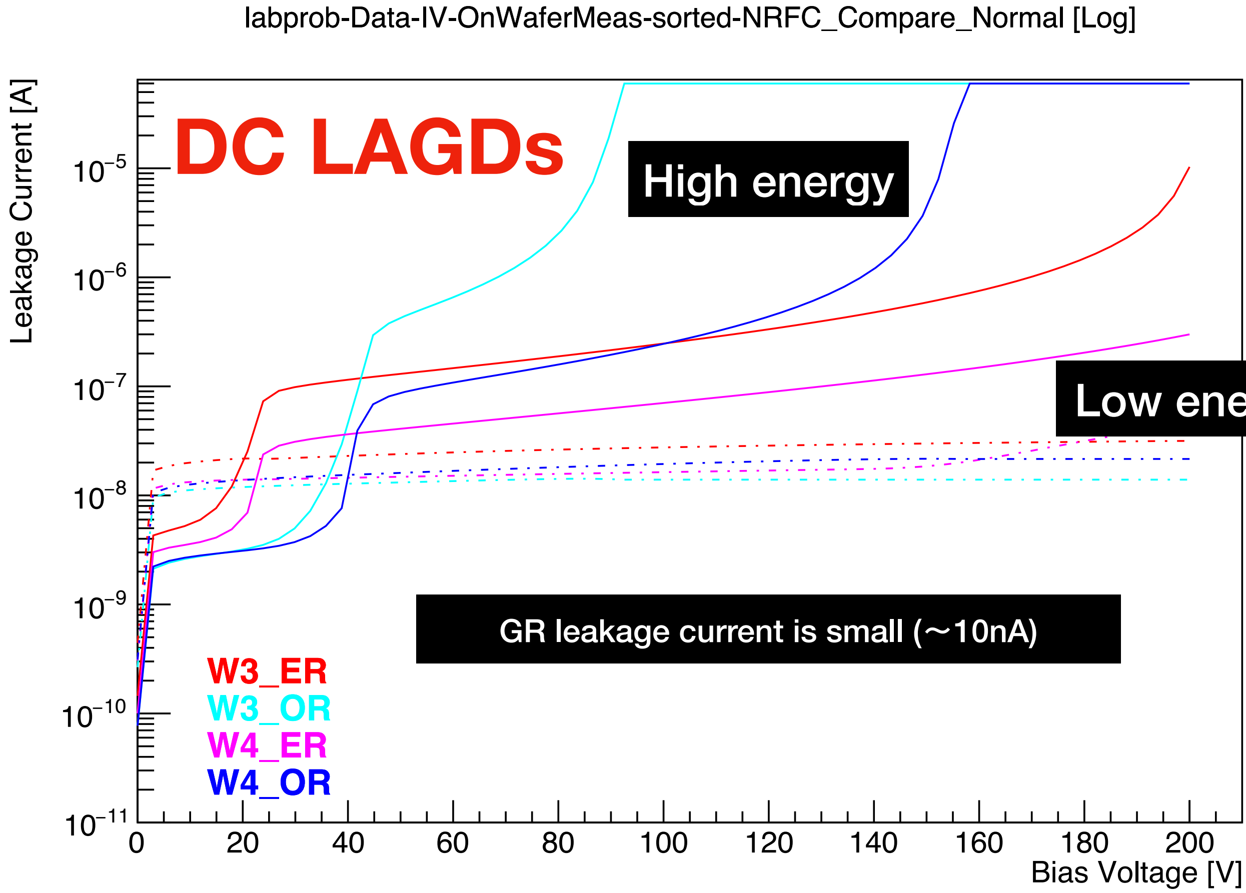


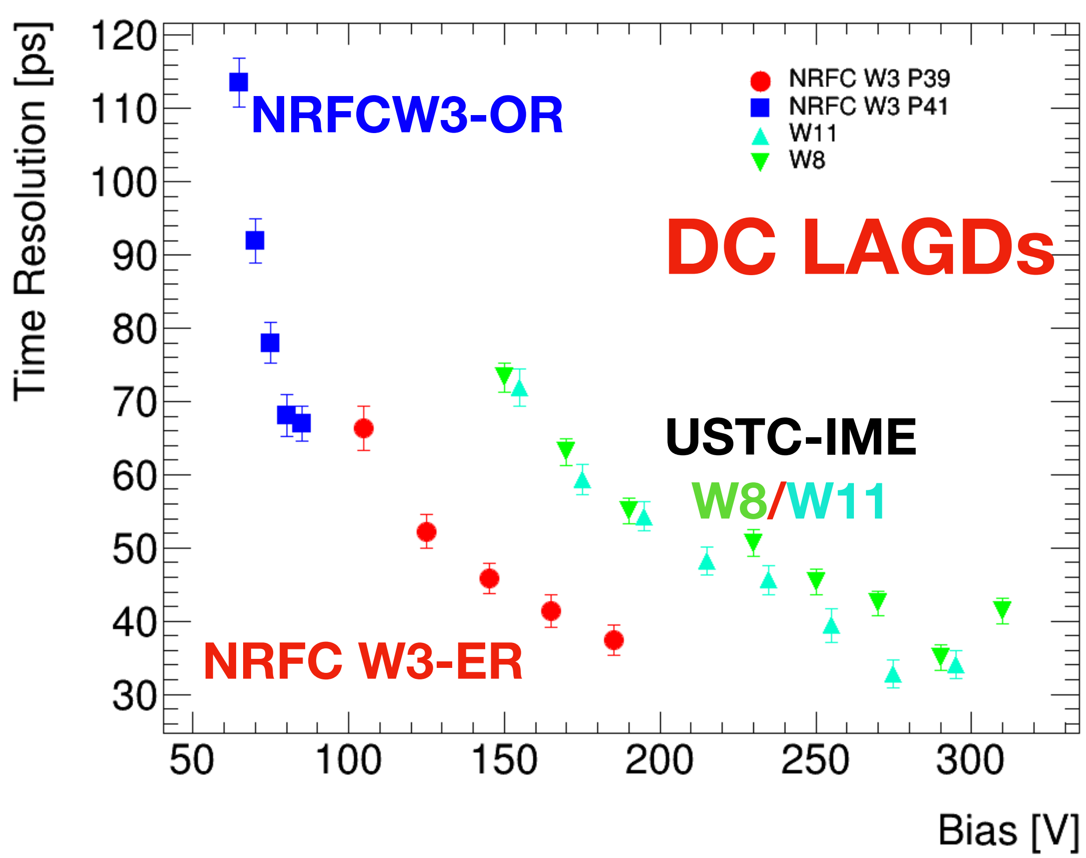
- LGAD Design&Fabricated at USTC NRFC

Splits	Wafer	Rows	GL.Energy	GL.Dose	Measured VBD[V]
a	W3	Odd	High	High	85
b	W4	Odd	High	Low	150
c	W3	Even	Low	High	200
d	W4	Even	Low	Low	>200
e	W5	—	Low	Low, AC	~145
f	W6	—	Low	Low, AC	~145

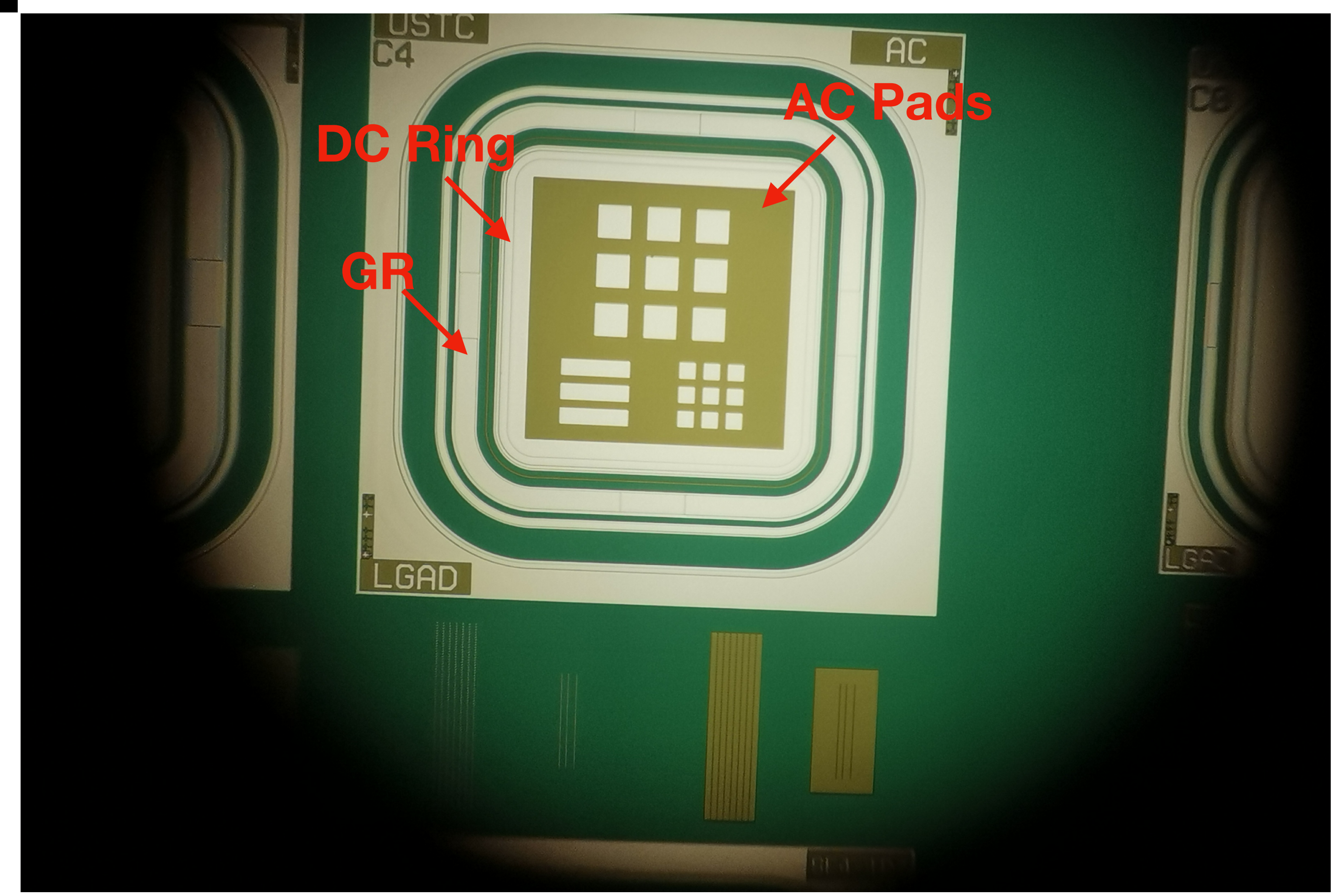
USTC-NRFC Preliminary Results

Measured at Room T.

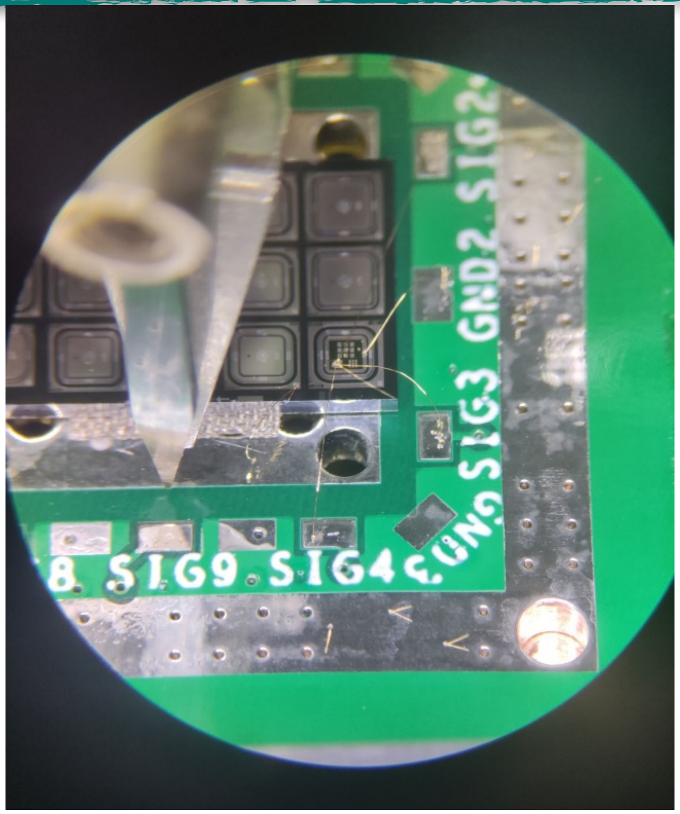




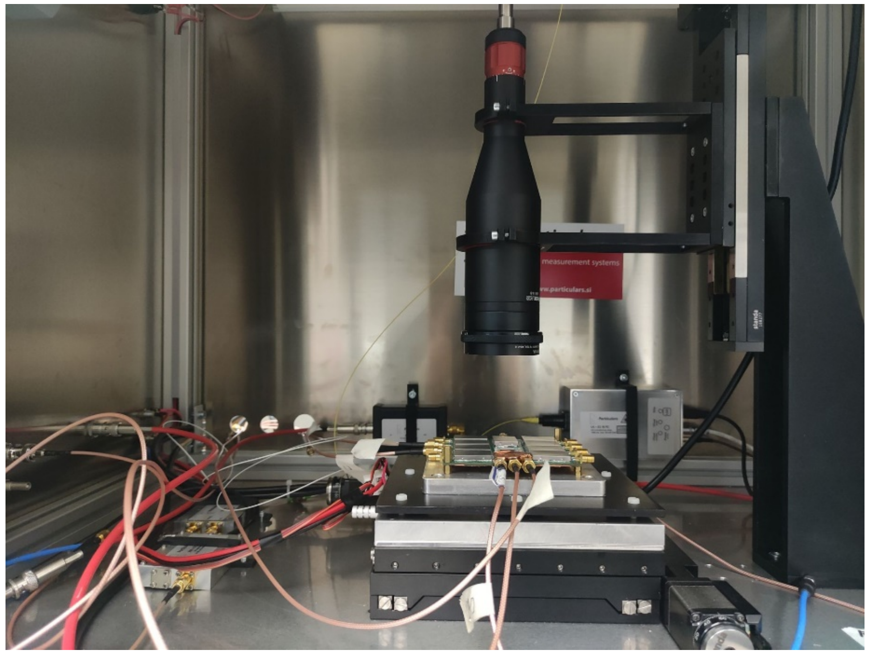
AC LAGDs



AC LGAD Testing Setup

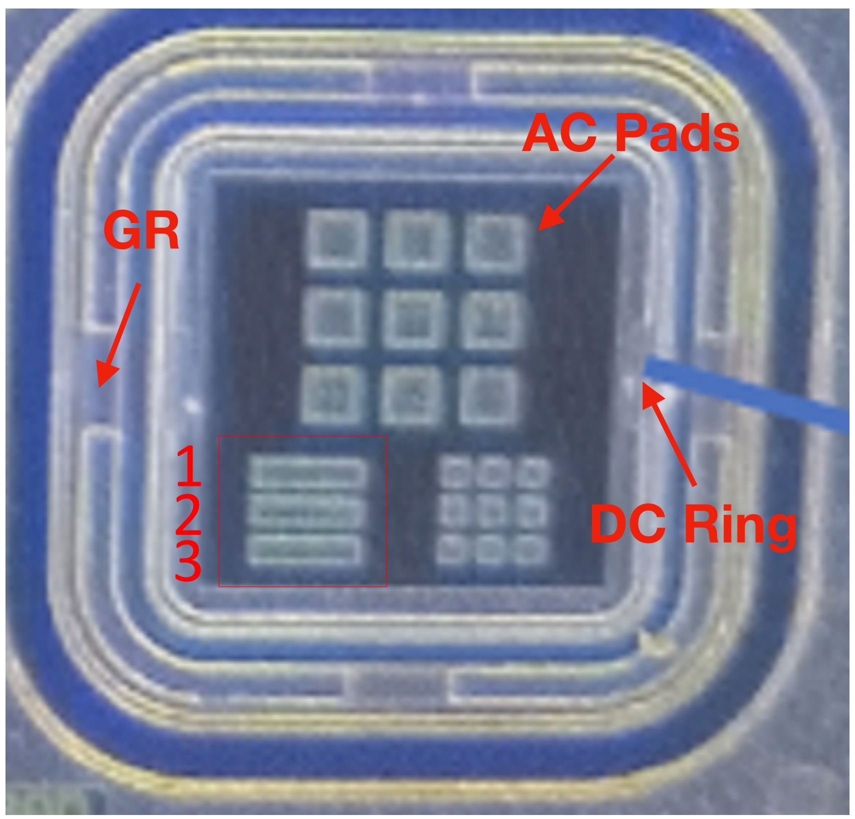


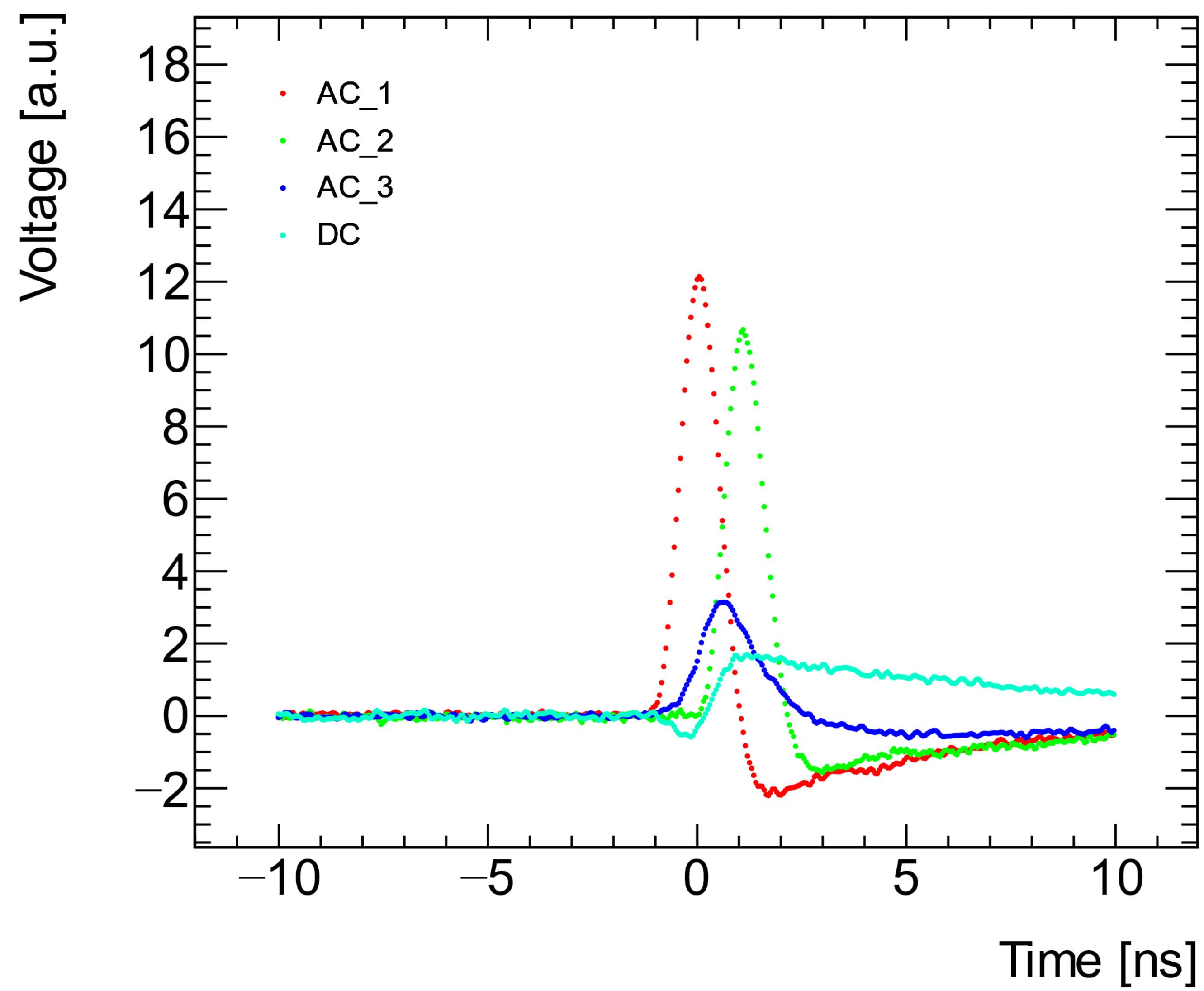
- Room temperature
- Laser
  - Wavelength: 1064 nm
  - Beam spot size: ~10 um
- Focusing with the lens group
- DUT
  - Sensor: NRFC W6 P92 AC, un-irradiated@130 V
  - USTC 9-channel amplifier board (Designed by Jiajin Ge)
- Trigger: Laser sync pulse
- Oscilloscope
  - Sampling rate: 20 Gs/s
  - Bandwidth: 1 GHz



AC & DC signal of the strips

3 AC strip pads and DC pad connected to oscilloscope



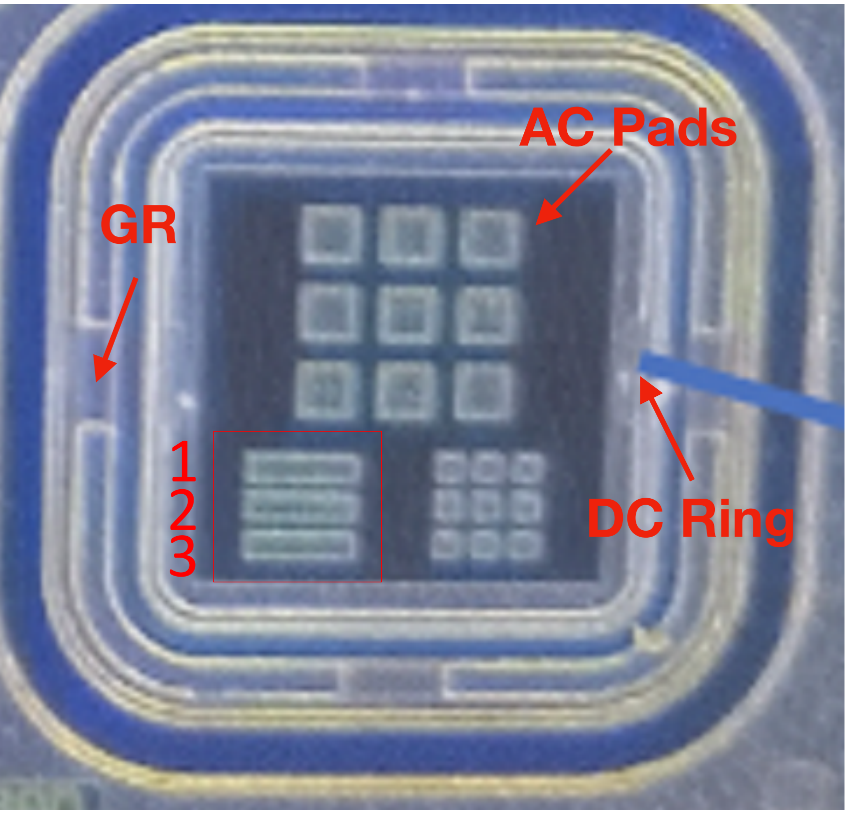


Strip width: 50 μm

Pitch: 75 μm

Test of the AC Strips

3 AC strip pads and DC pad connected to oscilloscope

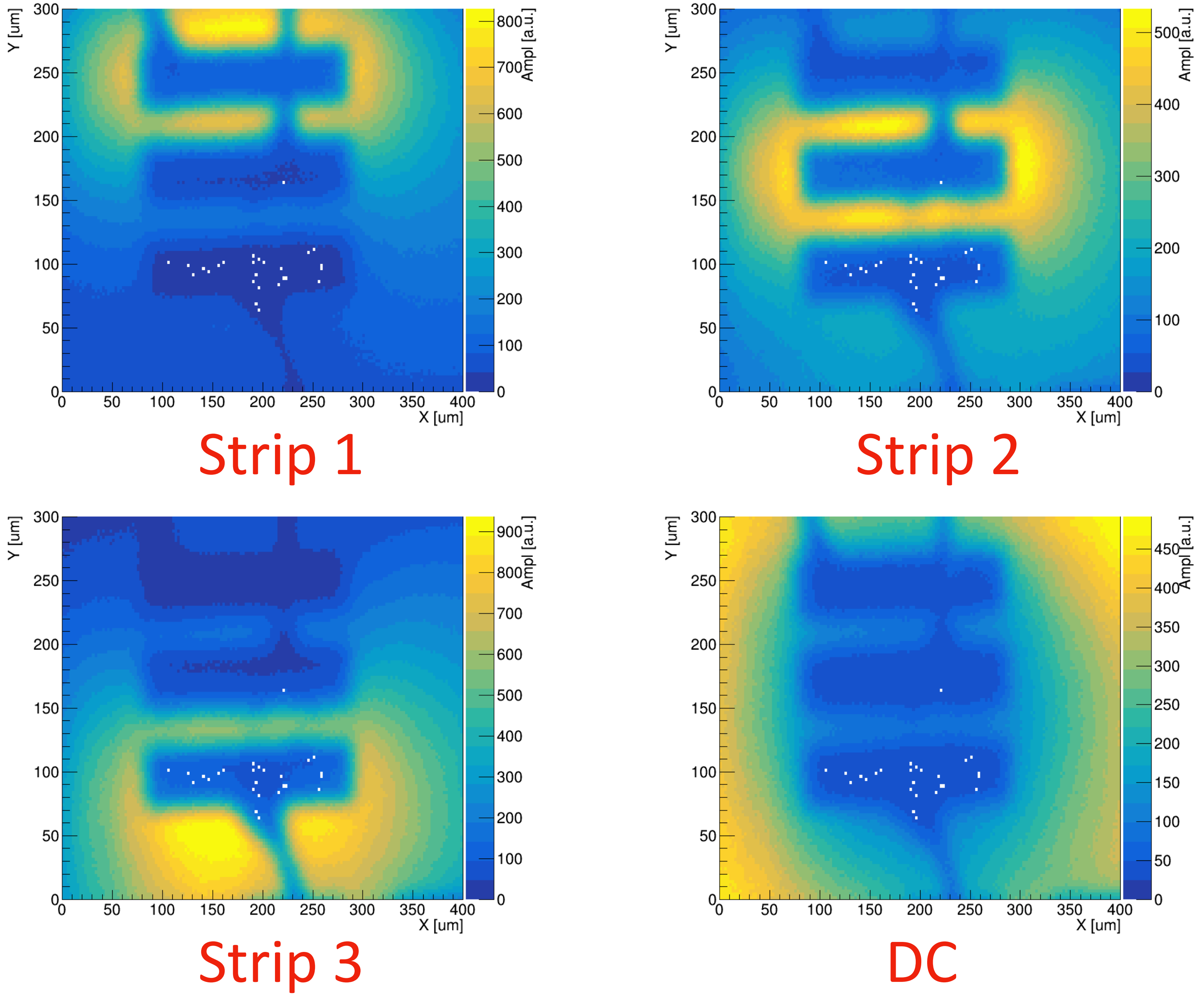


Strip width: 50 μm

Pitch: 75 μm

Scanning step: 2.5 μm

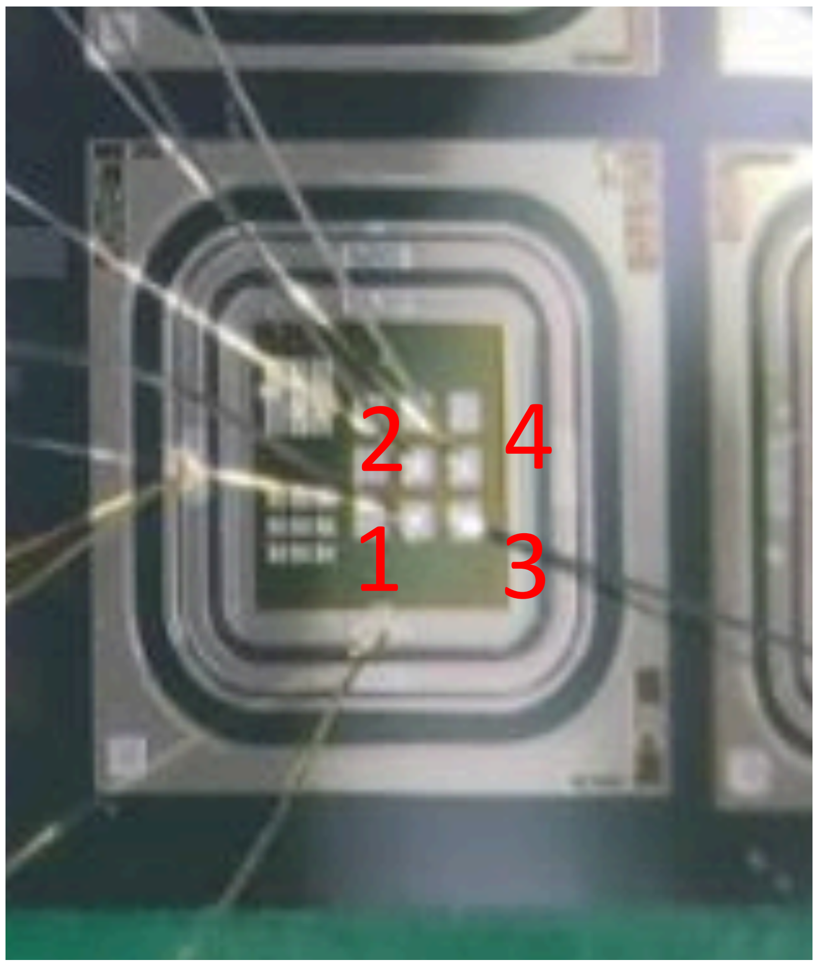
2D scan



Signal amplitude on different laser inject position for each AC strip or DC ring

AC Pixels — 2D Scan

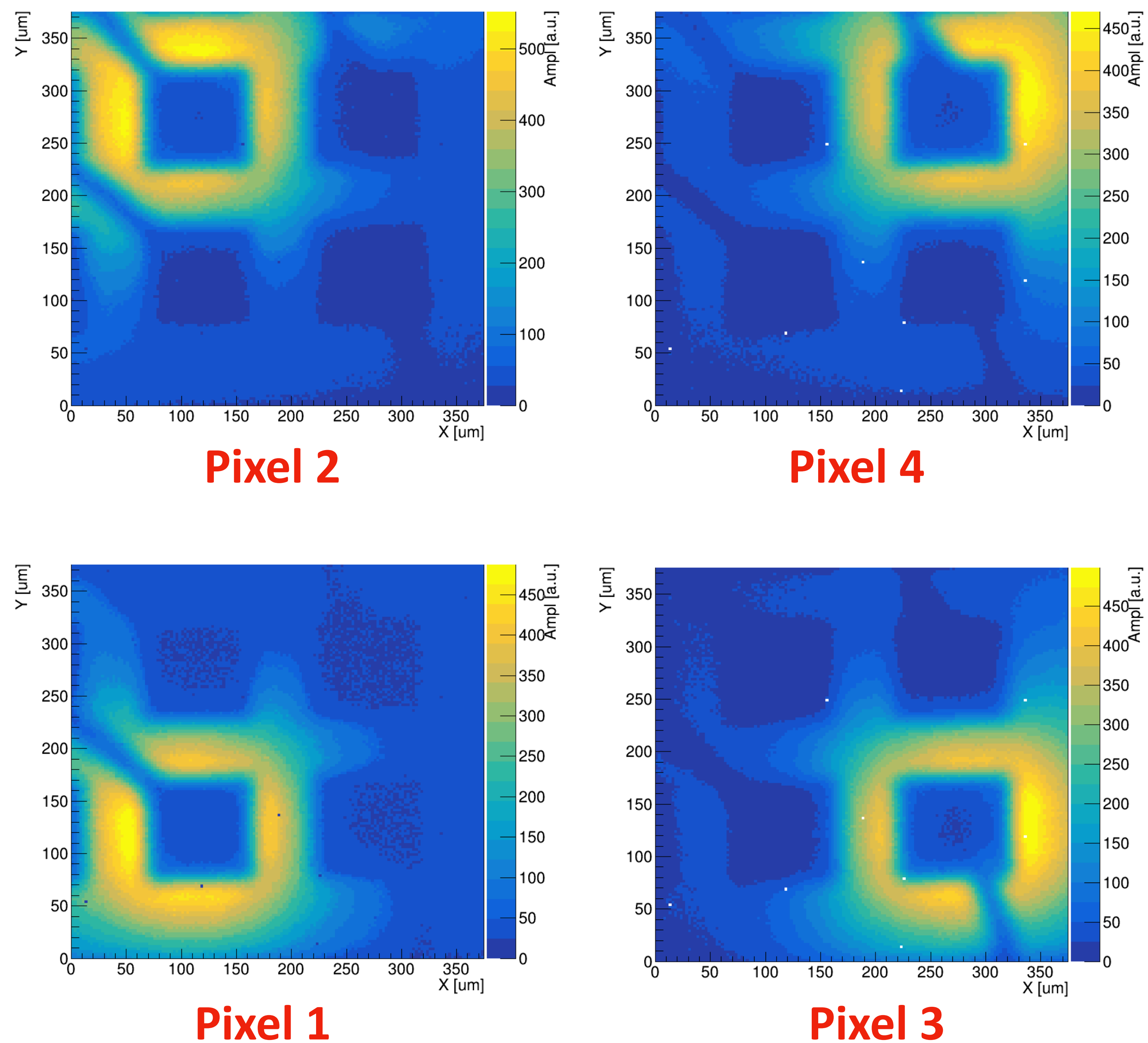
4 AC pixel pads
connected to oscilloscope



Pad size: 100*100 μm^2

Pitch: 150 μm

Scanning step: 2.5 μm

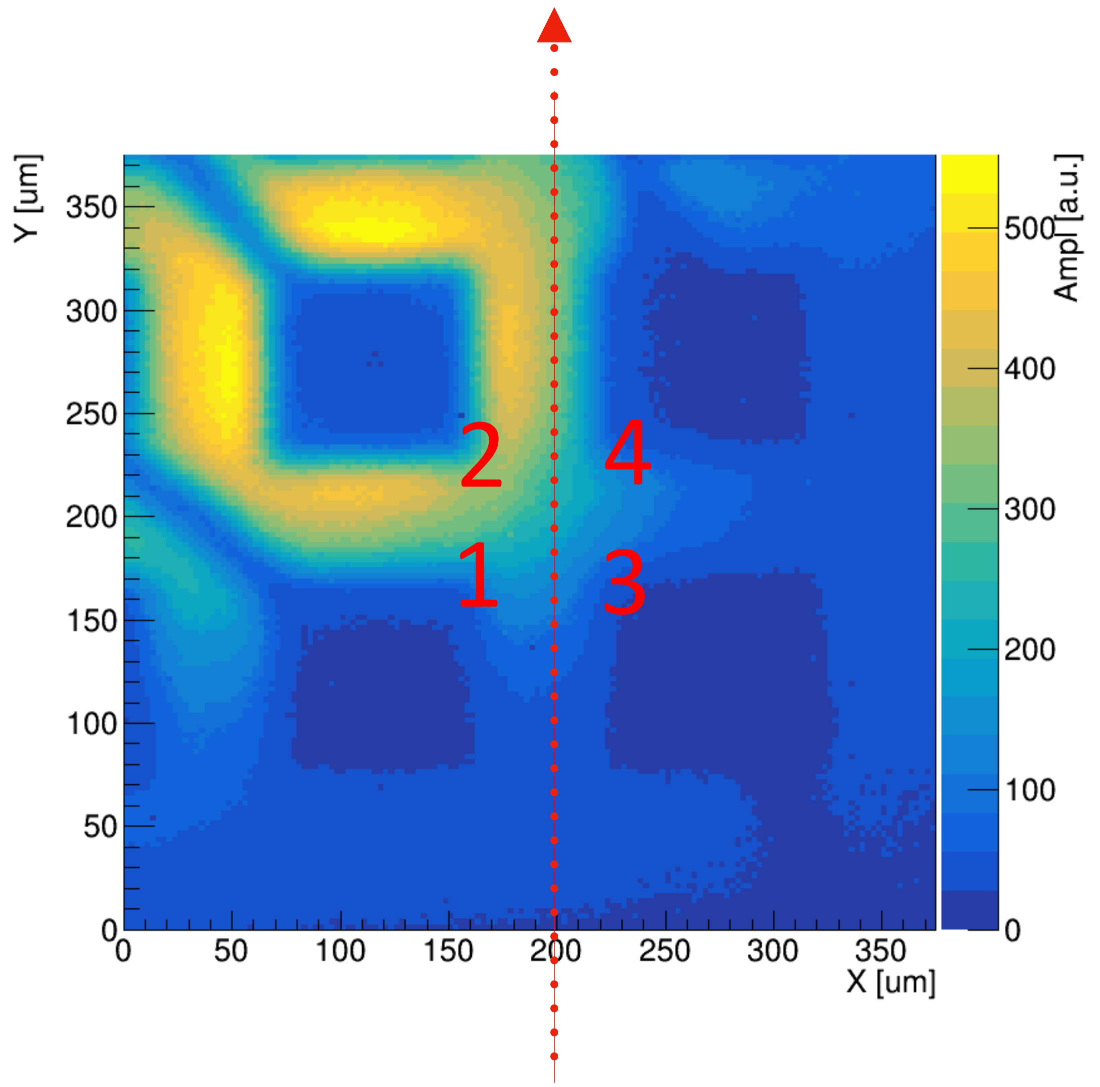


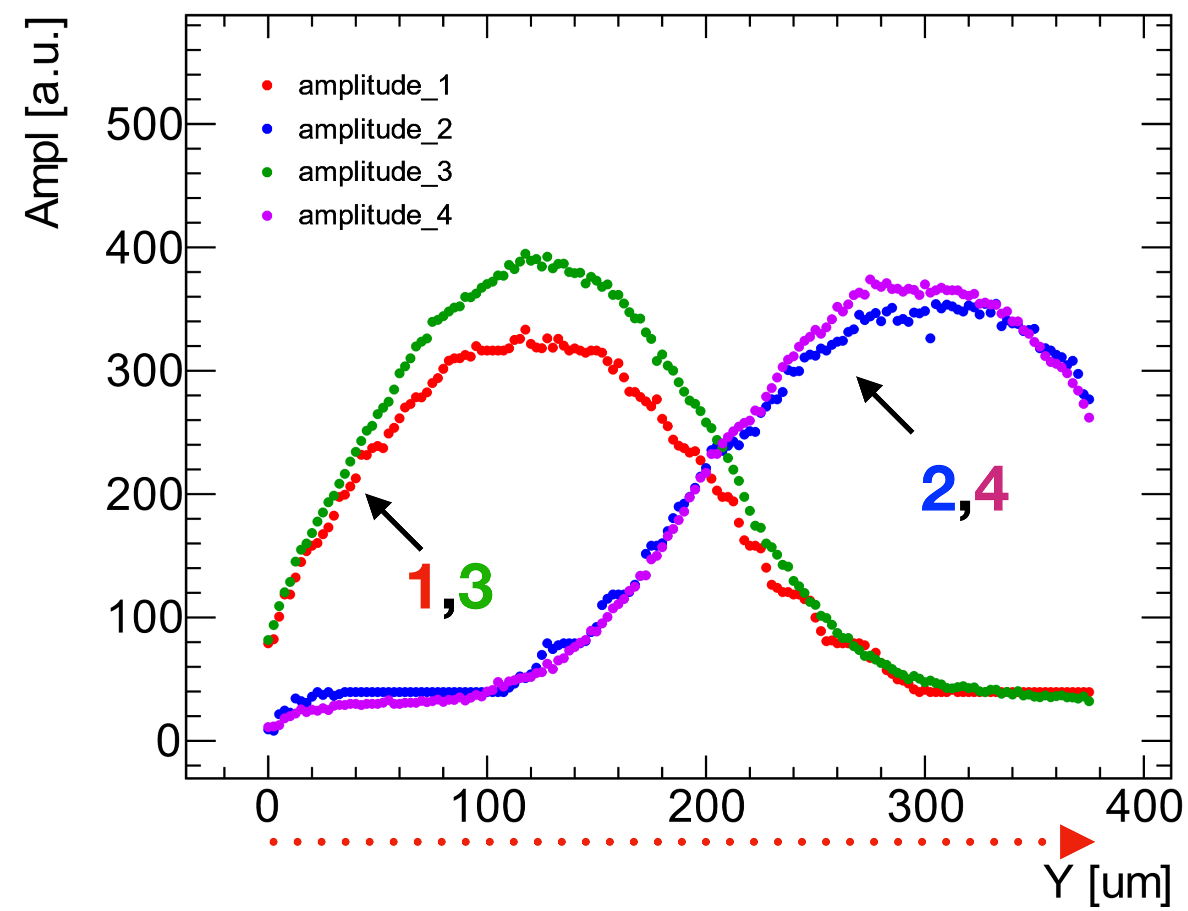
Signal amplitude on different laser inject position for each AC pad

Laser are injected from the font side of the sensor

(backside test ongoing)

AC Pixels — 1D profile

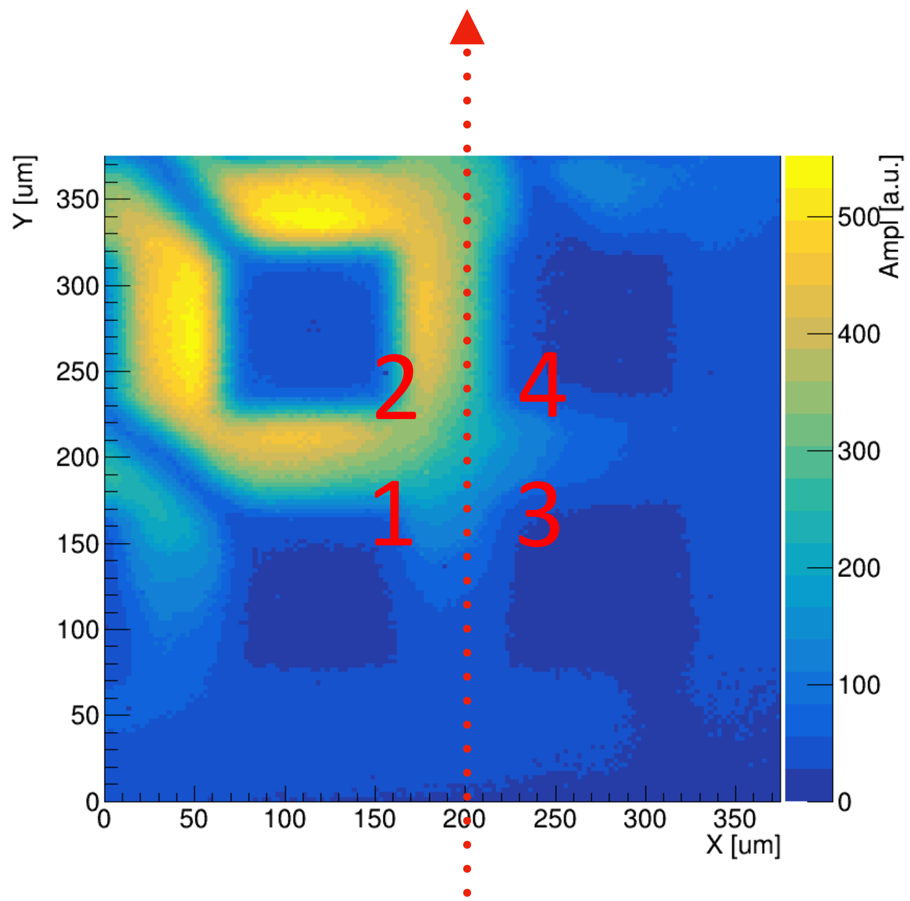


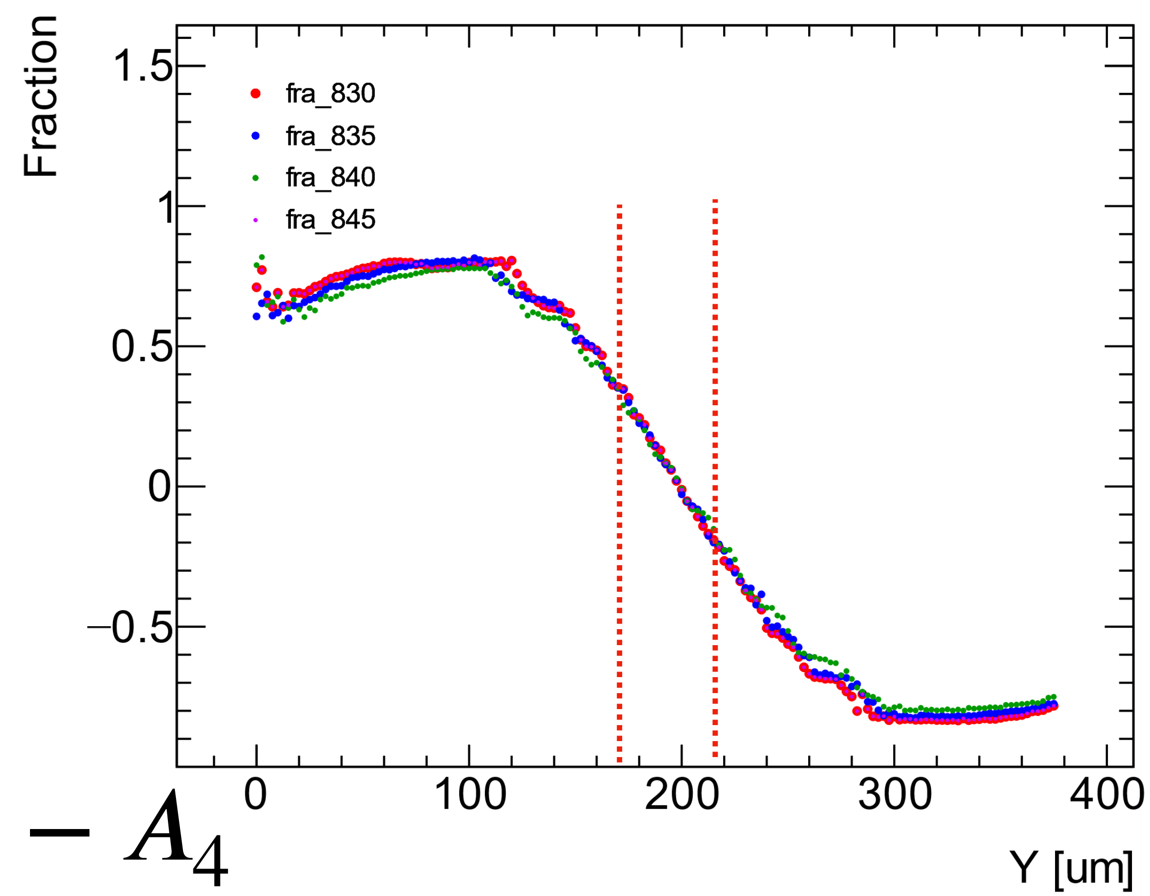


$x = 200\ \mu m$

Laser scanned along Y direction (x-200μm)

AC Pixels — Position reconstruction





- Fraction: $F = \dfrac{A_1 + A_3 - A_2 - A_4}{A_1 + A_3 + A_2 + A_4}$

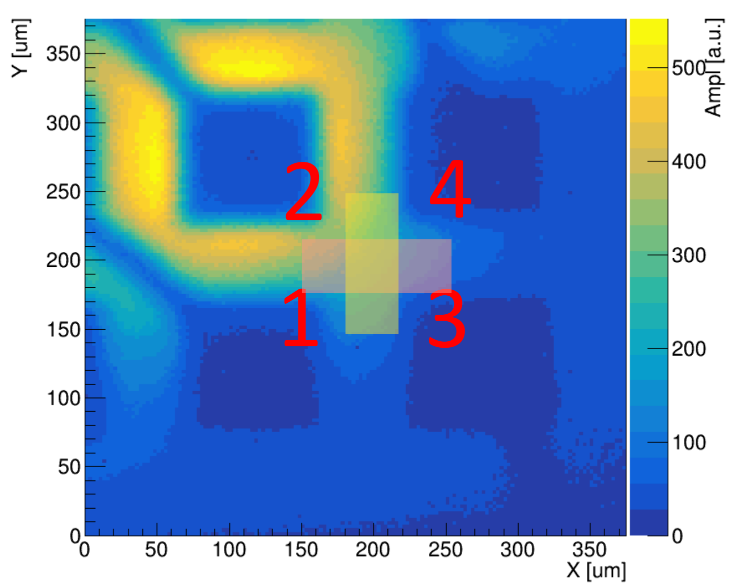
  (A_i is the signal amplitude on pad i)

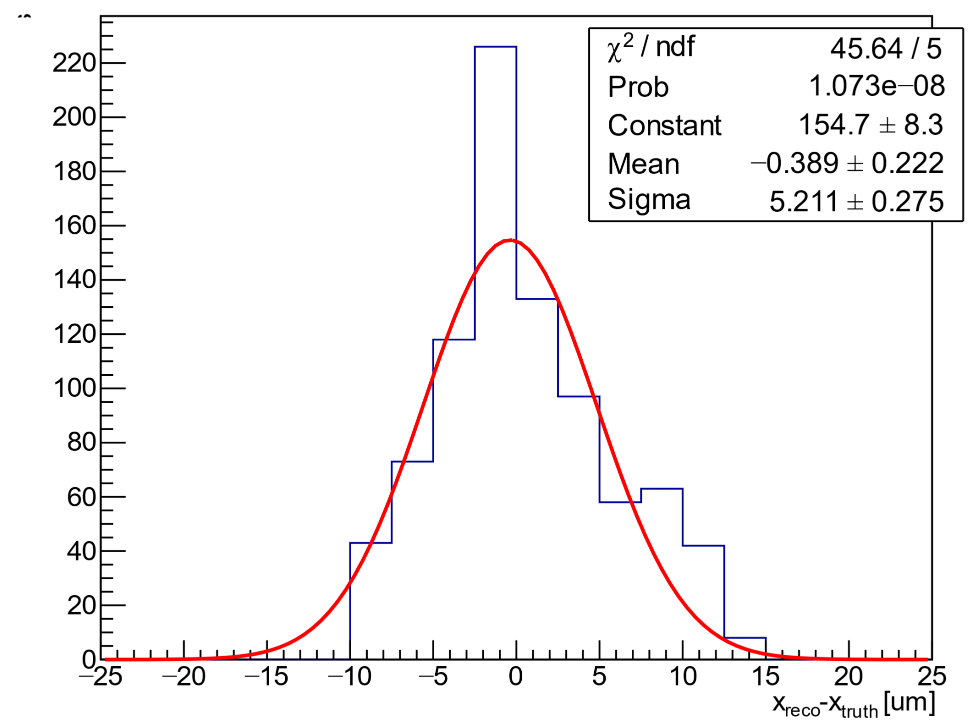
- Fraction results are stable in the middle region ($x = 175 \sim 215\ \mu m$)

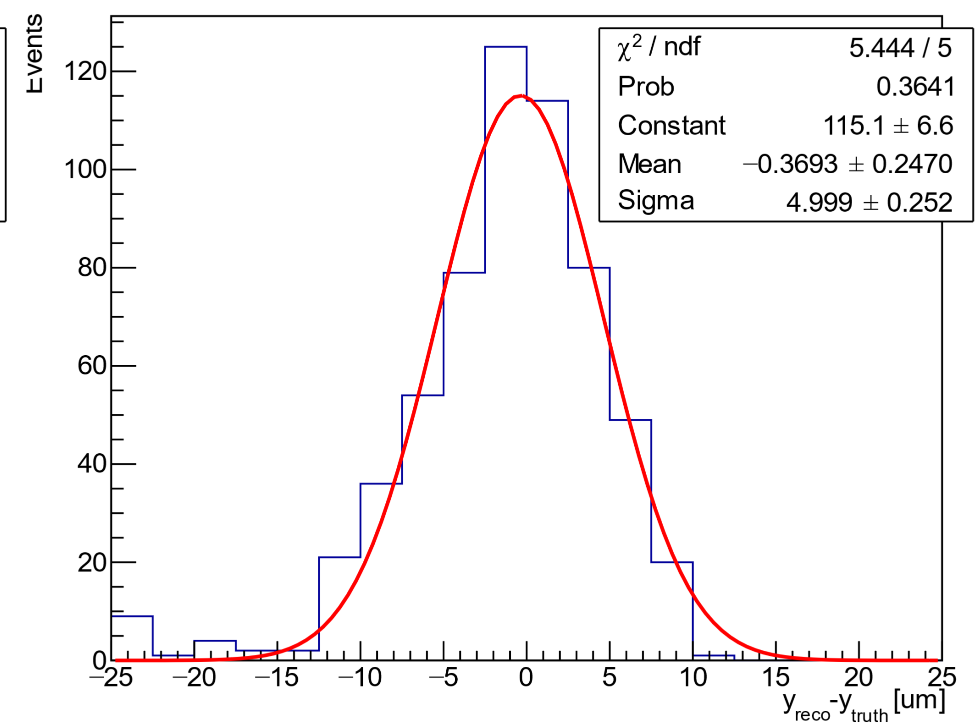
AC Pixels — Position resolution

Preliminary

$$x(y)_{\text{reco}} = \frac{\text{pitch}(150\ \mu m)}{2} * F$$







640 points from x: [150, 250] μm, y: [175, 215] μm

$\sigma_x = 5.2\ \mu m$

640 points from x: [175, 215] μm, y: [150, 250] μm

$\sigma_y = 5.0\ \mu m$

Summary

- The USTC group is **deeply involved** in the LGADs R&D for the ATLAS HGTD upgrade and produced a nice candidate sensor for the project.
- The USTC group focus on the radiation hard LGAD development **carbon diffusion** and **different gain layer depth** have been realised at both IME and NRFC.
- **Carbon** diffused LGAD USTC W17 show impressive radiation hardness(**12fC** @ 2.5E15 neq/cm^2), meeting the HGTD requirement, c-factor: **1.23E-16** cm^2, charge collection and timing resolution have been measured, **50 ps** @ 2.5E15 neq/cm^2 achieved (requirements 70 ps).
- USTC-2.x show good uniformity(<**1-3% VBD** variation), yield (**35%**) for 15x15 array. This type is proved to meet **all HGTD specifications**, we are preparing for the pre-production of our final design for the upgrade
- The USTC **NRFC** produced novel LGADs are proved to have the AC coupling with preliminary position resolution **~5 µm** measured with the laser TCT scan, further algorithm development on-going to fully use the AC advantage

Thanks for your attention!

中国科学技术大学微纳研究与制造中心

NANO · USTC

USTC Center for Micro- and Nanoscale Research and Fabrication

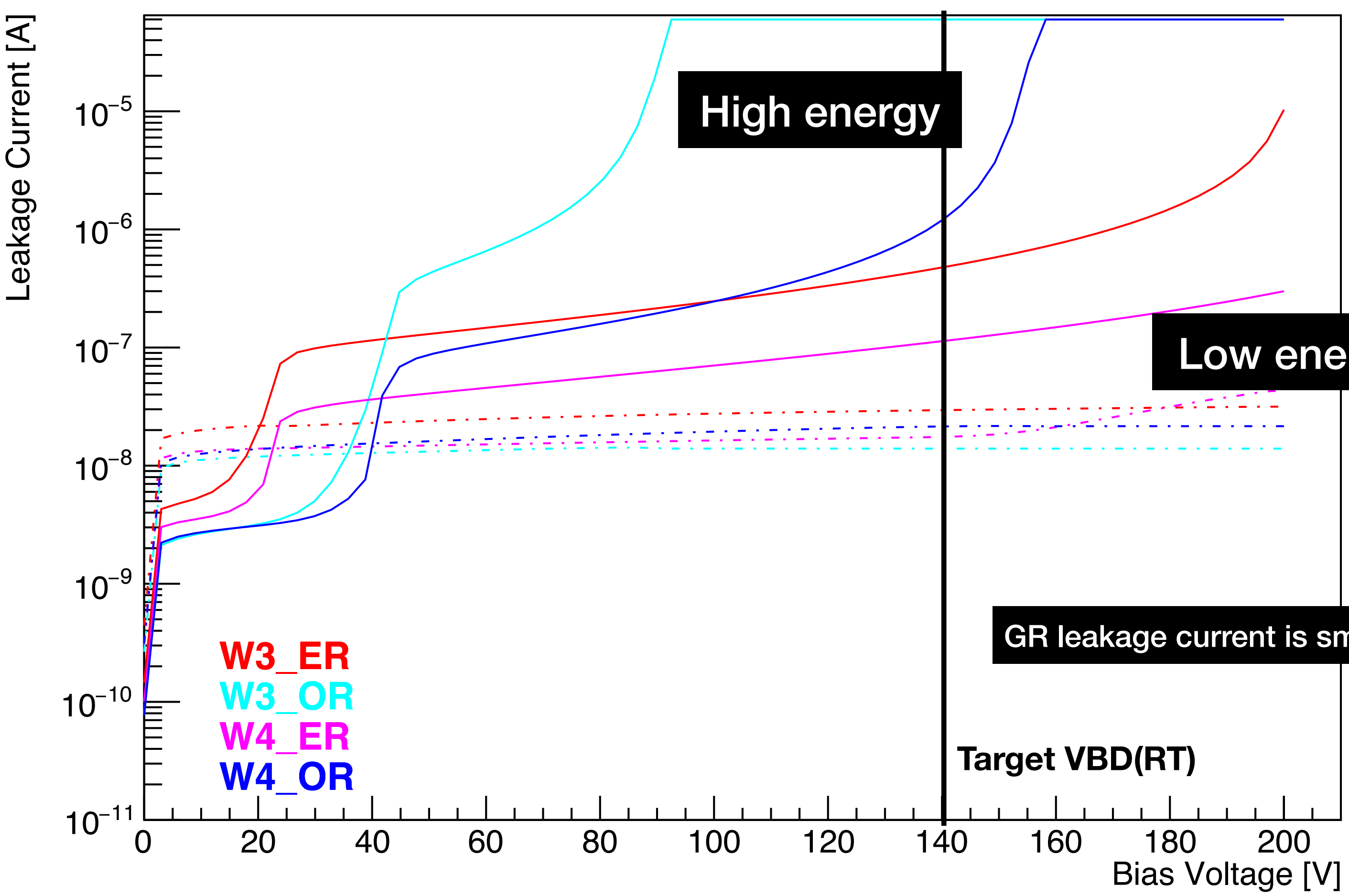
中国科学院微电子研究所

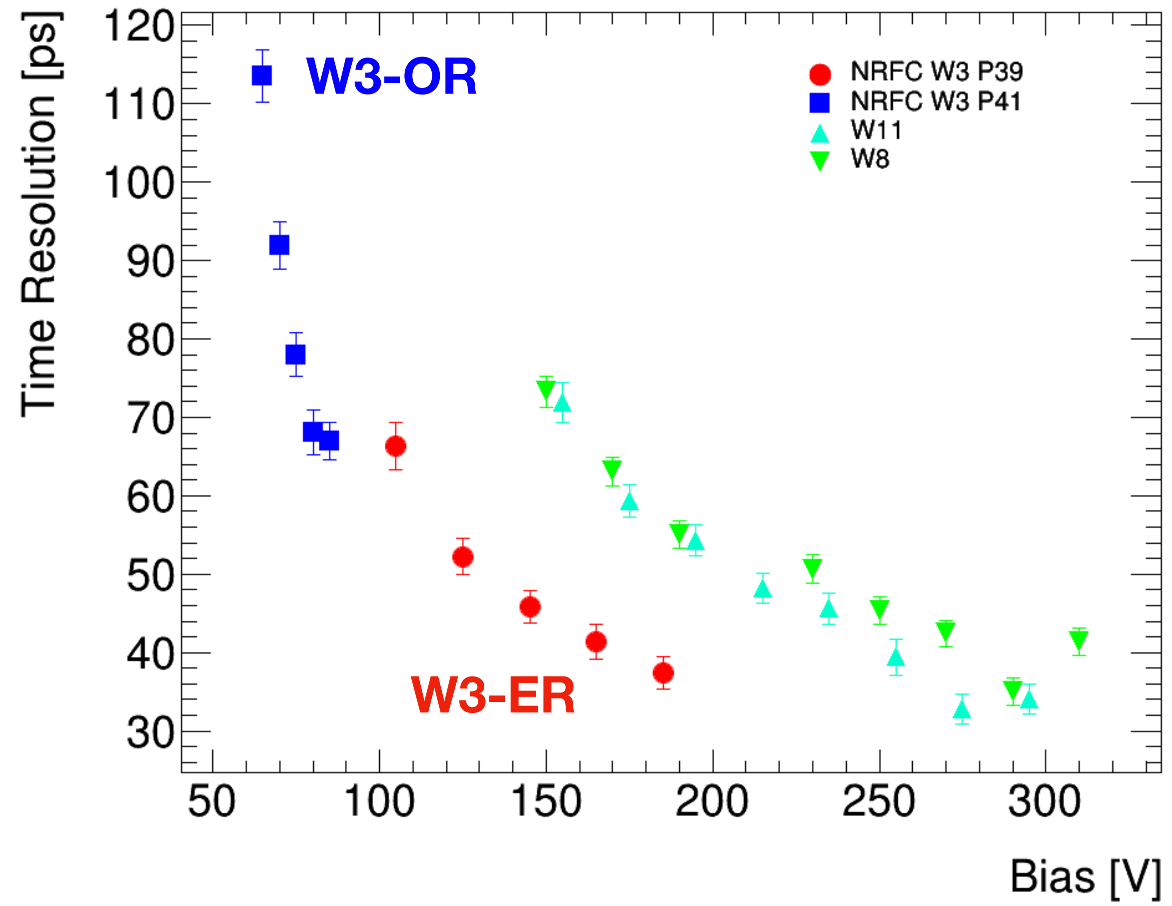
INSTITUTE OF MICROELECTRONICS OF THE CHINESE ACADEMY OF SCIENCES

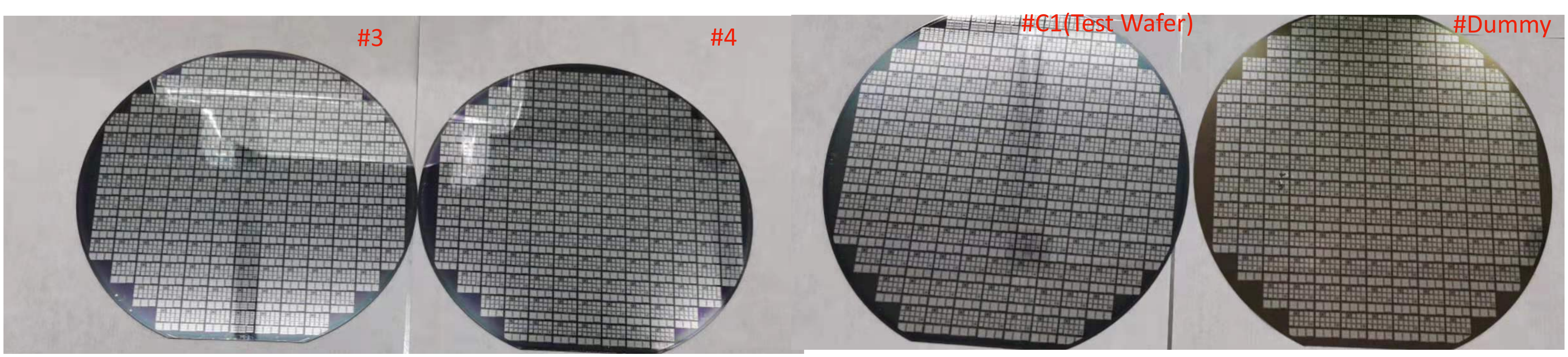
USTC-NRFC Preliminary Results

labprob-Data-IV-OnWaferMeas-sorted-NRFC_Compare_Normal [Log]

Measured at Room T.



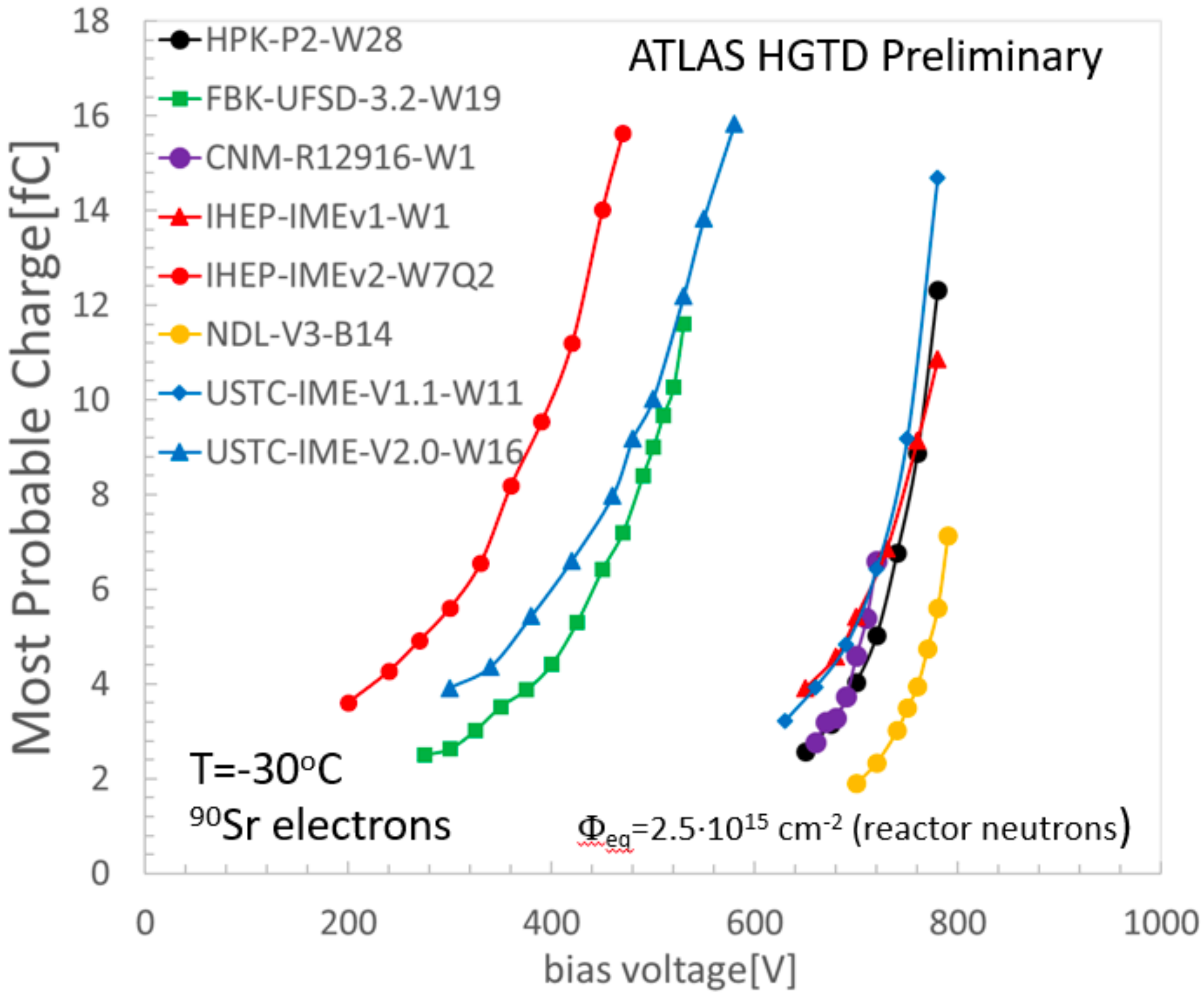


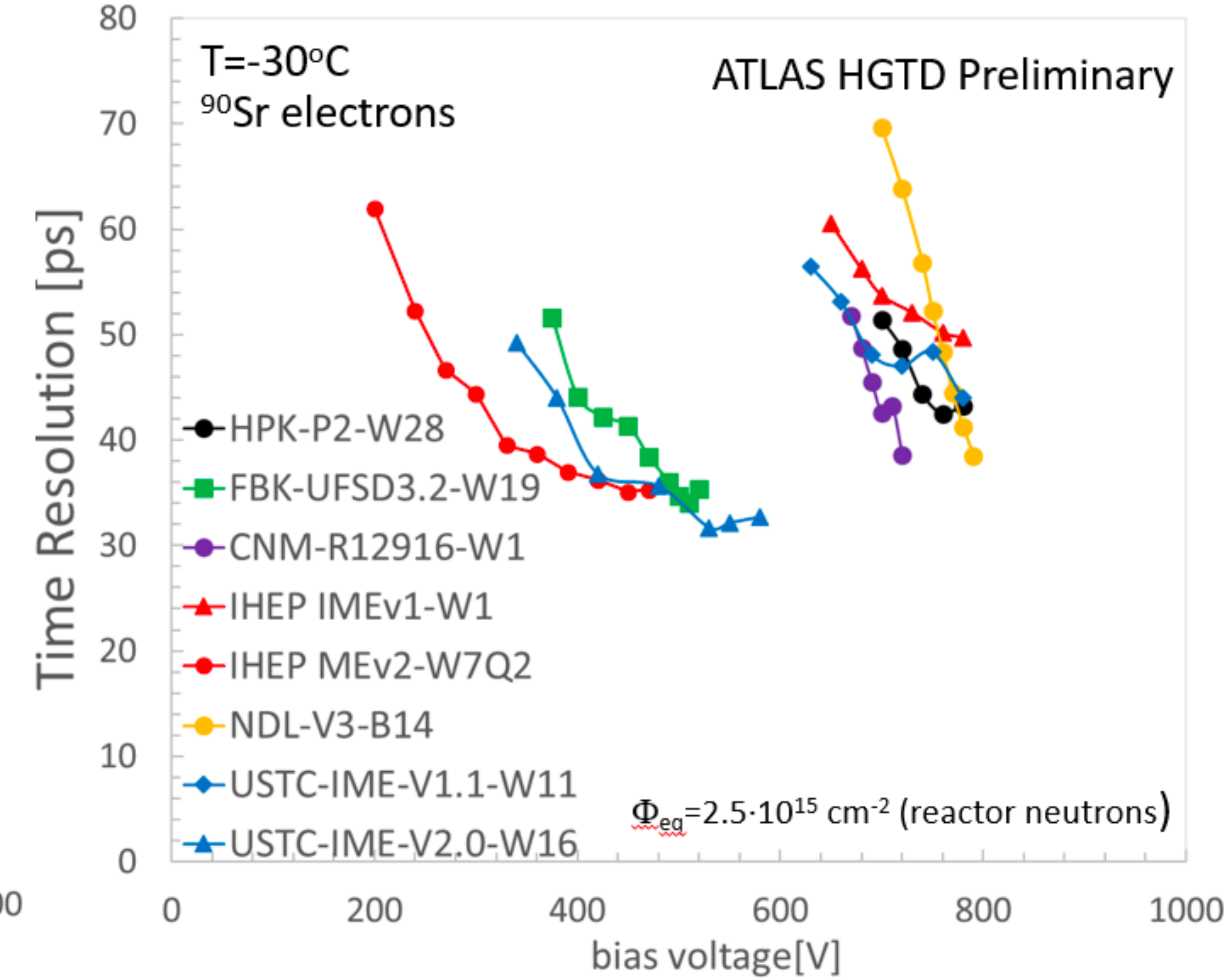


Comparison of the performance with other vendors

[ATLAS HGTD Public Plots]

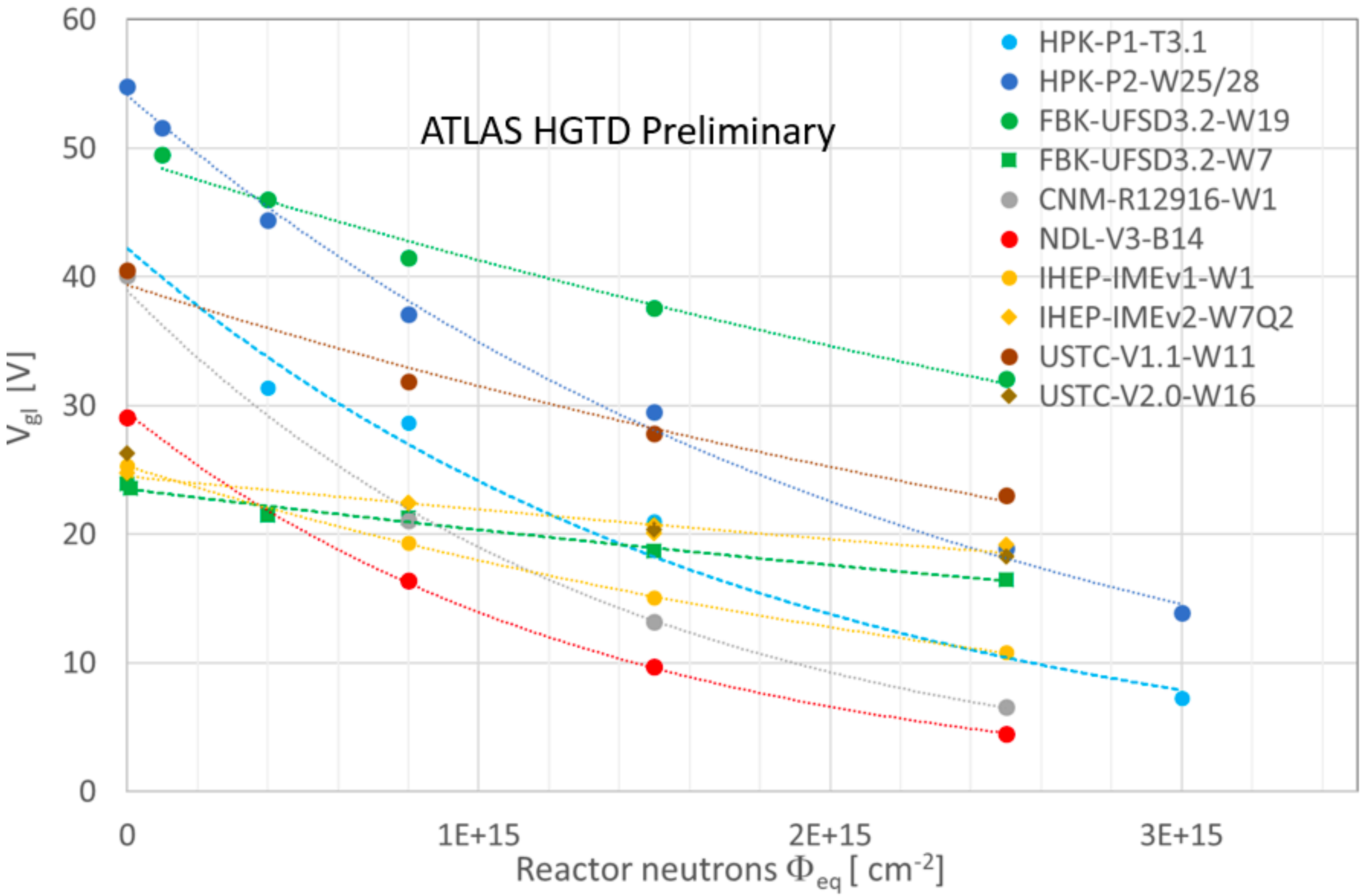
Performance at highest fluence (2.5E15 neq/cm^-2)





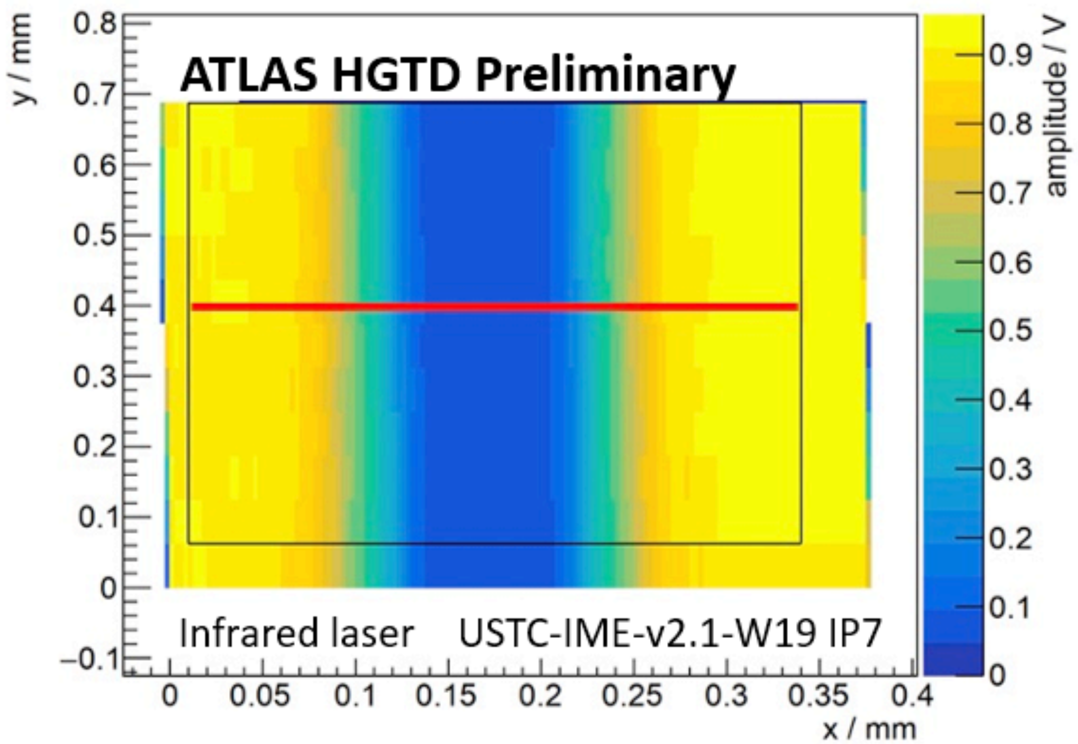
Comparison of the performance with other vendors

VGL-fluence used for calculate the c-factor [ATLAS HGTD Public Plots]

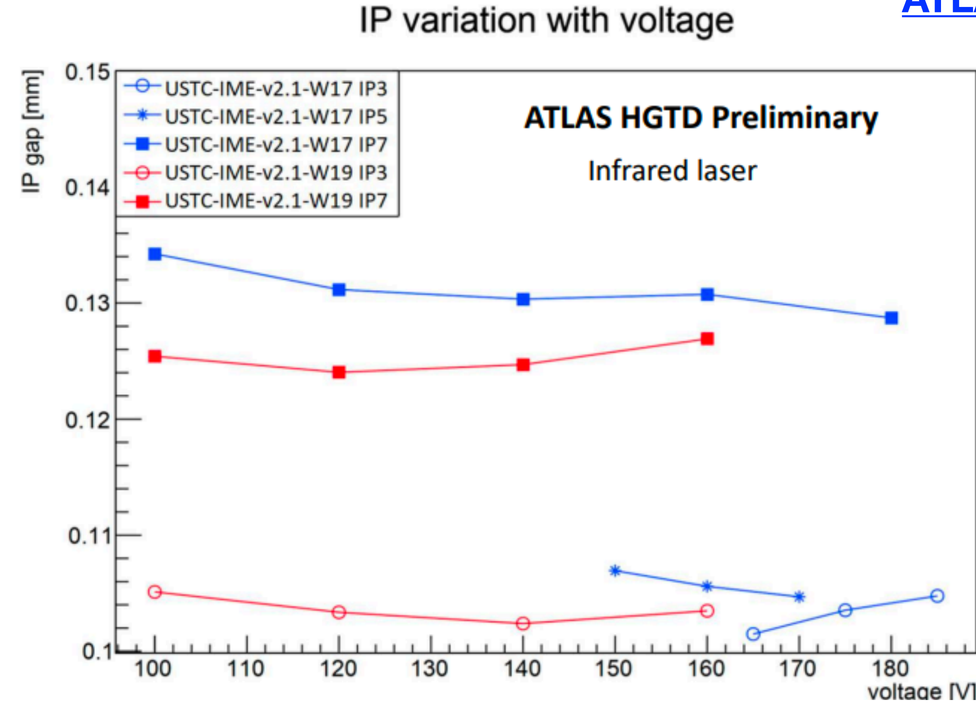


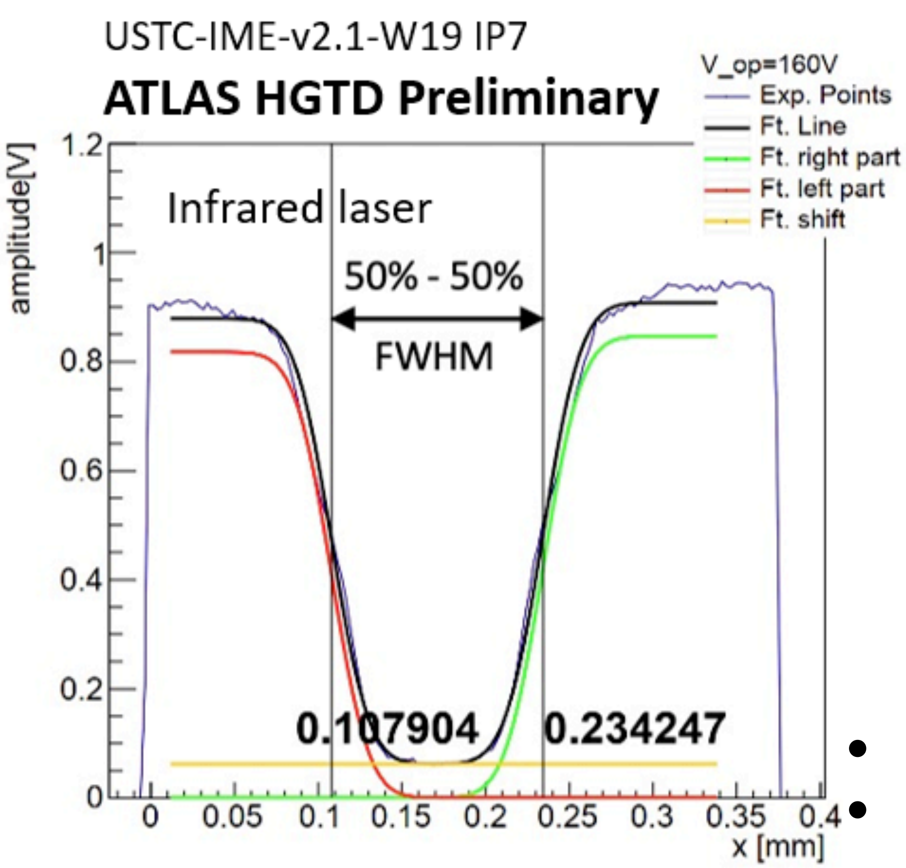
Inter-pad gap

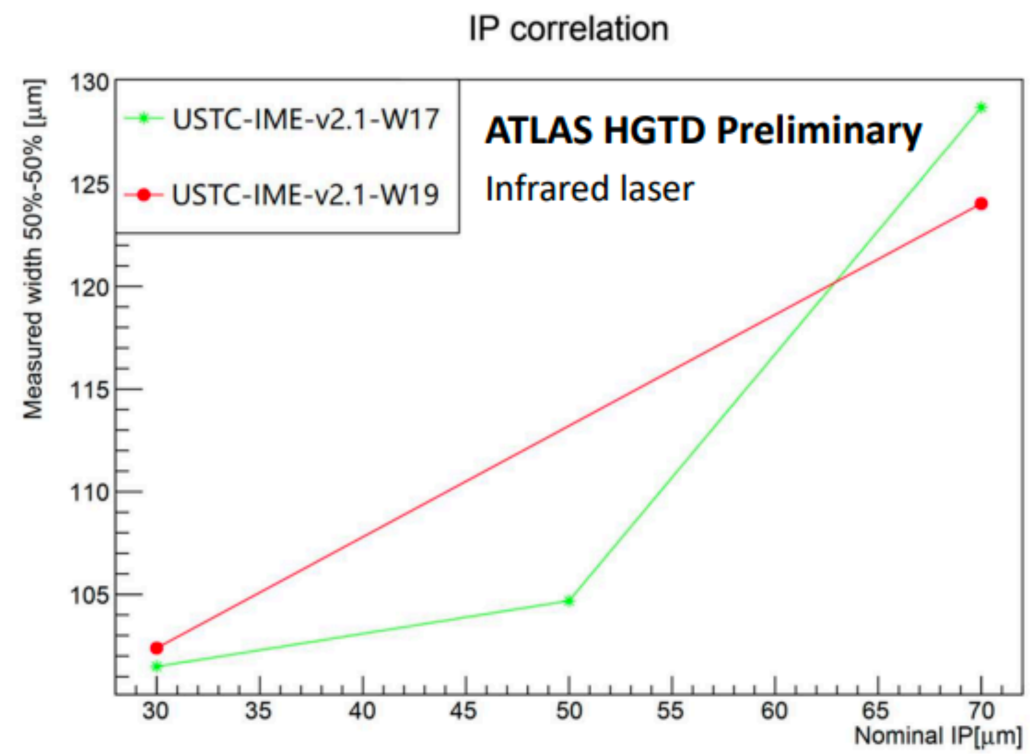
@160V



[ATLAS HGTD Public Plots](#)

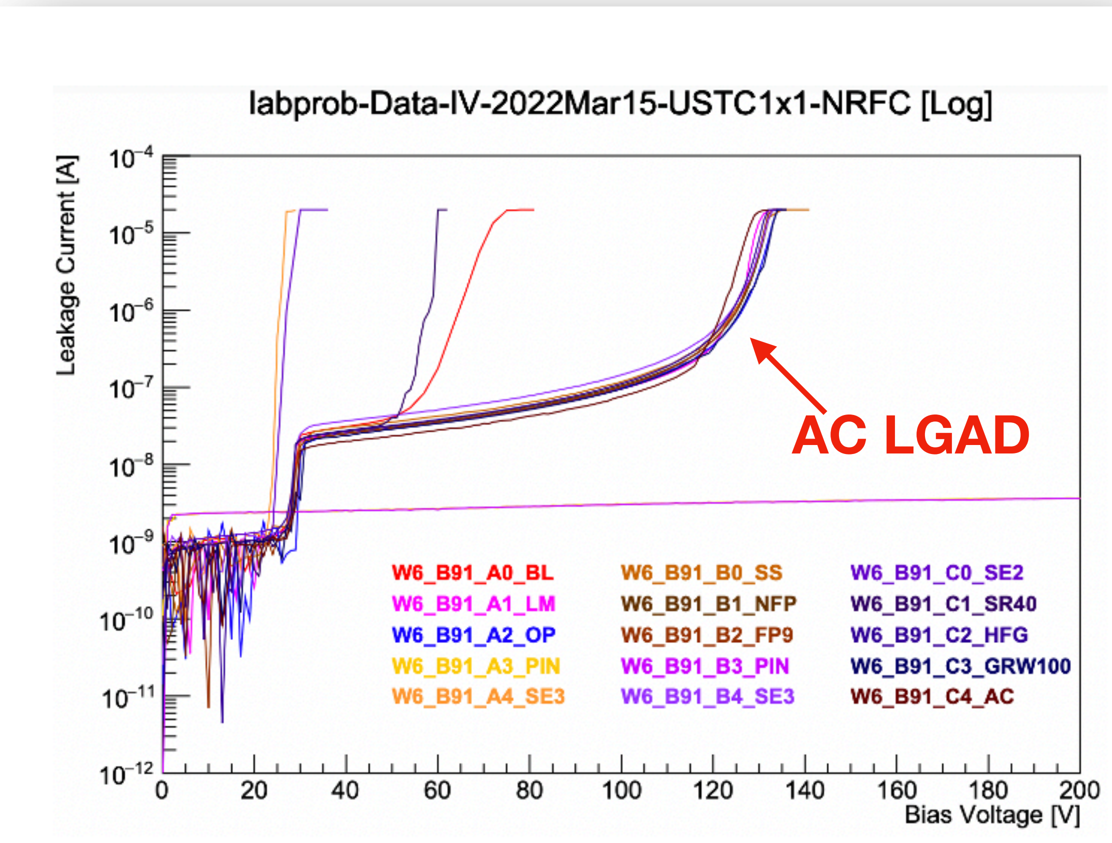


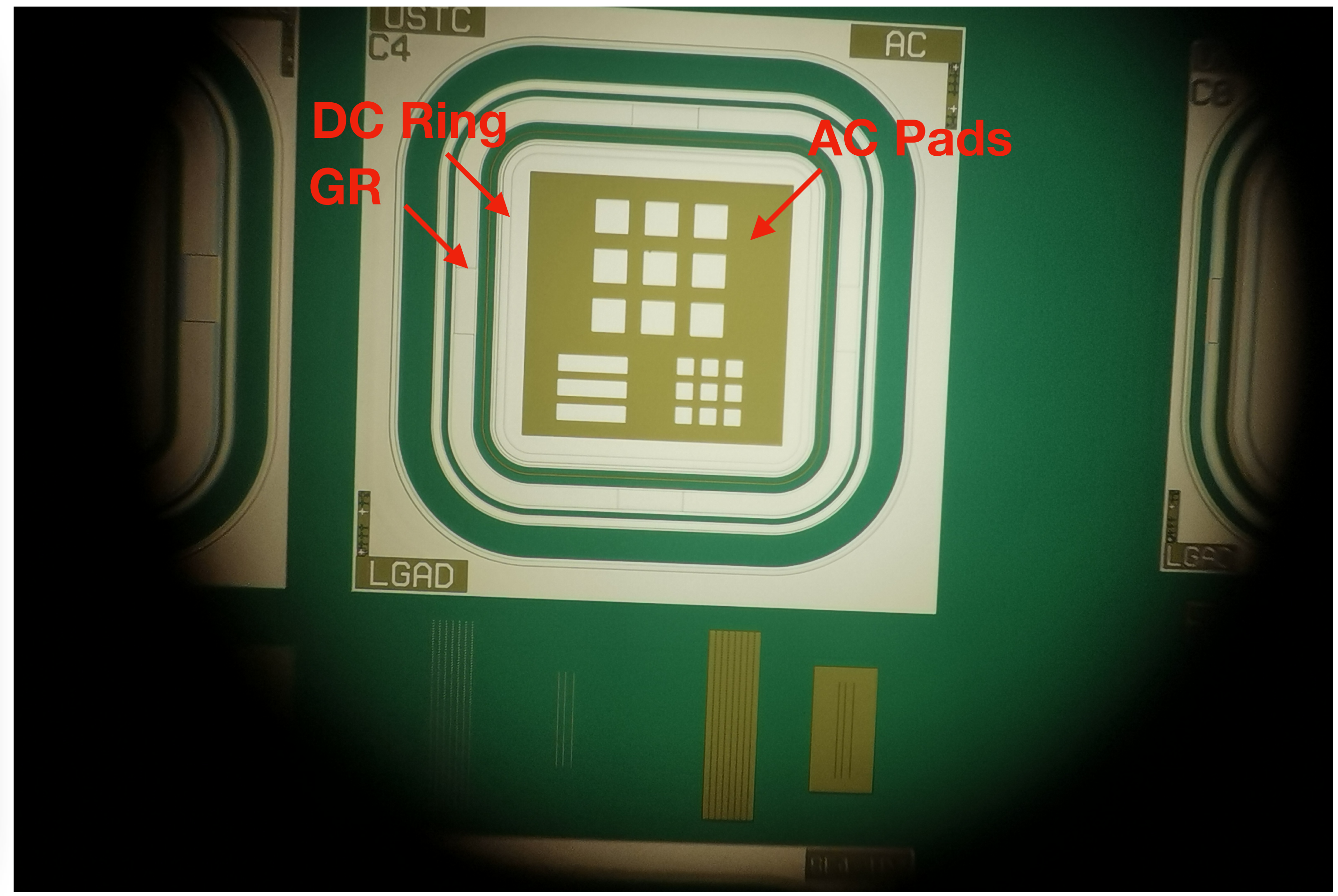




- The intrepad gap measured is around **～102 µm**, (close HGTD requirement 100 µm)
- The intrepid gap after irradiation should be smaller and test ongoing

The AC LGADs Produced





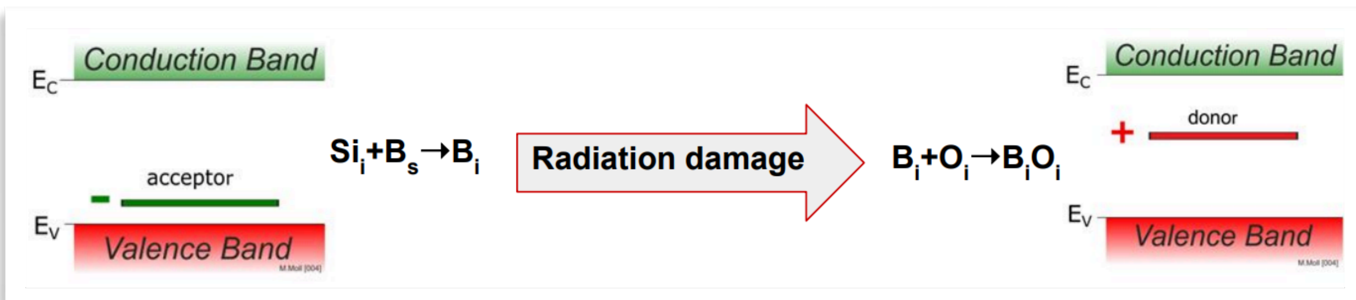
- IV measured from DC pad show VBD@140V

LGAD Sensor R&D

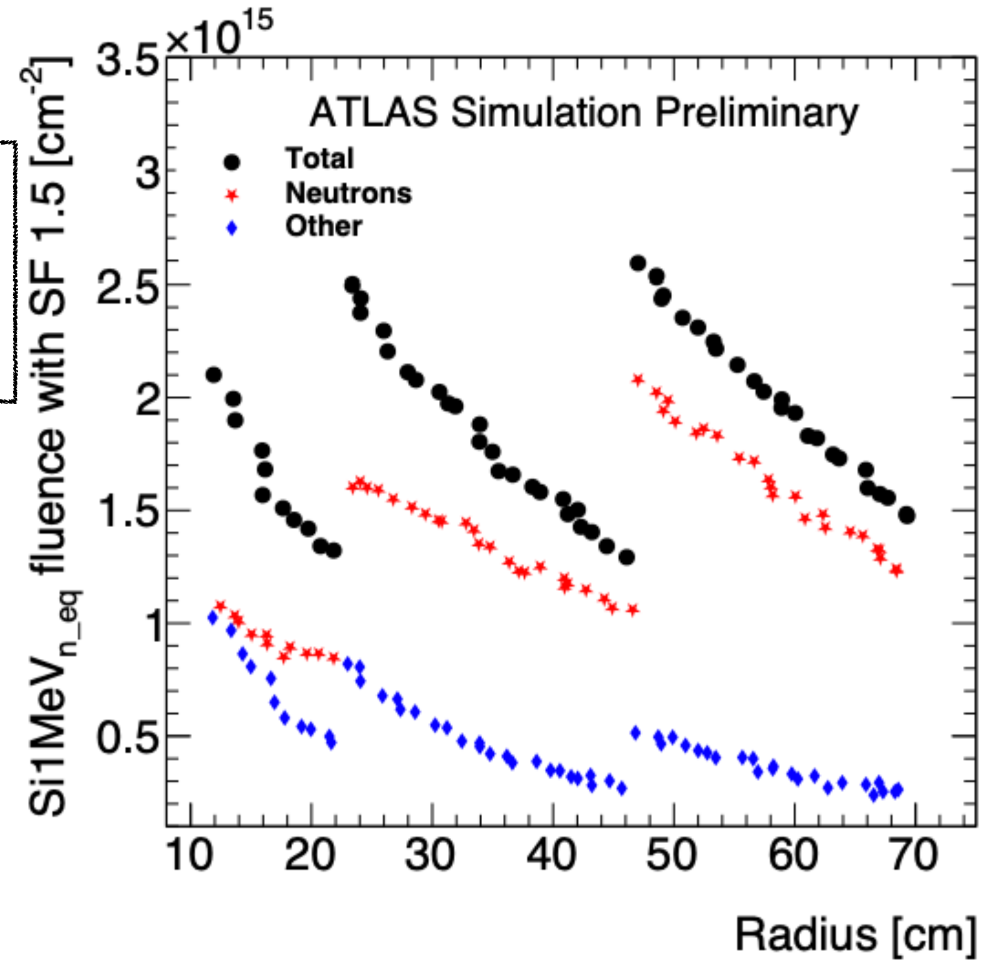
Challenges on LGAD Design

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

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



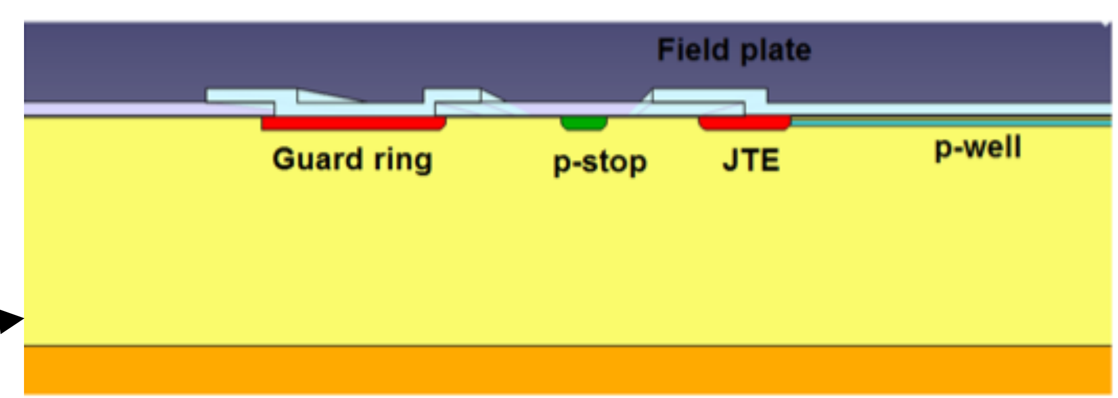
Carbon can protect boron by the competing reactions with Si_i !



HGTD's requirement on the NIEL fluence

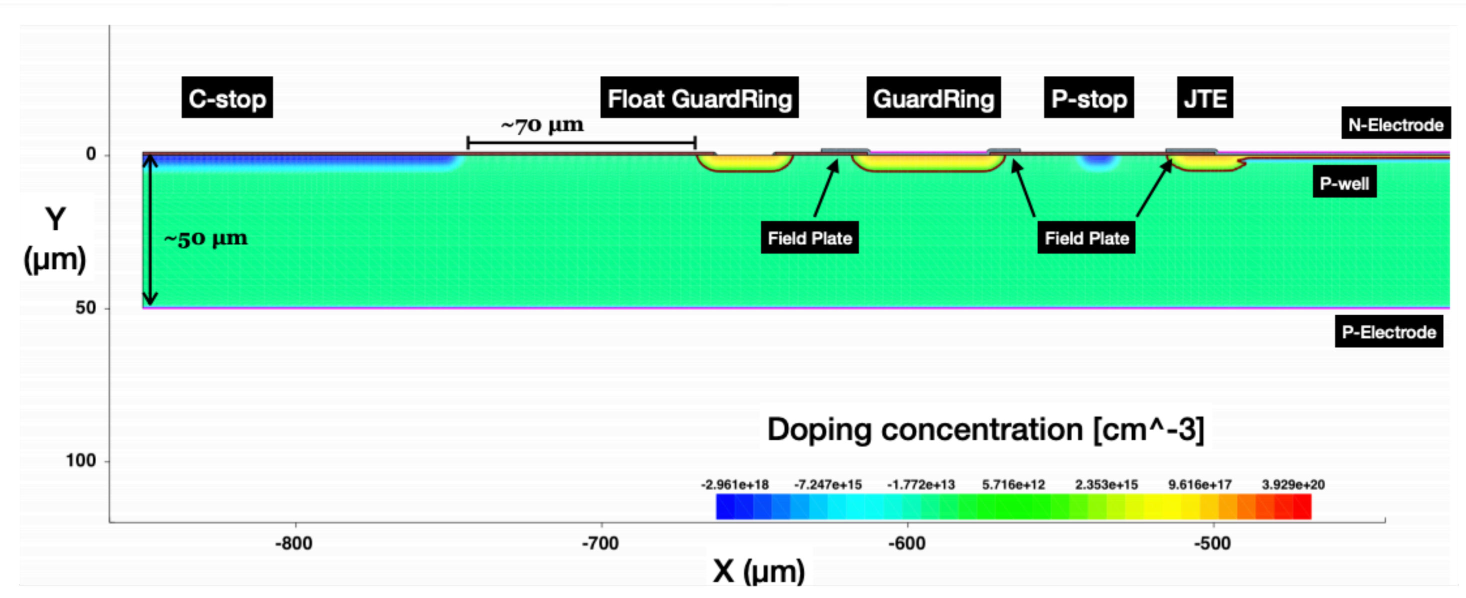
- **Premature breakdown**:
  - Optimization of the peripheral region to prevent premature breakdown
  - Implementation of the structures commonly used in ***power semiconductor device***:

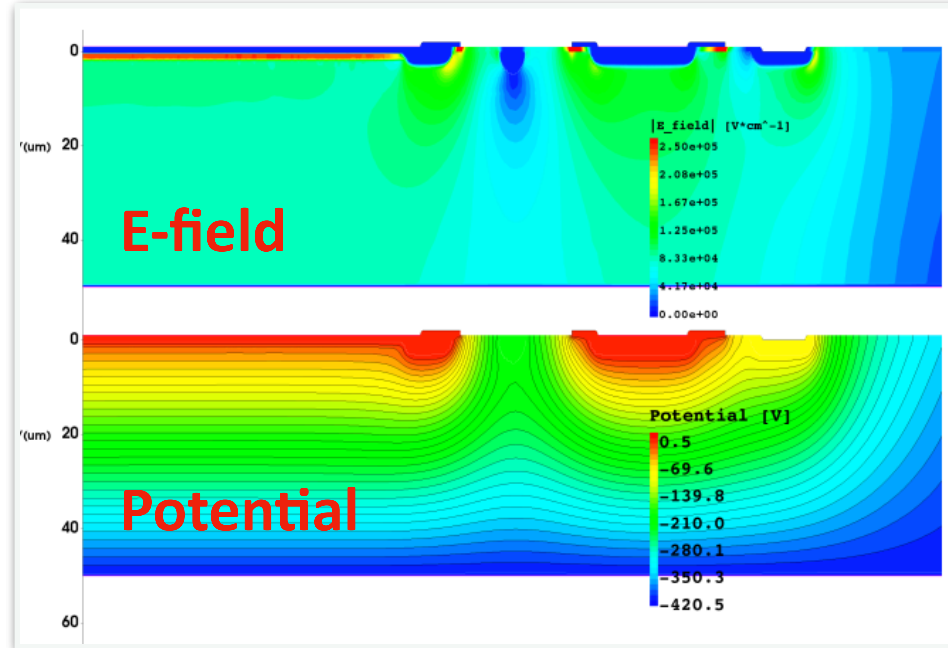
Guard ring, JTE, Field plate



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

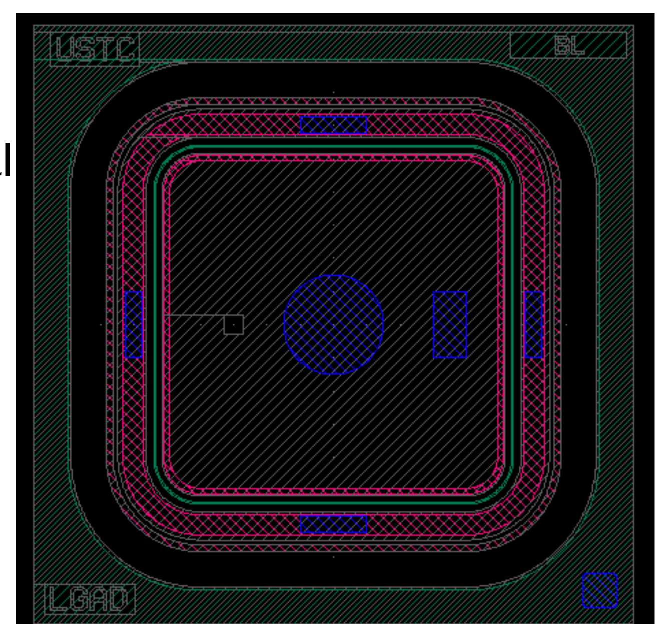
➡**Recommendation:**

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

•Schedule:

Simulation → • **Layout Mask** • **Fab. Process** → **Functional USTC LGADs**

- April 2019: Simulation work done
- 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 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**



Designed mask

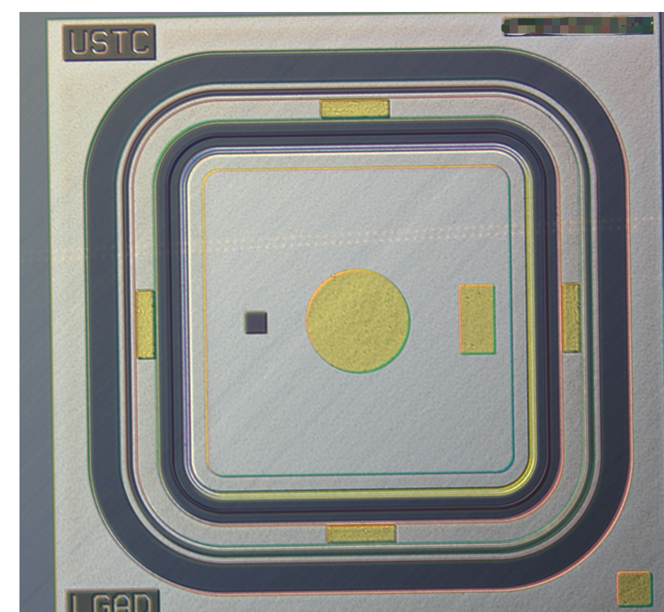
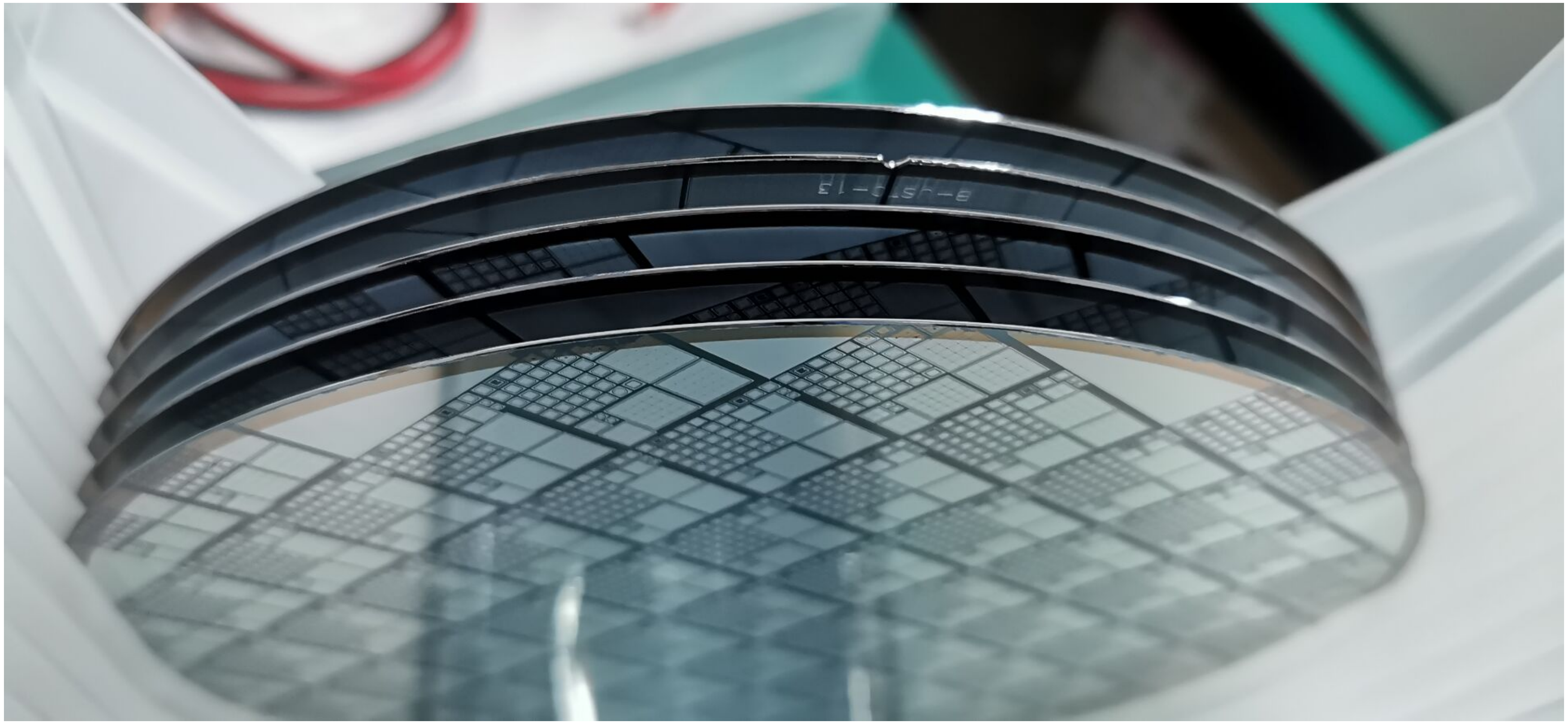


Photo of the device produced

Photo of the five wafers received

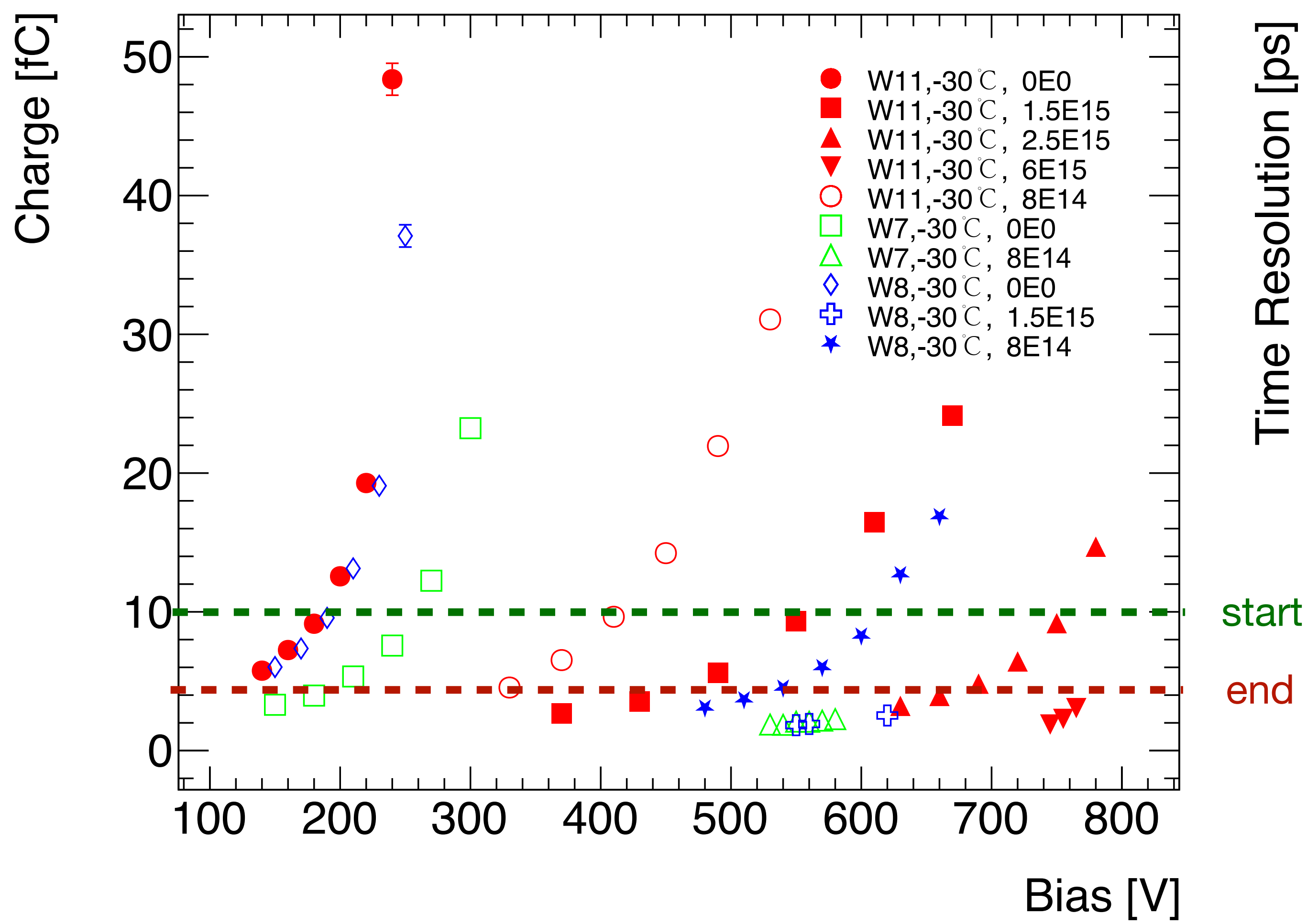


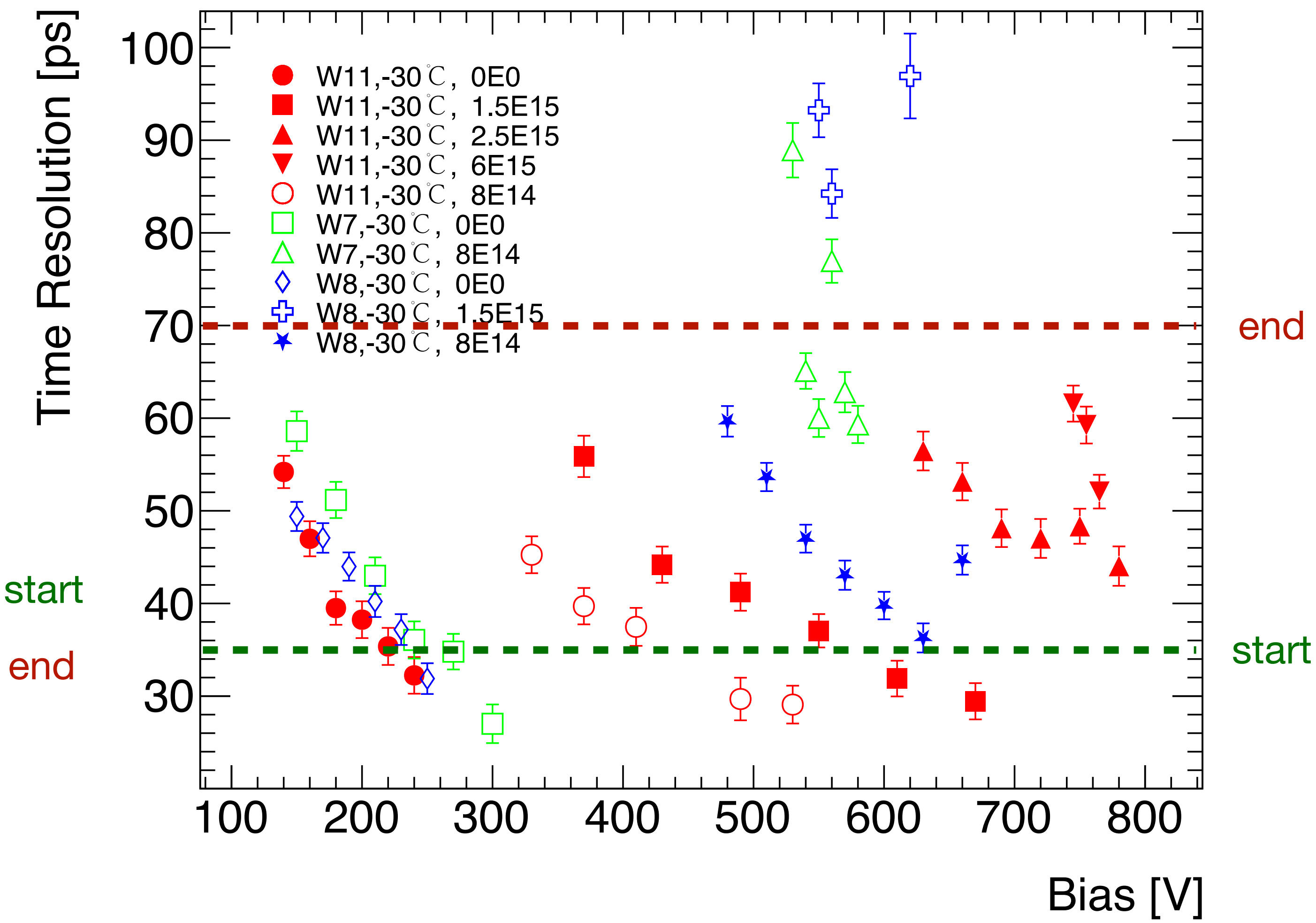
Charge collection and timing resolution (v1.1)

W11 (carbonated), most promising for v1.1

*Measured at -30°C with Sr90 source

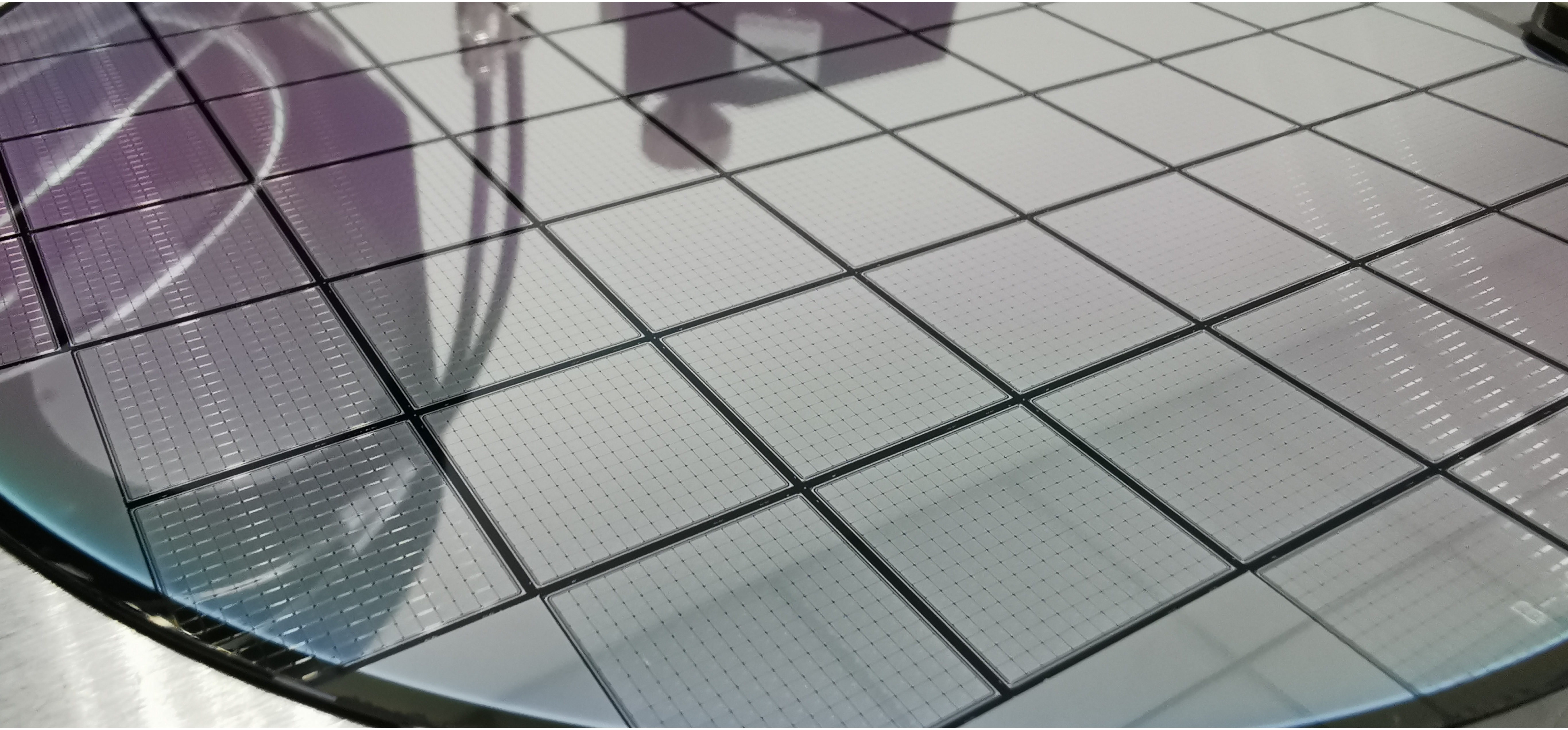
* Dashed lines indicated the specification of HGTD sensors, at the start/end of the operation





- The carbonated USTC W11 LGADs have fulfilled the radiation hardness requirement of HGTD.
  > The σ_t can reach 50 ps within 650V bias after the 2.5E15 fluence
- Even after the 6E15 fluence, the detector can still provided σ_t below 70 ps with higher bias.
- If we can further lower the VBD, the detector can perform even better. => USTC-IME batch 2 => v2.0/2.1

Photo of the full 15x15 LGAD wafer



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

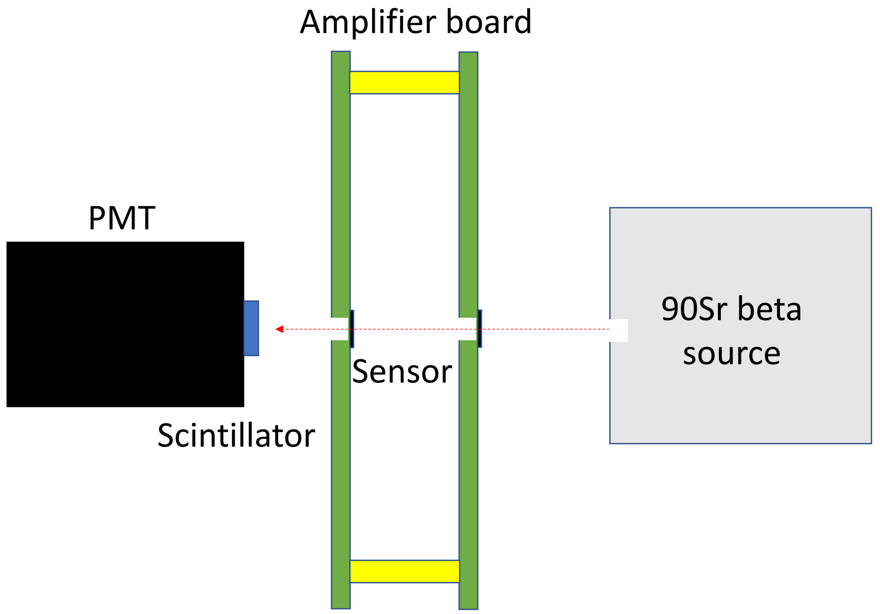
- UCSC pre-amplifier & USTC-1.1 single, un-irradiated
- With the 2nd stage amplifier

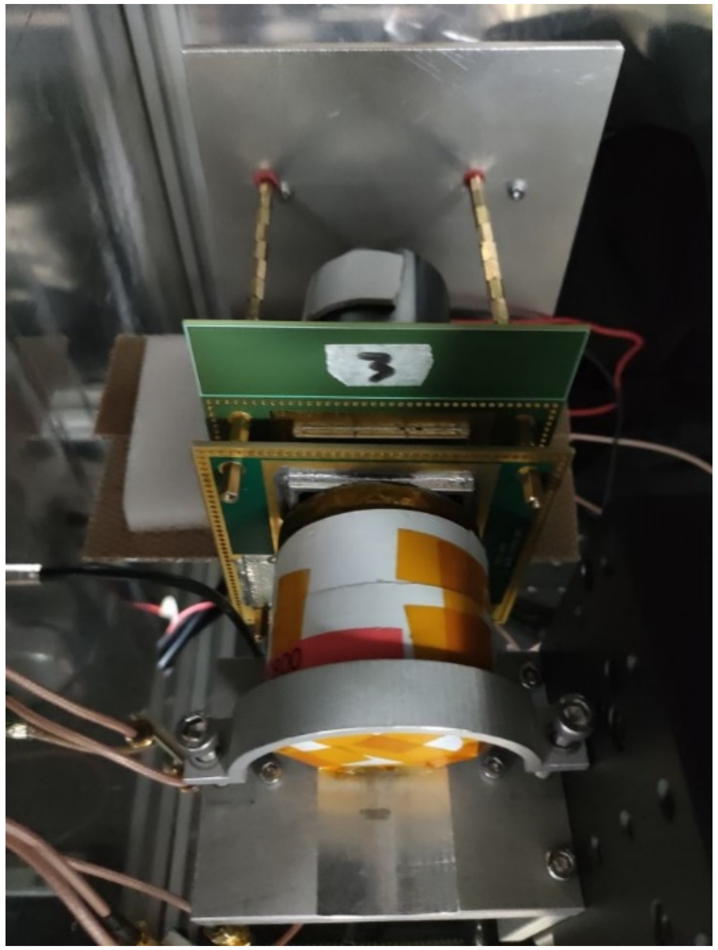
Trigger (Coincidence with reference)

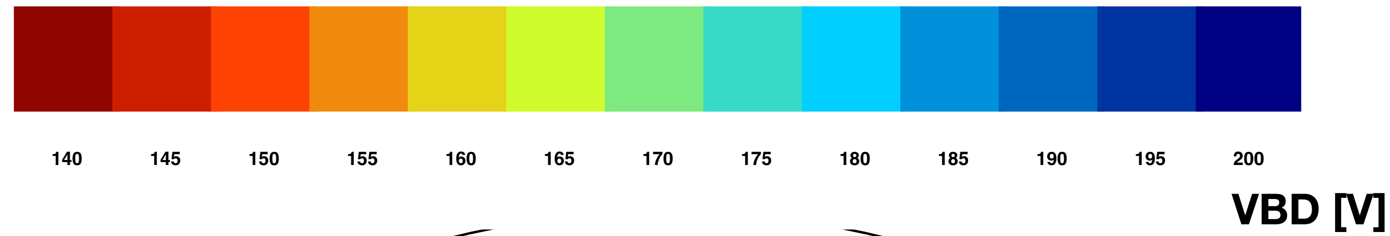
- R5924 PMT & EJ 232 Scintillator
- With the attenuator
- HV: +2000V
- Threshold: 350 mV

Oscilloscope

- Sampling rate: 20 Gs/s
- Bandwidth: 1 GHz





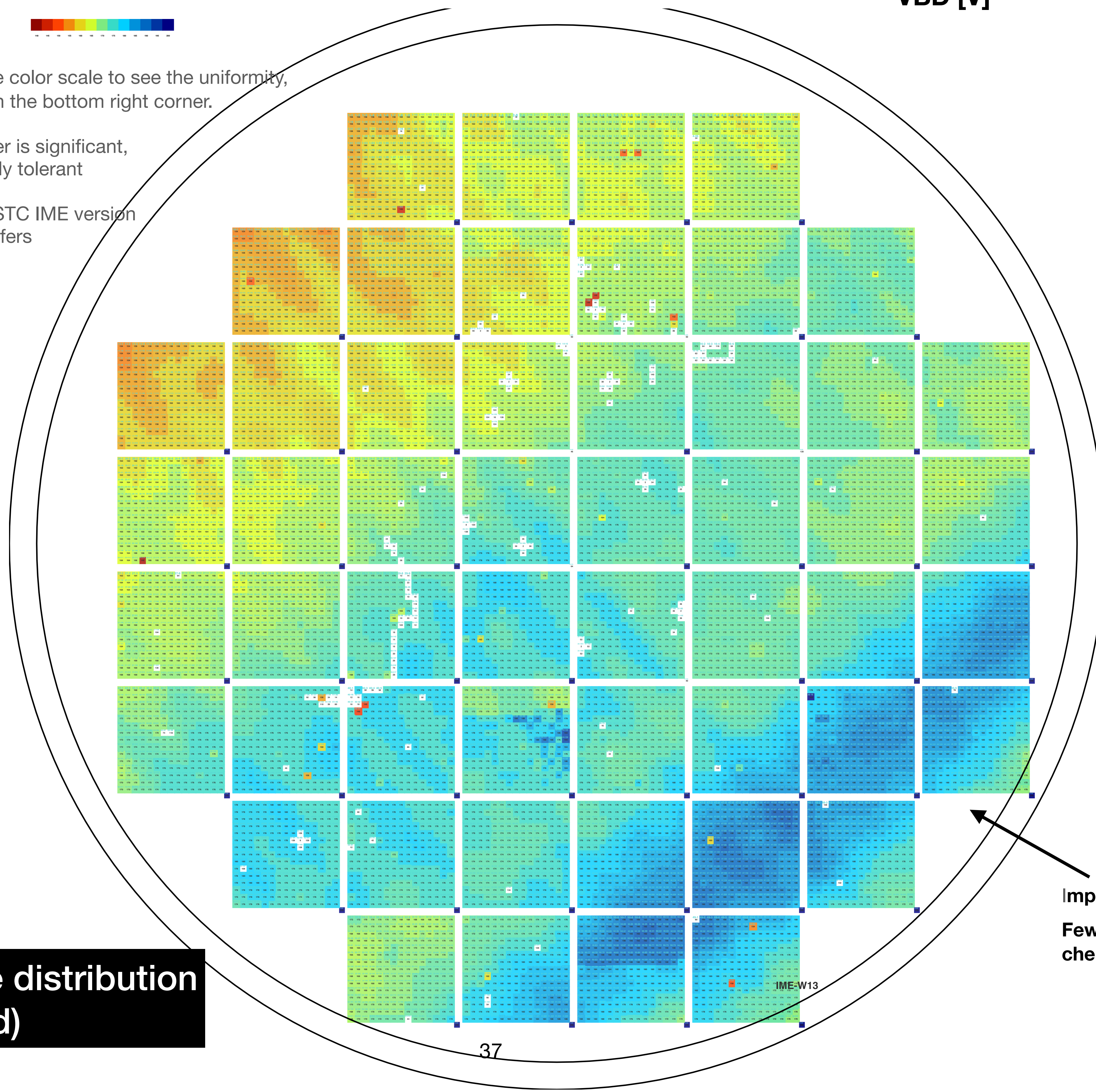


W13

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

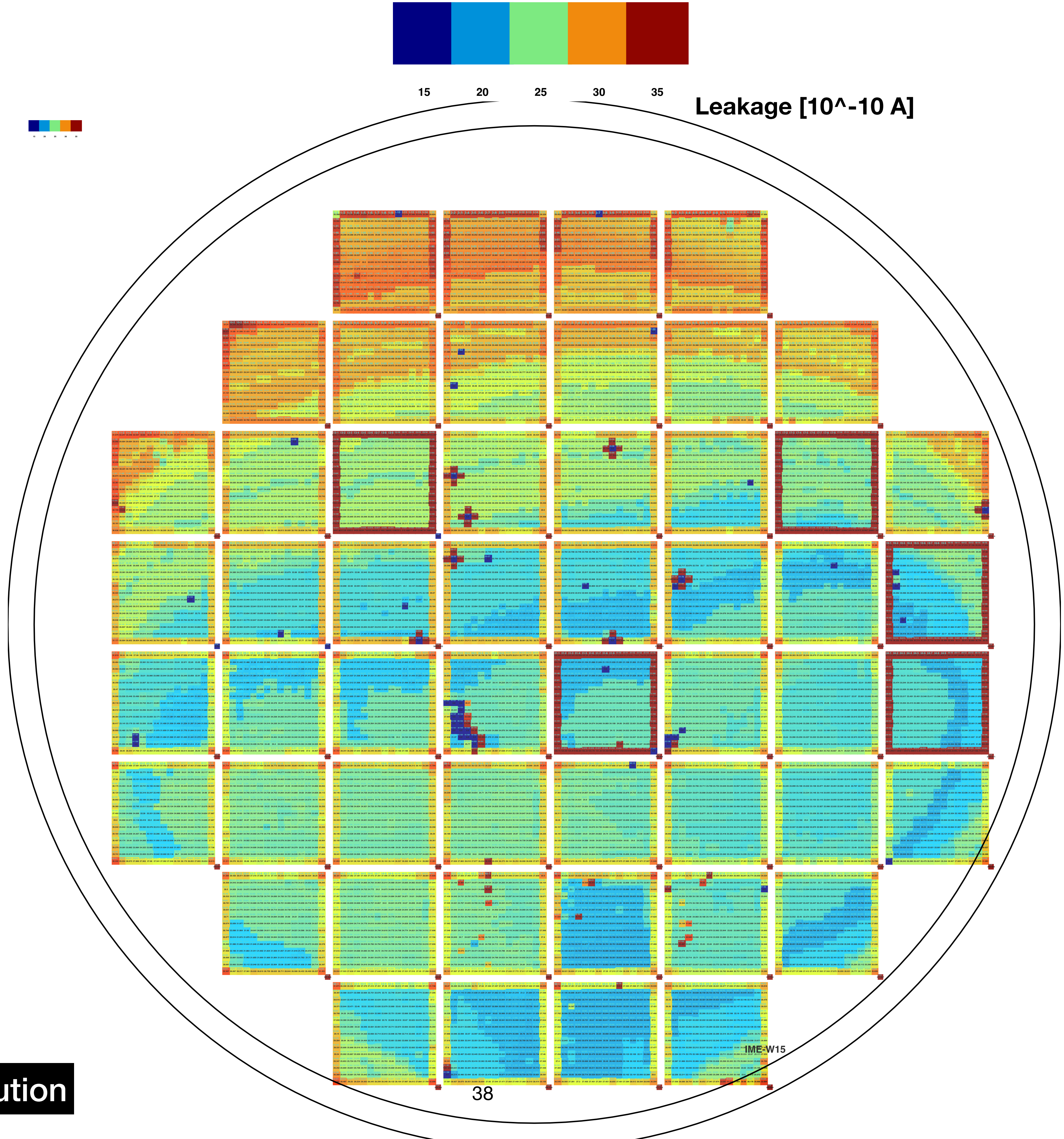
The same pattern shown up in all USTC IME version 2 wafers and seems also in IHEP wafers



Implantation valley

Fewer dose, Higher VBD checking ongoing

Breakdown voltage distribution (Zoomed)

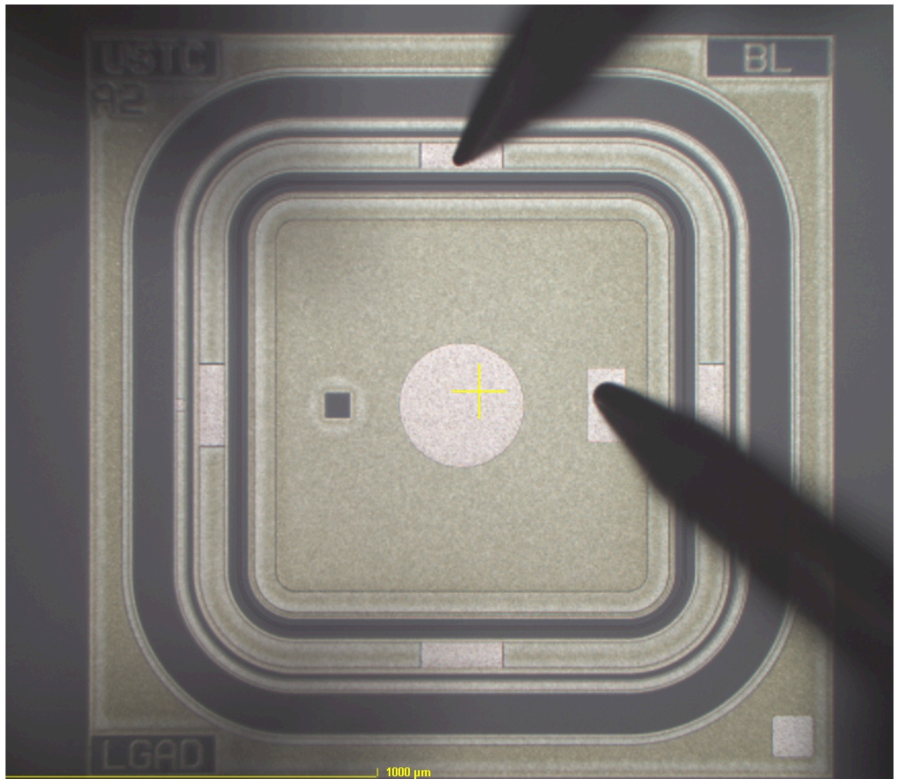


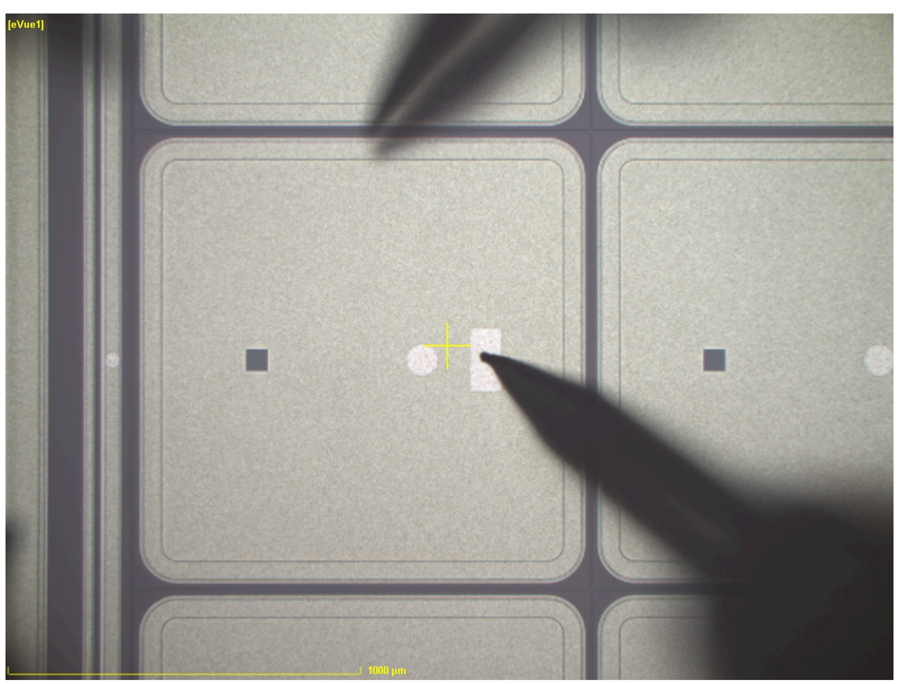
W15

35-50 V averaged

Leakage distribution

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