Characterization of USTC-IME LGAD pre-production sensors for the HGTD

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On behalf of the USTC HGTD Group
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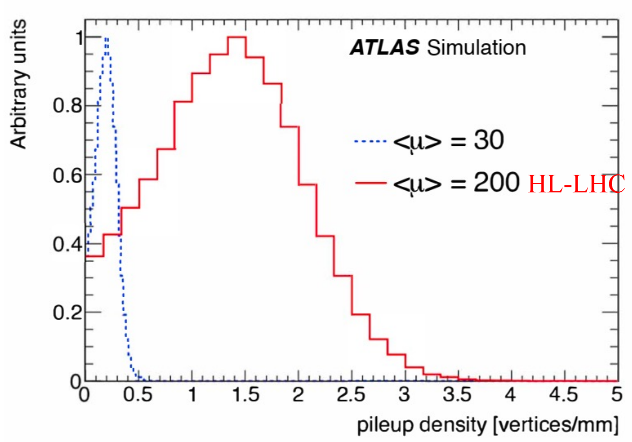
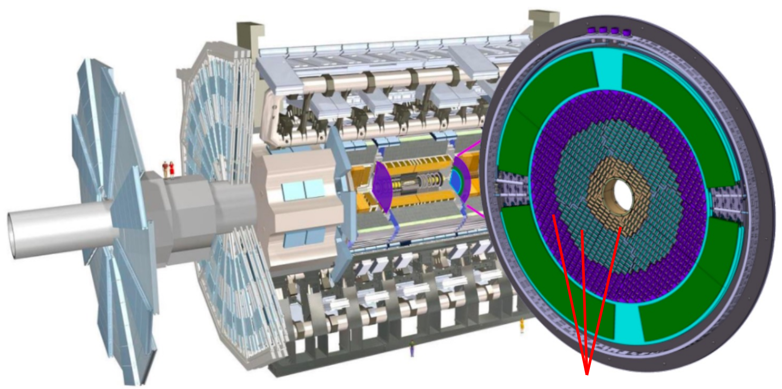
Outline

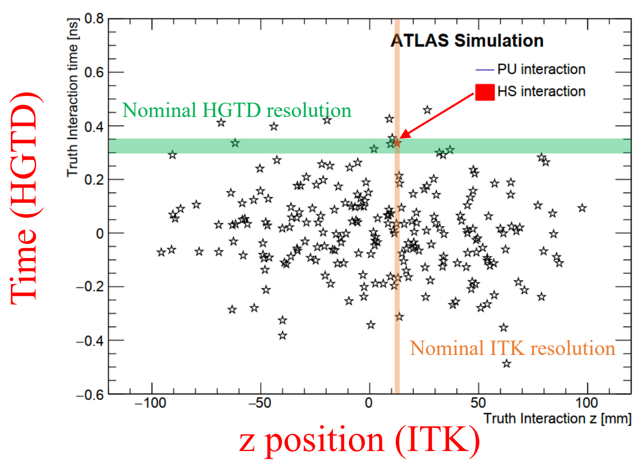
- ATLAS HGTD upgrade and sensor technology
- Radiation hardness evaluation
- Uniformity of large array sensors
- Inter-pad resistance
- Charge collection, timing resolution and hit efficiency
- Summary

ATLAS High Granularity Timing Detector (HGTD)

- **H**igh-**L**uminosity phase of **LHC** (**HL-LHC**): It's hard to associate track to primary vertex in high pileup environment, especially in the forward region (2.4 < |η| < 4.0).
- **H**igh-**G**ranularity **T**iming **D**etector (**HGTD**): to measure high-precision time of charged particles in the forward region, complementing the **I**nner **Trac**k**er** (ITk).







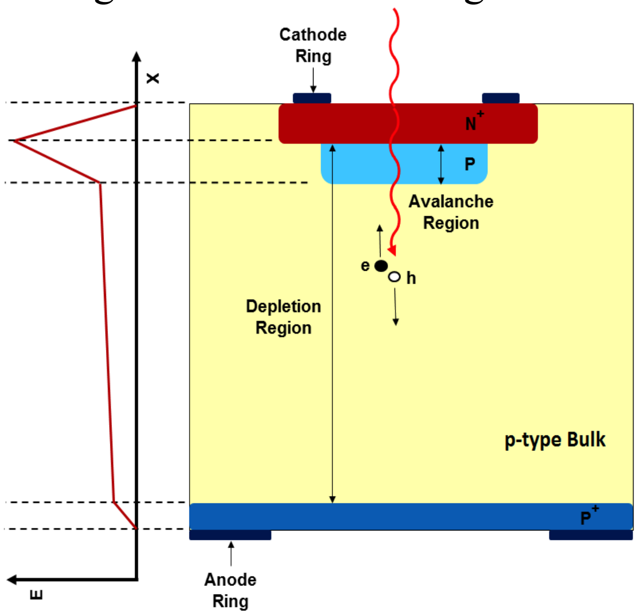
HGTD requirements:

- Withstand intense radiation environment
  - Maximum fluence: 2.5E15 n_{eq}/cm^2
  - Total Ionising Dose (TID): 2 MGy
- Collected charge per hit > 4 fC
- time resolution: 35 ps (start), 70 ps (end) per hit / 30 ps (start), 50 ps (end) per track
- Hit efficiency of 97% (95%) at the start (end)

Timing resolution of LGAD

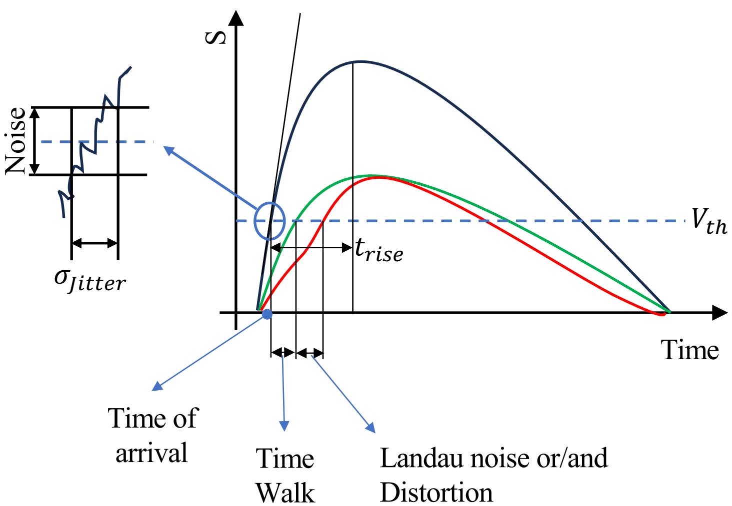
- N^{+}-P-P^{-}-P^{+} structure with **a moderately doped P-type layer** to produce a high electric field (>300 kV/cm).
- The gain is realized by the **impact ionization** of migrating carriers which acquire enough energy in the high electric field during the collection process.

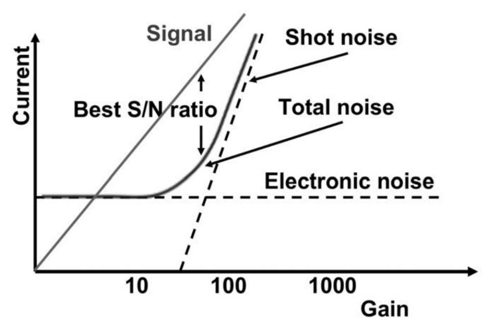
Solid-State Electronics 18 (1975) 161 NIMA 388 (1997) 79-90



$$\sigma_t^2 = \sigma_{Jitter}^2 + \sigma_{Time\ Walk}^2 + \sigma_{Landau}^2 + \sigma_{Distortion}^2 + \sigma_{TDC}^2$$

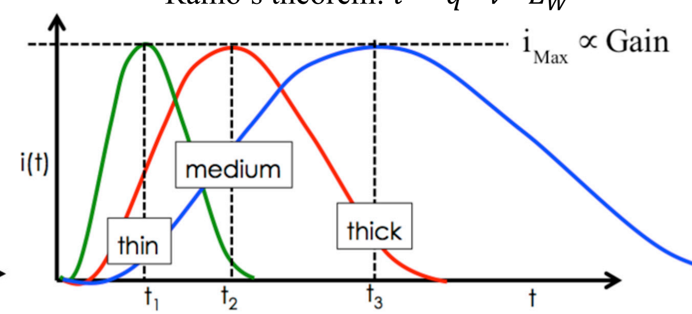
- $\sigma_{Jitter} \sim \frac{t_{rise}}{S/N}$, where t_{rise} is rise time and S/N is signal to noise ratio.
- $\sigma_{Time\ Walk} \sim \left[\frac{V_{th}}{S/t_{rise}}\right]_{RMS}$, where V_{th} is threshold.
- σ_{Landau}: caused by non-uniform energy deposition.
- $\sigma_{Distortion}$: caused by non-saturated velocity $\vec{v}$ and non-uniform weighting field $\vec{E}_W$.
- σ_{TDC}: TDC binning resolution, $25/\sqrt{12}$ (7.2) ps.





⇨ **Low gain**

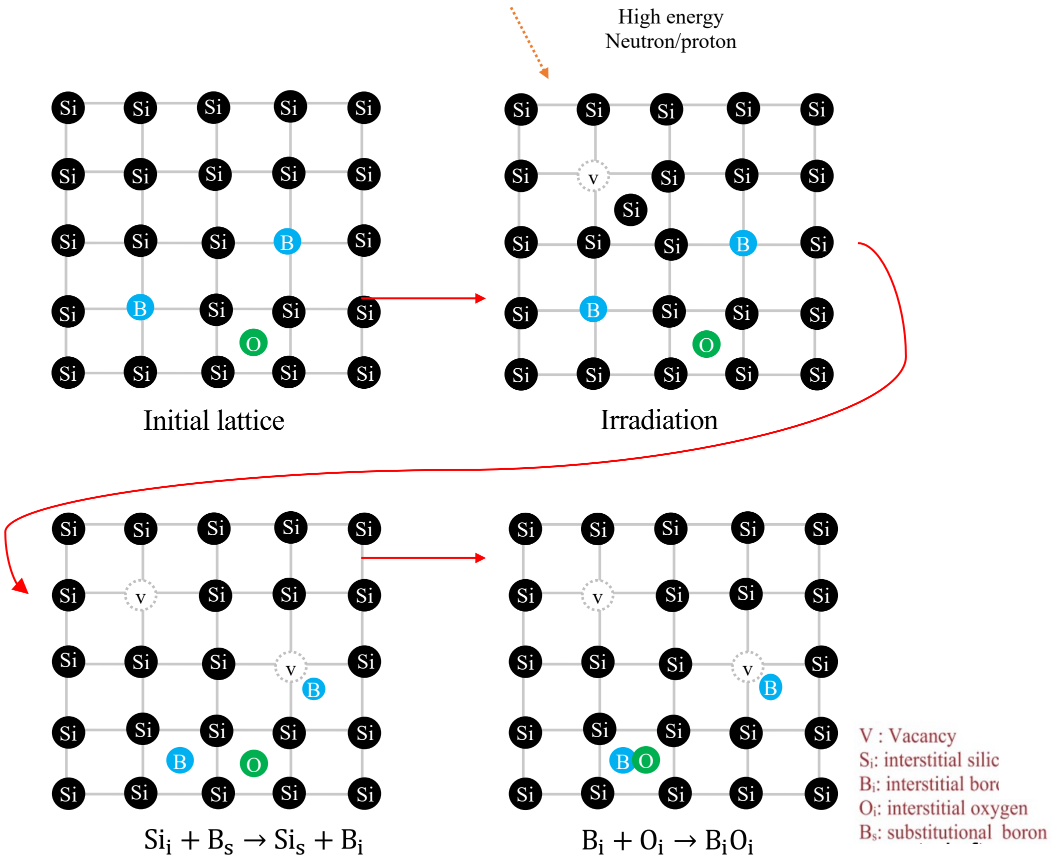
Ramo's theorem: $i = q \cdot \vec{v} \cdot \vec{E}_W$



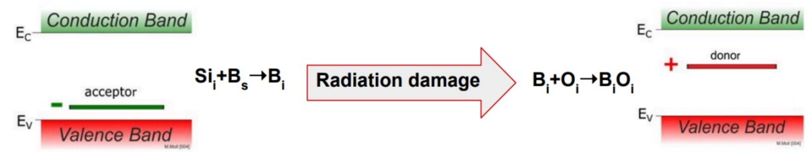
⇨ **Thin detector**

LGAD R&D

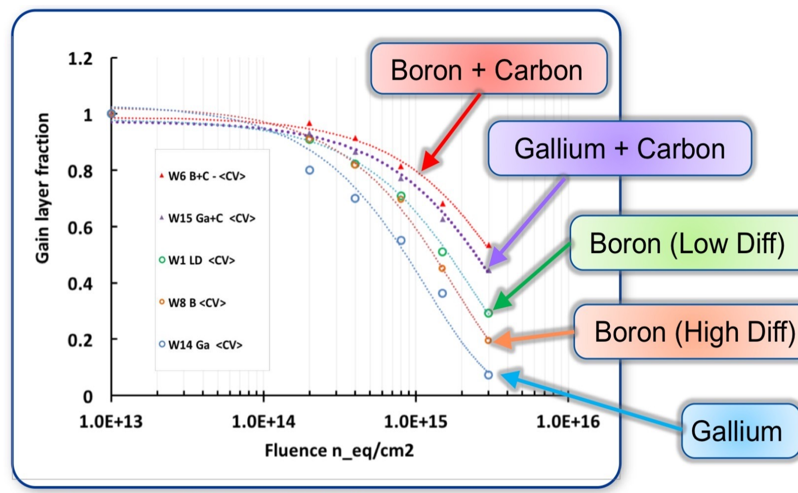
- The **reduction of effective doping** in the gain layer is caused by the "acceptor removal" process after irradiation → LGADs' gain reduces. NIMA 919 (2019) 16-26 2015 JINST 10 P07006
- Explored use of **different designs**, **doping materials** and **C-enriched substrates** → Boron + Carbon shows largest gain after irradiation ($C_i + O_i \rightarrow C_iO_i$ competes with $B_i + O_i \rightarrow B_iO_i$).



Acceptor (B_s) removal in the gain layer after irradiation

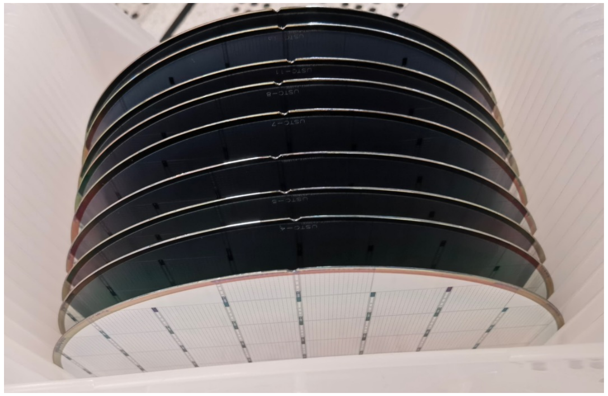


M. Moll, VERTEX2019

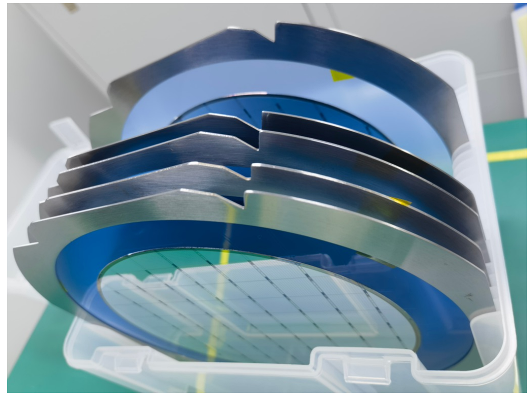


G.Paternoster, TREDI 2019

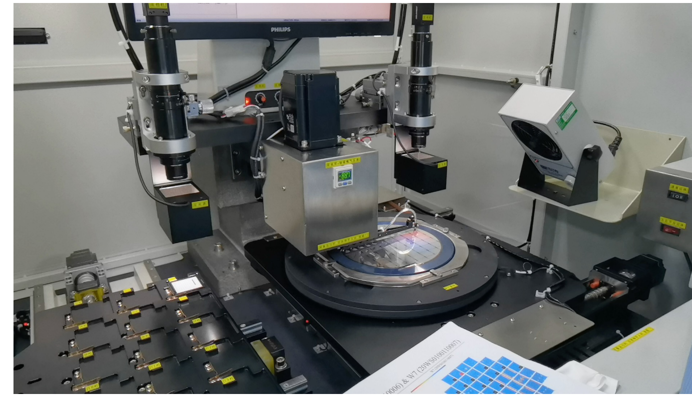
USTC-IME LGAD pre-production sensor for HGTD



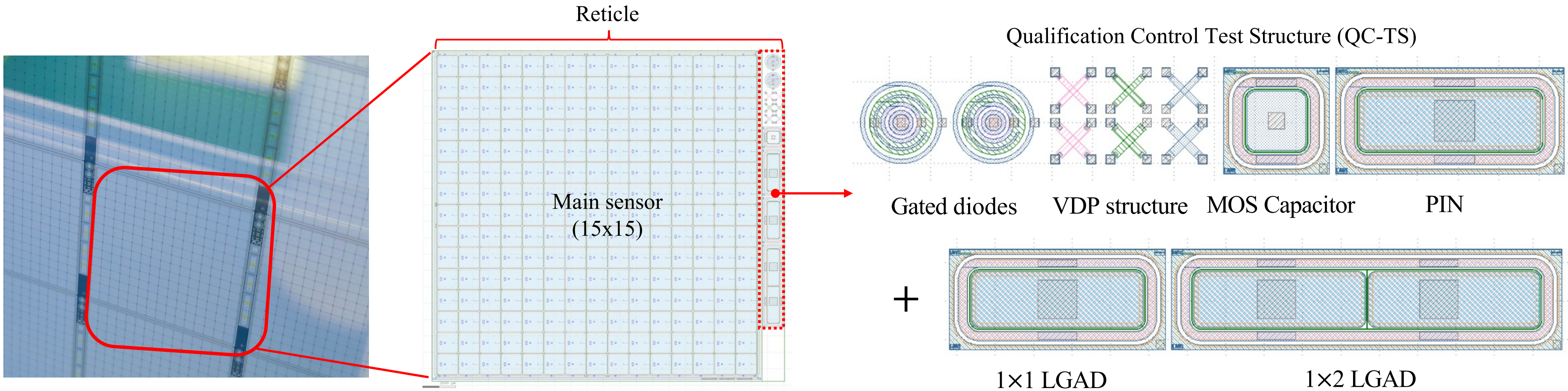
9 selected wafers



5 thinned, UBMed and diced wafers



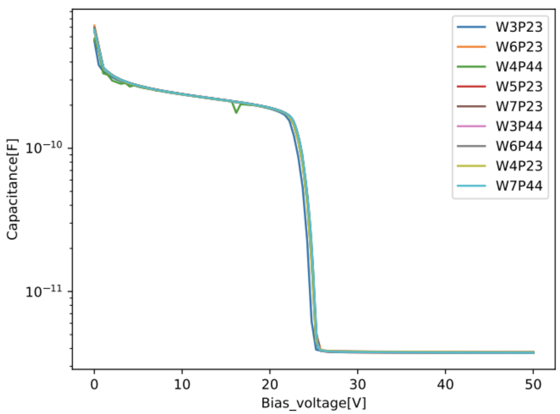
The mechine to pick and pack the sensors



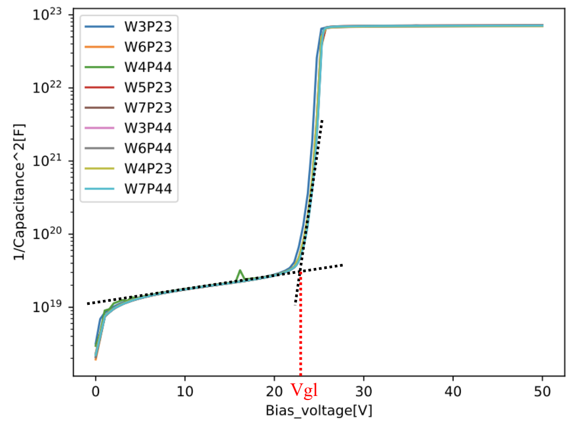
- The vender testing of USTC-IME LGAD pre-production sensors has been finished last year [link].
- ➢ The wafer with 18 good sensors has been selected out, thinned and metalized on backside last year.
- 5 wafers of them have UBMed and diced this year.
- ➢ This talk is focus on the recent LGADs testing results of these 5 wafers.

CV/IV measurements of QC-TS single LGADs

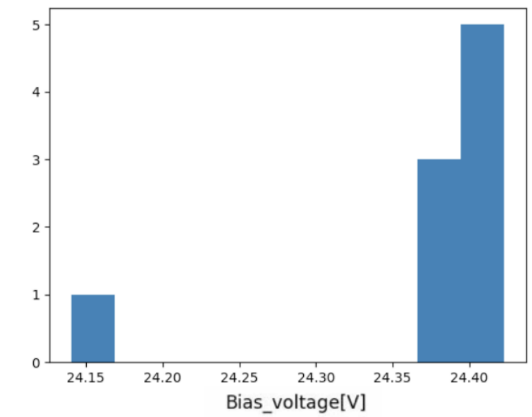
CV curves



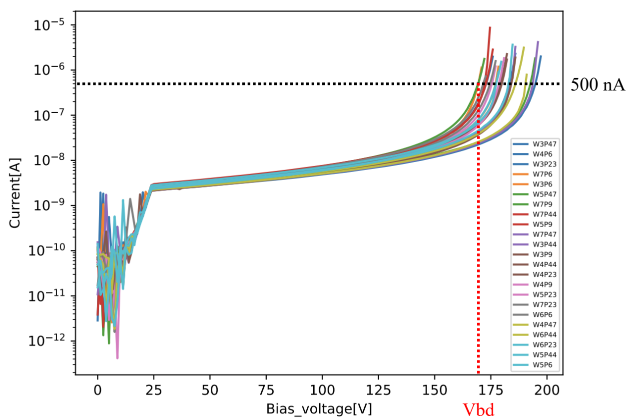
$1/C^2$-V curves



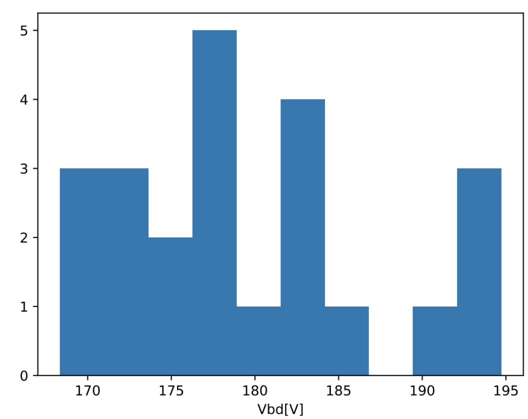
Vgl distribution



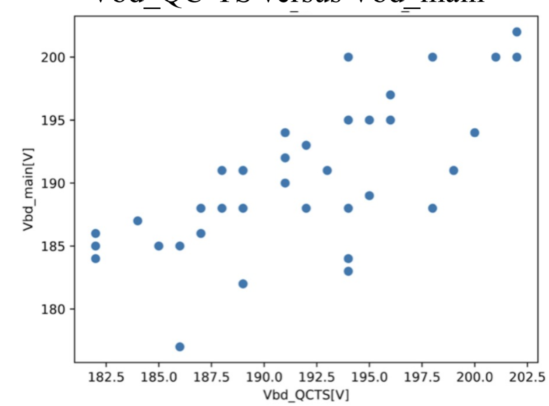
IV curves



Vbd distribution



Vbd_QC-TS versus Vbd_main



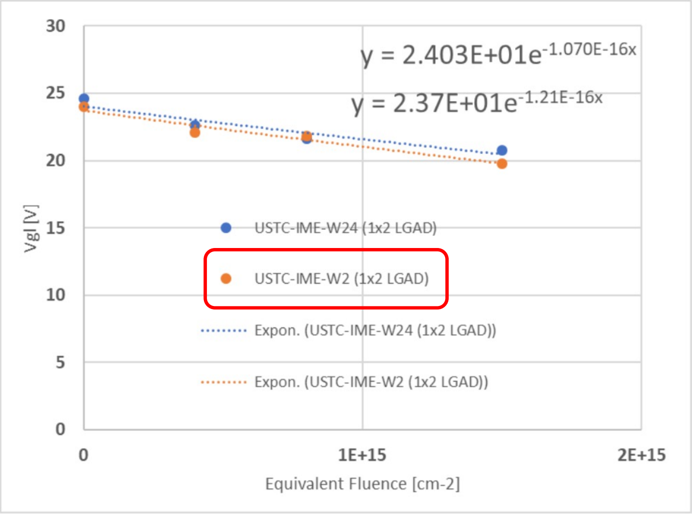
- The variation of these sensors' gain-layer depletion (Vgl) is 0.2% (within specification ~1%).
- The breakdown voltage (Vbd) spread is also within specification (± 8%).
- Positive correlation for Vbd between QC-TS and main sensors as expected.

Evaluation of radiation hardness

- USTC-IME QC-TS sensors were exposed to fluence up to 4×10^{14}, 8×10^{14}, 1.5×10^{15} n_{eq}/cm^2, and 2.5×10^{15} n_{eq}/cm^2 at the TRIGA reactor in Ljubljana, Slovenia with **neutrons.**
- **Acceptor removal constant (c-factor)** is extracted from the gain layer depletion voltages obtained from CV curves:

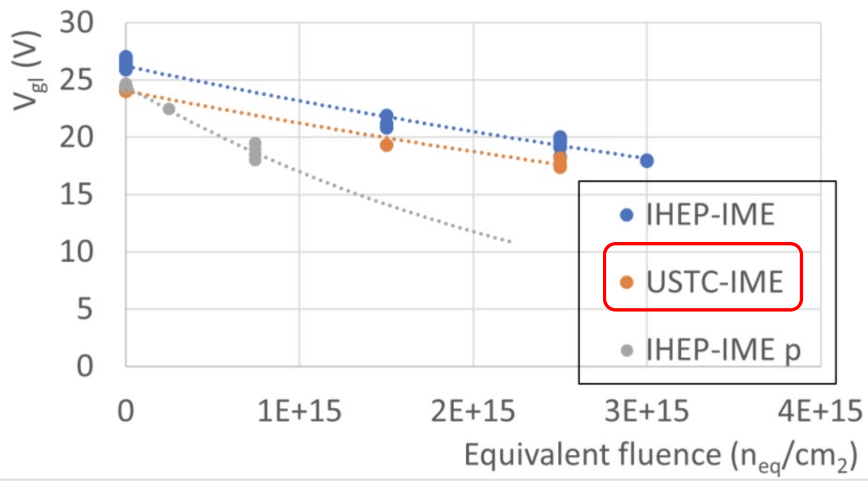
$$\frac{V_{gl}(\Phi_{eq})}{V_{gl}(0)} = e^{-c\cdot\Phi_{eq}}$$

No-UBMed and thick sensors



Measured by JSI@2023

UBMed and thin sensors

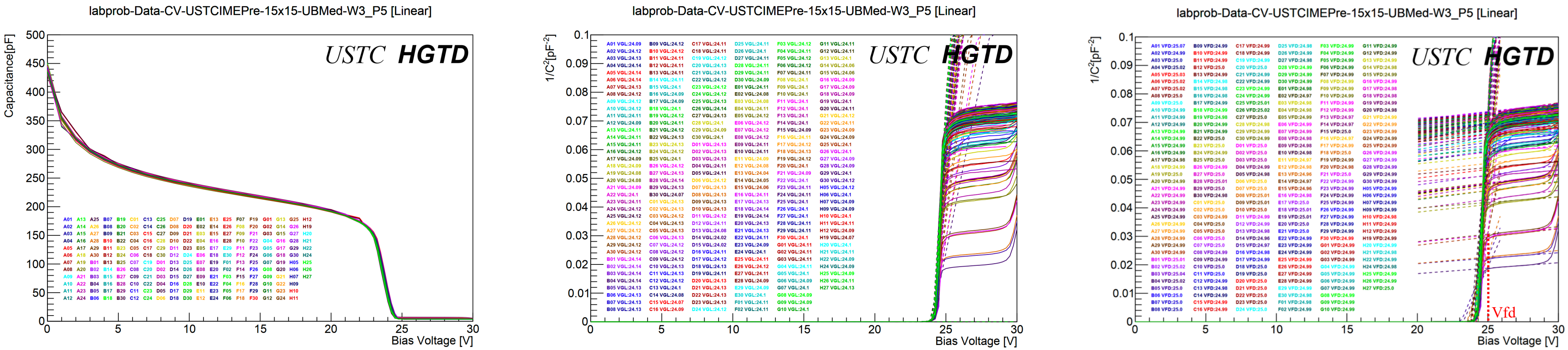


Measured by JSI@2024

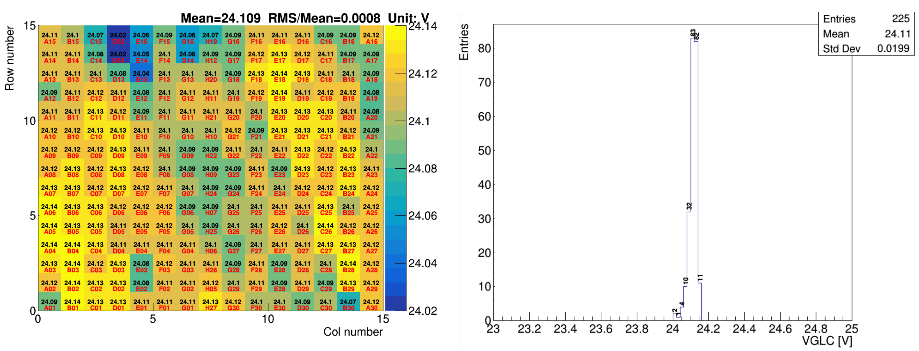
- Both the acceptor removal constant of the No-UBMed sensors (1.21×10^{-16} cm^2) and UBMed sensors (1.2×10^{-16} cm^2) is similar, which means the gain layer is radiation tolerant.

Uniformity of unirradiated main sensors (CV)

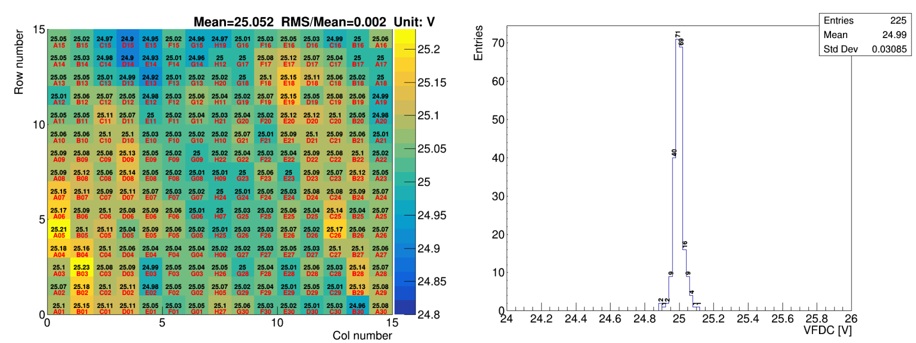
CV curves



Vgl distribution



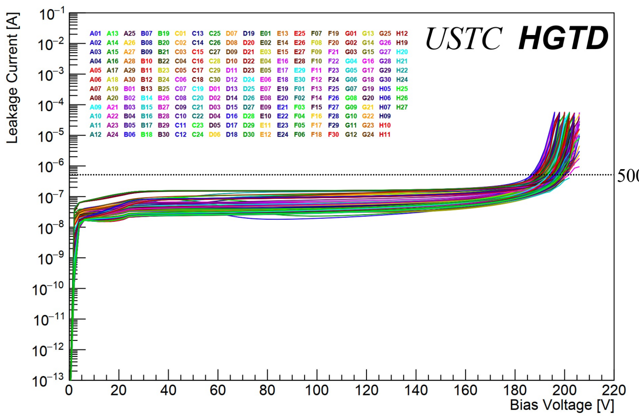
Vfd distribution



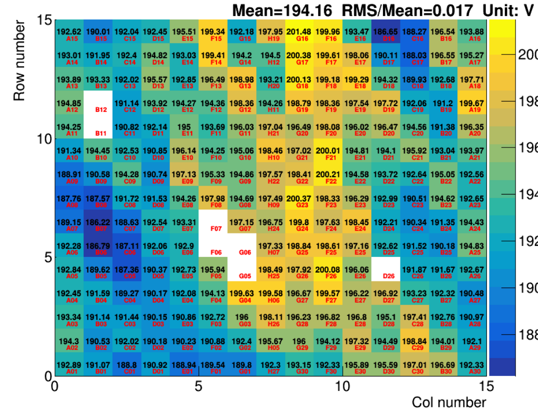
- Tested by 15×15 probe card, Temperature: 20 ^{o}C, Frequency: 10 kHz, VAC: 0.51 V, GR floating.
- The dashed lines in 1/C^2-V curves are the fitted lines.
- The Vgl spread over this sensors is 0.0008 which meets the specification (<0.005).
- And the full depletion voltage voltage (Vfd) spread over this sensor is about 0.002 which also shows the uniformity is good.

Uniformity of unirradiated main sensors (IV)

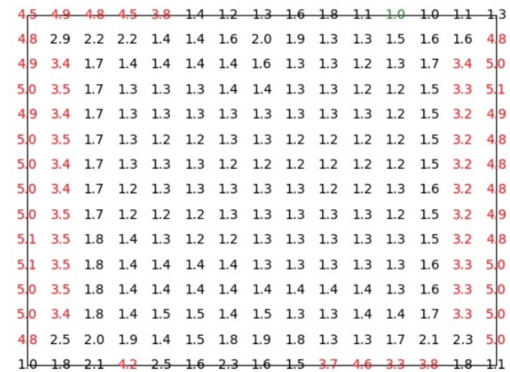
- Tested by **probe needles** while other pads and GR are floating, **R.T.**



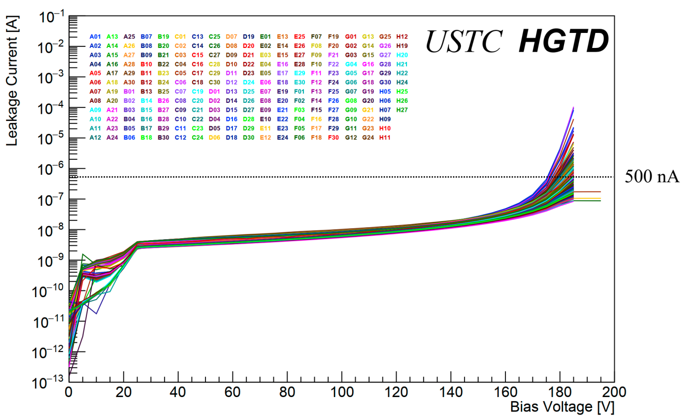
Vbd distribution



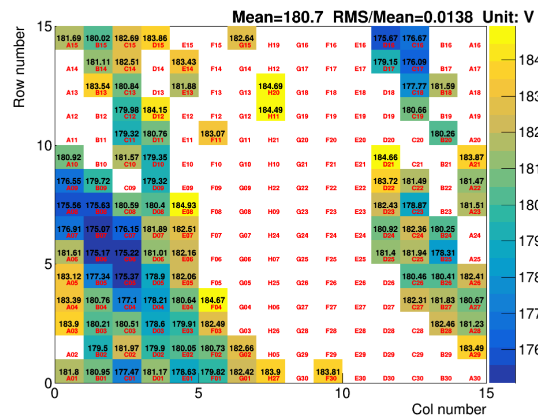
I@0.8 minimum Vbd / (I@0.8 minimum Vbd)$_{min}$



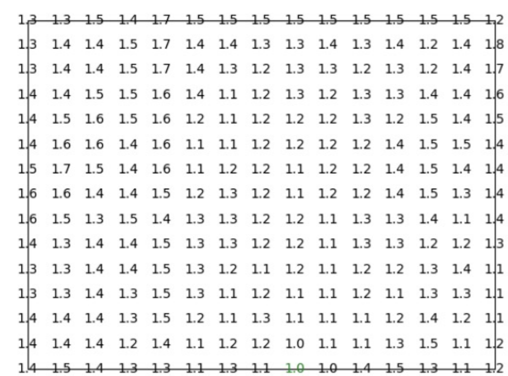
- Tested by **15×15 probe card** while other pads are grounded and GR is floating, **chuck at 20 ^{o}C**



Vbd distribution



I@0.8 minimum Vbd / (I@0.8 minimum Vbd)$_{min}$



- The blank boxes represent pads which don't break down at maximum applied bias voltage and the spread of obtained Vbd is good enough which is smaller than 0.05.
- The IV curves tested by probe card are more uniform after the full depletion voltage and the peak-to-peak I@0.8 minimum Vbd variation can be smaller than 3.

Summary of unirradiated main sensors' measured values

USTC-IME ID	ATLAS HGTD ID	$\langle V_{bd,pad} \rangle$ [V]	$RMS(V_{bd,pad})/\langle V_{bd,pad} \rangle$	Max/Min(I@0.8 minimum V_{bd})	$\langle V_{gl,pad} \rangle$ [V]	$RMS(V_{gl,pad})/\langle V_{gl,pad} \rangle$	$\langle V_{fd,pad} \rangle$ [V]
W3_P5	20WS3001000305	176.07	**0.0164**	1.6	24.11	**0.0008**	25.05
W3_P9	20WS3001000309	172.8	**0.0169**	1.7	24.15	**0.0008**	25.06
W4_P3	20WS3001000403	166.8	**0.0122**	1.7	24.3	**0.0003**	25.24
W4_P6	20WS3001000406	170.34	**0.0173**	1.7	24.16	**0.0008**	25.08
W5_P5	20WS3001000505	180.7	**0.0138**	1.8	24.1	**0.0009**	/
W5_P8	20WS3001000508	170.65	**0.0162**	1.9	24.17	**0.0007**	/
W6_P5	20WS3001000605	171.12	**0.0129**	2.1	24.14	**0.0011**	25.15
W6_P8	20WS3001000608	170.42	**0.0189**	1.7	24.19	**0.0006**	25.21
W7_P6	20WS3001000706	166.53	**0.0126**	2.5	24.34	**0.0010**	25.36
W7_P9	20WS3001000709	161.43	**0.0127**	1.8	24.37	**0.0007**	25.16
			< 0.05			**< 0.005**	

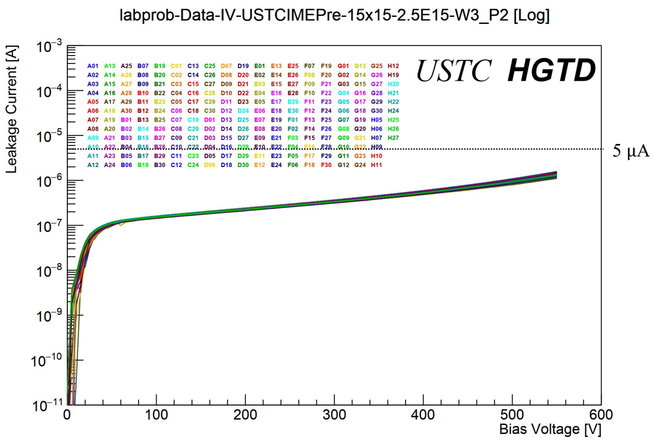
Parameters	Specification	Measured values	Statistics/Total measured sensors
Variation of the V_{fd} between different sensors	**±10%** from the average V_{fd}	**± 0.8%**	8/8
Variation of the V_{gl} between different sensors	**±1%** from the average V_{gl}	**± 0.7%**	10/10
Variation of the V_{bd} between different sensors	**±8%** from the average V_{bd}	**± 5.9%**	10/10

- Besides the spread of all the measured sensors, the variation of the Vgl, Vfd and Vbd between different sensors also meet the specification.

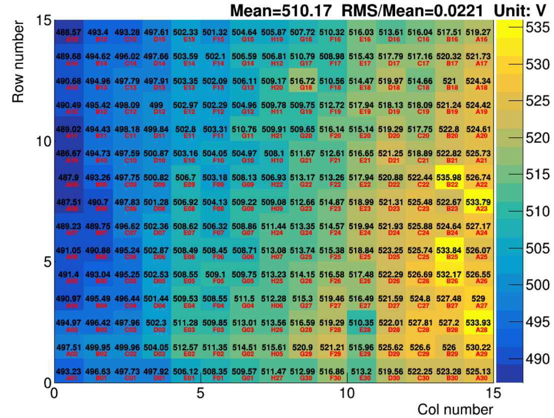
Uniformity of irradiated main sensor

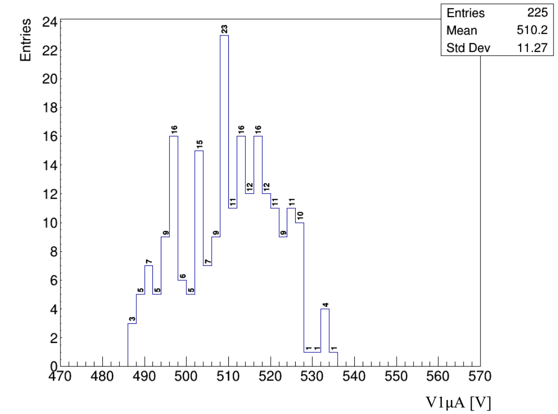
W3_P2@2.5E15 n_{eq}/cm^2

- Tested by 15×15 probe card, Temperature: **-30 °C**, Compliance: 600 μA

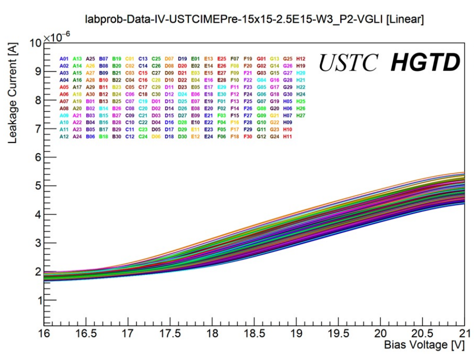


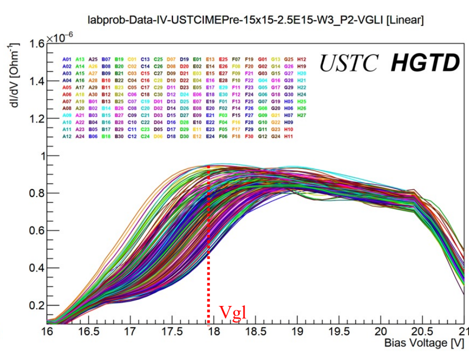
V @ 1 μA distribution



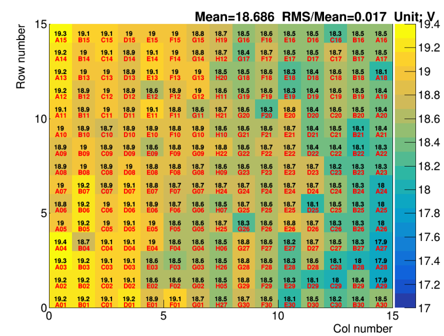


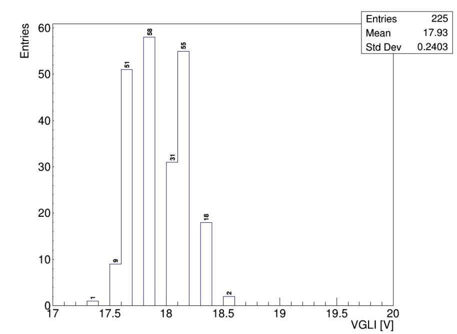
- Tested by 15×15 probe card, Temperature: **20 °C**, Compliance: 1.5 mA





Vgl (from IV) distribution

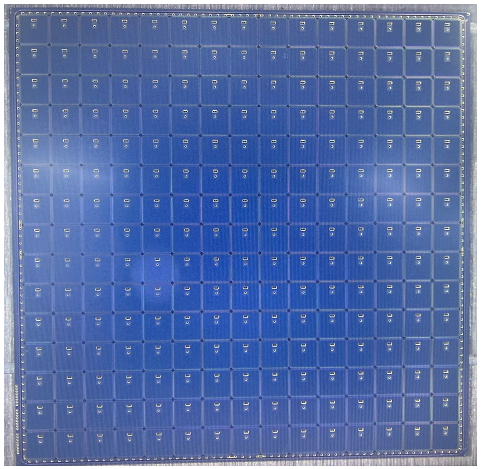


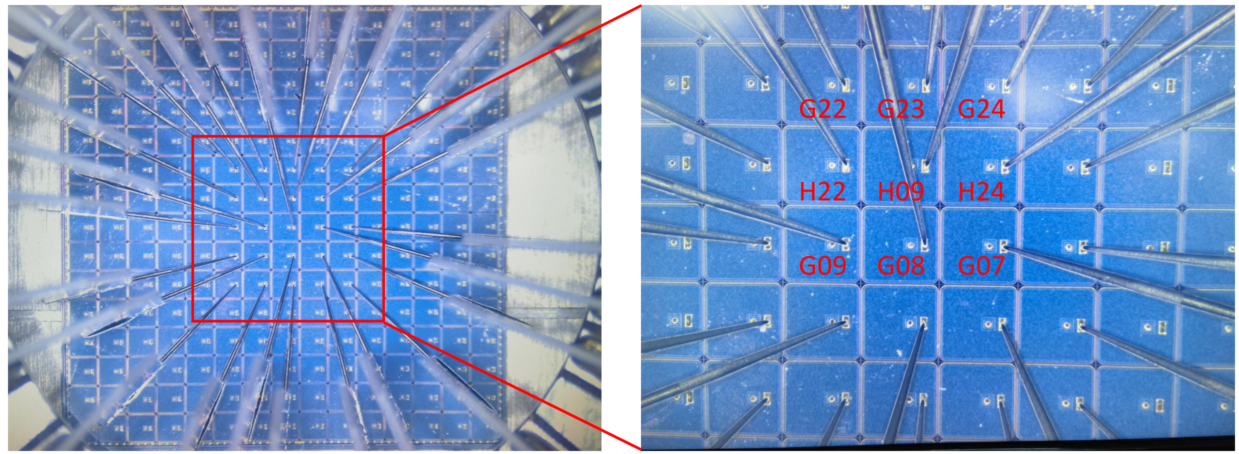


- The V1μA/Vgl spread over this sensor is about 0.022/0.017 including the contribution from the non-uniformity of irradiation fluence across the large array sensors. And the I@550 V of all pads is smaller than 5 μA.
- The power consumption is smaller than < 37 mW/cm^2 and the total maximum leakage curent is smaller than < 74 $\mu A/cm^2$ (Here we consider the Vop, min is V1μA and the sensor's area is 2×2 cm^2).

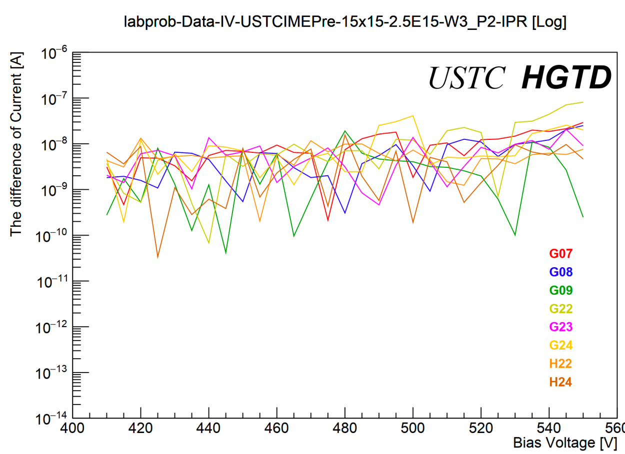
Inter-pad resistance of irradiated main sensors

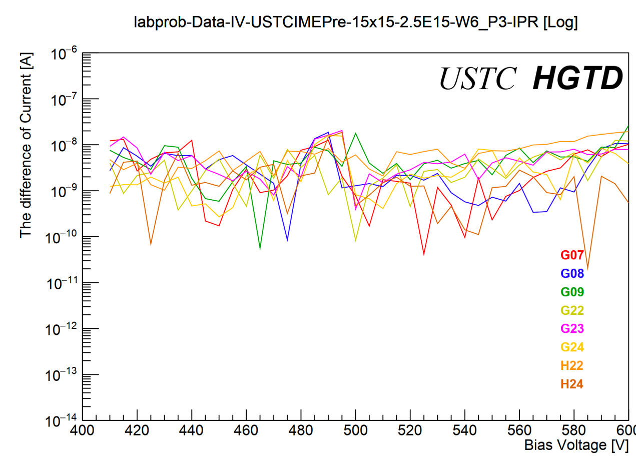
- Tested by 5×5 probe card, Temperature: -30 °C, Compliance: 600 μA
- Irradiate to 2.5E15 n_{eq}/cm^2 at Jožef Stefan Institute (JSI) with **reactor neutrons.**





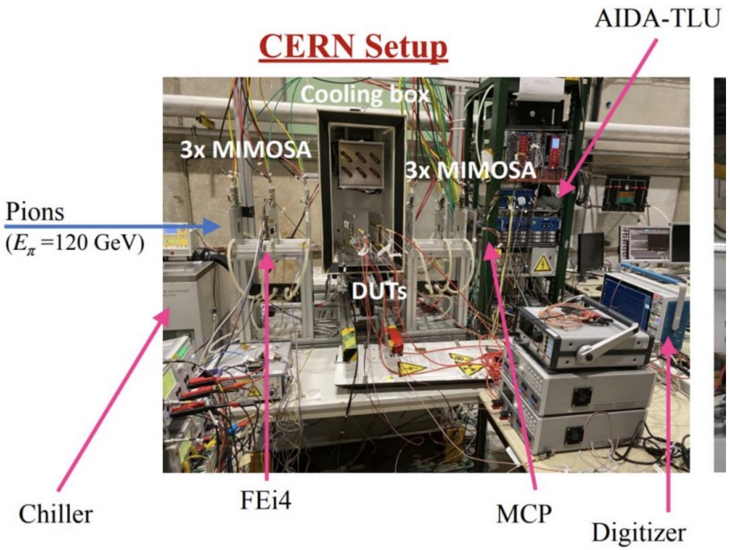
➢ **Configuration (Inter-pad resistance):**
- Apply negative high voltage to sensor's backside.
- Apply **0 or 1 V** to the central pad (H09) and measure the current of neighboring pads, respectively.

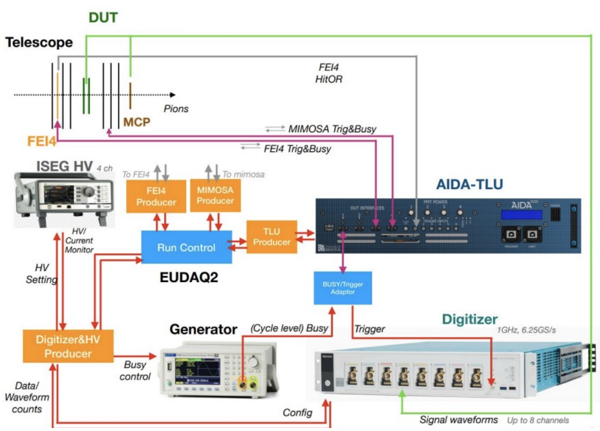


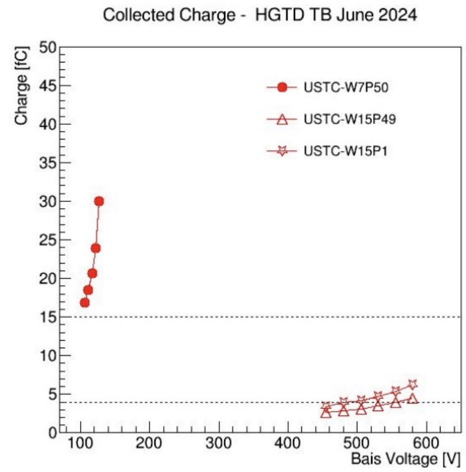


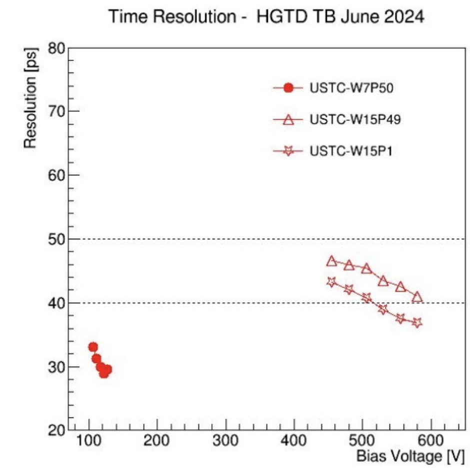
- The difference of current is lower than 100 nA which indicates that the inter-pad resistance is **larger than 10 MΩ**.

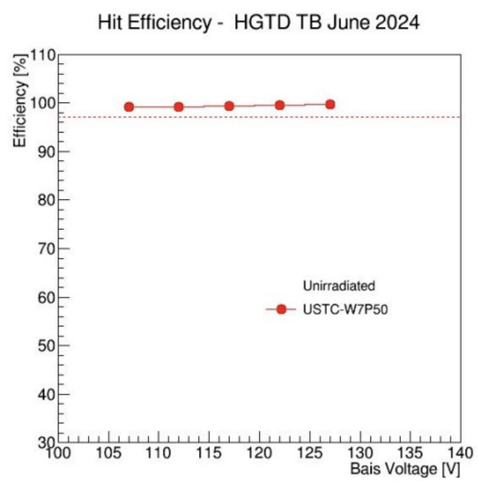
Charge collection, timing resolution and hit efficiency

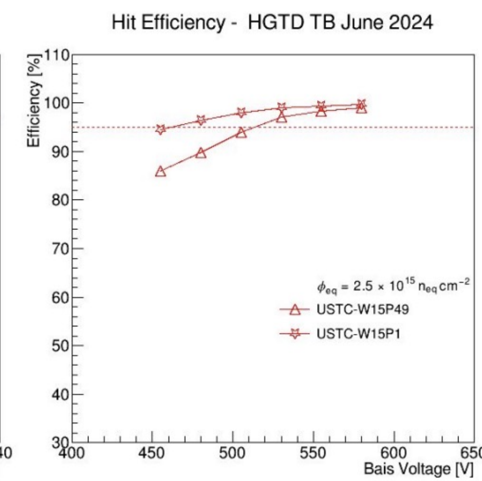












- The irradiated USTC sensor performance is evaluated at the 120 GeV pion beam at CERN-SPS.
- Hit Efficiency = (Rescontructed tracks with $q > Q_{cut}$)/(Total rescontructed tracks).
- The collected charge, efficiency and time resolution after irradiation can fulfill the requirement of HGTD well.

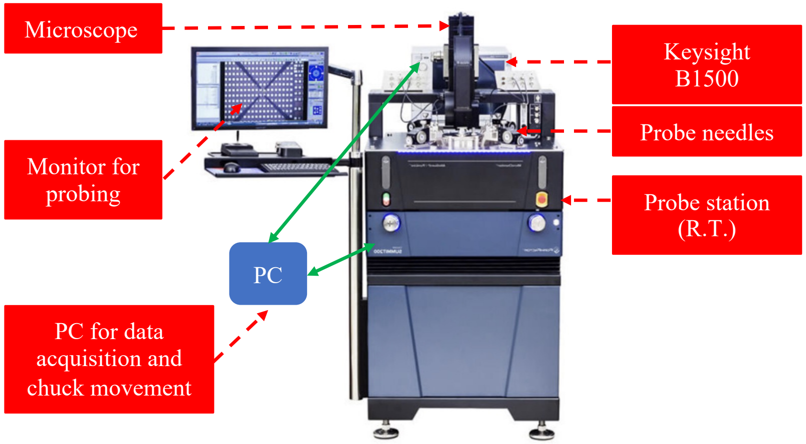
Summary

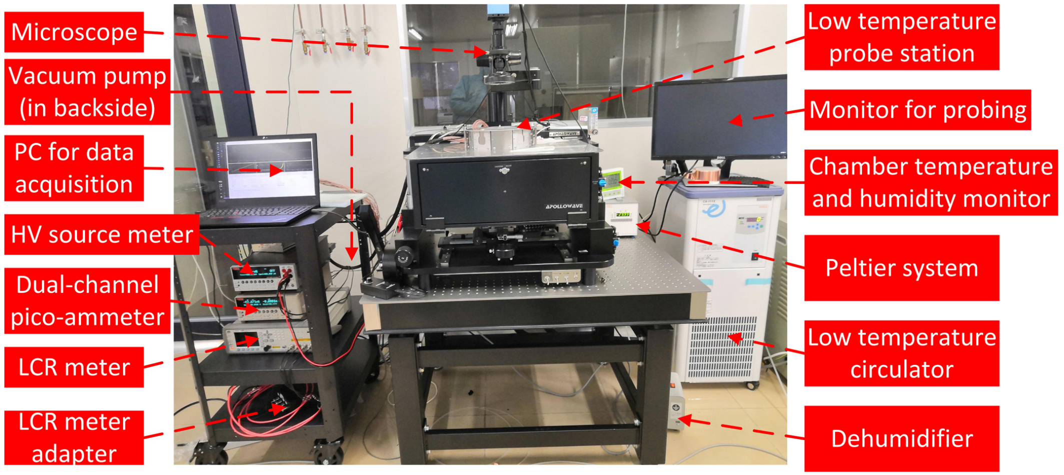
- The LGAD, as a **fast timing as well as radiation hard** silicon based detector, has reached a mature state in recent years.
- The characterization of USTC-IME LGAD pre-production sensors for the HGTD have been studied both in **laboratory** and **test beam**:
  - The uniformity of unirradiated main sensor is very well and the it can be affected by the non-uniformity of irradiation fluence.
  - The inter-pad resistance of sensors irradiated by reactor neutrons is larger than 10 MΩ.
  - **Sensors irradiated** at fluences of **2.5×10^{15} n_{eq}/cm^2** achieved the objectives of:
    - Collected charge of more than 4 fC while guaranteeing an optimal timing resolution better than 50 ps.
    - An efficiency larger than 95% over sensors' surface is obtained with a charge threshold of 2 fC.
- **All these results meet the HGTD specification** and **verify the good quality of USTC-IME LGAD pre-production sensors**.

Thanks for your attention!

Back up

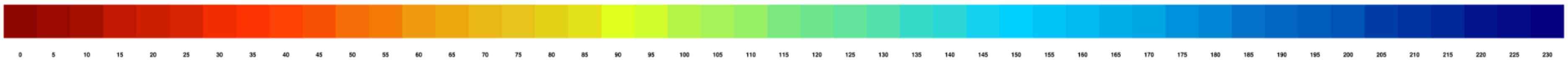
Probe station testing systems at USTC





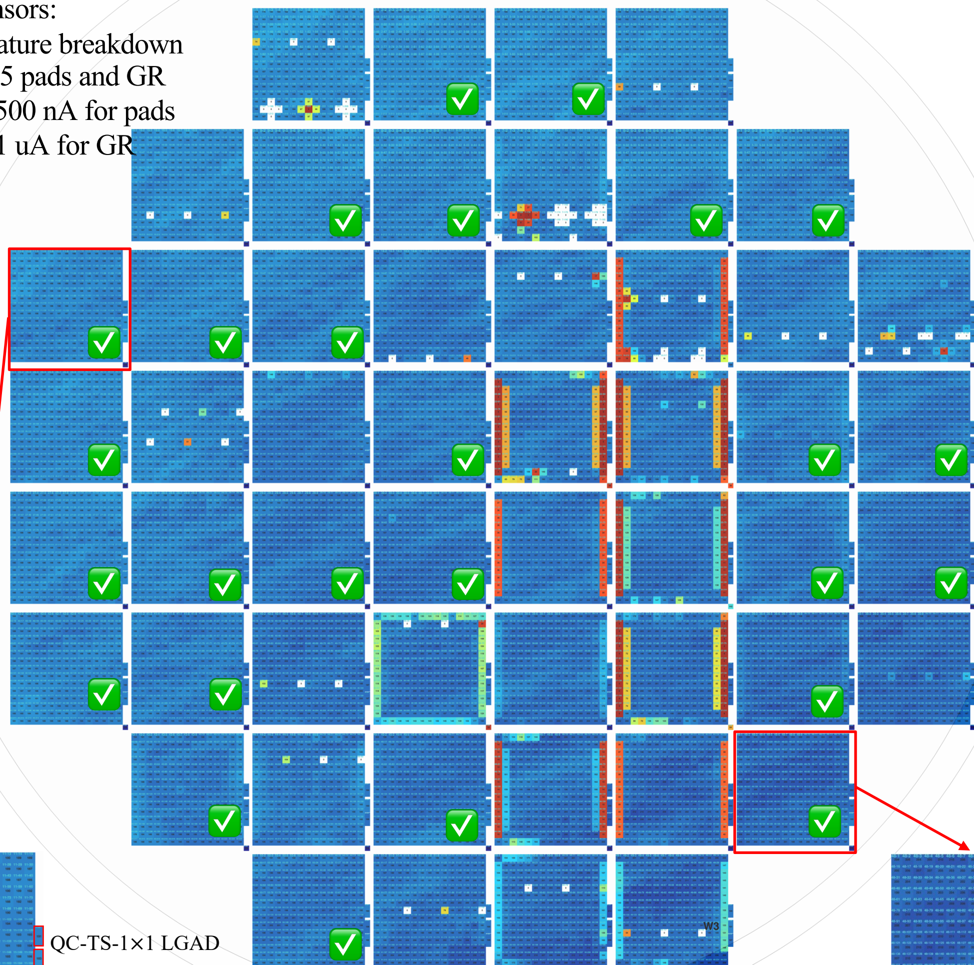
- **Semi-Automatic probe station** (Room Temperature, R.T.)
  - **Vender testing**
  - Cascade Summit 200 + Keysight B1500
  - **Three pads** were measured simultaneously so it took less time **(~ 4 hours for one wafer**)
  - Step: 2 V, Compliance: 60 μA (The current can reach to compliance when **at least one** of three pads is bad)
- **Mannual probe station** (Generally, chuck at 20 ^{o}C)
  - **Cross-check** vender testing results
  - **Test the main sensors by probe card** and compare results with three probe needles
  - Apollowave alpha-200CS + Keithley 2410 and 6482 (IV)/Keithley 2410 and Aglient E4980A (CV)
  - For single LGADs, step: 2 V, compliance: 10 μA. For 15x15 LGADs, step: 5 V, compliance: 600 μA

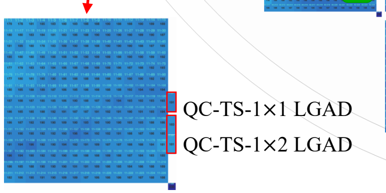
VBD Histogram (take W3 for example)

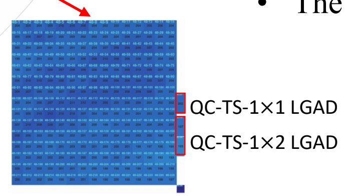


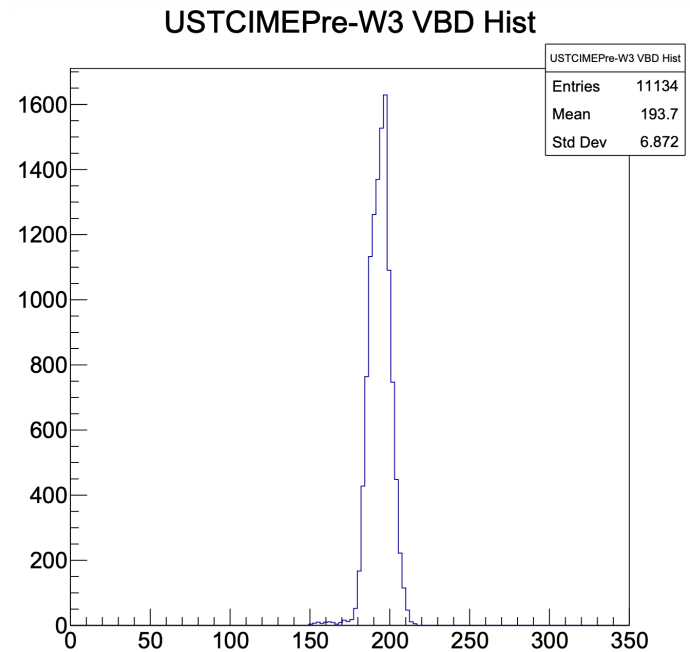
0
- VBD = VMAX (VMAX < 150 V) due to the limit of compliance

Good sensors:
No premature breakdown for all 225 pads and GR
- Ith = 500 nA for pads
- Ith = 1 uA for GR



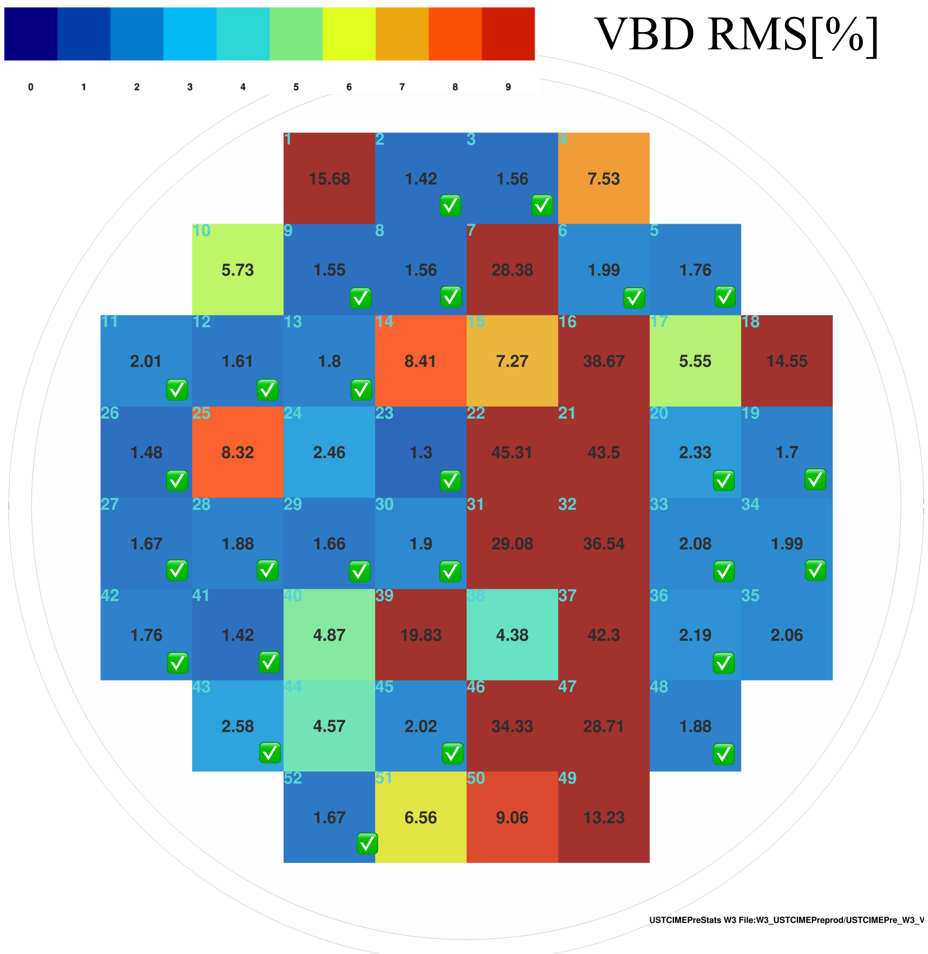


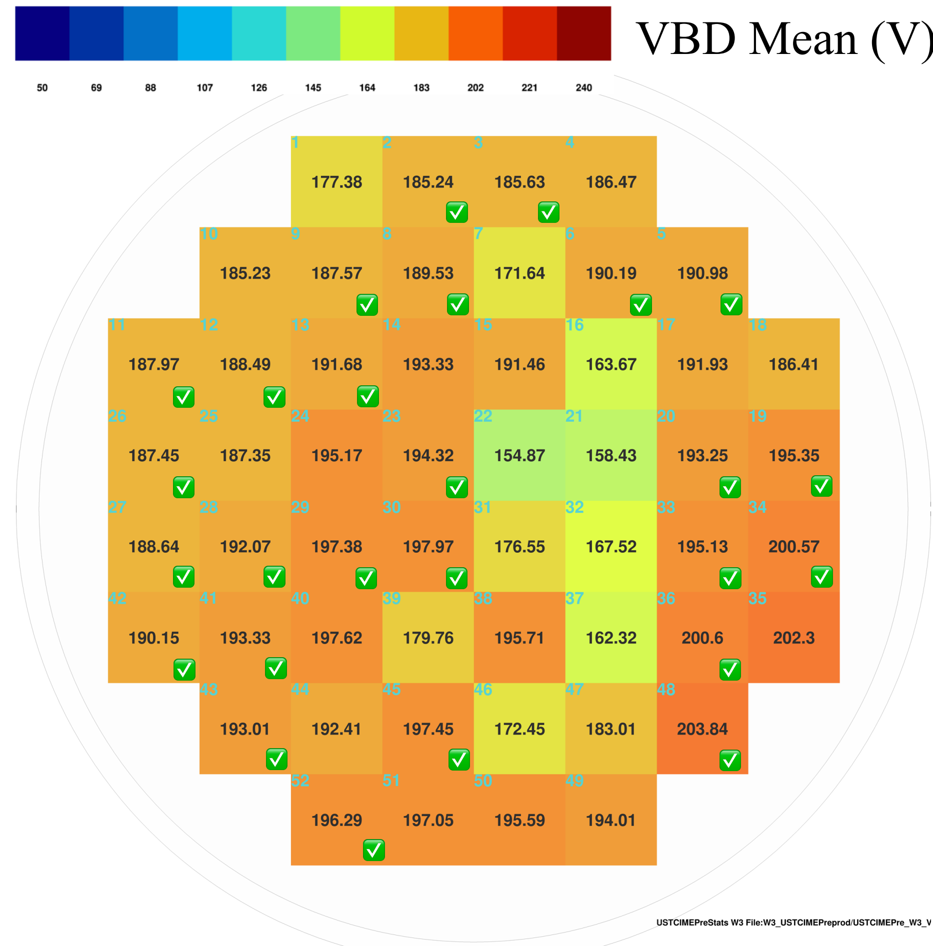




- Vth > 150 V to cut early breakdown pads
- The mean VBD of all good pads is 193.7 V

Yield estimation (take W3 for example)





$V_{bd,pad}$ spread over the Sensor*,¤	$RMS(V_{bd,pad})/\langle V_{bd,pad}\rangle < 0.05$

Good/Total: 26/52 ~ 50 %

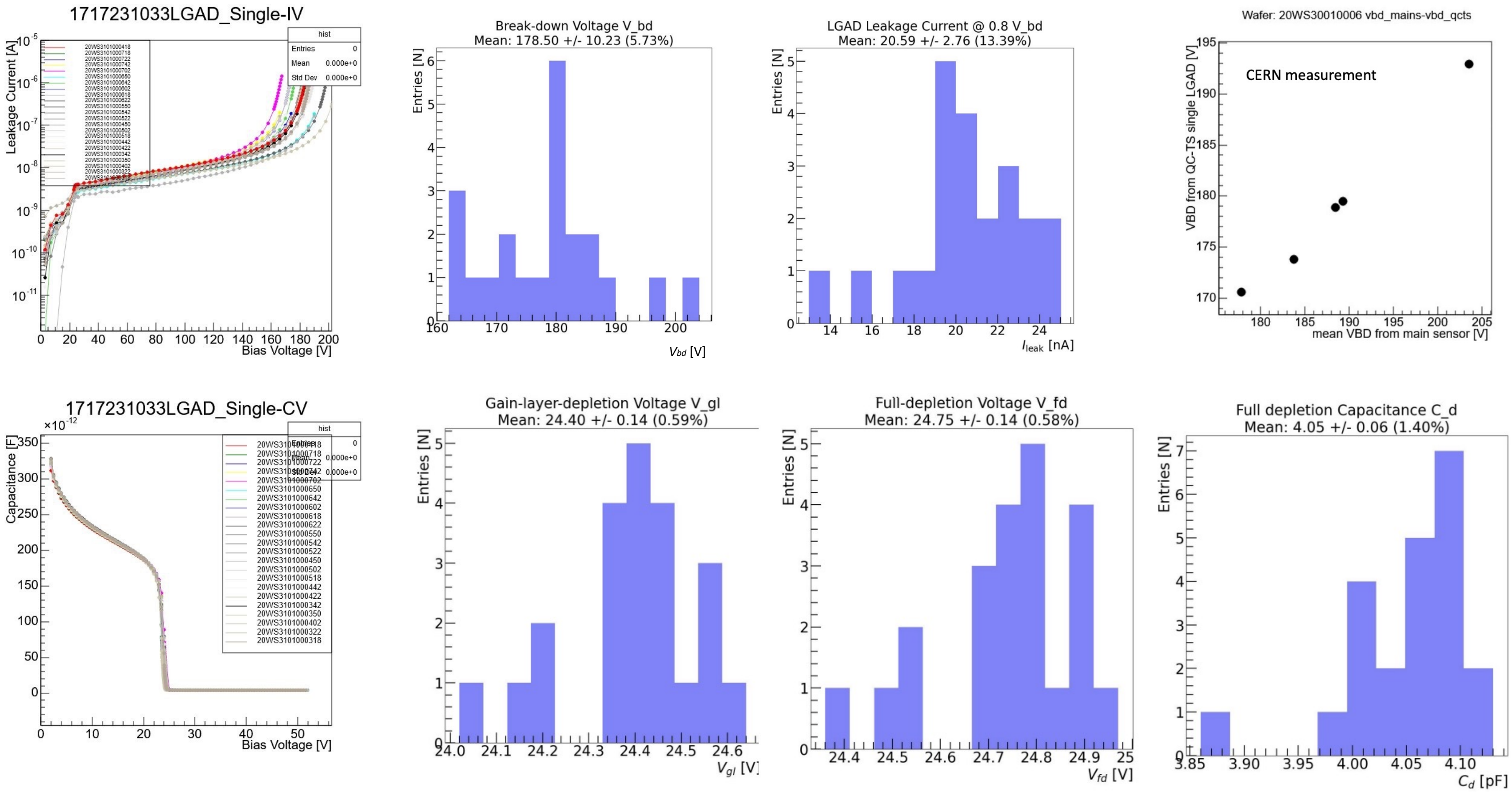
Variation of the V_{bd} between different sensors	±8% from the average V_{bd}

[178.20, 209.20] (V)

Good/Total: 26/52 ~ 50 %

- Combined results: yield ~ 50 %

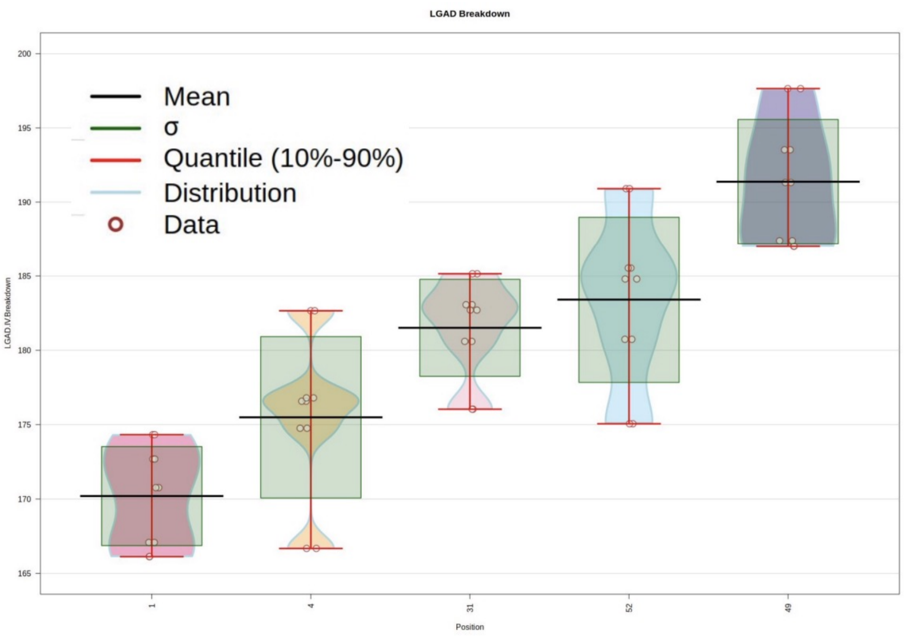
IV/CV measurements of QC-TS LGADs

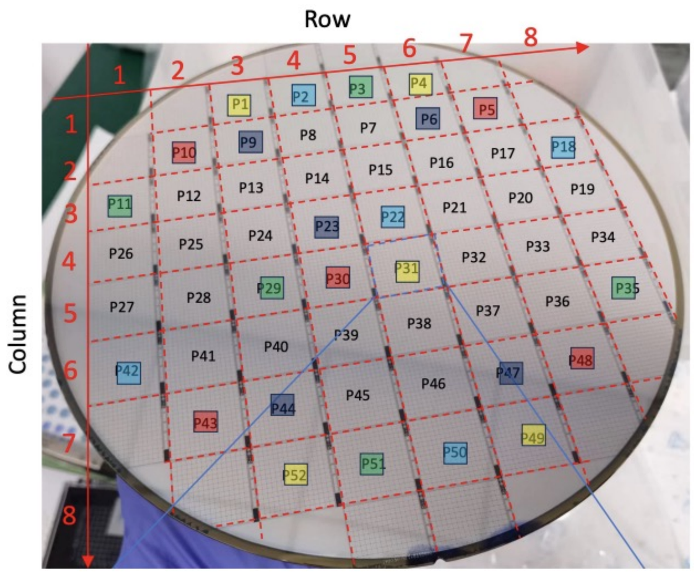


the shown results are measured at CERN

- Breakdown voltage (Vbd) spread within specs (± 8%) and leakage current @ 0.8 VBD spread within specs (< 3x).
- Gain-layer depletion (Vgl) RMS of 2.3-2.5% outside specs (1%); ~1% within wafers includes systematics from fit.
- Narrow distributions of depletion voltage Vfd (< 4%) within specs (10%).
- Good correlation for Vbd between QC-TS and main sensors.

Correction of break-down voltage with position on wafer

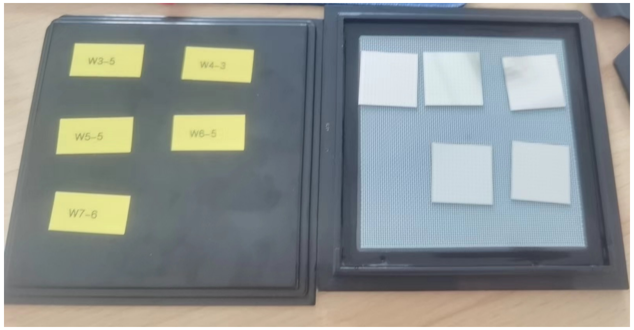




- Clear correlation of Vbd with position on wafer

HGTD UBMed main sensors at USTC

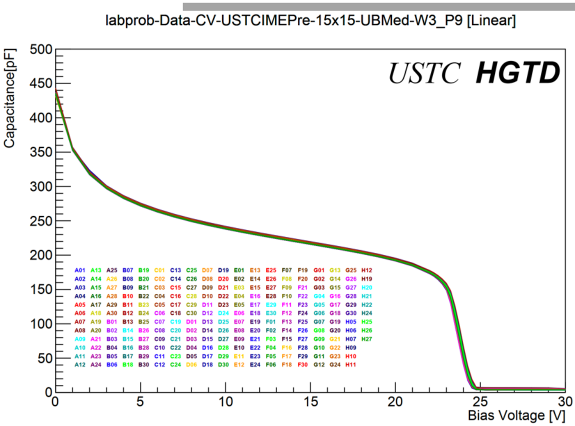
USTC-IME UBMed unirradiated sensors

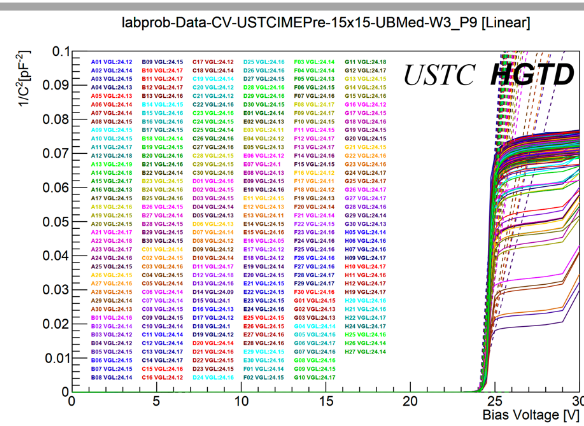


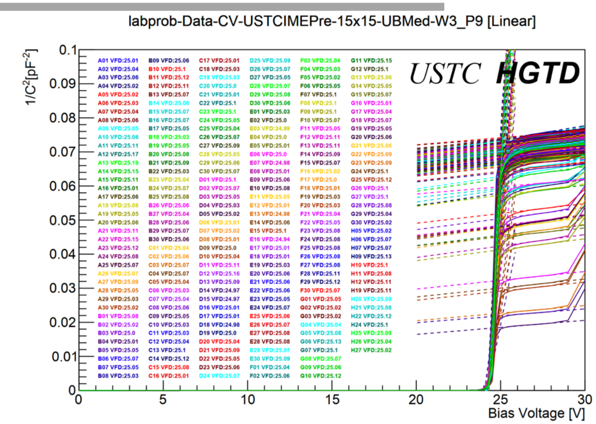
USTC-IME UBMed irradiated sensors

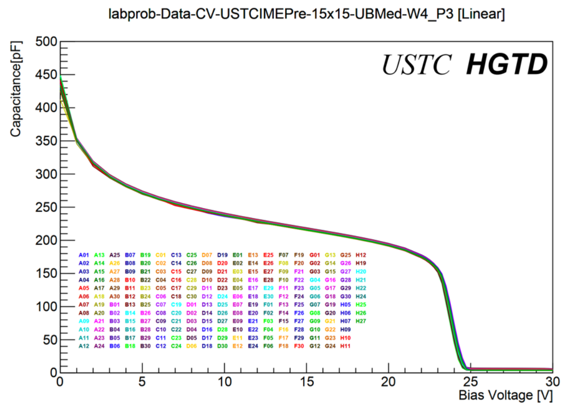
IHEP-IME UBMed irradiated sensors

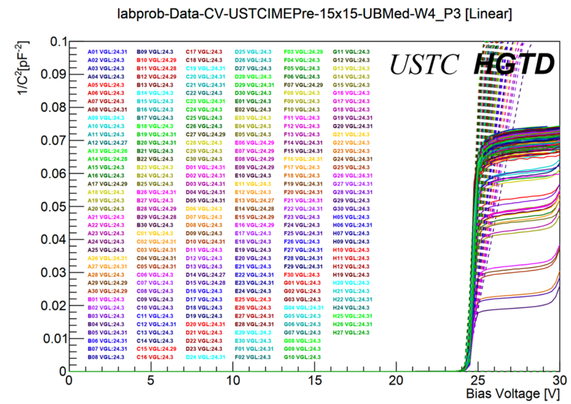
CV curves of unirradiated main sensors (I)

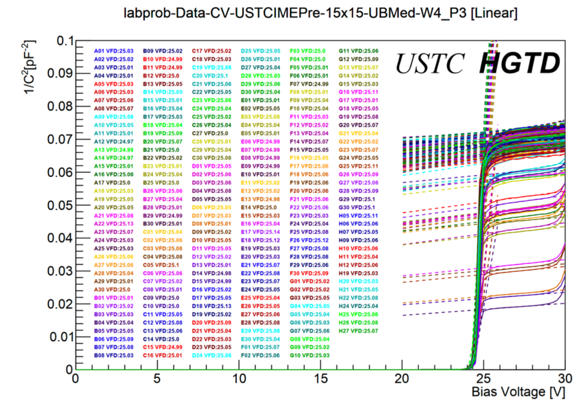


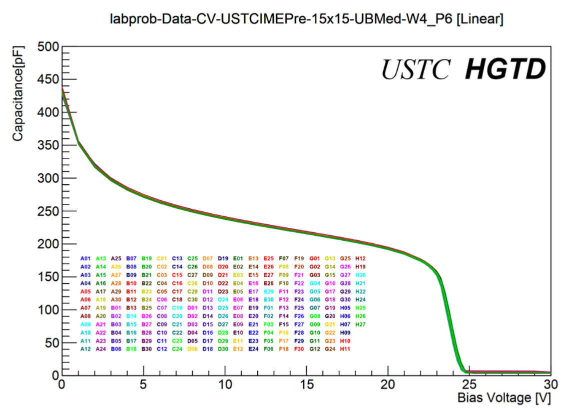


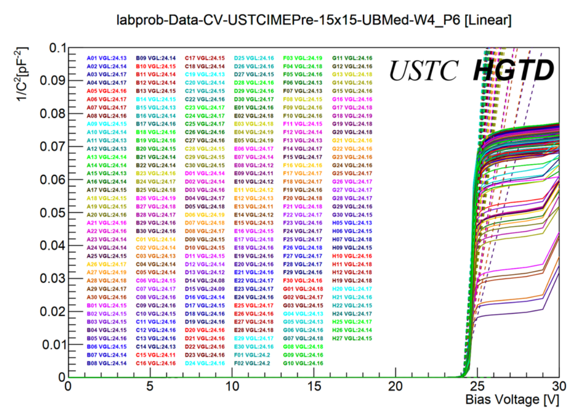




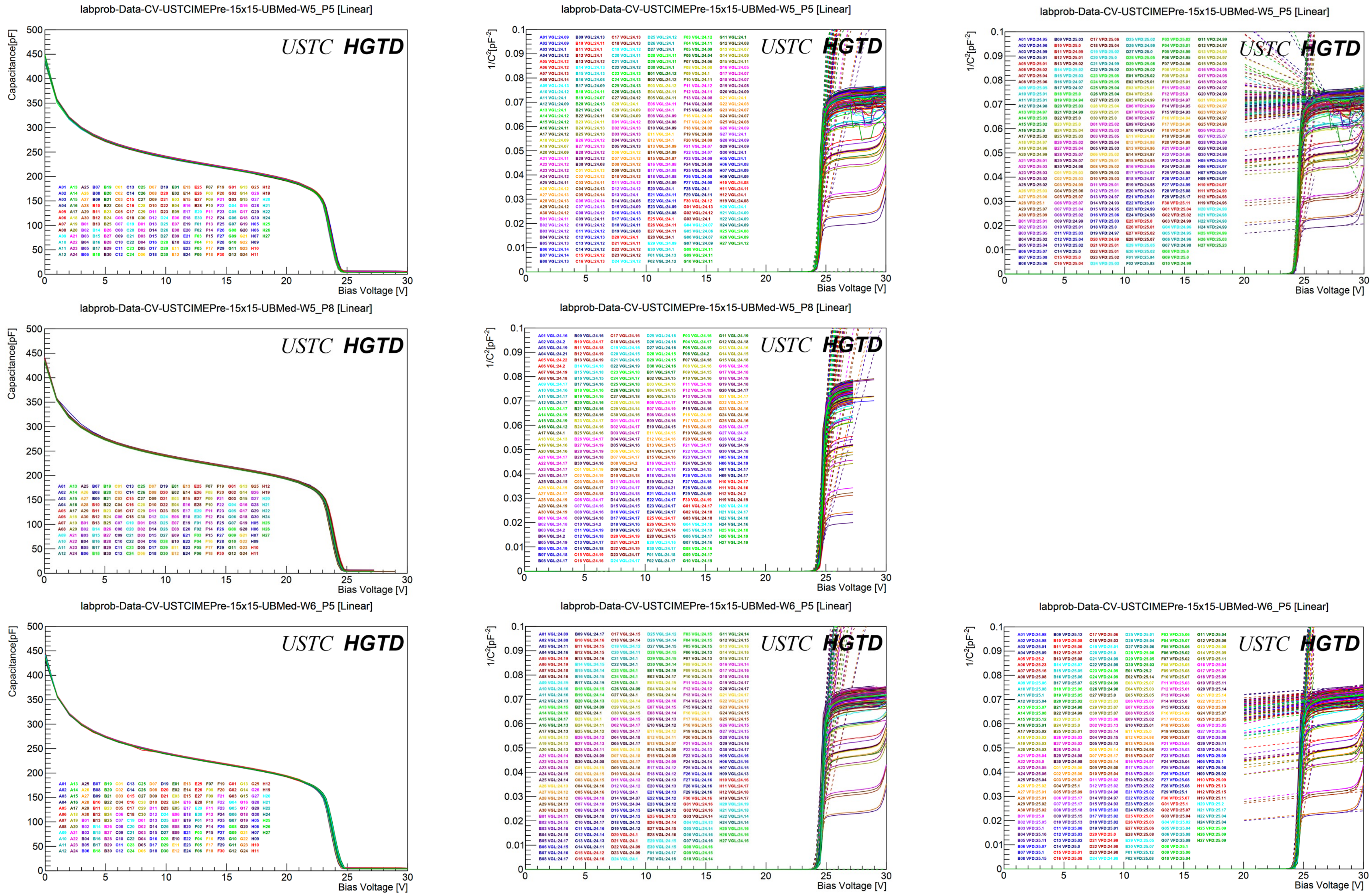






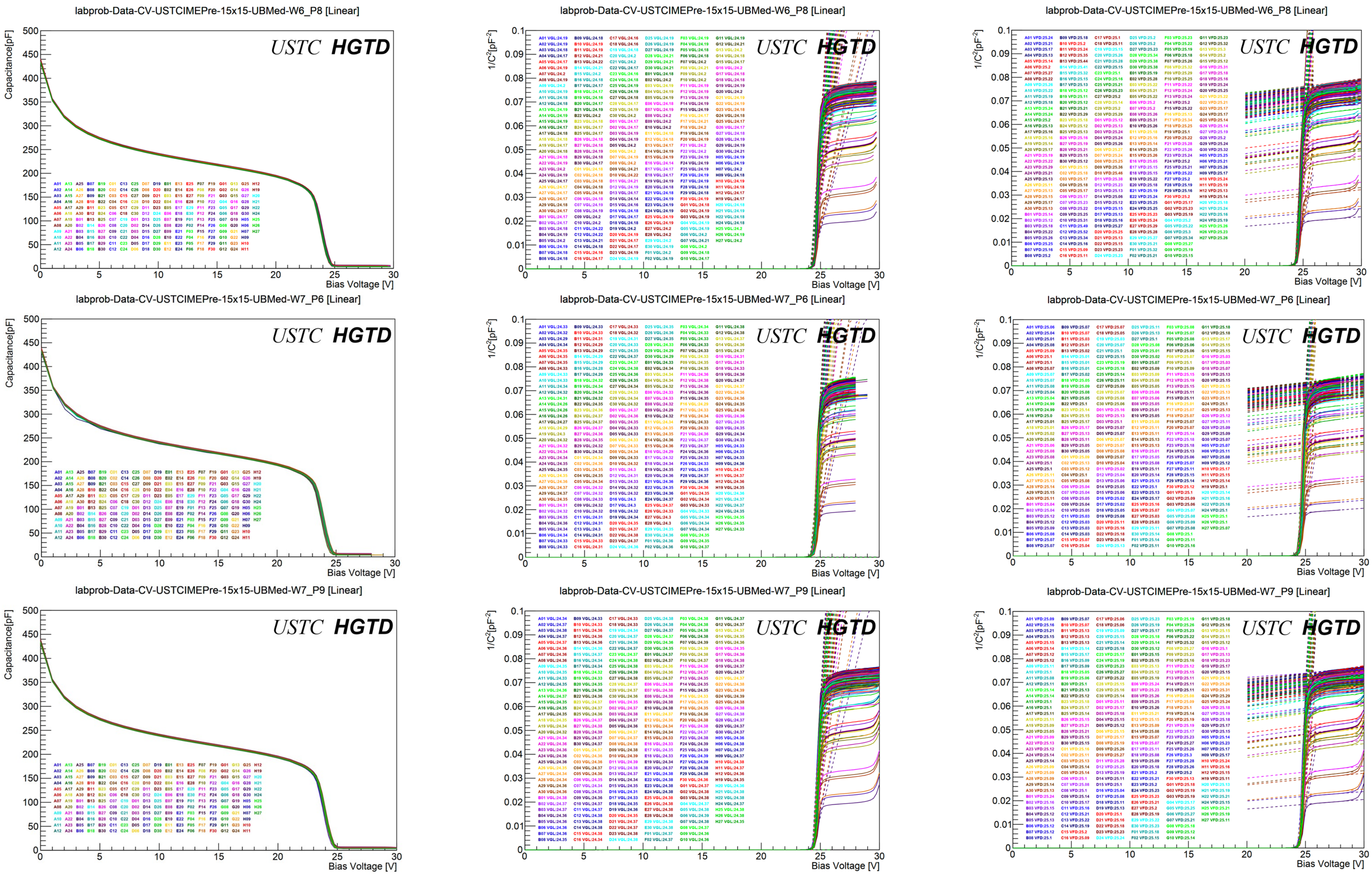


CV curves of unirradiated main sensors (II)



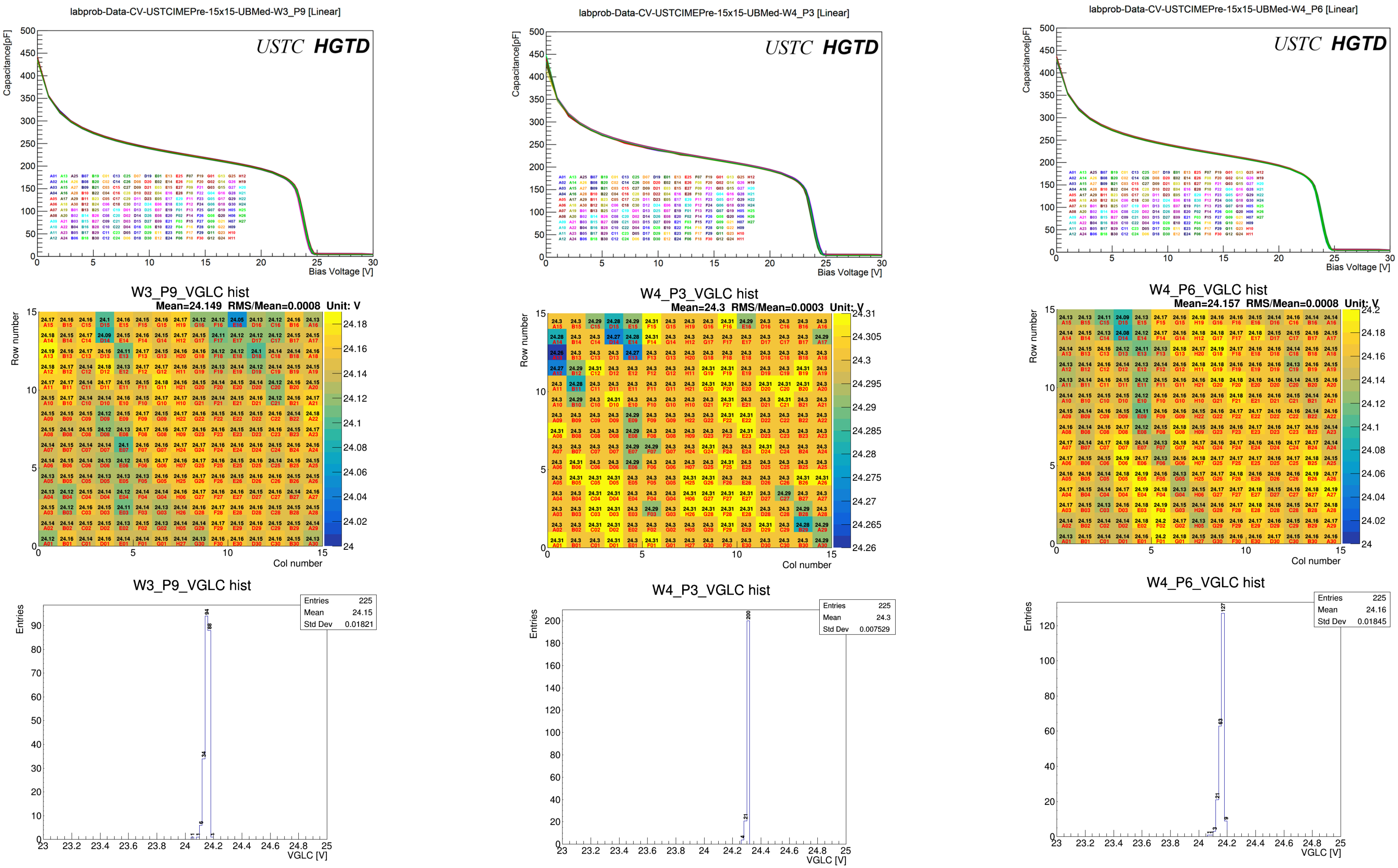
- Tested by 15×15 probe card, Temperature: 20 °C, Frequency: 10 kHz, VAC: 0.51 V, GR floating.
- The dashed lines in $1/C^2$-V are the fitted lines.

CV curves of unirradiated main sensors (III)



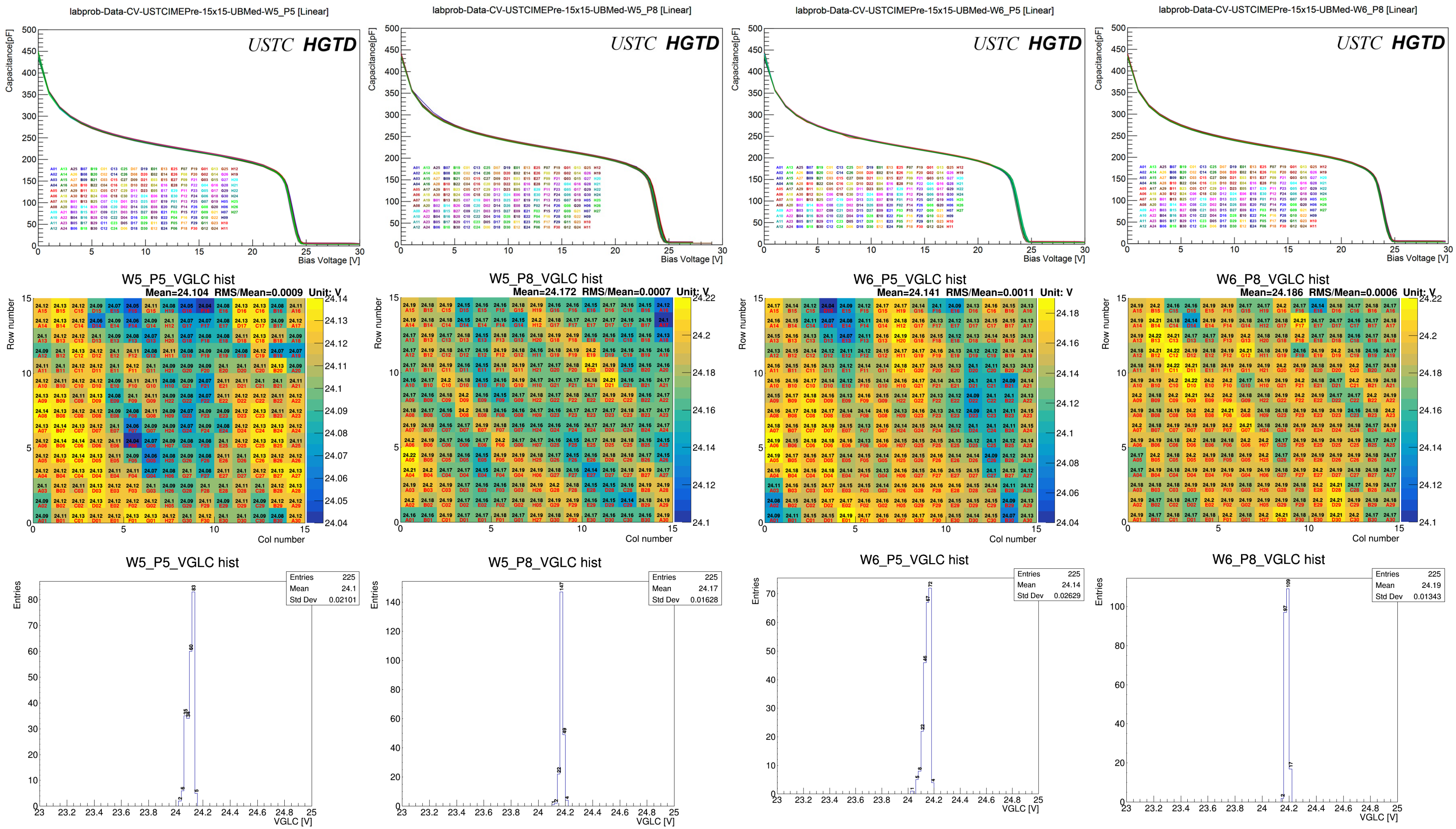
- Tested by 15×15 probe card, Temperature: 20 °C, Frequency: 10 kHz, VAC: 0.51 V, GR floating.
- The dashed lines in $1/C^2$-V are the fitted lines.

VGL spread over the sensors (I)



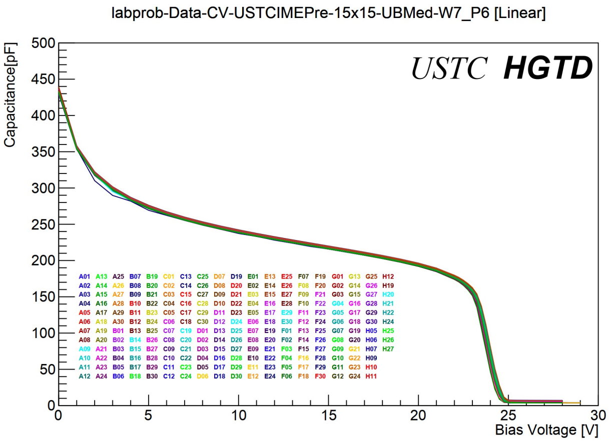
- Tested by 15×15 probe card, Temperature: 20 °C, Frequency: 10 kHz, VAC: 0.51 V, GR floating.
- 1D and 2D distribution are shown here (The $1/C^2$-V curves can be found in backup slides).
- The VGL spread over these sensors is 0.0008, 0.0008, 0.0003 and 0.0008, respectively which meets the specification.

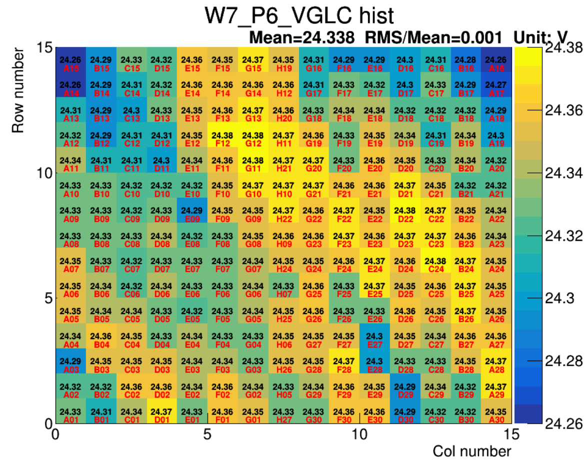
VGL spread over the sensors (II)

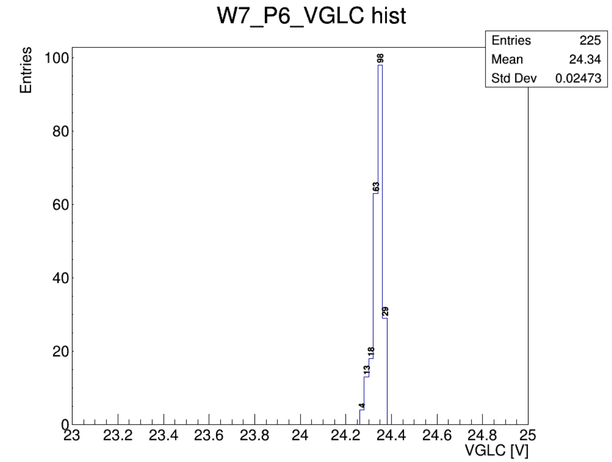


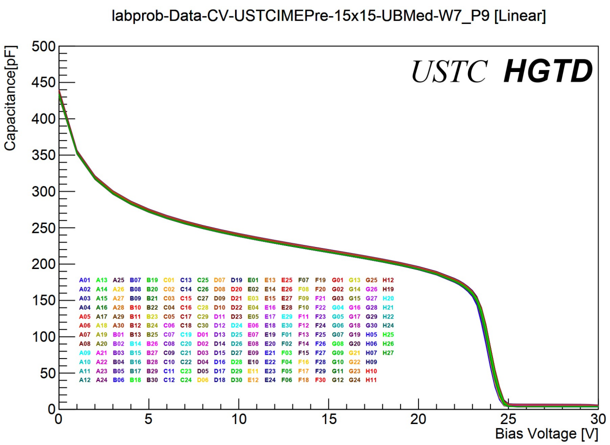
- Tested by 15×15 probe card, Temperature: 20 °C, Frequency: 10 kHz, VAC: 0.51 V, GR floating.
- 1D and 2D distribution are shown here (The $1/C^2$-V curves can be found in backup slides).
- The VGL spread over these sensors is 0.0009, 0.0007, 0.0011 and 0.0006, respectively which meets the specification.

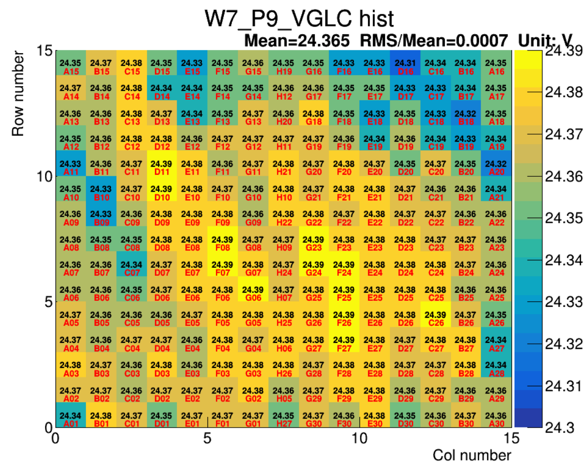
VGL spread over the sensors (III)

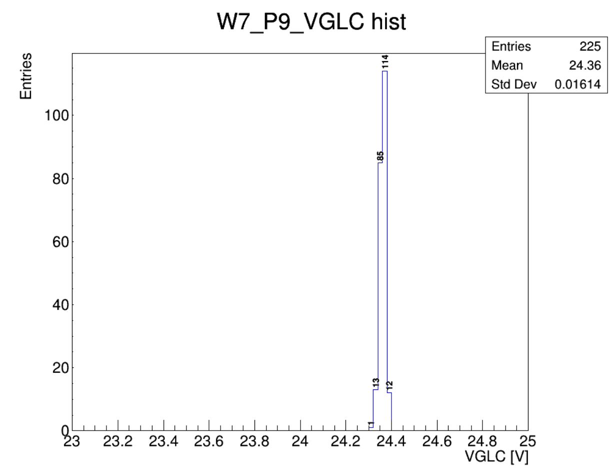






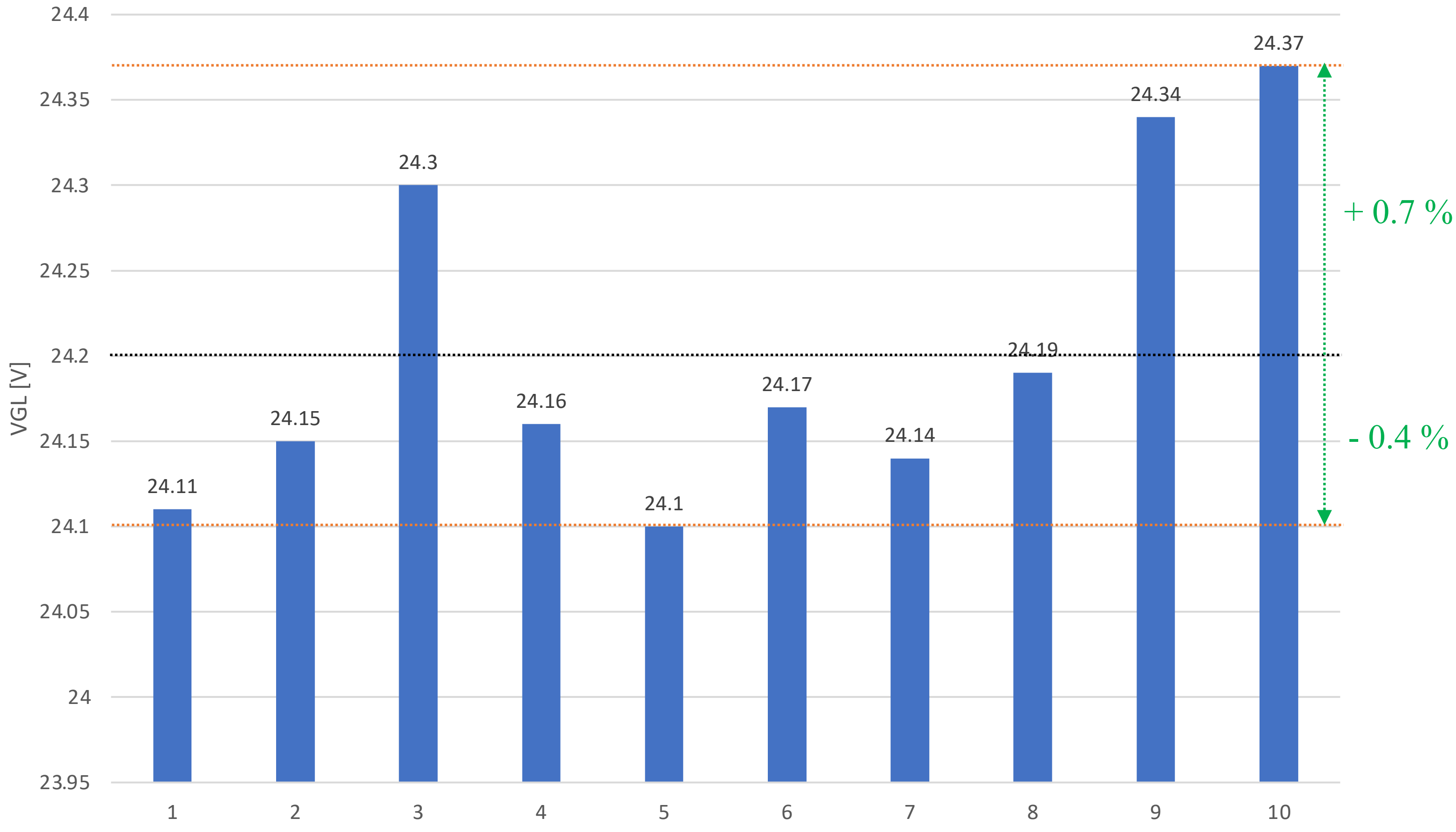






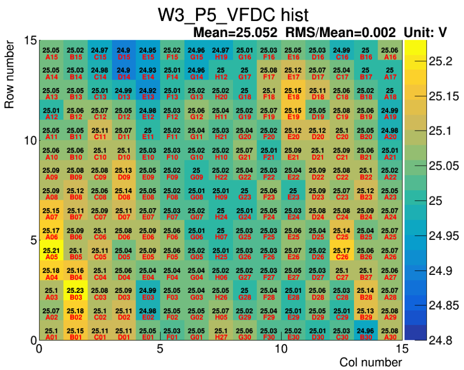
- Tested by 15×15 probe card, Temperature: 20 ^{o}C, Frequency: 10 kHz, VAC: 0.51 V, GR floating.
- 1D and 2D distribution are shown here (The 1/C^2-V curves can be found in backup slides).
- The VGL spread over these sensors is 0.0010 and 0.0007, respectively which meets the specification (<0.005).

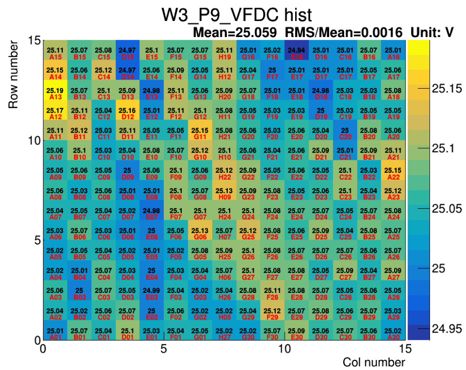
Variation of VGL between different sensors

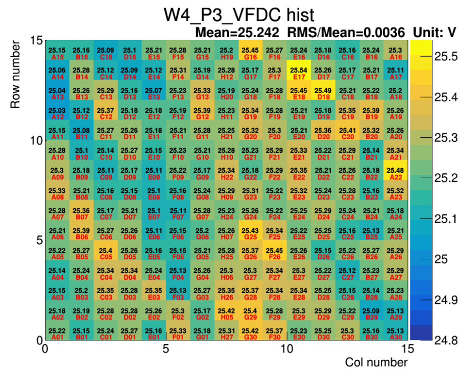


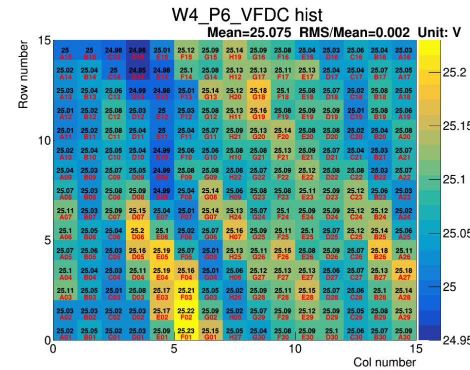
- The variation of VGL between sensors is within ±1%.

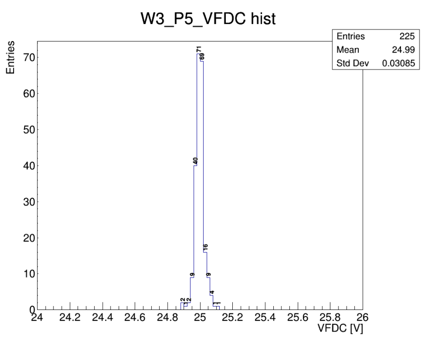
VFD spread over the sensors (I)

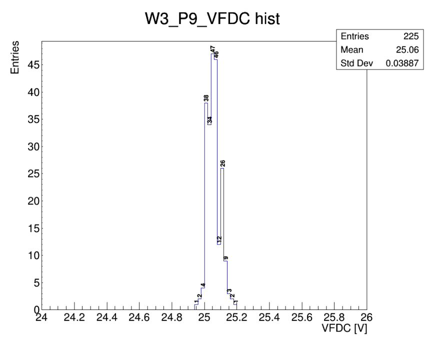


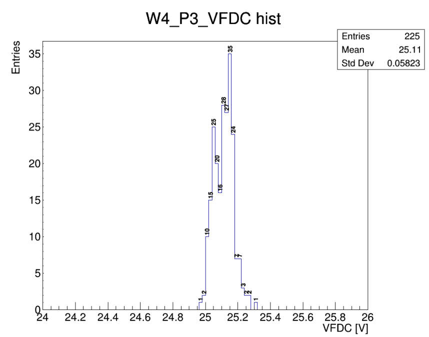


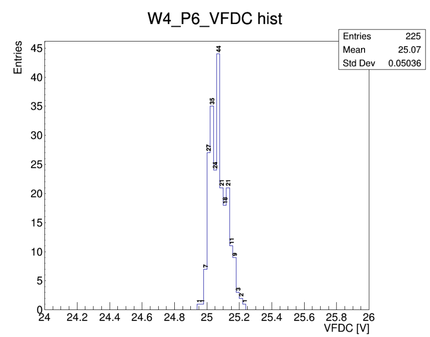






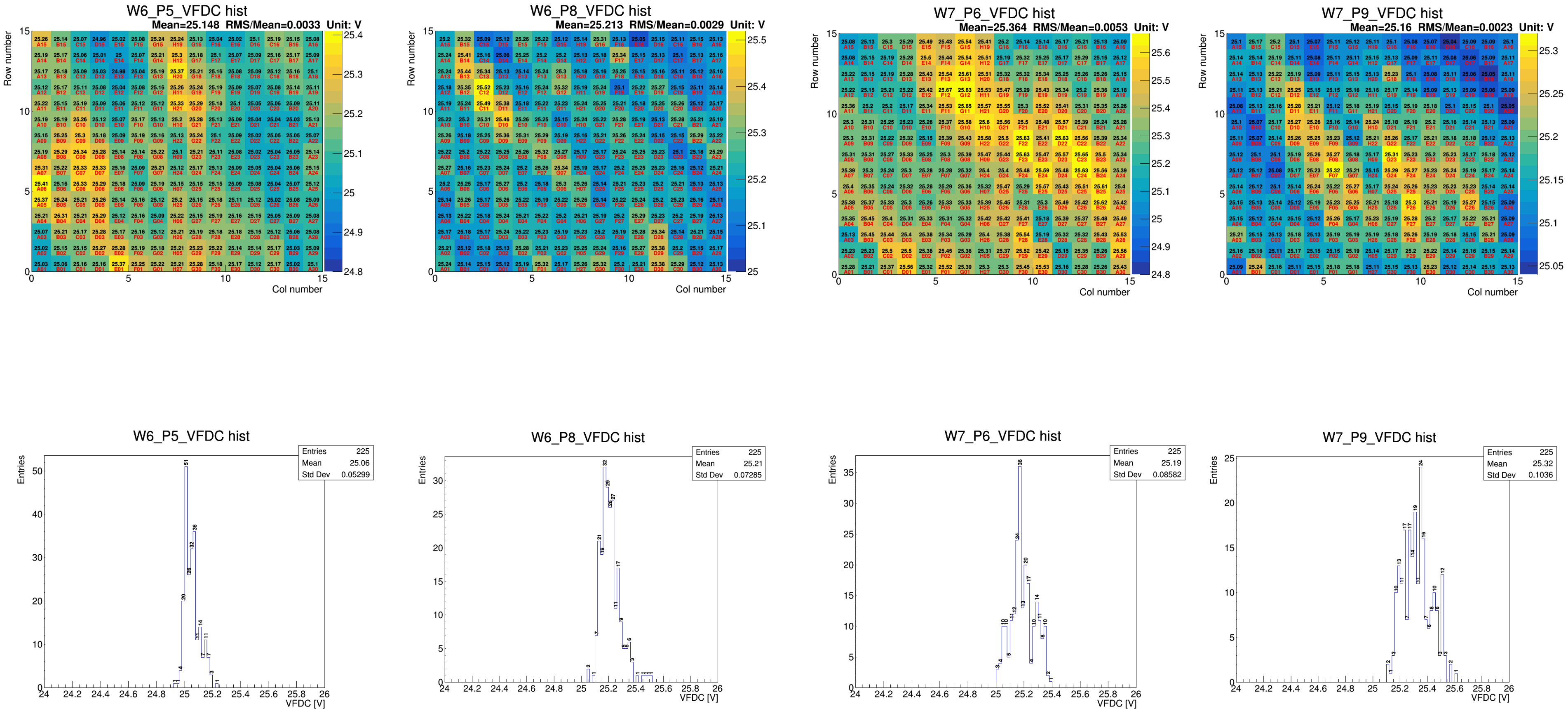






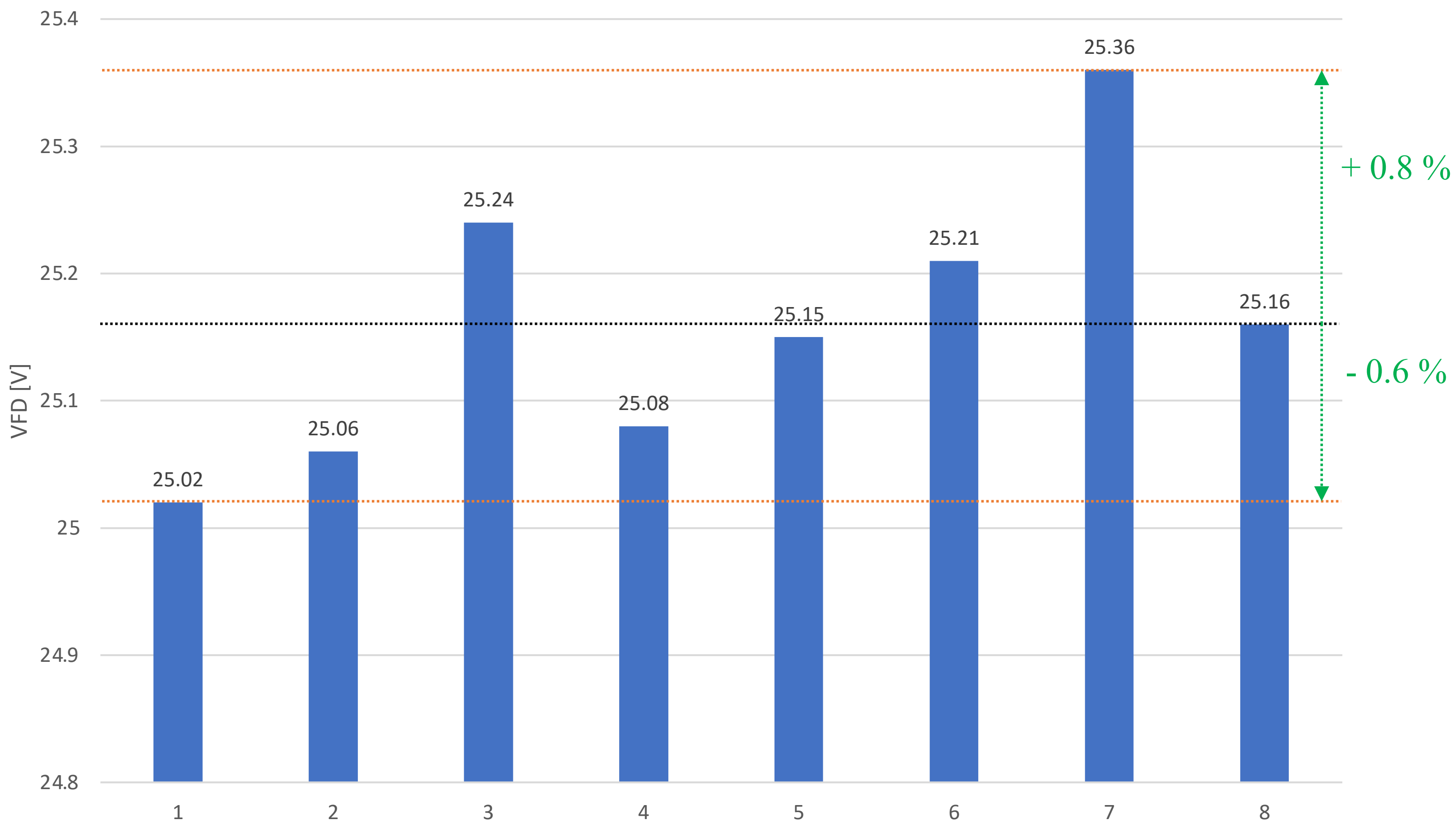
- Tested by 15×15 probe card, Temperature: 20 °C, Frequency: 10 kHz, VAC: 0.51 V, GR floating.
- 1D and 2D distribution are shown here (The $1/C^2$-V curves can be found in backup).

VFD spread over the sensors (II)



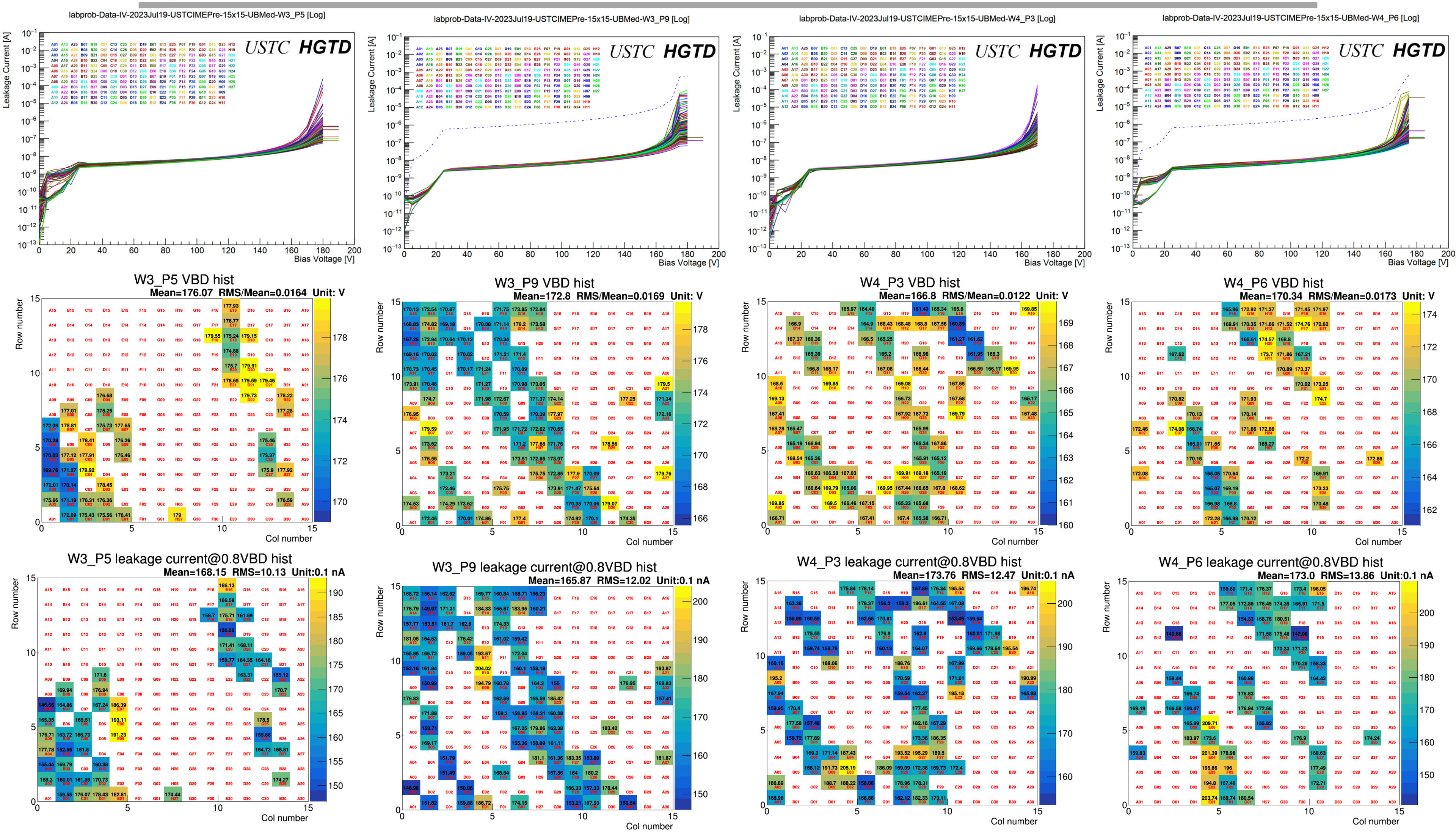
- Tested by 15×15 probe card, Temperature: 20 ^{o}C, Frequency: 10 kHz, VAC: 0.51 V, GR floating.
- 1D and 2D distribution are shown here (The 1/C^2-V curves can be found in backup).

Variation of VFD between different sensors



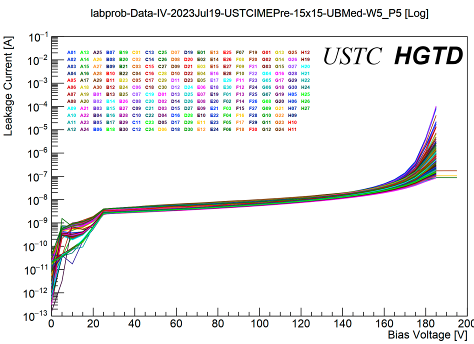
- The variation of VFD between sensors is within ±10%.

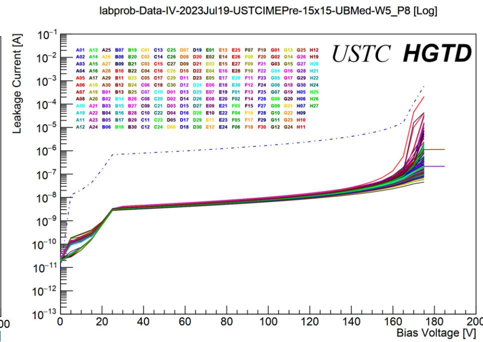
VBD and pad leakage current spread over sensors (I)

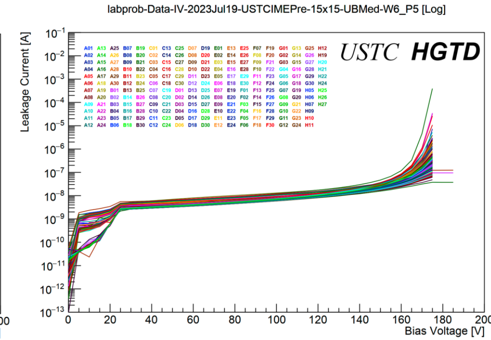


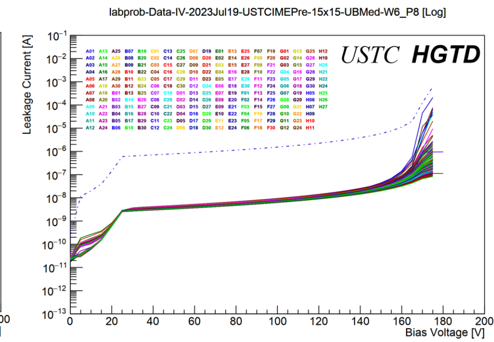
- Tested by **15×15 probe card** while other pads are grounded and GR is floating, **chuck at 20 ^{o}C**
- The blank boxes represent pads which don't break down at maximum applied bias due to the compliance of total current.
- The VBD spread over the pads which are break down is 0.0164, 0.0169, 0.0122 and 0.0173, respectively.
- The Max(I@0.8VBD)/Min(I@0.8VBD) over the pads which are break down is 1.32, 1.40, 1.34 and 1.49, respectively.

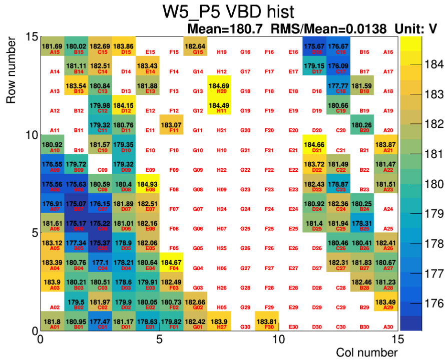
VBD and pad leakage current spread over sensors (II)

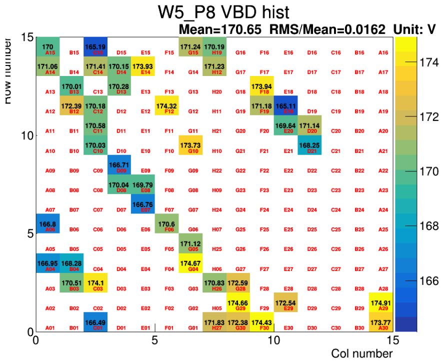


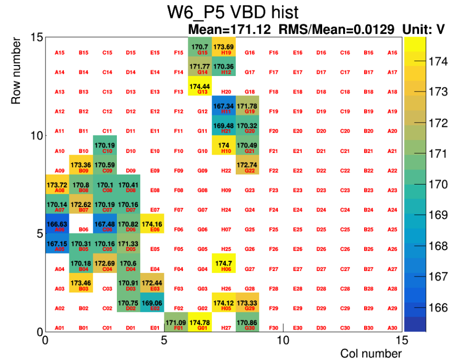


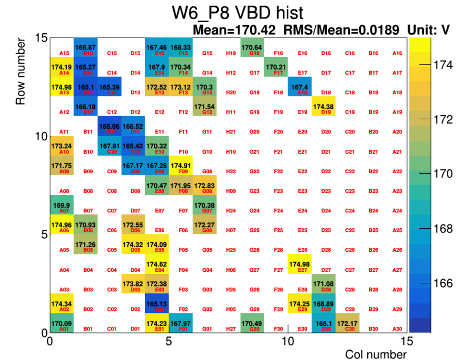


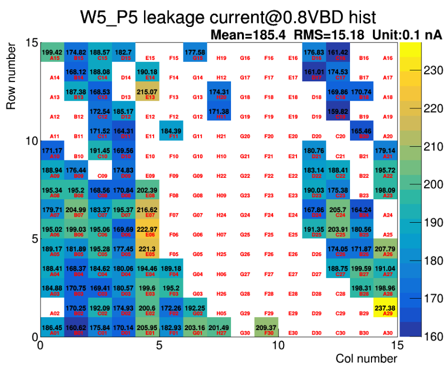


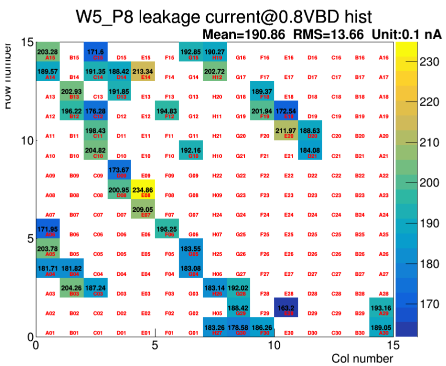


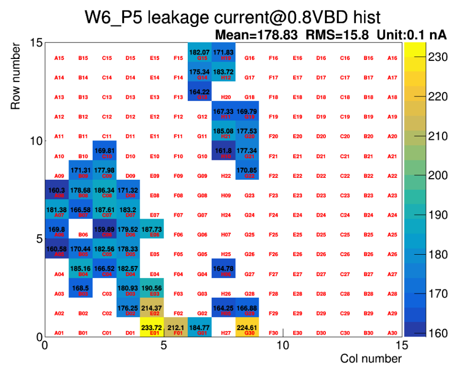


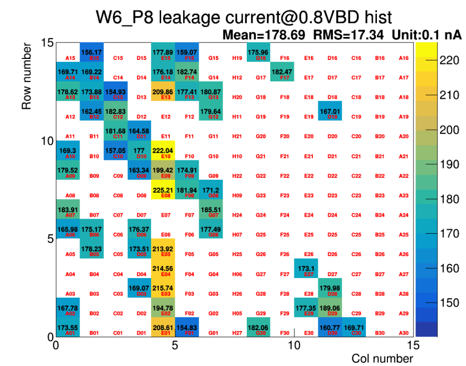






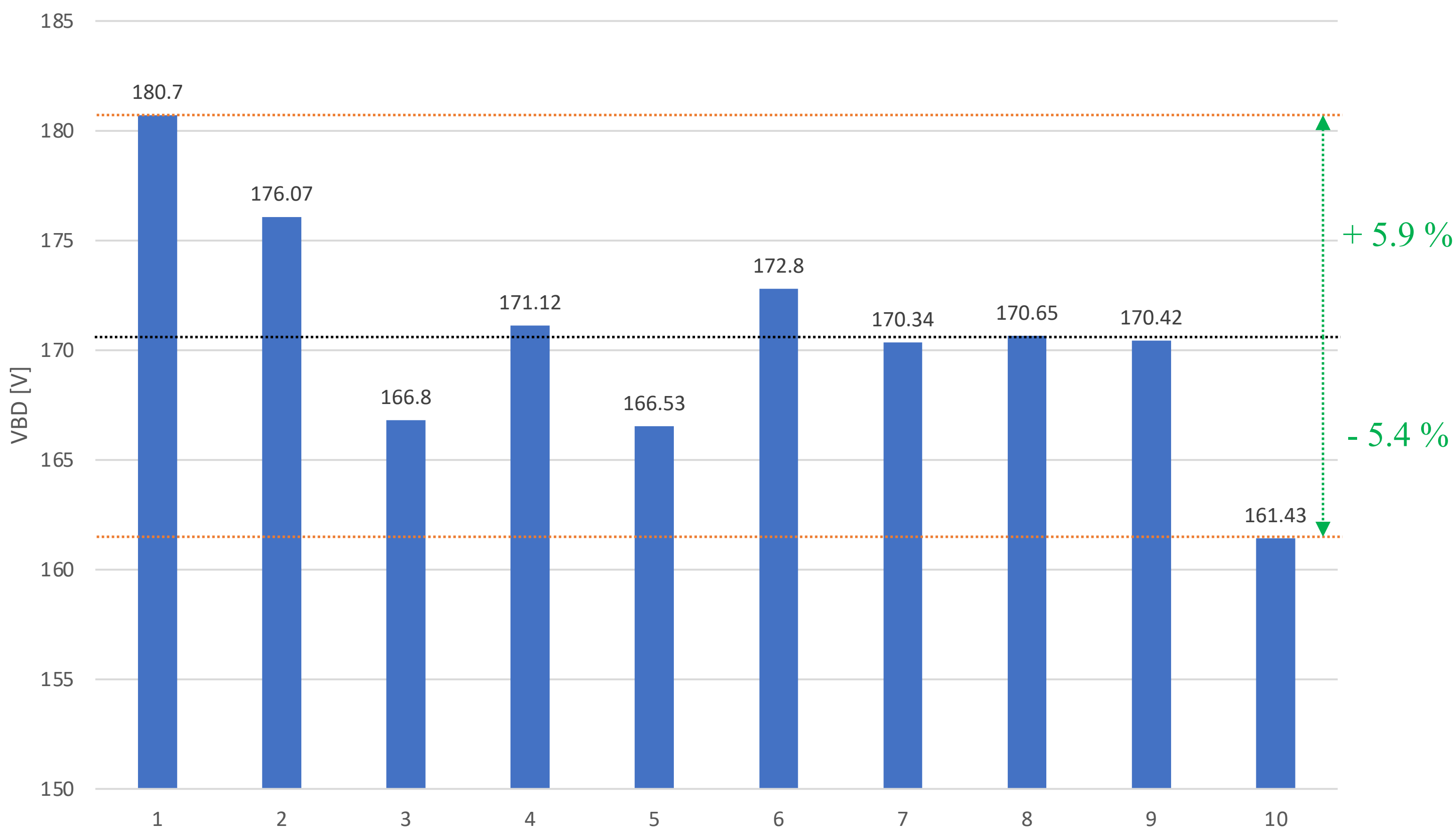






- Tested by **15×15 probe card** while other pads are grounded and GR is floating, **chuck at 20 ºC**.
- The blank boxes represent pads which don't break down at maximum applied bias due to the compliance of total current.
- The VBD spread over the pads which are break down is 0.0138, 0.0162, 0.0129 and 0.0189, respectively.
- The Max(I@0.8VBD)/Min(I@0.8VBD) over the pads which are break down is 1.49, 1.45, 1.46 and 1.61, respectively.

Variation of VBD between different sensors

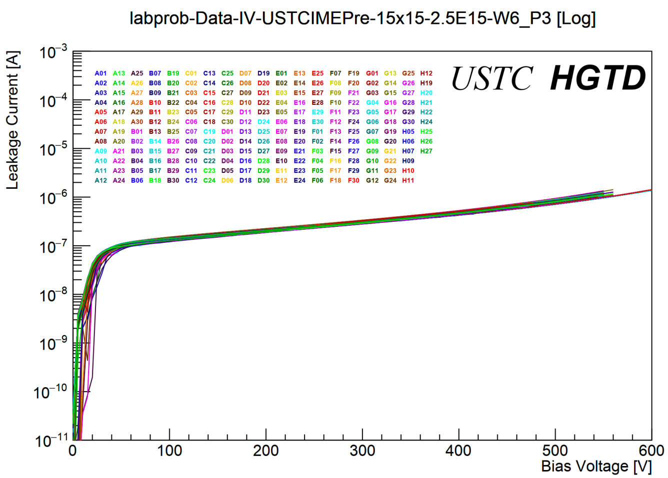


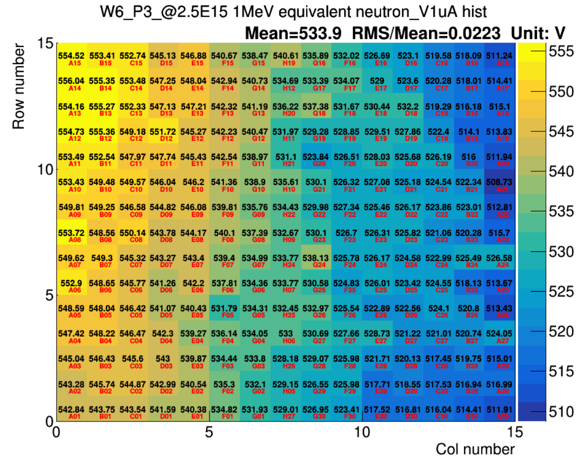
- The variation of VBD between sensors is within $\pm$8%.

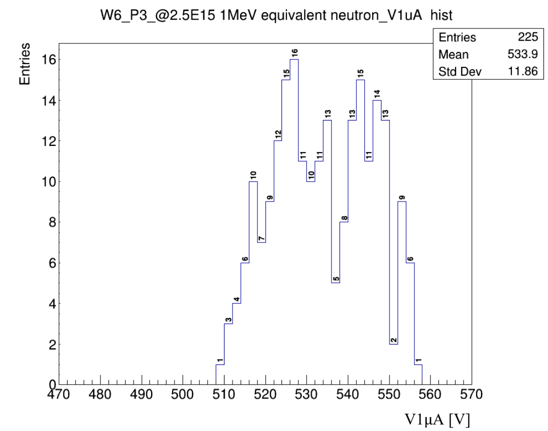
IV measurements of irradiated main sensor

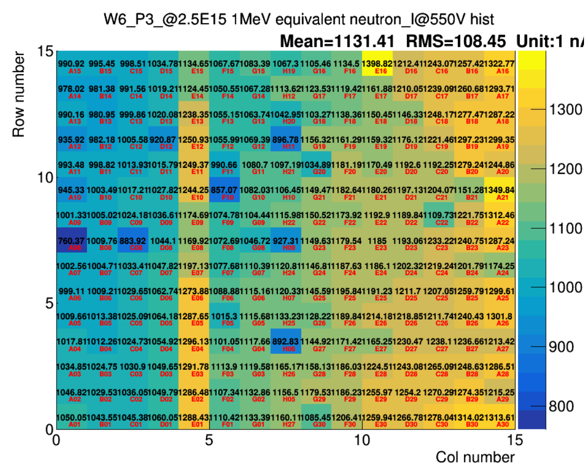
- Tested by 15×15 probe card, Temperature: -30 ^{o}C, Compliance: 600 μA

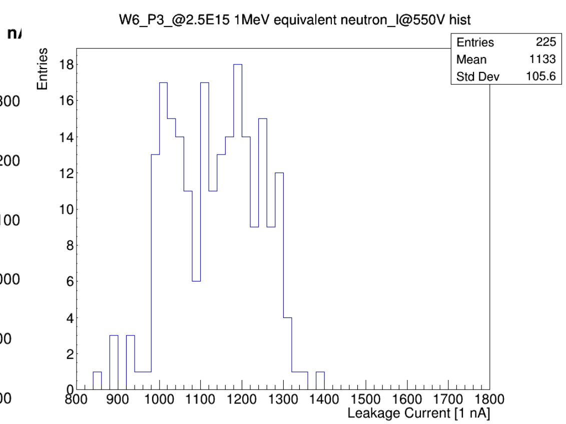
W6_P3@2.5E15 n_{eq}/cm^2









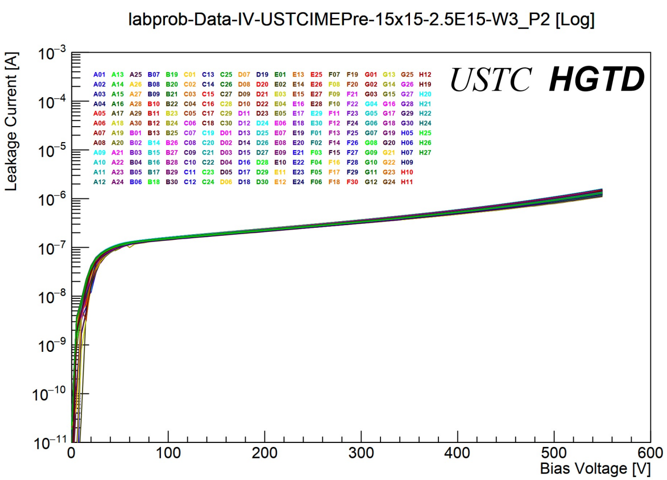


- The V1μA spread over this sensor is about 0.022 including the contribution from the non-uniformity of irradiation fluence across the large array sensors. And the I@550V of all pads is smaller than 5 μA.
- The power consumption is smaller than < 37 mW/cm^2 and the total maximum leakage curent is smaller than < 68 μA/cm^2 (Here we consider the Vop,min is V1μA and the sensor's area is 2×2 cm^2).

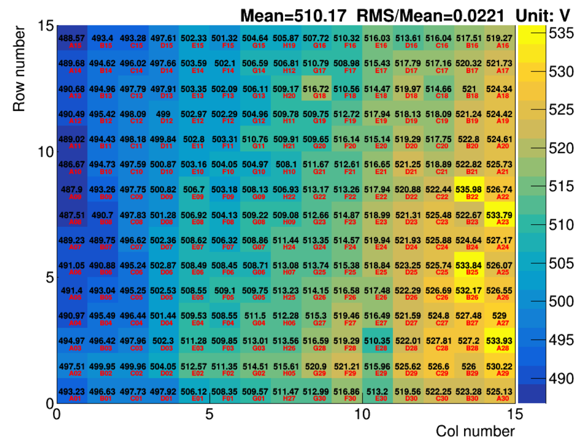
Uniformity of irradiated main sensor

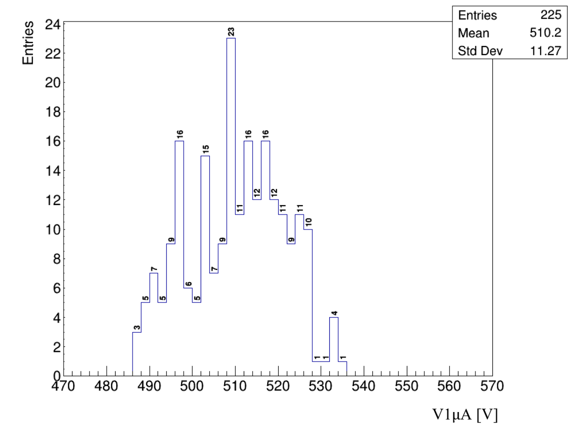
- Tested by 15×15 probe card, Temperature: -30 ^{o}C, Compliance: 600 μA

W3_P2@2.5E15 n_{eq}/cm^2

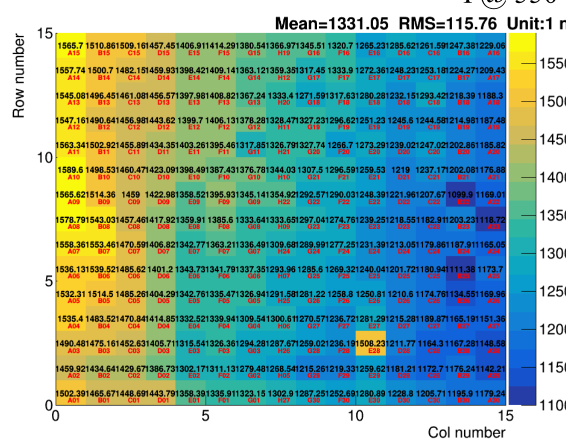


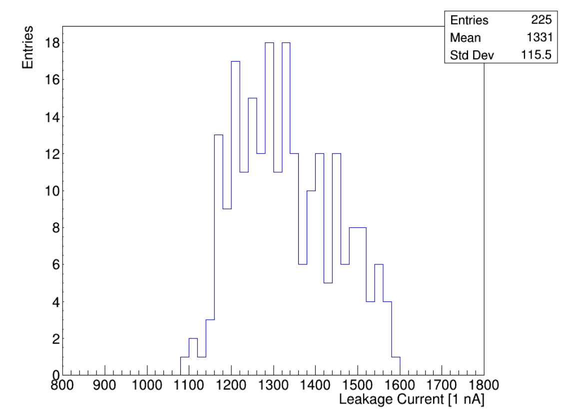
V @ 1 μA distribution





I @ 550 V distribution



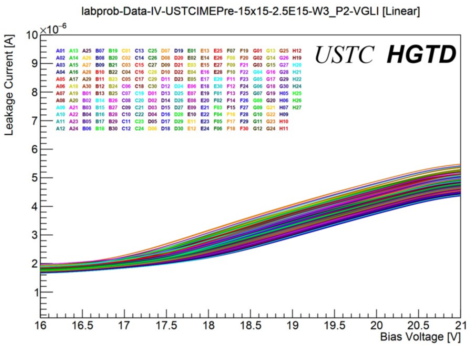


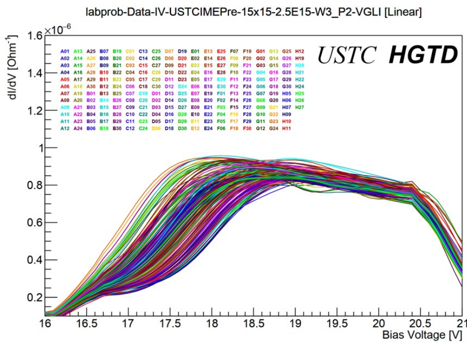
- The V1μA spread over this sensor is about 0.022 including the contribution from the non-uniformity of irradiation fluence across the large array sensors. And the I@550 V of all pads is smaller than 5 μA.
- The power consumption is smaller than < 37 mW/cm^2 and the total maximum leakage curent is smaller. than < 74 μA/cm^2 (Here we consider the Vop, min is V1μA and the sensor's area is 2×2 cm^2).

Vgl spread over irradiated main sensor

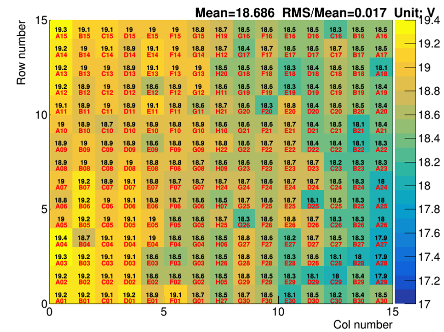
- Tested by 15×15 probe card, Temperature: 20 ^{o}C, Compliance: 1.5 mA

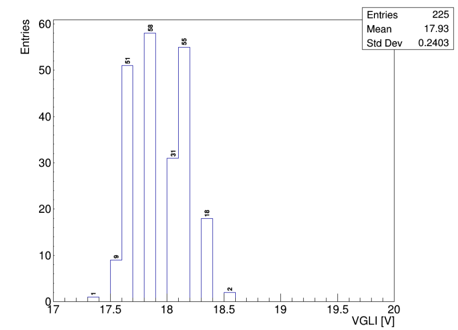
W3_P2@2.5E15 n_{eq}/cm^2





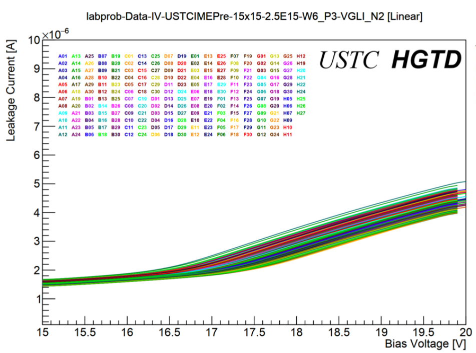
Vgl (from IV) distribution

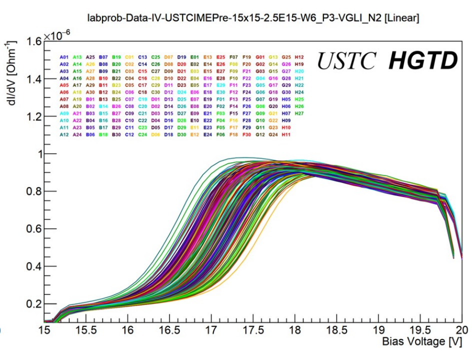




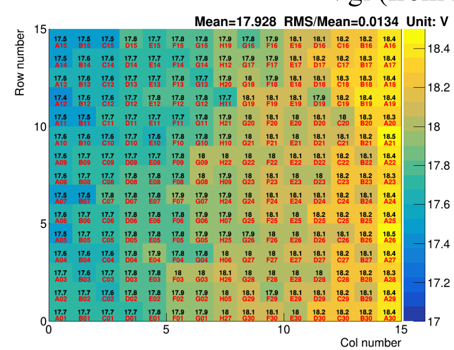
- Tested by 5×5 probe card, Temperature: 20 ^{o}C, Compliance: 1.5 mA

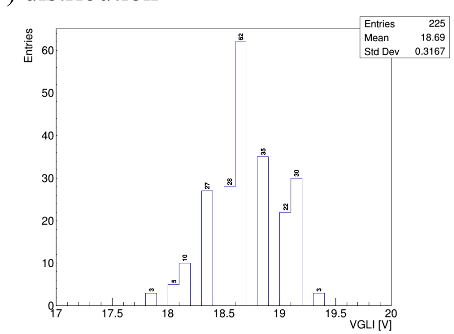
W6_P3@2.5E15 n_{eq}/cm^2





Vgl (from IV) distribution





- The VGL spread over this two sensors is 0.017 and 0.0134, respectively, which is larger than the spread over unirradiated sensors probably due to the contribution from the non-uniformity of irradiation fluence across the large array sensors.

Summary of main sensors' measured values

Parameters	Specification	UTSC-IME	
		Measured values	Statistics
Pad leakage current (V_{bd} condition)	< 500 nA	< 500 nA	
Break-down voltage (V_{bd})	V_{bd}>V_{fd} + D ·2 V/μm	VBD > 150V > 125.20V	4 sensors / 118 sensors
Device total leakage current	< 20 μA/cm^2 at bias voltage <V_{bd}	< 1.78 μA/cm^2@150V	5 sensors
$V_{gl,pad}$ spread over the Sensor*	RMS($V_{gl,pad}$)/<$V_{gl,pad}$> <0.005	< 0.0011	5 sensors
$V_{bd,pad}$ spread over the Sensor*,¤	RMS($V_{bd,pad}$)/<$V_{bd,pad}$> <0.05	< 0.0164	5 sensors
Pad leakage current spread at 0.8·V_{bd}	Peak-to-Peak within a factor of 3x	± 4.9%	5 sensors
Variation of the V_{fd} between different sensors	±10% from the average V_{fd}	± 0.7%	4 sensors
Variation of the V_{gl} between different sensors	±1% from the average V_{gl}	± 0.6%	5 sensors
Variation of the V_{bd} between different sensors	±8% from the average V_{bd}	± 4.9%	5 sensors

Required electrics properties of produced Sensors at room temperature (* applies also to irradiated sensors, ¤ for irradiated sensors at -30^{o}C)

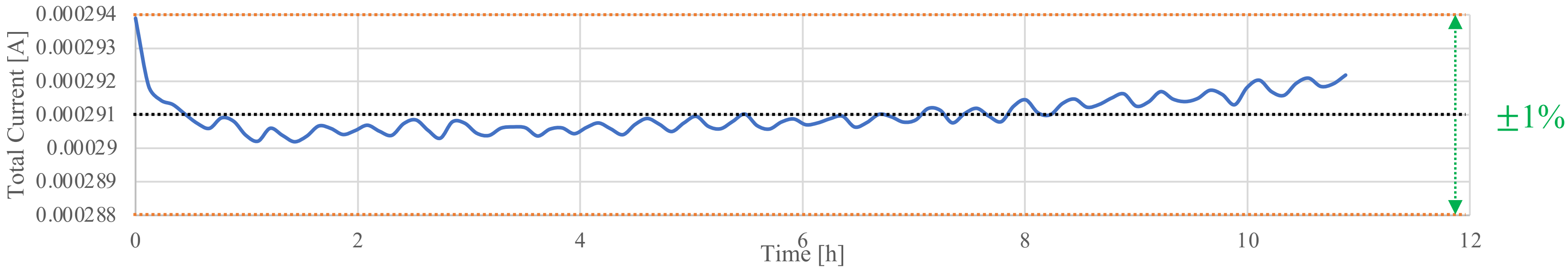
Parameters	Specification	USTC-IME	
		Measured values	Statistics
Power consumption at $V_{op,min}$	< 100 mW/cm^2	< 37 mW/cm^2	2 sensors
Total maximum leakage current (D=50 μm)	<160 μA/cm^2	< 72 μA/cm^2	
Pad leakage current at $V_{op,min}$	<5 μA	< 5 μA	
Interpad-resistance at $V_{op,min}$	>10 MΩ	> 10 MΩ	
Leakage current stability	to remain stable within +/-5% when corrected for temperature exhibiting no long-term drifts (on days scale) or prompt excursions	within ± 1.0% (on hours scale)	

Sensor performance requirements after irradiation to $2.5\cdot10^{15}$ n_{eq}/cm^2 at $V_{op.min}$ (The measured values are extracted at V1μA), -30°C.

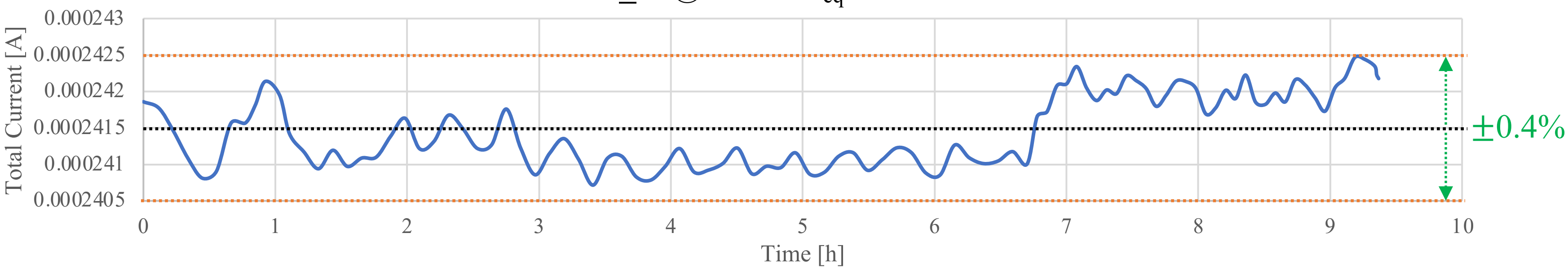
Preliminary long term stability measurements

- Tested by 15×15 probe card with all pads GND
- Temperature: -30 ^{o}C**,** Scanned all pads (225) with switching matrix

USTC-IME W3_P2@2.5E15 n_{eq}/cm^2 Bias: **550 V**



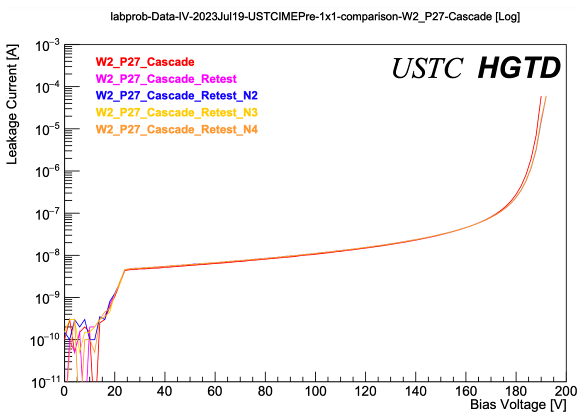
USTC-IME W6_P3@2.5E15 n_{eq}/cm^2 Bias: **550 V**

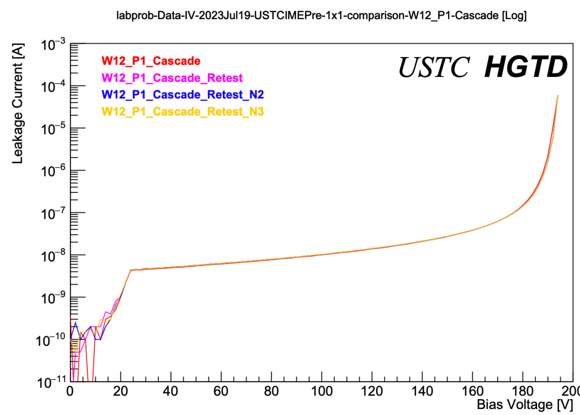


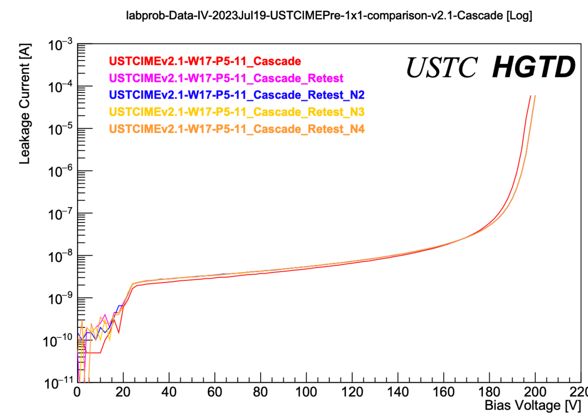
- The preliminary results (on hours scale) tested by 15×15 probe card shows that the total current stability is within ± 5%.

Comparison of single LGADs (IV)

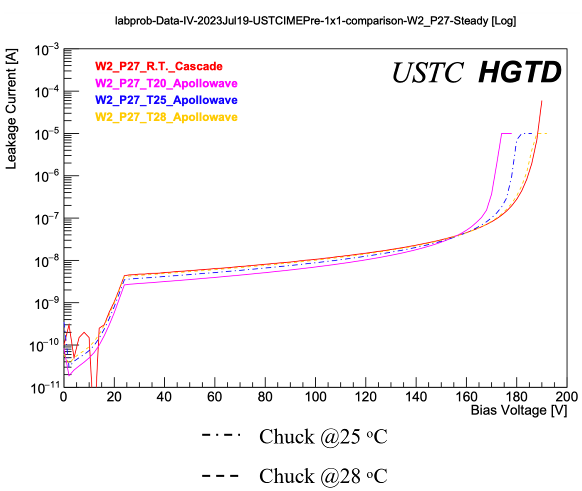
- Repeated testing on Cascade probe station at **R.T.** (vender test)

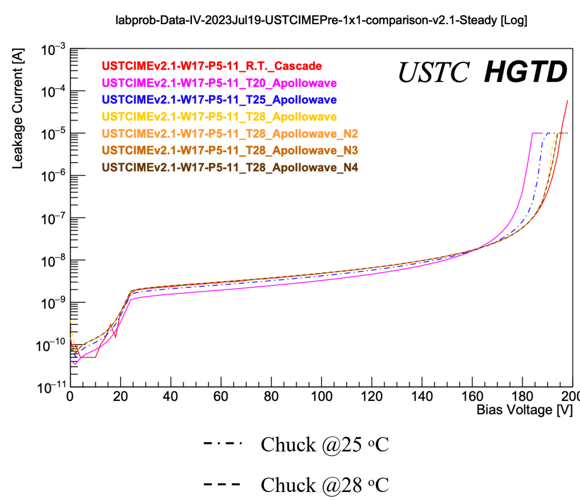






- Testing on Apollowave probe station **at different temperature of chuck** (cross-check)





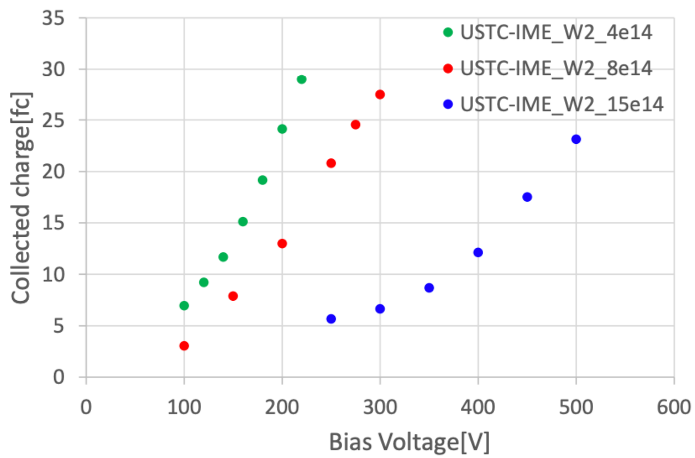
- The repeated vender test and cross check results is steady, respectively
- The difference of VBD is also in order of 10 V, which is **related to the temperature of the chuck**
- The ratio of I@0.8VBD is about 1.73

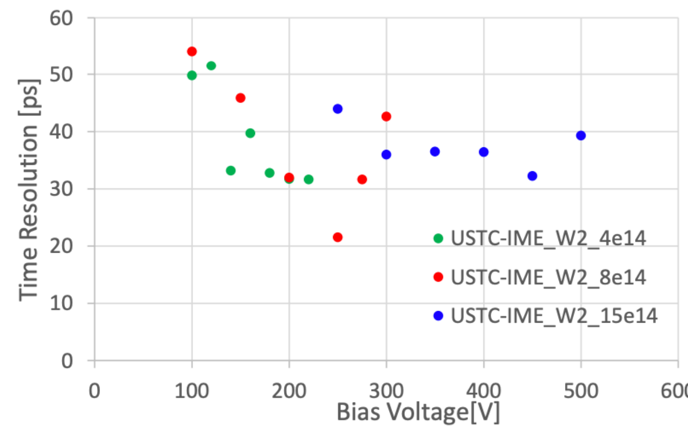
Collected charge and timing resolution – irradiated

Beta-scope (^{90}Sr) @ -30 °C

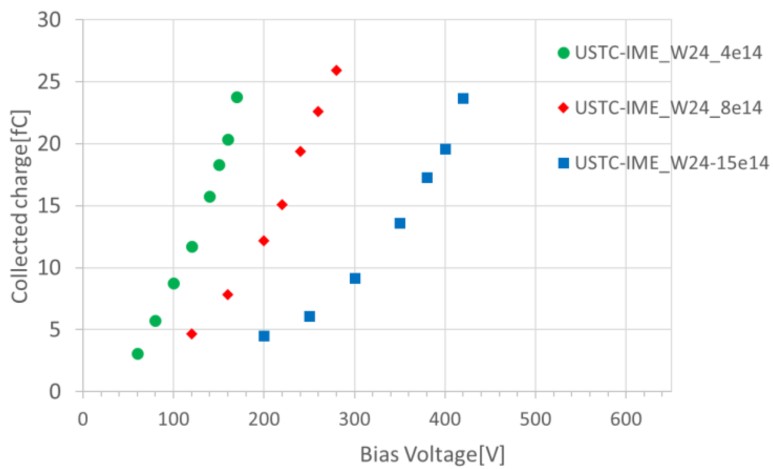
Measured by JSI

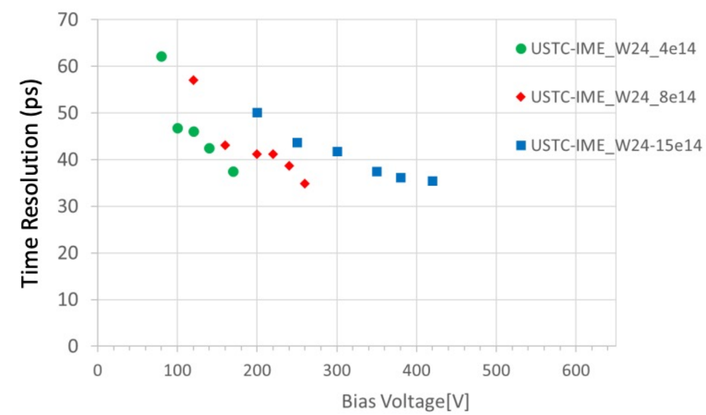
W2





W24





- The collected charge can be greater than 4 fC and timing resolution can be better than 70 ps after irradiation (fluences up to $1.5\times10^{15}\ n_{eq}/cm^2$) at safe bias