LGAD sensor status

MEI ZHAO

2025-12-05

Contract

- CERN procurement part: 54% of total sensors[585+11723]
- IME and CERN contract be signed at beginning of 2025.

INSTITUTE OF MICROELECTRONICS OF CHINESE ACADEMY OF SCIENCES

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Title: Director of Integrated Circuit Advanced Process R&D Center of IMECAS

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Date:

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

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Date: 06 February 2025

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Date: 06 February 2025

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE ★ CERN

BEIJING QIU SHI HIGH ENERGY TECH-DEVELOPING COMPANY

Name: Zhao Jianhong

Title: Legal Representative

Signature:

	Milestones	Latest delivery date
T0	Notification of the award of the Contract to IME (Letter of Intent already released)	Done
	Delivery of Detailed Design File and Quality Plan (already received)	Done
T1	Acceptance by CERN of the abovementioned documentation	Done
	Delivery of Pre-Series at CERN and associated documentation (see § 5.1 of the Technical Specification – Annex I)	Done
T2	Authorisation by CERN to manufacture the Series on the basis of Pre-Series acceptance	30 January 2025
	Delivery of pilot batch (batch no. 0) of Series units at CERN and associated documentation (see § 5.1 of the Technical Specification – Annex I)	30 April 2025
	Delivery of first batch (batch no. 1) of Series units at CERN and associated documentation (see § 5.1 of the Technical Specification – Annex I)	30 July 2025
	Delivery of second batch (batch no. 2) of Series units at CERN and associated documentation (see § 5.1 of the Technical Specification – Annex I)	30 October 2025
	Delivery of third batch (batch no. 3) of Series units at CERN (70% of the total Supply) and associated documentation (see § 5.1 of the Technical Specification – Annex I)	30 January 2026
	Delivery of fourth batch (batch no. 4) of Series units at CERN and associated documentation (see § 5.1 of the Technical Specification – Annex I)	30 April 2026
	Delivery of fifth batch (batch no. 5) of Series units (last batch of Production units) at CERN and associated documentation (see § 5.1 of the Technical Specification – Annex I)	30 July 2026

Delivery timeline

Contract signed

Pilot batch: done

First batch

Second batch

Third batch

Fourth batch

Fifth batch

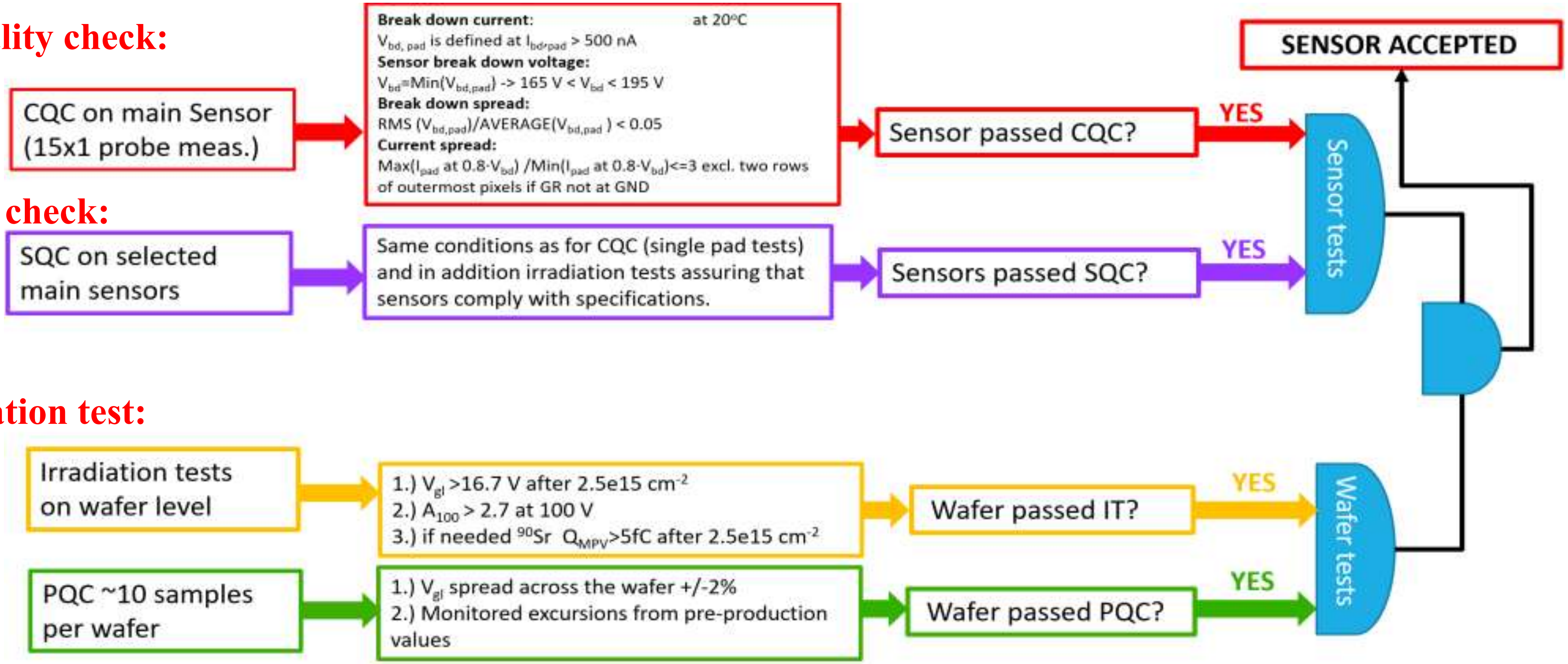
Acceptance criteria for LGAD sensors

- Wafers and sensors passing the following qualification tests will be accepted

Company quality check: CQC

Sensor quality check: SQC

Sensor irradiation test: IT



Acceptance criteria for LGAD sensors

➢ **Main sensors be separated as 3 classes: A, B1 and B2, C.**

➢ A: sensor passes all the acceptance criteria.

at 20°C

Break down current:

$I_{bd,15\ pad} = 15 \cdot I_{pad,bd} \rightarrow V_{bd,15\ pad}$ is defined at $I_{15\ pad} > 7500$ nA, where $I_{pad,bd}$ is the pad current breakdown threshold.

- **Sensor break down voltage:**

$V_{bd} = \mathrm{Min}(V_{bd,15\ pad}) \rightarrow 165V < V_{bd} < 195V$

- **Break down spread:**

$\mathrm{RMS}(V_{bd,15\ pad})/\mathrm{AVERAGE}(V_{bd,15\ pad}) < 0.05$

- **Current spread:**

$\mathrm{Max}(\mathbf{I}_{15\ pad}\ \text{at}\ 0.8 \cdot \mathbf{V}_{bd})/\mathrm{Min}(\mathbf{I}_{15\ pad}\ \text{at}\ 0.8 \cdot \mathbf{V}_{bd}) \leq 2.5$

Lower V_{bd}

➢ B1: sensor with $150V < V_{bd} < 165V$, fills the leakage current requirement

Larger leakage current ratio

➢ B2: sensor fill Current spread criteria with

$2.5 < \mathrm{Max}(I_{15pad}\ \text{at}\ 0.8 \cdot V_{bd})/\mathrm{Min}(I_{15pad}\ \text{at}\ 0.8 \cdot V_{bd}) < 10.$

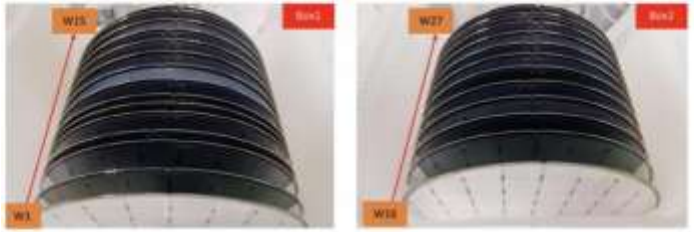
CERN will accept the sensors if they are of category A.

CERN reserves the right to review and possibly accept sensors of quality B if the need emerges.

Production status: next batches

Batch	Required sensor number	Delivered time on contract	Status
Pre-production	586		Accepted by HGTD group, and be delivered to hybridization sites.
Pilot batch	400	30 April 2025	403 sensors has been delivered to IHEP
1st batch	2736	30 July 2025	~2700 sensors. First 50 wafers been packaged, QC-TS be delivered to IHEP. Next 50 wafers under picking, will be delivered by **15 Dec. 2025**
2nd barch	2736	30 October 2025	2376 sensors[100 wafers] have completed UBM and dicing, will be ready to delivery by **30 Jan. 2026.** [three months delay]
3rd batch	2736	30 January 2026	2736 sensors[100 wafers] are under UBM in NCAP and will be ready to shipped on **30 Mar. 2026**
4th batch	1757	30 April 2026	Sensors are manufactured in IME, will be will be ready to shipped on **30 Apr. 2026**
5th batch	1757	30 July2026	Plan to be shipped on **30 July 2026**

Pre-production sensor status



ATLAS ID	IHEP-IME ID	thickness(um)	Average Vbd (V)	# of good sensors	sensor yield	UBM
20WS0000110002	v1-R2(w1)	775	212.7	19	37%	no
20WS0000110003	v1-R3(w2)	775	222.5	25	48%	no
20WS0000110016	v1-A16(w3)	775	196	18	35%	no
20WS0000200012	v2-12(w4)	775	180.8	39	75%	no
20WS0000110015	v1A15	775	217.7	22	48%	yes
20WS0000110005	v1R5	300	190	42	80.77%	yes
20WS0000200016	v216	300	201.7	40	76.92%	yes
20WS0000300010	V310	300	196.1	31	59.62%	yes
20WS0000400007	V4-7	300	169.9	31	59.62%	yes
20WS0000400009	V4-9	300	168.2	33	63.46%	yes
20WS0000400011	V4-11	300	170.8	39	75.00%	yes
20WS0000400012	V4-12	300	170.7	33	63.46%	yes
20WS0000400014	V4-14	300	162.1	30	57.69%	yes
20WS0000400015	V4-15	300	172	39	75.00%	yes
20WS0000400020	V4-20	300	177.8	28	53.85%	yes
20WS0000400022	V4-22	300	160	26	50.00%	yes
20WS0000400024	V4-24	300	178.1	31	59.62%	yes
20WS0000400001	V4-1	300	178.1	43	82.69%	yes
20WS0000400003	V4-3	300	167.4	6	11.54%	yes
20WS0000400013	V4-13	300	174.9	40	76.92%	yes
20WS0000400023	V4-23	300	164.8	34	65.38%	yes
20WS0000300001	V3-1	300	178.1	43	82.69%	yes
20WS0000300005	V3-5	300	172.3	36	69.23%	yes
20WS0000300015	V3-15	300	177.6	38	73.08%	yes
20WS0000300022	V3-22	300	176.6	44	84.62%	yes
20WS0000300023	V3-23	300	171.1	39	75.00%	yes
20WS0000300024	V3-24	300	174.3	41	78.85%	yes

Production version	Wafer No.	Implantation	LGADs	VBD mean	Labelled	Thinned	Backside (Al)	UBMed	Diced	Yield	Quality
USTC-IME Pre-production	W1	B+1C	15x15	~ 182.8 V	Done					17/52 ~ 33 %	
	W2	B+1C	15x15	~ 186.5 V	Done	Done	Done		Done	2/52 ~ 4 %	
	W3	B+1C	15x15	~ 193.7 V	Done	Done	Done	Ready		26/52 ~ 50 %	Good
	W4	B+1C	15x15	~ 190.8 V	Done	Done	Done	Ready		24/52 ~ 46 %	Good
	W5	B+1C	15x15	~ 191.7 V	Done	Done	Done	Ready		24/52 ~ 46 %	Good
	W6	B+1C	15x15	~ 188.5 V	Done	Done	Done	Ready		22/52 ~ 42 %	Good
	W7	B+1C	15x15	~ 184.9 V	Done	Done	Done	Ready		22/52 ~ 42 %	Good
	W8	B+1C	15x15	~ 186.2 V	Done	Done	Done	Ready		22/52 ~ 42 %	Good
	W9	B+1C	15x15	~ 195.6 V	Done					13/52 ~ 25 %	
	W10	B+1C	15x15	~ 193.6 V	Done					16/52 ~ 31 %	
	W11	B+1C	15x15	~ 192.3 V	Done	Done	Done	Ready		26/52 ~ 50 %	Good
	W12	B+1C	15x15	~ 193.1 V	Done	Done	Done		Done	13/52 ~ 25 %	
	W13	B+1C	15x15	~ 188.8 V	Done	Done	Done	Ready		21/52 ~ 40 %	Good
	W14	B+1C	15x15	~ 191.6 V	Done	Done	Done	Ready		18/52 ~ 35 %	Good
	W15	B+1C	15x15	~ 193.0 V	Done					12/52 ~ 23 %	
	W16	B+1C	15x15	~ 152.4 V	Done					23/52 ~ 44 %	
	W17	B+1C	15x15	~ 150.4 V	Done					27/52 ~ 52 %	
	W18	B+1C	15x15	~ 137.7 V	Done					25/52 ~ 48 %	
	W19	B+1C	15x15	~ 146.5 V	Done					26/52 ~ 50 %	
	W20	B+1C	15x15	~ 138.9 V	Done					20/52 ~ 36 %	
	W21	B+1C	15x15	~ 127.5 V	Done					18/52 ~ 35 %	
	W22	B+1C	15x15	~ 143.6 V	Done					21/52 ~ 40 %	
	W23	B+1C	15x15	~ 130.6 V	Done					15/52 ~ 29 %	
	W24	B+1C	15x15	~ 151.8 V	Done	Done	Done		Done	21/52 ~ 40 %	
	W25	B+1.3C	15x15	~ 116.9 V	Done	Done	Done		Done	10/52 ~ 19 %	
	W26	B+1.5C	15x15	~ 111.8 V	Done	Done	Done		Done	13/52 ~ 25 %	
	W27	B+0.7C	15x15	~ 158.1 V	Done	Done	Done		Done	25/52 ~ 48 %	

USTC-IME 27 wafers fabricated:
9 wafers core preproduction – all finished in accordance with specs and requirements

IHEP-IME: 90 wafers fabricated.
22 wafers: core preproduction – all finished in accordance with specs and requirements

Finished in 2024

Pre-production sensor status

Thick wafers: be distributed for hybridization with ASIC at IFAE and NCAP

IHEP-IME:
12 wafers, 402 sensors

Be distributed:
IFAE: 5 wafers, 164 sensors
IHEP: 7 wafers, 238 sensors

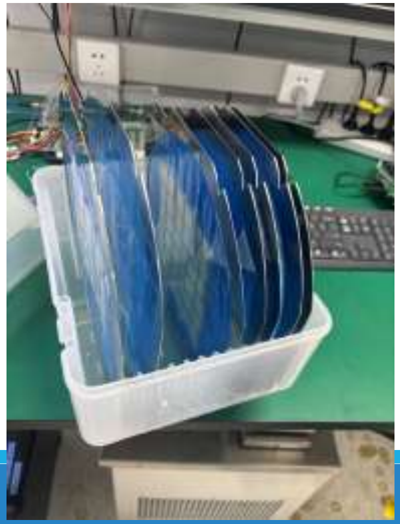
USTC-IME:
6 wafers, 167 sensors

Be distributed:
IFAE: 5 wafers, 104 sensors
IHEP: 2 wafers, 63 sensors

For IFAE:268 sensors,
IHEP: 301 sensors

IHEP-IME (B5-W)	Number	Status
2	37	At NCAP
3	32	At IFAE
4	30	IHEP
5	34	IFAE
6	38	IFAE
7	27	IHEP
9	22	IFAE
14	38	IFAE
15	35	IHEP
18	41	IHEP
22	36	IHEP
24	32	IHEP

USTC-IME	Number	Status
16	23	At IFAE
17	34	IHEP
18	29	IHEP
19	30	IFAE
20	25	IFAE
21	26	IFAE
22	25	At USTC



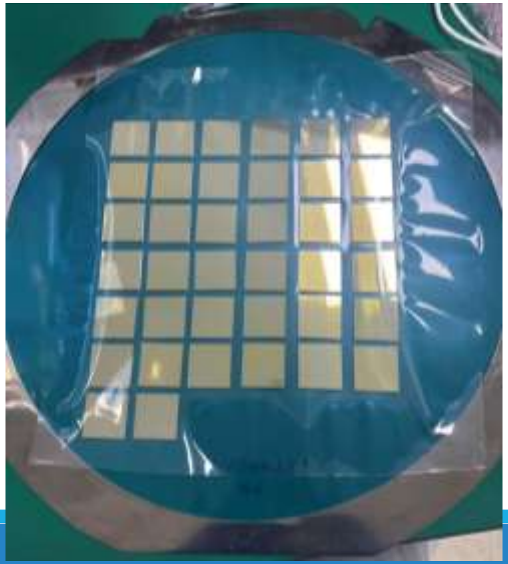
Production status: pilot batch

- **IHEP-IME Pilot batch** been delivered to IHEP on 15th May, including main sensors and QC-TS.
- **17 wafers: 403 good sensors** and 17x25 QC-TS.
- Sensor quality check be done by IHEP. 17x25 QC-TS will be distributed to CERN, USP and JSI for process quality check and irradiation test.

Table 1: Number of good sensors for wafers [from B4-W2 to B4-W19]

Wafer serial number	W2	W3	W4	W5	W6	W8
Number of good sensors	20	12	25	22	26	35
Wafer serial number	W9	W10	W11	W12	W13	W14
Number of good sensors	27	26	27	29	22	29
Wafer serial number	W15	W16	W17	W18	W19	Total
Number of good sensors	26	15	16	24	22	403

Yield: 403/884 = ~45%



Pilot batch: SQC

SQC: sensors quality check, done by IHEP

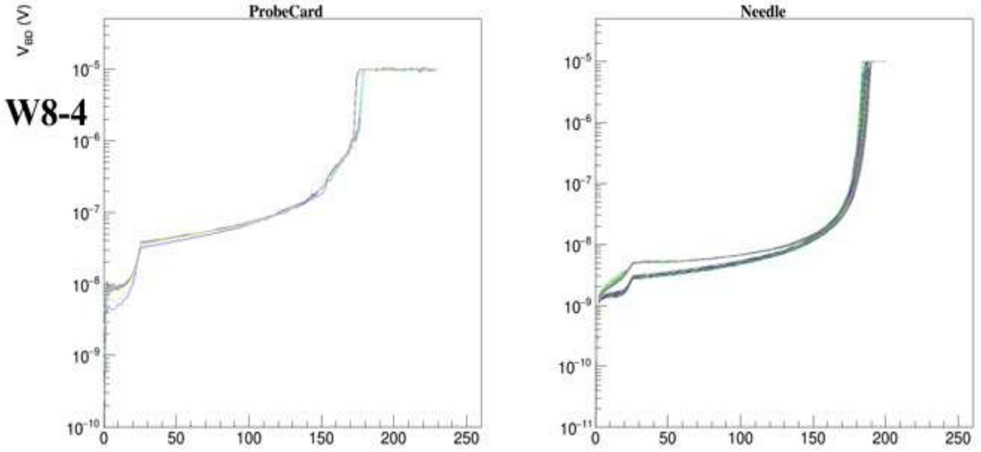
1、Used probe station to measure the I-V curve of each channel【per-pad needle test】

Calculate the sensor information: V_{bd}, V_{bd} spread, I_{ratio}

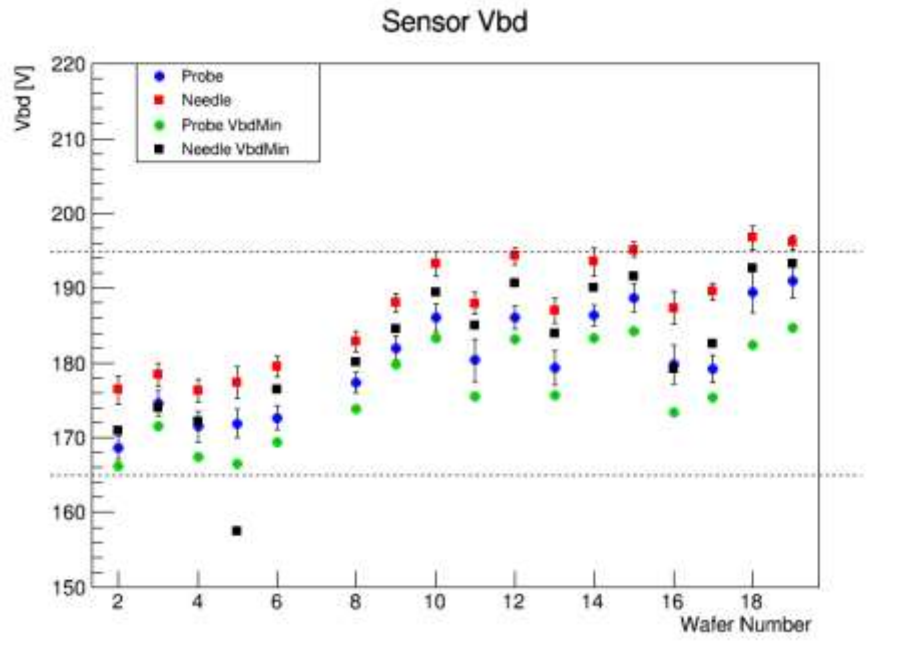
2、20 Class-A been tested and results compared with IME's

19 remain A; 1 (W5P7) → B1(V_{bd} < 165V);

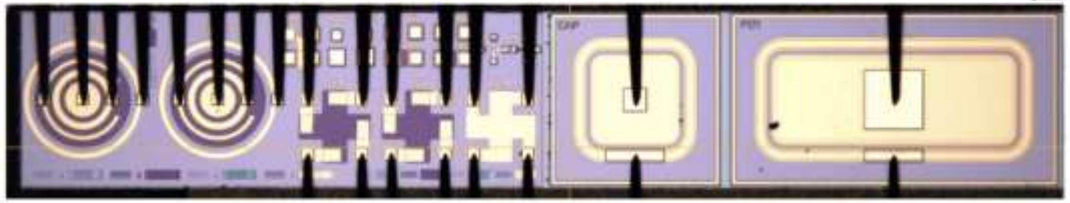
Wafer Serial Number (B4)	Sensor Number	Probe Card			Needle				
		V_{bd} Min[V]	RMS/ $\langle V_{bd} \rangle$	I ratio	V_{bd} Min[V]	RMS/ $\langle V_{bd} \rangle$	I ratio	I ratio-o	Class
W2	5	166.22	0.90%	1.07	170.97	1.08%	3.43	1.49	A
W4	5	167.34	1.20%	1.10	172.17	0.89%	3.72	1.41	A
W5	7	166.54	1.12%	1.16	157.52	1.20%	3.59	1.35	B1
W6	6	169.45	0.95%	1.09	176.46	0.78%	3.44	1.32	A
W13	3	175.74	1.25%	1.24	183.98	0.89%	3.51	1.42	A
W16	5	173.43	1.42%	1.50	179.25	1.19%	3.75	1.44	A
W19	8	184.77	1.15%	2.58	193.24	0.48%	4.23	1.35	A
W3	28	171.60	0.98%	2.11	174.01	0.82%	3.28	1.32	A
W8	4	173.84	0.77%	1.20	180.05	0.77%	3.09	1.34	A
W9	6	179.74	0.89%	1.90	184.53	0.62%	3.37	1.28	A
W10	6	183.31	0.95%	1.91	189.46	0.87%	3.66	1.38	A
W11	6	175.47	1.57%	1.29	184.97	0.74%	3.34	1.36	A
W12	6	183.19	0.83%	2.38	190.66	0.56%	3.90	1.31	A
W14	4	183.29	0.76%	1.70	190.03	0.99%	3.33	1.39	A
W15	6	184.25	1.01%	2.41	191.62	0.53%	3.49	1.29	A
W17	6	175.30	1.04%	1.59	182.52	0.60%	3.36	1.28	A
W18	3	182.47	1.45%	3.15	192.62	0.80%	4.17	1.37	A



3、V_{bd} from the needle test(IHEP) was 2~10 V higher than the probe card test(IME);



Pilot batch: process quality check



- **17 wafers of IHEP-IME Pilot batch**
- 10 QC-TS/wafer tested by CERN and 10 QC-TS/wafer at CERN USP

- Wafer acceptance criteria on spread of gain-layer depletion voltage：

$$\text{Spread} = \frac{\text{RMS}(V_{gl})}{\text{AVERAGE}(V_{gl})} < 2\%$$

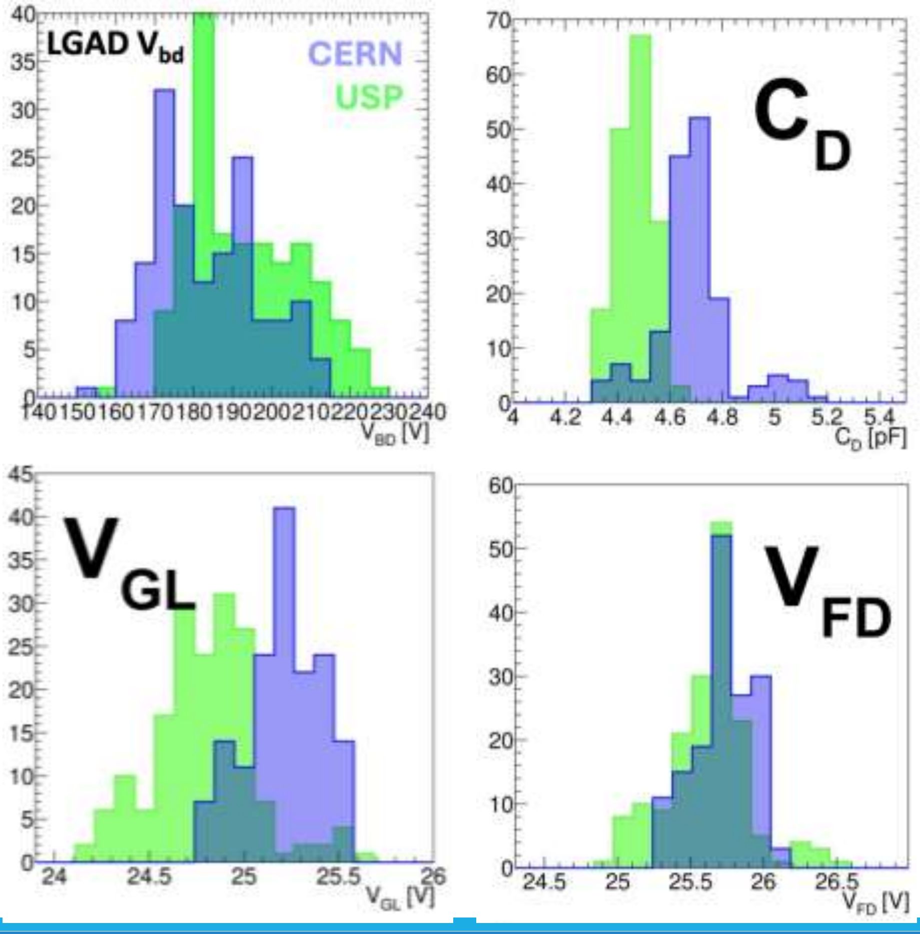
- LGAD IV and CV: Results for sites individually ok, slight discrepancy between USP and CERN in V_{gl} and C_D

V_{gl} spread

✓ USP 17/17 wafer would **pass** PQC

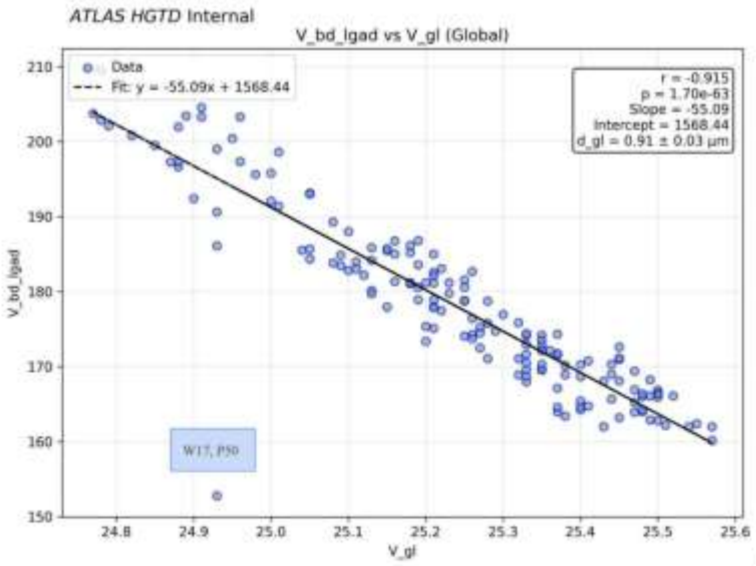
✓ CERN 17/17 wafer would **pass** PQC

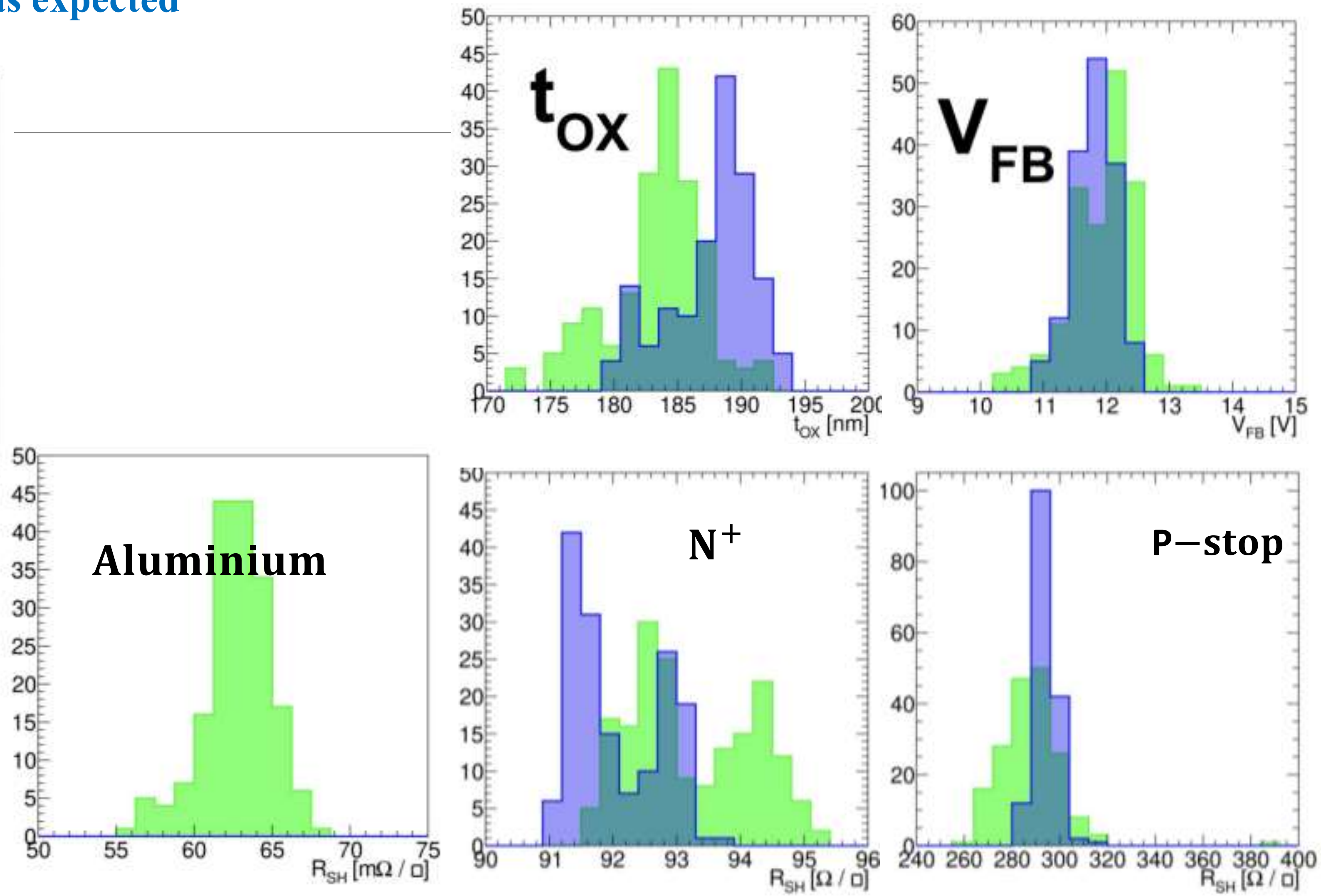
C_D : average of 4.45 pF



Pilot batch: process quality check

- ➢ **V_{gl} vs. V_{bd} : strong correlation observed as expected**



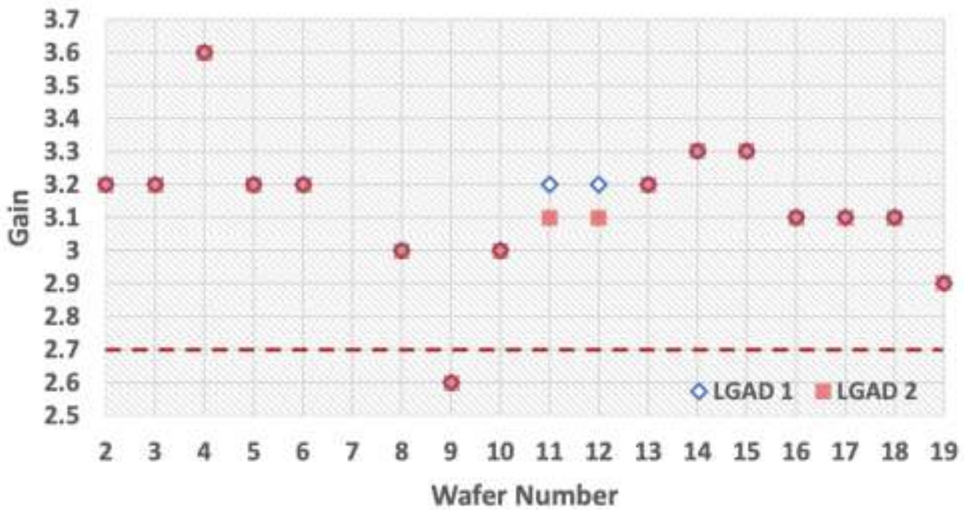


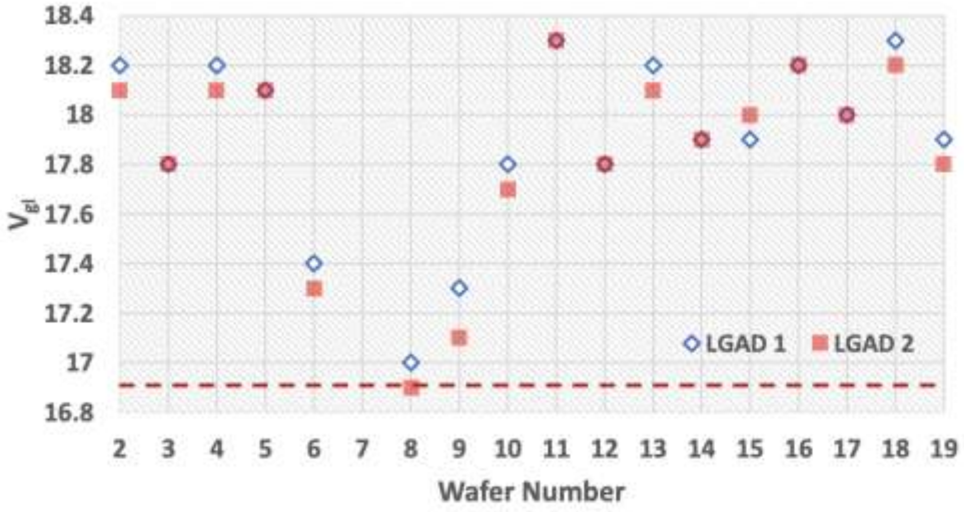
- ➢ **Other process parameters**: VFB, Oxide thickness, N+, p-stop and Aluminium sheet resistance:
- Very low spread, indicating uniform process parameters
- Good agreement between sites
- with same spread as pre-production

Pilot batch: Irradiation Test

- Irradiation Test: QC-TS are irradiated at JSI with neutrons at end-of-life fluence($2.5 \times 10^{15}\ n_{eq}/cm^2$) (annealed for 80min at 60°C)
- 5 QCTS/wafer at JSI, 1 QC-TS/wafer tested by JSI
- Transient Current Technique (TCT) measurement:
  - Gain @ 100V measured with the TCT method in the inter-pad region of the 1x2 LGAD of the QC-TS
  - Inter-pad region: no gain layer → PIN diode
- CV measurement: V_{gl}
- Acceptance Criteria：

Design	Gain @ 100 V	V_{gl}
IHEP	≥ 2.7	≥ 16.9V
USTC	≥ 1.4	≥ 16.6V





- All wafers pass V_{gl} requirements
- One wafer (9) barely fails gain criteria(to do Sr90 measurements on W9)

Issues: in-kind Contract

In-kind contract:

24% IHEP: 5232 sensors, 10% USTC: 2180 sensors

1、Middle of this year, IME provided the price for this part, which is too high, 10 times of CERN price.

2、The contract of this part need to be signed promptly, as it is subject to the funding timeline.

Solution：

- B1 sensors been tested to check if these sensors also can be used. In fact these sensors with lower BV at beginning have good radiation performance.
- Together with A type sensors， many B1 sensors been fabricated.

B1 sensors may be accepted for in-kind sensors.

Pilot batch [884 sensors]
Class A 371.00 [42%]
Class B1 131.00 [14.8%]
Class B2 101.00

For CERN: total 11723 A sensors
Follow this yield, then more than 4000 B1 sensors will be fabricated.

In fact, 6 batches(150 wafers) are all B1 wafers

Acceptance of B1 sensors

Test of B1 sensors:

Main sensor + Hybrid test

Total: 19 B1 tested, 12 good B1(actually A type).
63% yield.

	B1		CQC: Probe card			SQC: Needle, per-pad				
		V_{bd}Min(V)	RMS/<V_{bd}>	I_{ratio}	V_{bd}Min(V)	RMS/<V_{bd}>	I_{ratio}	class	
IHEP test	w3-8	163.36	0.72%	1.23	174.08	3.62	1.31	A	
IHEP test	w3-18	154.63	1.09%	1.1	167.67	3.51	1.30	A	
JSI test	w5-5	163.9	1.49%	1.17	13.5(171)			C	One bad pixel: near GR
JSI test	w5-8	162.8	1.36%	1.09		Be damaged during test			
JSI test	w5-17	153.7	1.89%	1.15	136.7(169)			C	One bad pixel: near GR
JSI test	w5-20	155.8	1.50%	1.33	167.2			A	
JSI test	w5-35	153.4	1.59%	1.37	161.9			B2	

type	Hybrid number	good	issue
B1	13	9(69%)	1 with large leakage current(w6-18) 3 with current steps [w5-44,w5-50,w6-49]

IT test of B1 sensors(JSI):

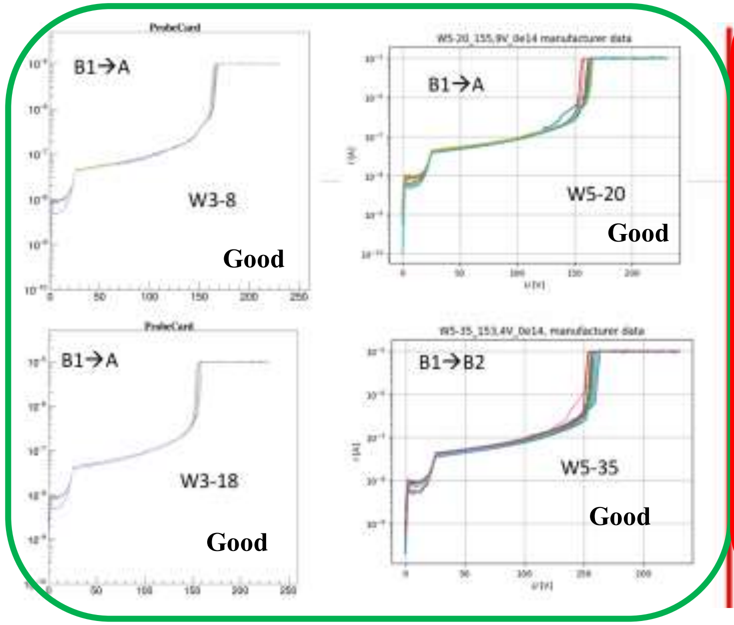
	CQC	SQC	SQC 4e14	Vbd CQC	Vbd SQC Average V_{bd}($V_{bd,min}$)	Mean V@95uA [V]	ΔV_{op} [V]	RMS V@95uA	<I>@0.8*V95uA	RMS<I>@0.8*V95uA
W3-27	Class A	Class A	"Class A IV"	169.3	170.5	221.8	~51	0.79	34.8	0.35
W10-5	Class A	Class A	"Class A IV"	175.7	182.8	233.6	~52	2.1	33.8	0.92
W5-5	Class B1	Class C	"Class A IV"	163.9	172.0 (25*)	224.2	~52	2.1	35.3	0.92
W5-17	Class B1	Class C	"Class A IV"	153.7	172.2 (137*)	218.1	~48	1.7	35	0.73
W19-47	Class B2	Class C	"Class A IV"	182.2	203 (90*)	250.4	~47	1.74	32.6	0.8
W19-49	Class B2	Class C	"Class A IV"	179.7	204 (145*)	246.5	~42	2.2	33.8	0.94

After moderate irradiation the detectors of all three classes[A, B1, B2] have similar performance, all are suitable for use!

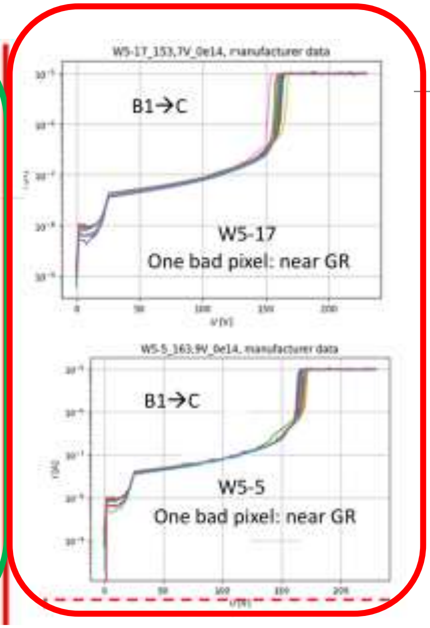
Beam test, Stefano(CERN): first glance of the hybrids look fine (with A sensors, B1 and B2 sensor).

Acceptance of B1 sensors

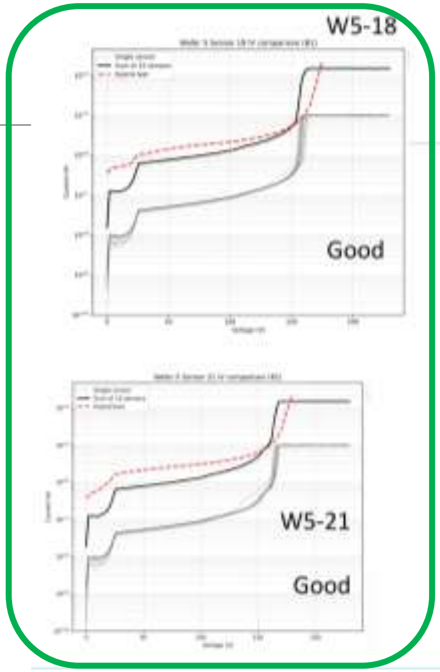
CQC results for B1 sensors:



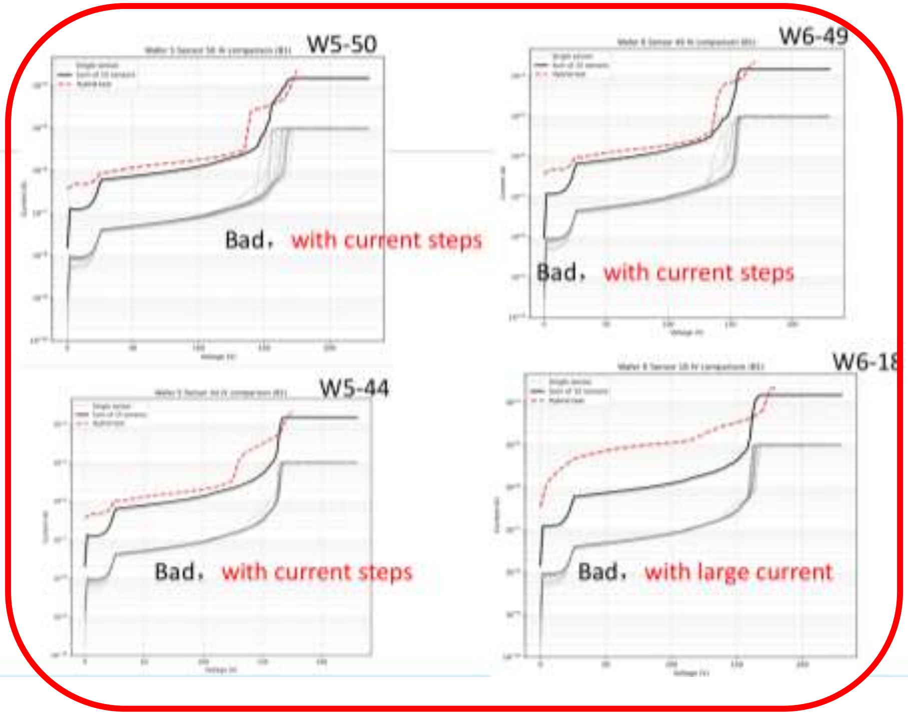
CQC:B1
SQC: A type



CQC:B1
SQC: C type



CQC:B1
hybrid: A type



CQC:B1
Hybrid: C type

- Good B1 has lower V_{bd} spread.
  V_{bd} Spread for A is 5%, for B1, RMS(Vbd)/<Vbd> < 1.5 % ?

- More statistics are needed to get conclusion of Acceptance criteria for B1 sensors.
- 50 B1 sensors hybrid will be done, 30 B1 sensors plan to be tested in this month.

LGAD sensor status-summary

- **Contract**

IME and CERN contract be signed at beginning of 2025.

- **Pre-production**

LGAD sensors' pre-production is finished in2024, and IHEP-IME(19 wafers) and USTC-IME(5 wafers) sensors fulfills the project requirement.

Sensors from 12 IHEP-IME and 6 USTC-IME thick wafers being used for hybridization now.

- **Production**

Pilot batch is finished; sensors be distributed to IHEP in May 2025. Quality test done, results show the A type sensors pass the requirement. [SQC,PQC, IT]

- **Next batches for CERN part will be finished before August 2026.**
- **In-kind contract need to be signed soon, B1 sensors may be accepted as in-kind part sensors. More cross check test need to be done on B1 sensors and decide the Acceptance criteria .**