

Status of the HGTD Sensors upgrade



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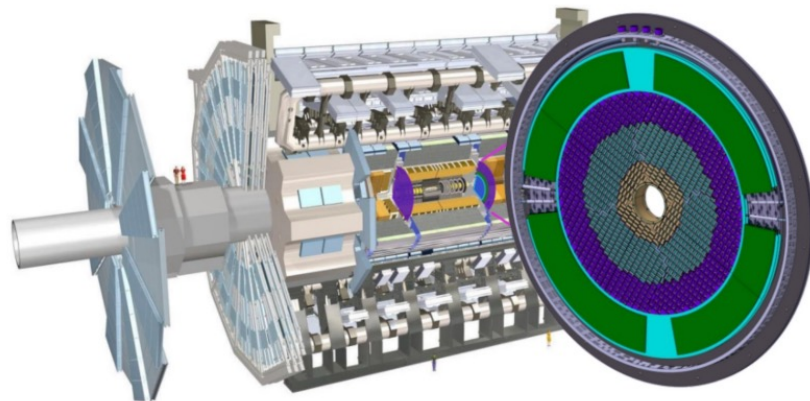
on behalf of HGTD Sensor Group

30-10-2025



- Introduction
- Company Quality Control (CQC)
- Sensor Quality Control (SQC)
- Process Quality Control (PQC)
- Irradiation Tests (IT)
- Summary

High-Granularity Timing Detector (HGTD)

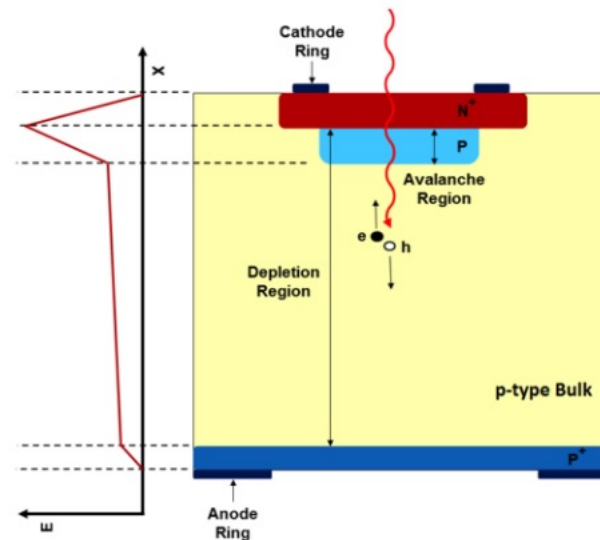


Following the HL-LHC upgrade,

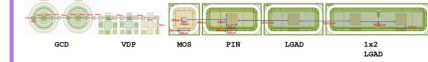
- The collisions per Bunch Crossing(BX): 140~ 200 with 1.5 vertex/mm on average along the z axis;
- The High-Granularity Timing Detector based on Low Gain Avalanche Detector (LGAD): provides timing information to enhance vertex reconstruction and luminosity monitoring.

Sensor production:

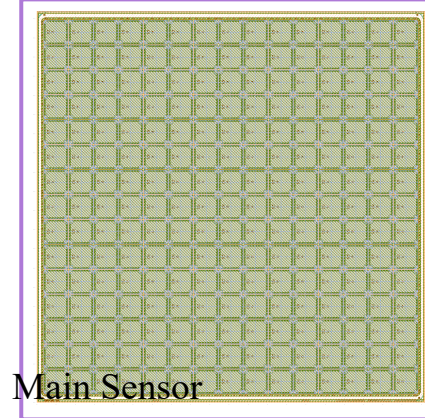
- About 21800 sensors;
- IHEP-IME: 90% (pilot batch + 5 batches);
- USTC-IME: 10%.



QC Test Structure



Main Sensor



LGAD Technology:

- N-in-P diode structure with extra p-type gain-layer;
- Gain: 10 ~ 20.

LGAD sensor for HGTD:

- Active thickness: 50 μm ;
- 15x15 pads with $1.3 \times 1.3 \text{ mm}^2$ cells;
- Carbon-enriched gain-layer for radiation hardness;
- Radiation tolerance : $2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, 200Mrad
- Time resolution: $\approx 35\text{ps}$ (start); $\approx 70\text{ps}$ (end of lifetime);
- Min. charge: 4fC;

HGTD Sensor Acceptance Criteria



IME → Some companies
Wafer processing, **Company** Dicing, picking, and
Quality Control (CQC) packing

IME, USTC
Sensor Quality
Control (SQC)

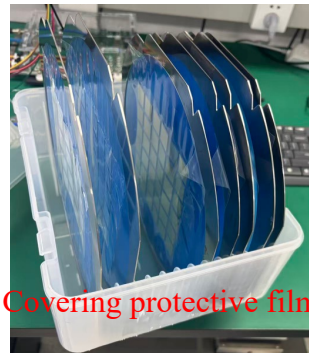
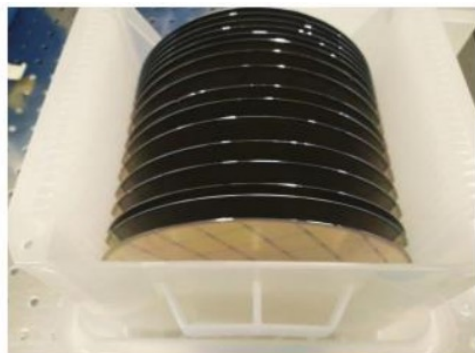
CERN
• LGAD CV → $\frac{\text{RMS}(V_{gl})}{\text{AVERAGE}(V_{gl})} < 2\%$
• LGAD IV
• MOS CV
• Sheet resistors

USP
Process Quality Control (PQC)

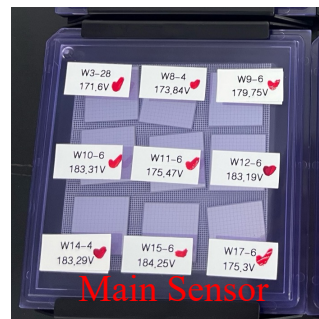
JSI
Irradiation Test (IT)

- $V_{bd} = \text{Min}(V_{bd,15 \text{ pad}}) \rightarrow 165V < V_{bd} < 195V, \frac{\text{RMS}(V_{bd,15 \text{ pad}})}{\text{AVERAGE}(V_{bd,15 \text{ pad}})} < 5\%$
- Current spread: $\text{Max}(I_{15 \text{ pad}} \text{ at } 0.8 \cdot V_{bd}) / \text{Min}(I_{15 \text{ pad}} \text{ at } 0.8 \cdot V_{bd}) \leq 2.5$

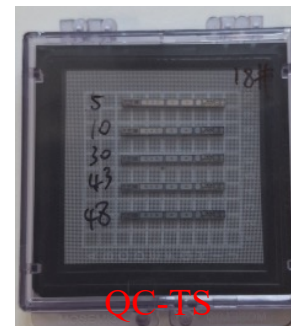
- Gain @ 100V(TCT)
- V_{gl} (CV after irradiation)



Covering protective film



Main Sensor



QC-TS

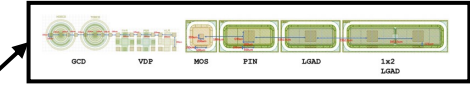
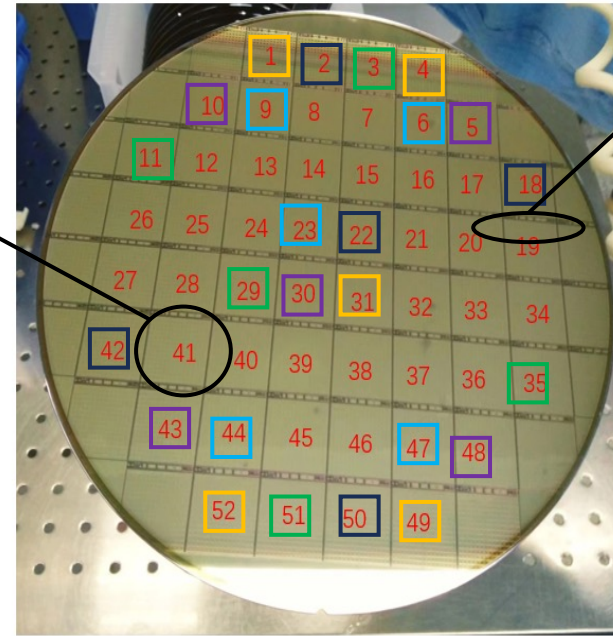
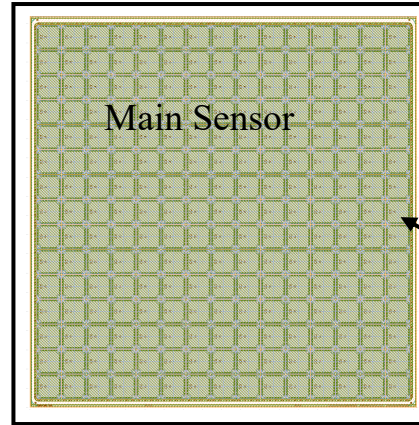


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Company quality control(CQC)

Wafer layout

- 52 complete sensors on the entire wafer;
- One sensor consisting of a main sensor and Quality Control Test Structures (QC-TS).

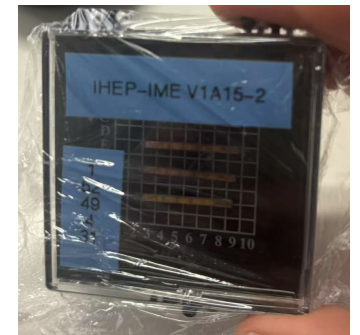
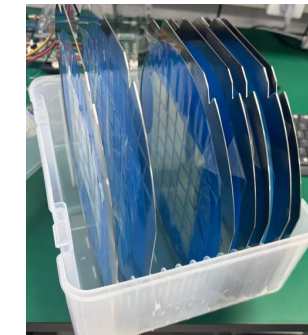


- Five QC-TS structures are selected at five distinct positions on the wafer.

Allocated to	TS grouping	TS Position Number
CERN	1	2、18、22、42、50
	2	6、9、23、44、47
USP	1	1、4、31、49、52
	2	3、11、29、35、51
JSI	1	5、10、30、43、48

IV test

- **IHEP**: 15x1 probe card IV measurements on sensors by IME before dicing;
- **USTC**: single-needle per-pad measurements on all sensors by IME before dicing.
- IME uploads the IV test data to HGTD database;
- IME provides classification results based on IV test data without temperature correction;
- Some companies perform dicing, selecting Class A sensors and QC-TS structures from five different positions are gathered together.



Sensor Acceptance Criteria

- **A**: sensor passes all the acceptance criteria.

Break down current:

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

- **Sensor break down voltage:**

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

- **Break down spread:**

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

- **Current spread:**

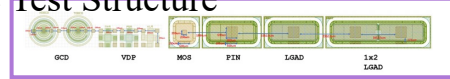
$$\text{Max}(I_{15\text{ pad}} \text{ at } 0.8 \cdot V_{bd}) / \text{Min}(I_{15\text{ pad}} \text{ at } 0.8 \cdot V_{bd}) \leq 2.5$$

- **B1**: sensor with $150\text{V} < V_{bd} < 165\text{V}$, fills the leakage current requirement
- **B2**: sensor fill Current spread criteria with
$$2.5 < \text{Max}(I_{15\text{ pad}} \text{ at } 0.8 \cdot V_{bd}) / \text{Min}(I_{15\text{ pad}} \text{ at } 0.8 \cdot V_{bd}) < 10.$$
- **C**: sensor fills any of the tests and are not of category B.

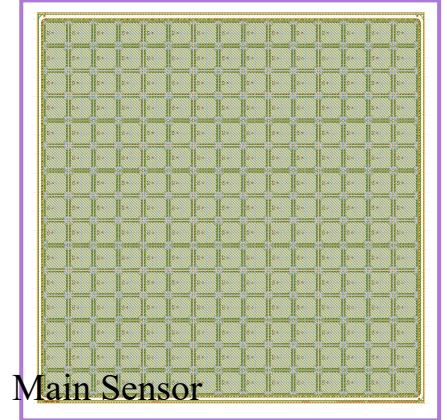
at 20°C



QC Test Structure



Main Sensor



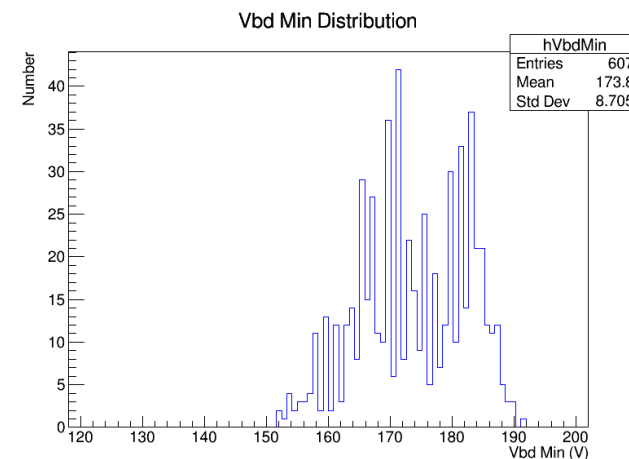
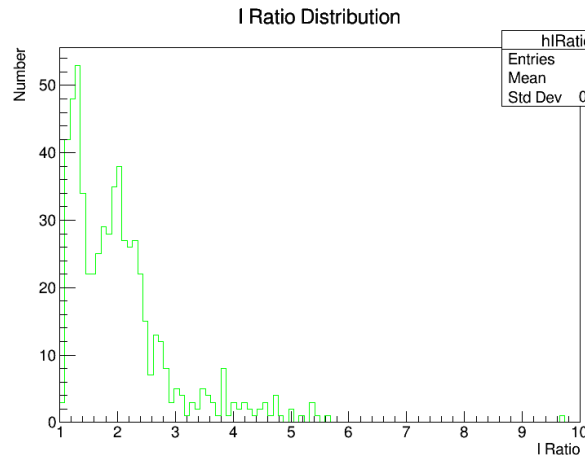
Company Quality Control (CQC)

17 wafers of IHEP Pilot Batch

- Class A sensors according to IME analysis results is 403;
- Class A sensors according to IHEP analysis results **with temperature correction** is 372;
- Information of sensors from 17 wafers from IME test data
 - V_{bd} distribution:
 - A+B1+B2: from 152V to 192V;
 - Leakage current ratio at $0.8V_{bd}$:
 - Except for one main sensor(type B2) with an IRatio of 9.7, the rest (A+B1+B2) are less than 5.8.

Temperature correction:

Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	
3	168.267	166	1.23648	0.0073484	Pass	A	3	167.501	164.612	1.38395	0.0082623	B1
6	170.4	166	2.2151	0.0129994	Pass	A	6	169.567	165.77	1.95126	0.0115073	B1
7	168.667	166	1.88562	0.011796	Pass	A	7	167.969	165.221	1.76974	0.0105361	B1
8	166.533	164	1.35974	0.008165		B1	8	165.668	163.361	1.19347	0.007204	B1
10	167.467	166	1.54344	0.0092164	Pass	A	10	166.943	164.855	1.52418	0.00913	B1
12	170.4	166	1.49666	0.0087832	Pass	A	12	169.664	165.674	1.42311	0.0083878	B1
Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	
4	172.533	166	2.799	0.0123164	Pass	A	4	171.691	165.651	1.94607	0.012347	B1
38	168.8	166	1.67994	0.0094787	Pass	A	38	168.015	165.52	1.52607	0.009	B1
Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	
4	170.267	166	2.04831	0.010728	Pass	A	4	169.566	165.231	1.8905	0.0111	B1
11	169.6	166	1.30639	0.00728	Pass	A	11	168.71	165.392	1.24451	0.0075	B1
12	171.6	166	2.55082	0.0140645	Pass	A	12	170.878	165.56	2.52853	0.0147973	B1
30	169.6	166	1.30639	0.0077028	Pass	A	30	168.877	165.436	1.38202	0.0081836	B1
34	172	166	2.73252	0.0158867	Pass	A	34	171.339	164.932	2.76023	0.0161098	B1
36	169.733	166	2.61958	0.0154335	Pass	A	36	169.202	165.29	2.69894	0.015951	B1
43	166.8	166	1.22202	0.0073263	Pass	A	43	166.215	164.824	1.24506	0.0074907	B1
Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	
2	171.467	166	2.24697	0.0131044	Pass	A	2	170.869	165.131	2.22895	0.0130445	B1
3	168.933	166	1.76887	0.0104708	Pass	A	3	168.274	165.4	1.52287	0.0090499	B1
4	171.467	166	2.12498	0.012393	Pass	A	4	170.834	165.891	1.90845	0.0111714	B1
32	169.467	166	1.7075	0.0100757	Pass	A	32	168.619	165.263	1.66522	0.0098757	B1
34	170.533	166	2.87209	0.0168418	Pass	A	34	169.96	164.631	2.82947	0.0166478	B1
Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	Sensor	Vbd_Avera	Vbd_Min	Vbd_Rms	Vbd_Rms_oVbd_Status	Final_Sta	
18	168.933	166	2.61958	0.0155066	Pass	A	18	168.222	165.173	2.4304	0.0144475	B1



Class	A	Yield
A	372	42.08%
B1	119	13.46%
B2	116	13.12%
total	607	68.66%



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Sensor Quality Control (SQC)



- SQC: IHEP per-pad tested one Class-A sensor per wafer from 17 wafers;

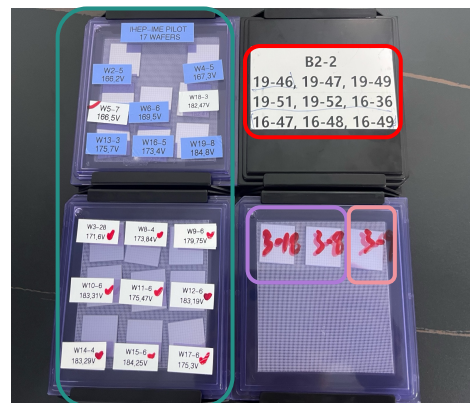
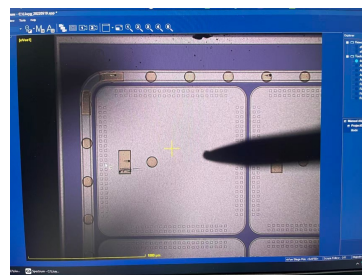
SQC:

Class A : 17 in total;

Class B1 : 2 in total;

Class B2 : 4 in total;

Class C : 1 in total;

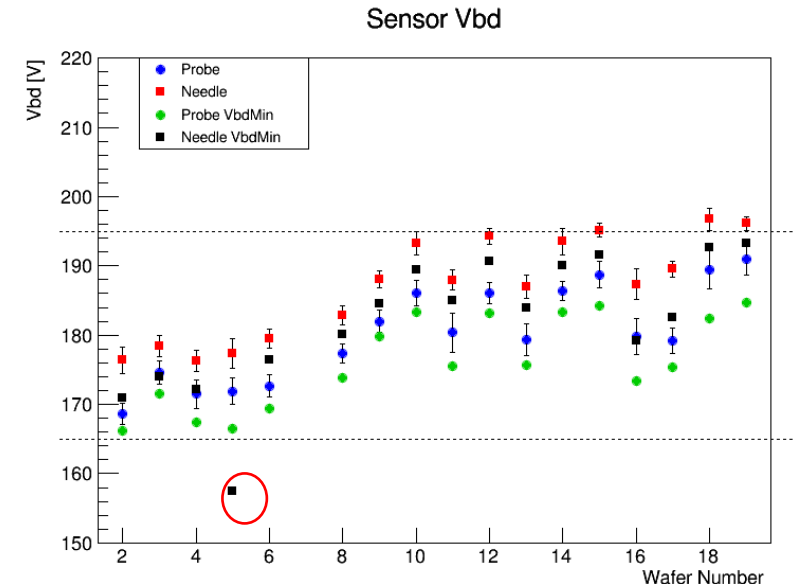
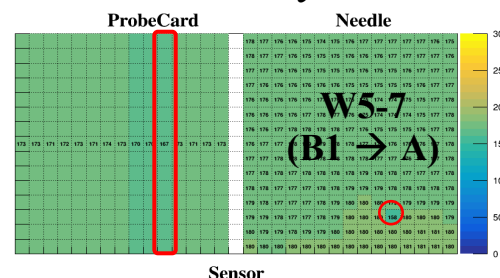


- Single needle per-pad IV measurements at 20°C
- GR: floating, identical to IME
- Each sensor requires approximately 2 hours for needle test.

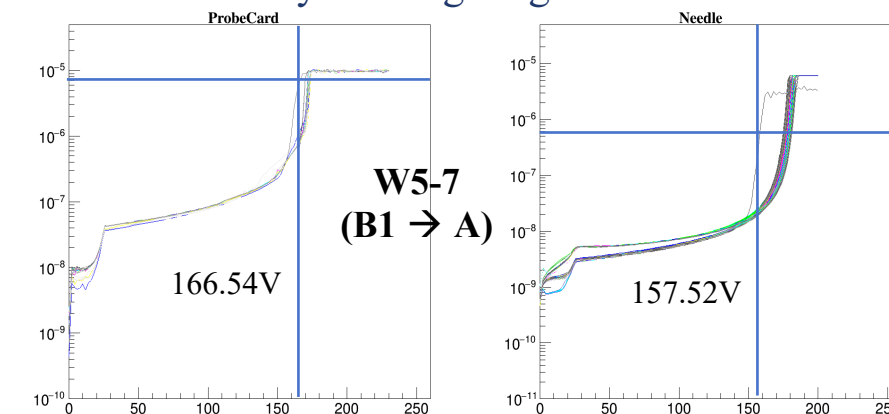
- Research into B1 and B2 class sensors to determine whether they can be accepted

17 Class-A at IHEP, 3 Class-A at JSI:

- 19 remain A;
- 1 (W5P7) → B1($V_{bd} < 165V$);
- V_{bd} from the needle test (by IHEP and JSI) was 2.41~10.15 V higher than the probe card test;



The V_{bd} values from IHEP's needle test results are higher than those from IME's probe card test results. We are currently investigating the reason.



Sensor Quality Control (SQC)



2 Class-B1 at IHEP, 5 Class-B1 at JSI :

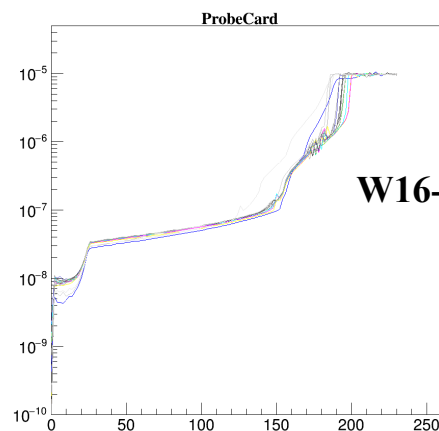
- 3 B1 $\rightarrow$ A($V_{bd} > 165V$); 2 B1 $\rightarrow$ B2; 2 B1 $\rightarrow$ C(with one bad pad near GR);

4 Class-B2 at IHEP, 5 Class-B1 at JSI :

- 5 B2 $\rightarrow$ A;
- 4 B2 $\rightarrow$ C(early breakdown);

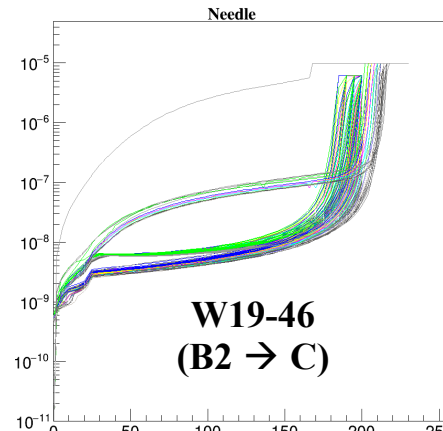
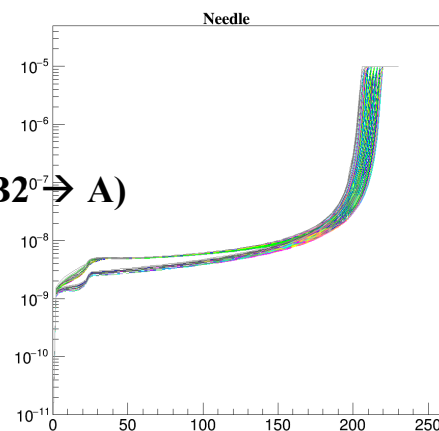
1 Class-C:

- Remains C;
- Probecard test and needle test yielded identical lower columns of the V_{bd} .



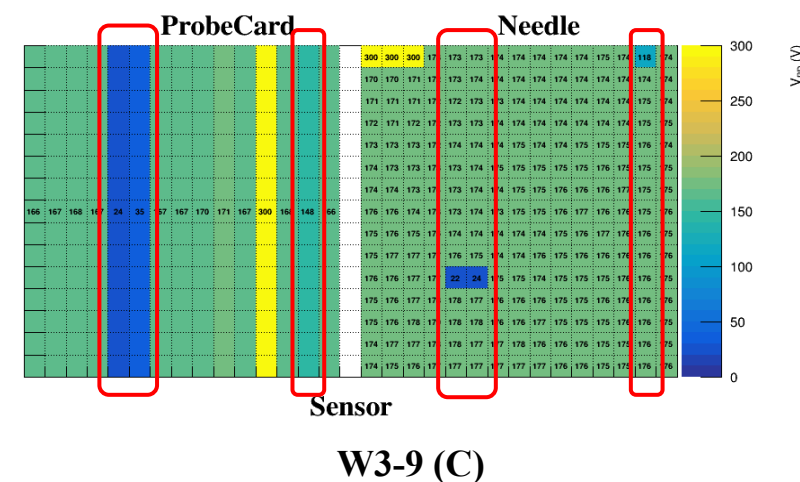
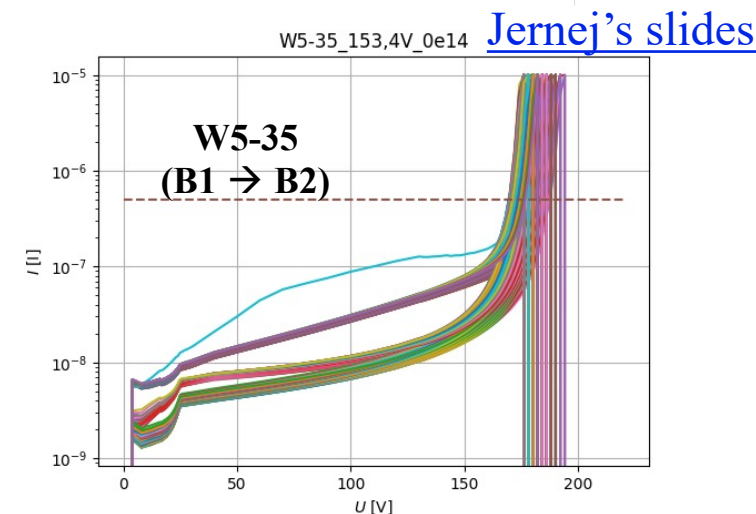
W16-48(B2 $\rightarrow$ A)

become smoother



W19-46
(B2 $\rightarrow$ C)

Early breakdown





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17 wafers of IHEP-IME Pilot batch

- 10 QC-TS/wafer at CERN and USP
- Probe card: needles contacting all 30 pads
- 5 minutes/structure
- 80-position stencil from USP
- Temperature: $T=20^{\circ}\text{C}$
- The acceptance of the wafers will be based on spread of gain-layer depletion voltage:

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



Van der Pauw (VDP)

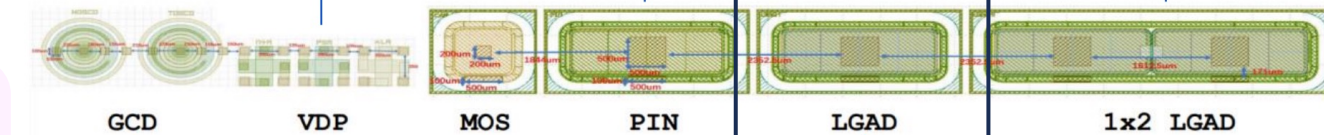
- Resistance of n+,p-stop substrates and aluminium

Pin Diode

- I-V measurements
- Like LGAD but no gain layer (gain =1)
- Used to understand gain

1 x 2 LGAD

- Study the properties of the inter-pad region



Gate-Control-Diodes

- Purpose: Measure surface currents
- Only used in initial measurements
 - Showed that GCD design doesn't allow for useful measurements of surface currents

Metal-Oxide-Semiconductor Capacitor

- flat-band voltage (V_{fb}) and oxide thickness (t_{ox})

LGAD

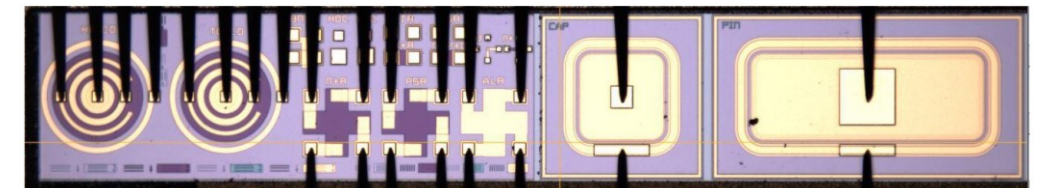
- Same area as main sensor pad just longer
- I-V $\rightarrow V_{bd}$, I meas at operational voltage
- C-V $\rightarrow$ Gain layer depletion voltage, V_{fd} , C_d



USP



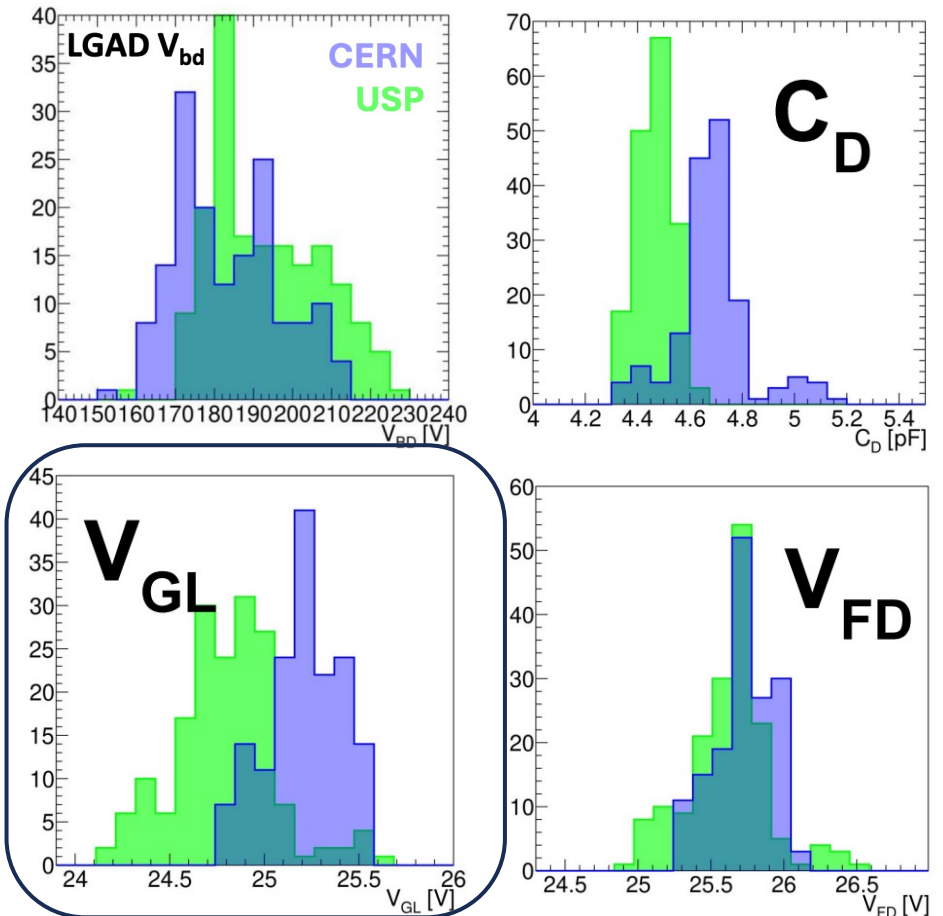
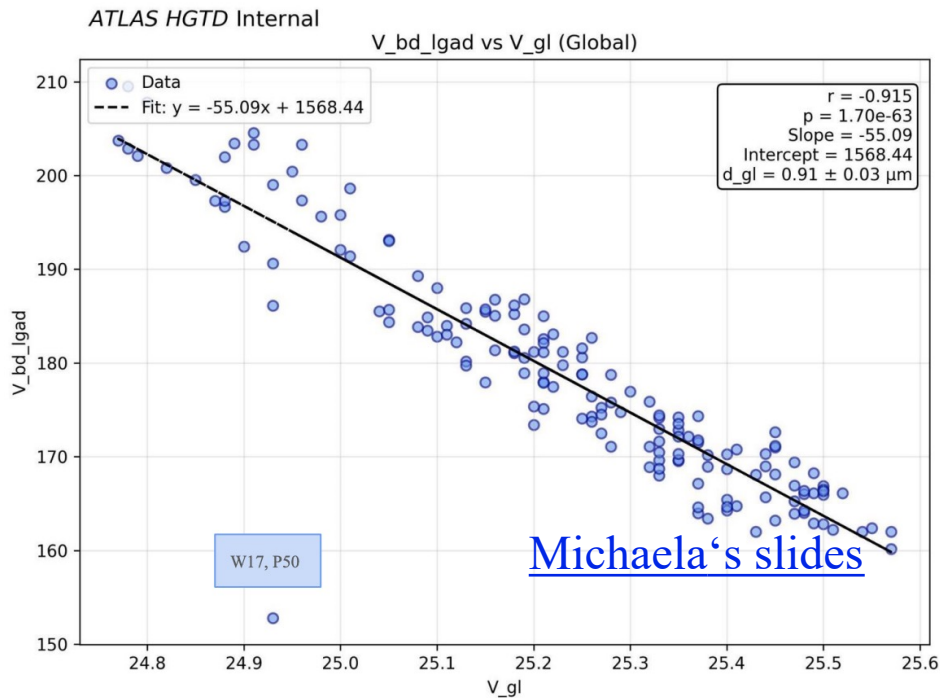
CERN



Process Quality Control (PQC)



- 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
- V_{gl} vs. V_{bd} : strong correlation observed as expected (unlike for preproduction)

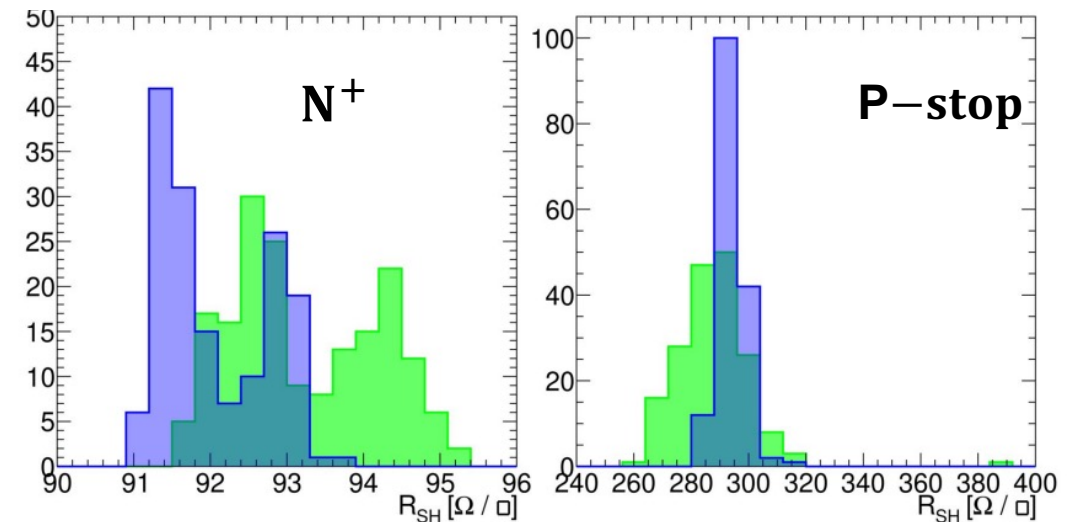
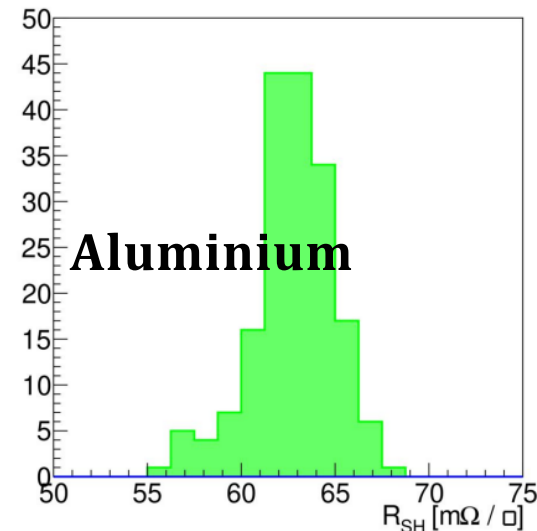
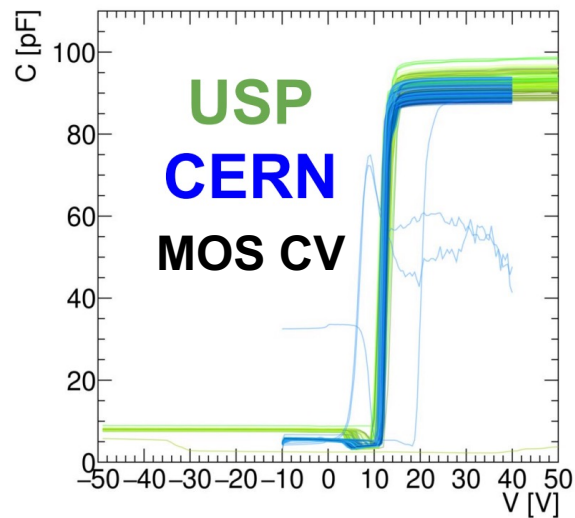
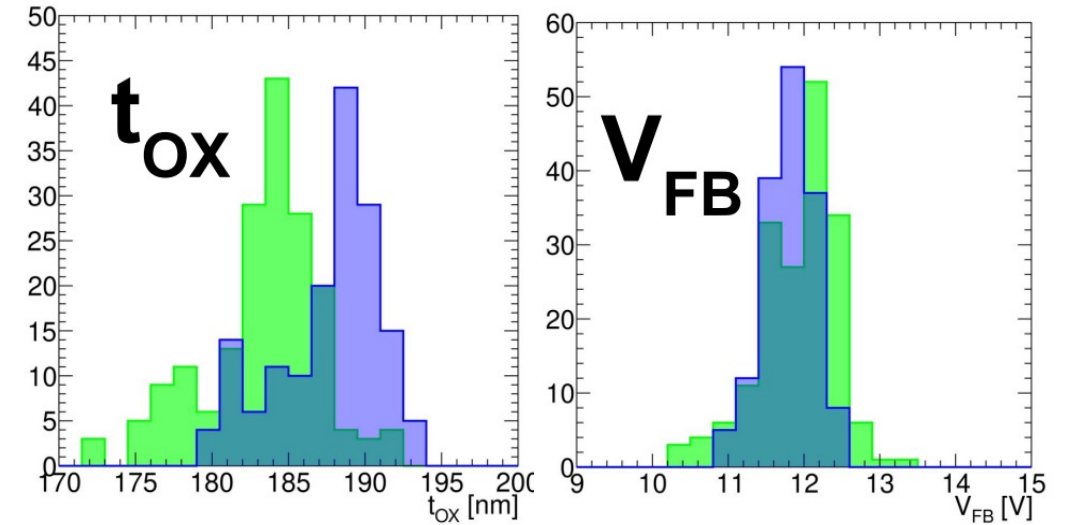


[Guilherme's slides](#)

Process Quality Control (PQC)



- MOS CV: Much more stable measurement w.r.t. preproduction
 - V_{FB} : Good agreement between sites
 - Oxide thickness: slight tension between sites
- Sheet resistors:
 - N^+ : Very low spread, indicating uniform doping profile
 - P-stop: Good agreement between sites
 - Aluminium sheet resistance with same spread as pre-production



[Guilherme's slides](#)



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Irradiation Test (IT)

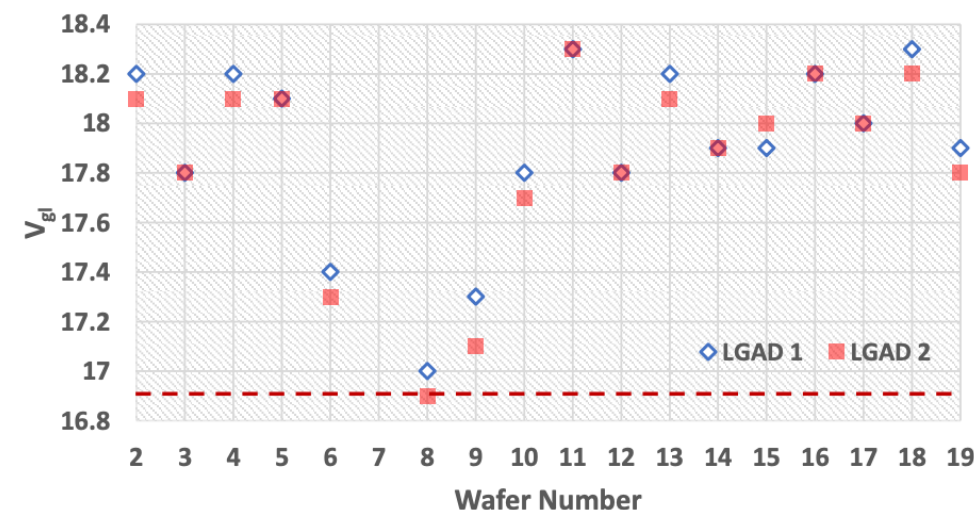
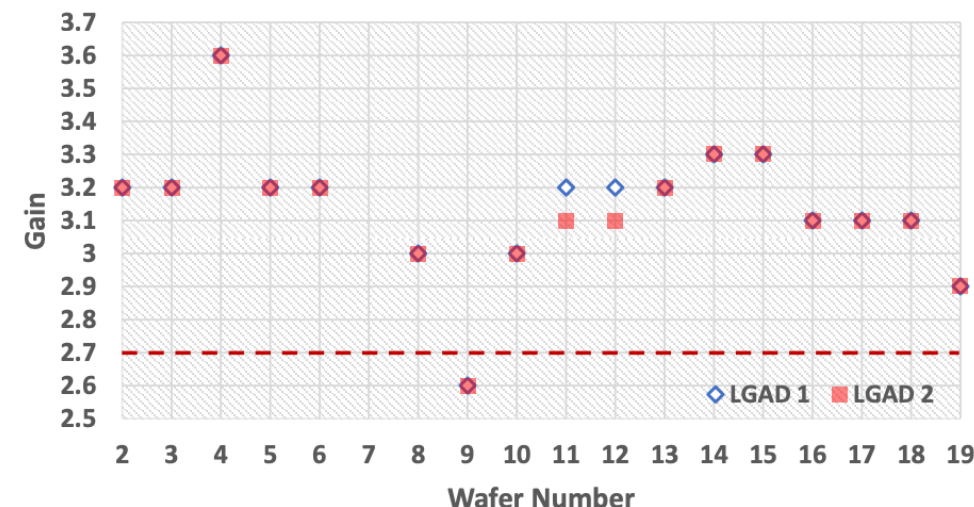


17 wafers of IHEP-IME Pilot batch

- Irradiation Test: QC-TS are irradiated at JSI with neutrons at end-of-life fluence ($2.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$) (and are annealed for 80min at 60°C)
- Transient Current Technique (TCT) measurement:
 - Gain @ 100V measured the 1x2 LGAD of the QC-TS
- CV measurement: V_{gl}
- Defined after ^{90}Sr measurements on pre-production QC-TS:

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

- 5 QCTS/wafer at JSI, 1 QC-TS/wafer tested by JSI
- Always position 30 measured – center of the wafer
- All wafers pass V_{gl} requirements
- One wafer (9) barely fails gain criteria (to do ^{90}Sr measurements on W9)





Pilot Batch

- PQC: done --- **all wafer accepted.**
- IT: done --- **all wafer accepted.**
 - 16/17 wafers passed – need to do ^{90}Sr for one wafer.
- CQC:
 - IME is testing A, B1 and B2 sensors that were tested also at IHEP.
- SQC:
 - **20 Class A sensors from 17 wafers passed SQC testing by IHEP and JSI.**
 - **SQC gives 2~10V higher V_{bd} than CQC(confirmed by IHEP and JSI).**

First Batch

- 50 wafers (containing a total of 1,371 Class A sensors) are currently undergoing dicing and picking by some companies.

Thanks!

Test temperature



Wafer Temperature(°C)

B4-2	20. 5
B4-3	21. 3
B4-4	21. 6
B4-5	21. 0
B4-6	21. 6
B4-8	21. 1
B4-9	21
B4-10	21. 1
B4-11	21

Wafer Temperature(°C)

B4-12	20. 7
B4-13	21. 4
B4-14	21. 2
B4-15	21
B4-16	20. 9
B4-17	21. 1
B4-18	21
B4-19	21. 1

WAFER 9 – additional tests

Position 5

ATLAS ID	Wafer	Position	Vgl 1	Vgl 2	Gain 1	Gain 2
20WS2104000905	9	5	17.7	17.7	2.7	3.0
20WS2104000905 (repeat)	9	5	17.8	17.9	2.9	2.9

Position 30

ATLAS ID	Wafer	Position	Vgl 1	Vgl 2	Gain 1	Gain 2
20WS2104000930 (repeat 1)	9	30	17.1	17.2	2.6	2.6
20WS2104000930 (repeat 2)	9	30	17.1	17.3	2.6	2.6
20WS2104000930 (repeat 3)	9	30	17.3	17.2	2.8	2.7
20WS2104000930 (repeat 4)	9	30	17.4	17.3	2.8	2.8

Acceptance criteria (IHEP):
Vgl ≥ 16.9 V Gain (100 V) ≥ 2.7