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LGAD measurements from different producers

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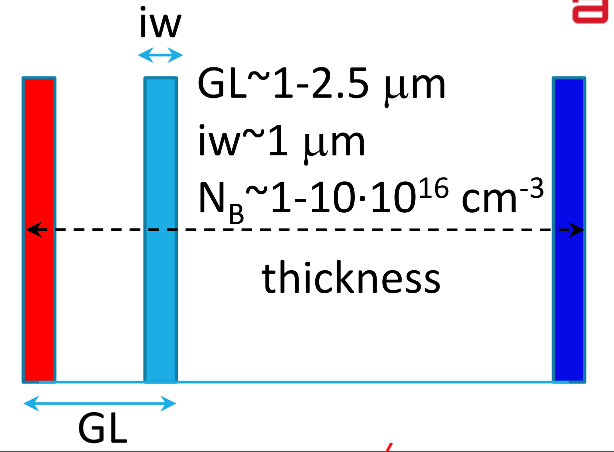
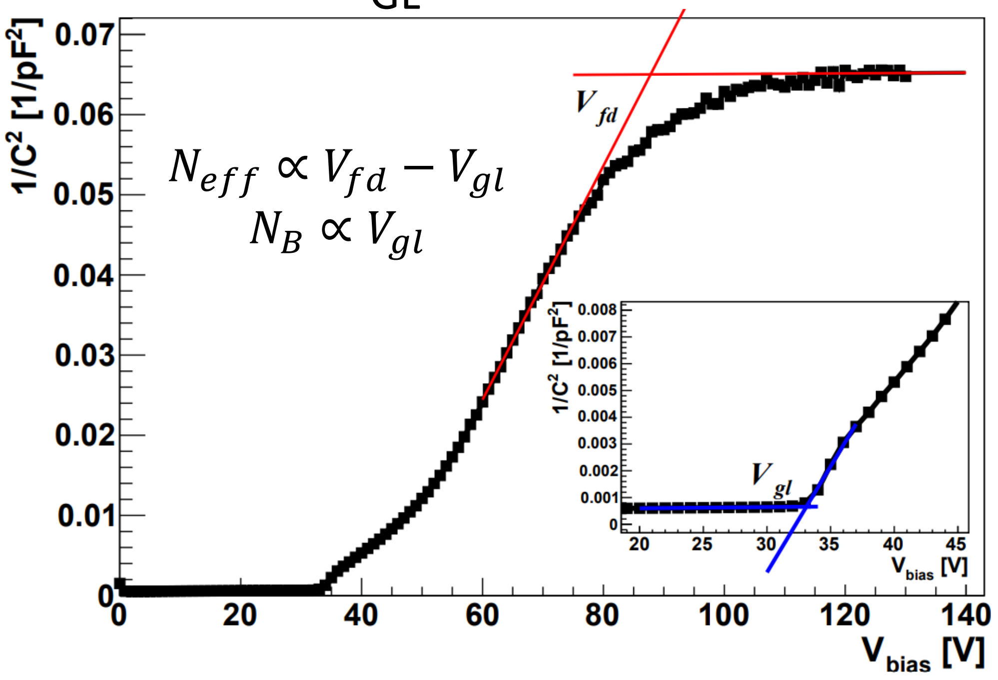
A WORK PERFORMED IN COLLABORATION WITH CMS-ETL AND ATLAS-HGTD GROUPS: INFN-TORINO, USCS, IHEP-BEJING, CNM

Motivation for the studies

- ATLAS and CMS upgrades require sensors to withstand ϕ_{eq}=2.5e15 cm^{-2} and TID 200 Mrad -> significant decrease of gain
- Gain decreases as boron substitutional atoms get deactivated ("acceptor removal") –> reduction of the field
- Ways to mitigate degradation of gain layer:
  - Make the implant thinner (IW->"0") and more doped N_B (~1e17 cm^{-3}), reduces the acceptor removal constant (c~2-7·10^{-16} cm^2)
  - Increase the bias voltage -> after depletion increase of electric field in the GL is $\Delta E \sim \Delta V_{bias}$/thickness
  - Make the implant deeper (increase of GL)
    - Larger multiplication region
    - Easier to recuperate the electric field ΔV_{gl}/GL compensated by ΔV_{bias}/thickness
  - Replacement of gain layer implantation material or co-implantation of material that decreases the acceptor removal rate (carbon)

We want to compare the producers, which have choosen different approaches to achieve sufficient radiation hardness.

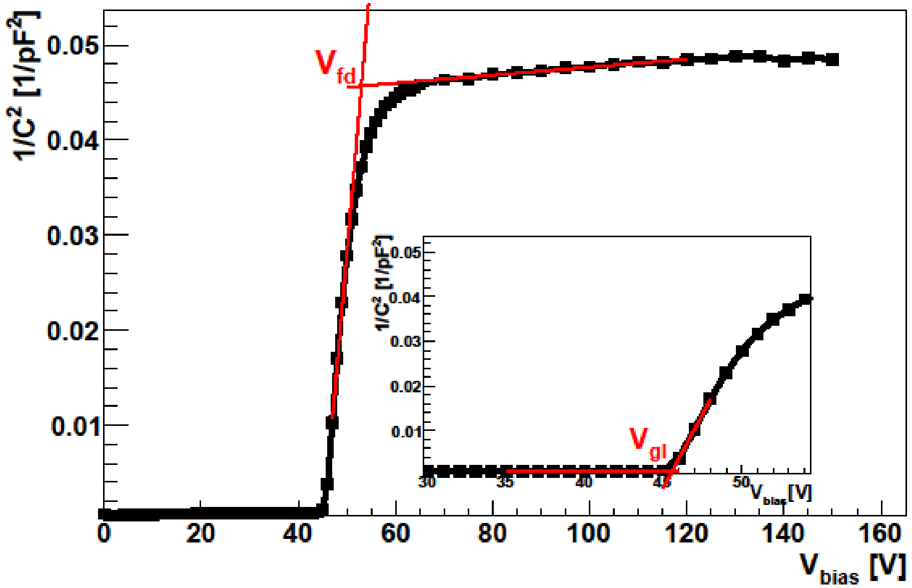


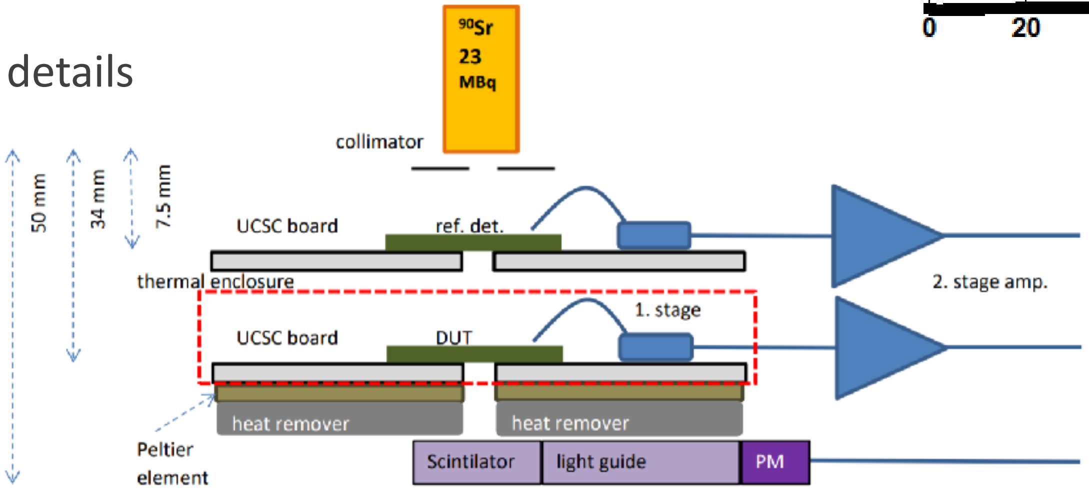


Experimental Procedure

- Irradiated with neutrons (at JSI Triga II reactor)
- Annealed for 80 mins @ 60˚C and kept cold
- CVIV:
  - 20˚C/500mV/10kHz
  - V_{gl}/V_{fd} determined from CV
- Timing/CC :
  - -30˚C/^{90}Sr source
  - See Gregor's talk for details

Example of Vgl/Vfd determination:

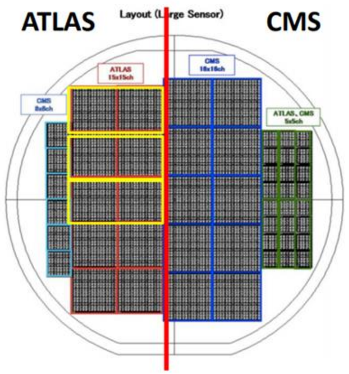


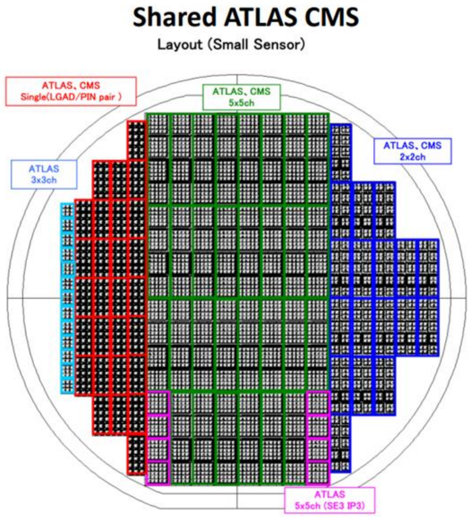


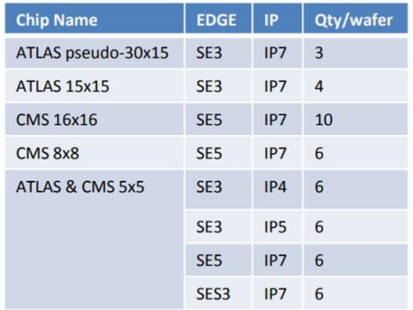
HPK-P2 – Samples

- HPK-Prototype 2
  - 4 different doping profile (“Splits”)
  - 50µm
- 7 fluences [1e14, 4e14, 8e14, 15e14, 25e14, 30e14, 40e14]
- Sensors were irradiated together (W28,33) and (W37,43) and were packed close together to minimise fluence uncertainty.
- Difference in sensors V_{GL} was small and measured V_{BR} was close to targeted

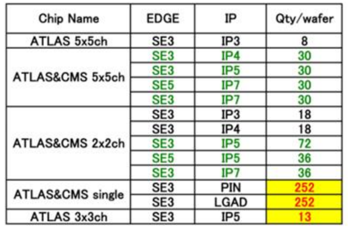
Wafer	Wafer Layout	Split	Vgl	Target Vbr	Measured Vbr
28	Small	1	50.5V	160V	85-155V
33	Small	2	51.0V	180V	85-170V
37	Small	3	53.7V	220V	155-205V
43	Small	4	54.5V	240V	170-235V



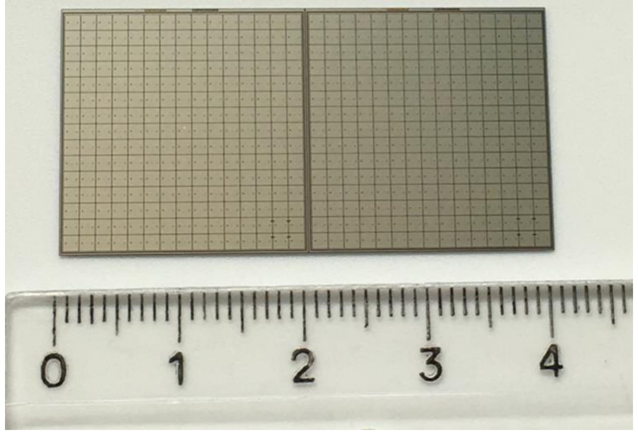




Chip Name	EDGE	IP	Qty/wafer
ATLAS pseudo-30x15	SE3	IP7	3
ATLAS 15x15	SE3	IP7	4
CMS 16x16	SE5	IP7	10
CMS 8x8	SE5	IP7	6
ATLAS & CMS 5x5	SE3	IP4	6
	SE3	IP5	6
	SE5	IP7	6
	SES3	IP7	6



Chip Name	EDGE	IP	Qty/wafer
ATLAS 5x5ch	SE3	IP3	8
ATLAS&CMS 5x5ch	SE3	IP4	30
	SE3	IP5	30
	SE5	IP7	30
	SE3	IP7	30
ATLAS&CMS 2x2ch	SE3	IP3	18
	SE3	IP4	18
	SE3	IP5	72
	SE5	IP5	36
	SE3	IP7	36
ATLAS&CMS single	SE3	PIN	252
	SE3	LGAD	252
ATLAS 3x3ch	SE3	IP5	13



HPK-P2 – V_{gl} and Neff vs fluence

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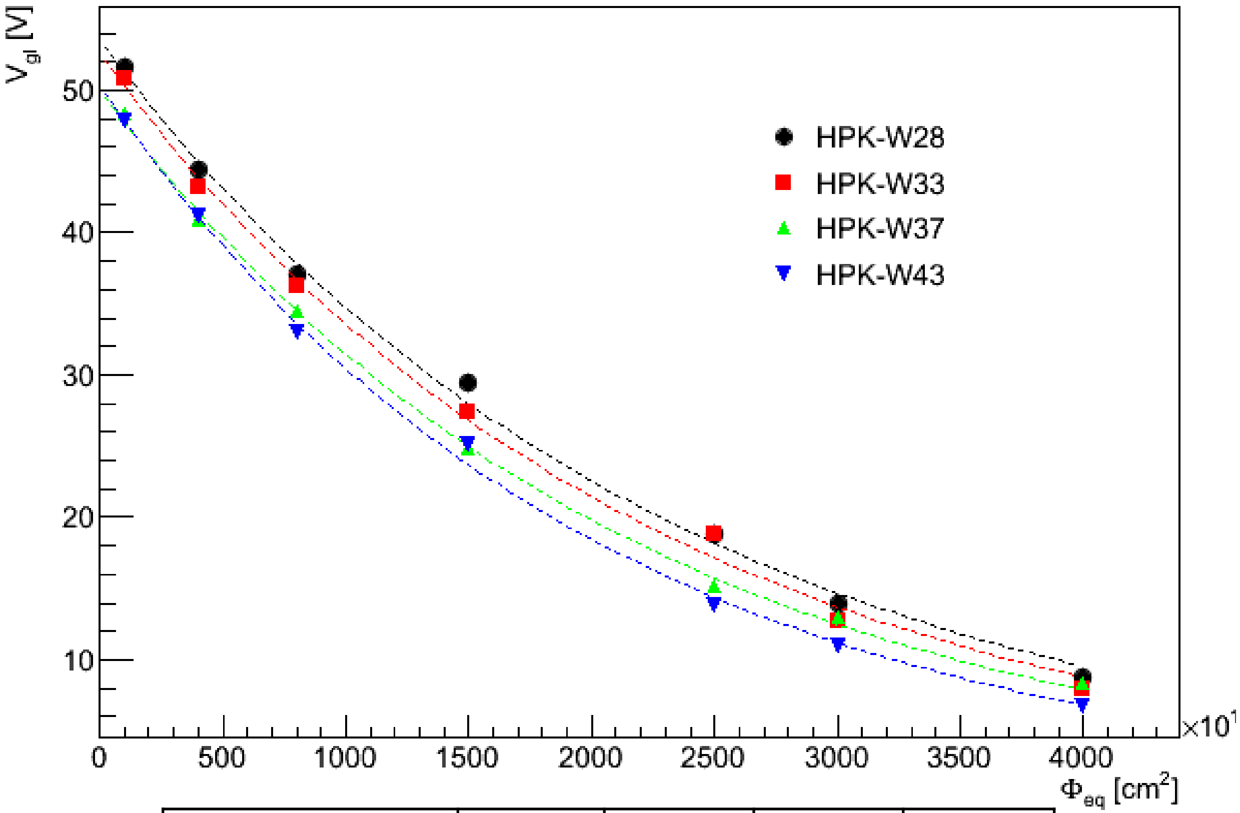
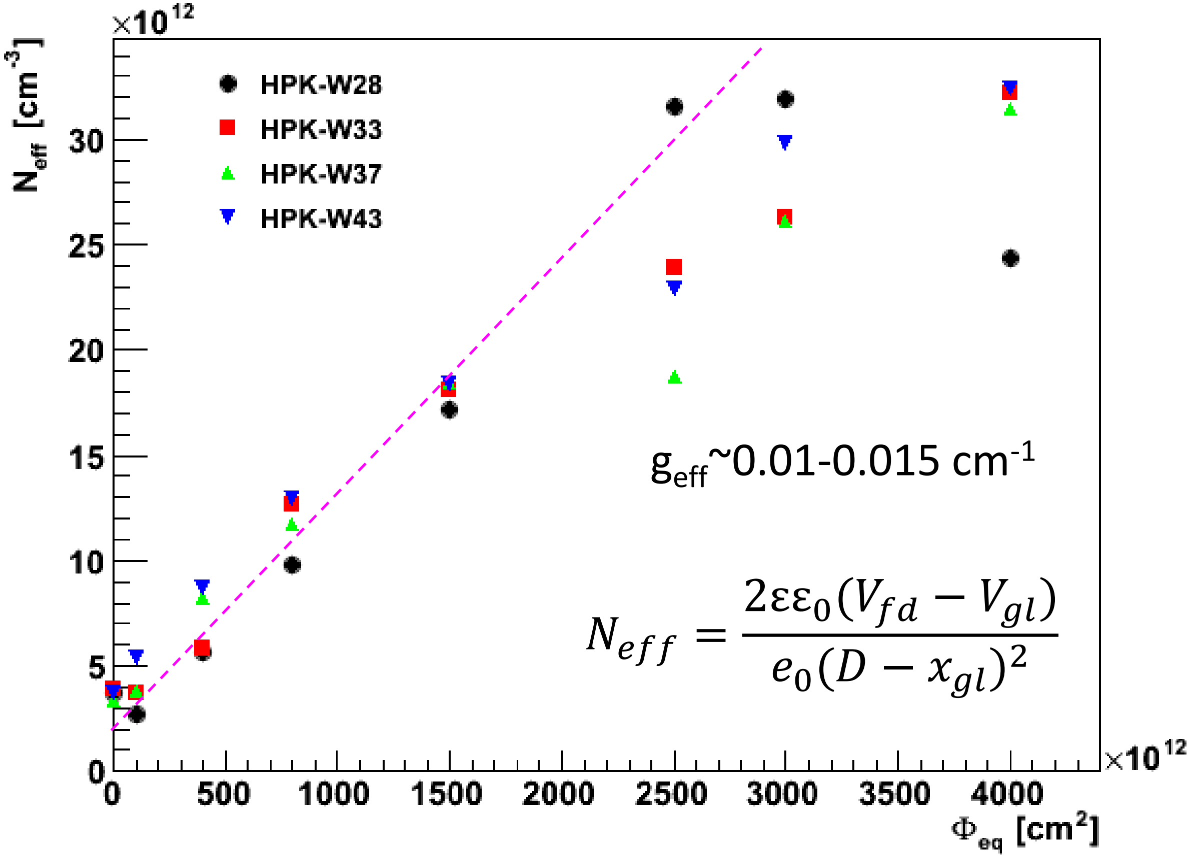
- Dashed line is fit of $V_{gl}(\phi)=V_{gl}(t=0)\exp(-c^*\phi)$



HPK-P2	W28	W33	W37	W43
c [10^{-16} cm^{-2}]	4.3	4.5	4.6	5.0



g_{eff}~0.01-0.015 cm^{-1}

$$N_{eff} = \frac{2\varepsilon\varepsilon_0(V_{fd}-V_{gl})}{e_0(D-x_{gl})^2}$$

D=Sensor thickness

x_{gl}=gain layer thickness (assume 2 µm)

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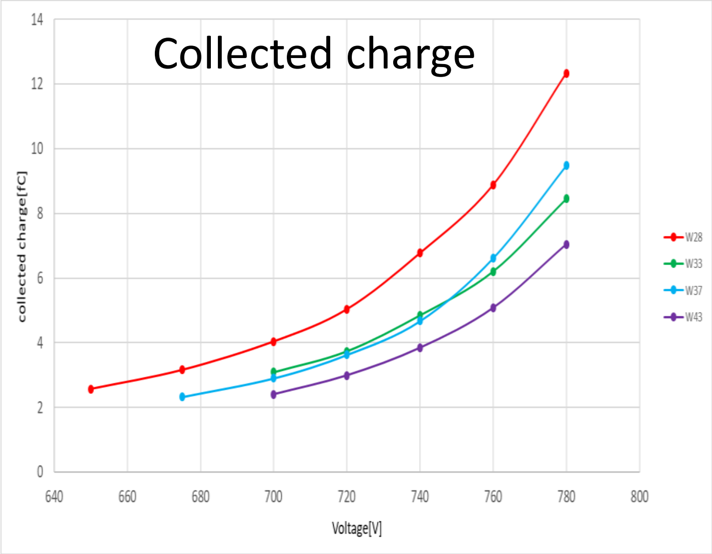
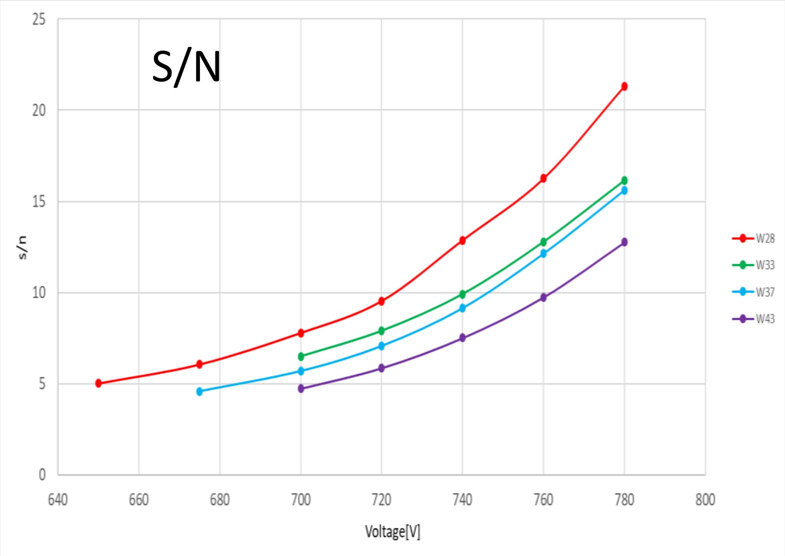
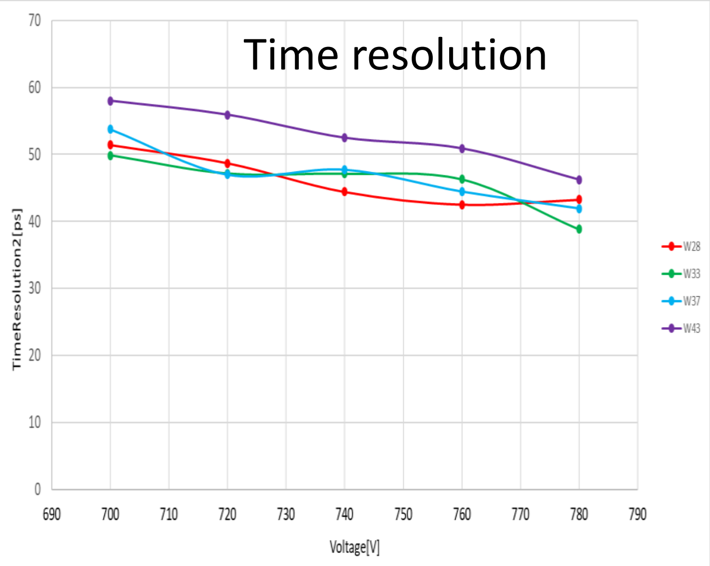
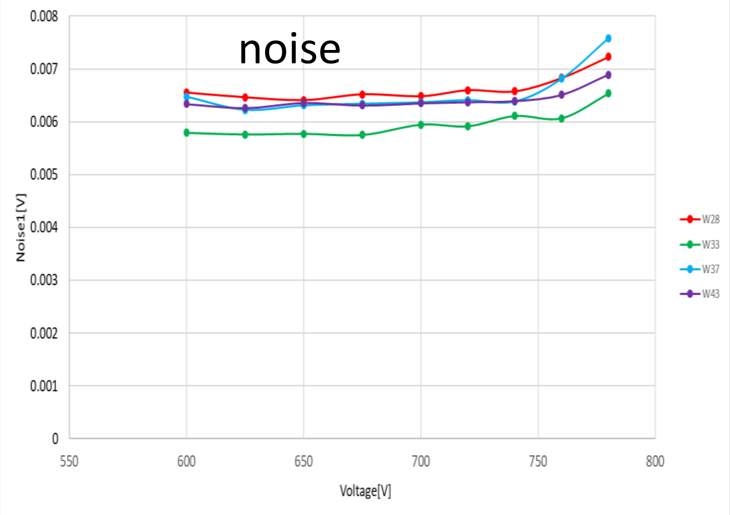
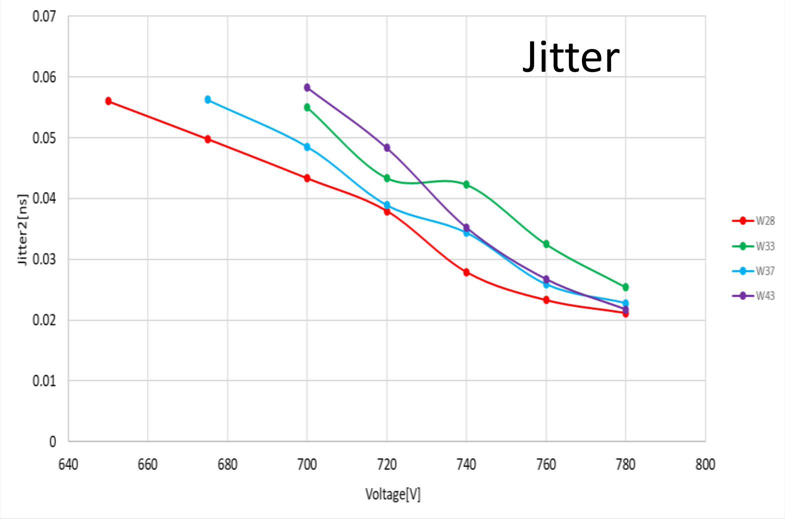
HPK-P2 – Timing/CC (at 2.5e15 cm-2)

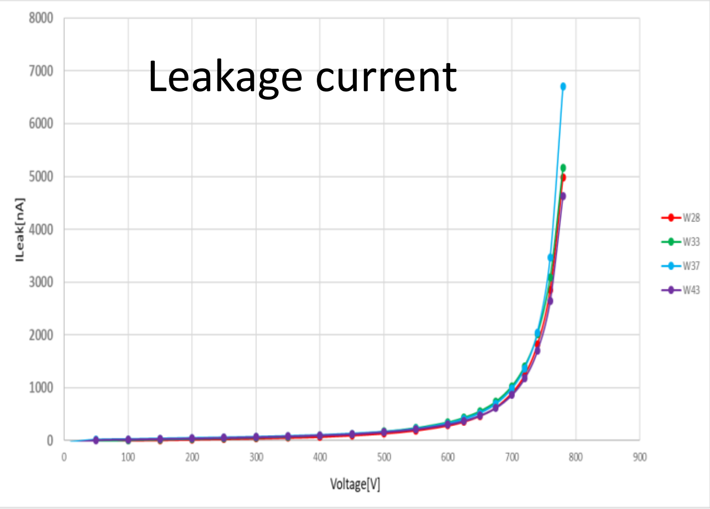

Collected charge


S/N


Time resolution


noise

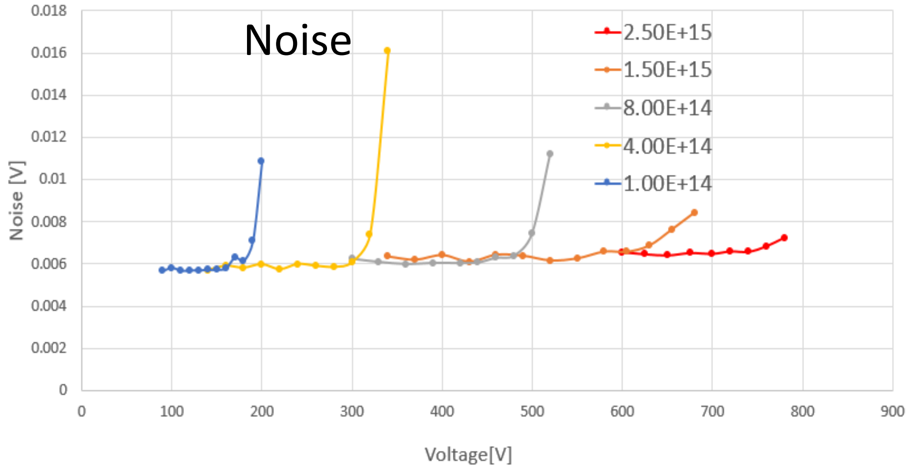

Jitter

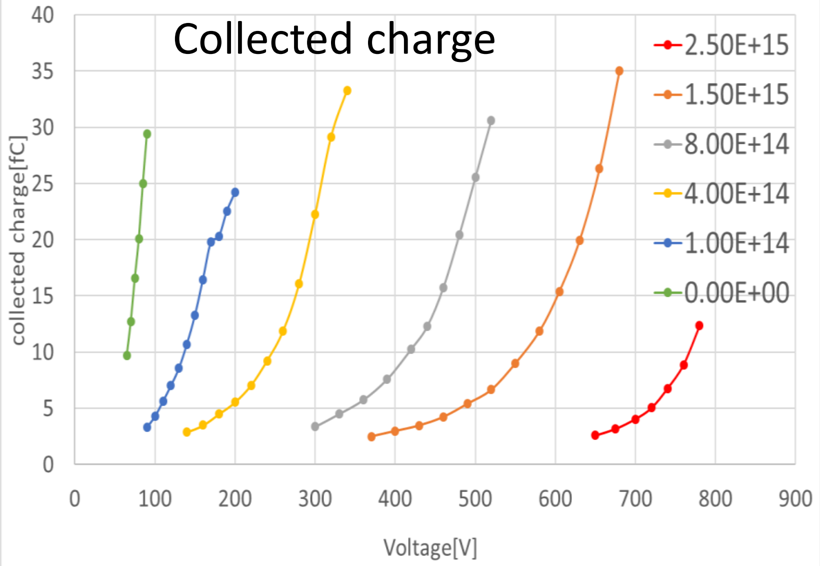

Leakage current

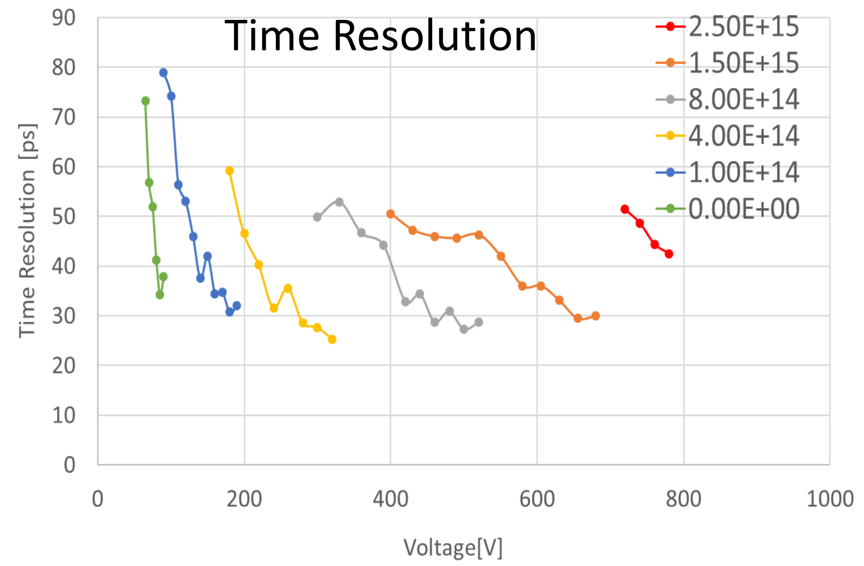
- W28 is slightly better in CC , but all sensors are very close in performance.

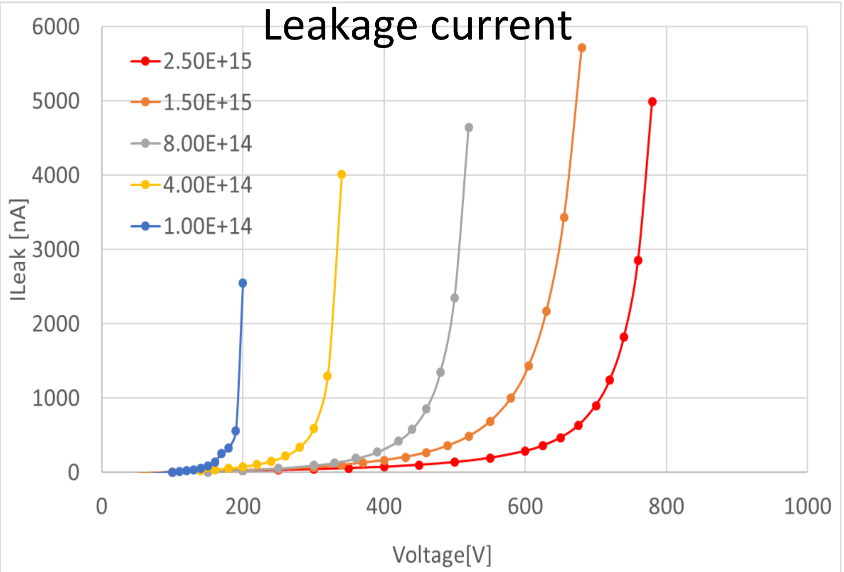
HPK-P2 – Timing/CC (W28)

- W28 - highest gain layer doping
- **HPK-P2 run satisfies HGTD –TDR requirements (pre and post radiation!)**
  - 4fC @ 720 V and σ_t<50 ps after 2.5e15 cm-2
  - I_{leak}<5 μm, P_{dis}<100 mW cm^2 , S/N > 10
  - safe operation voltage V_{op}~780 V for the highest fluence

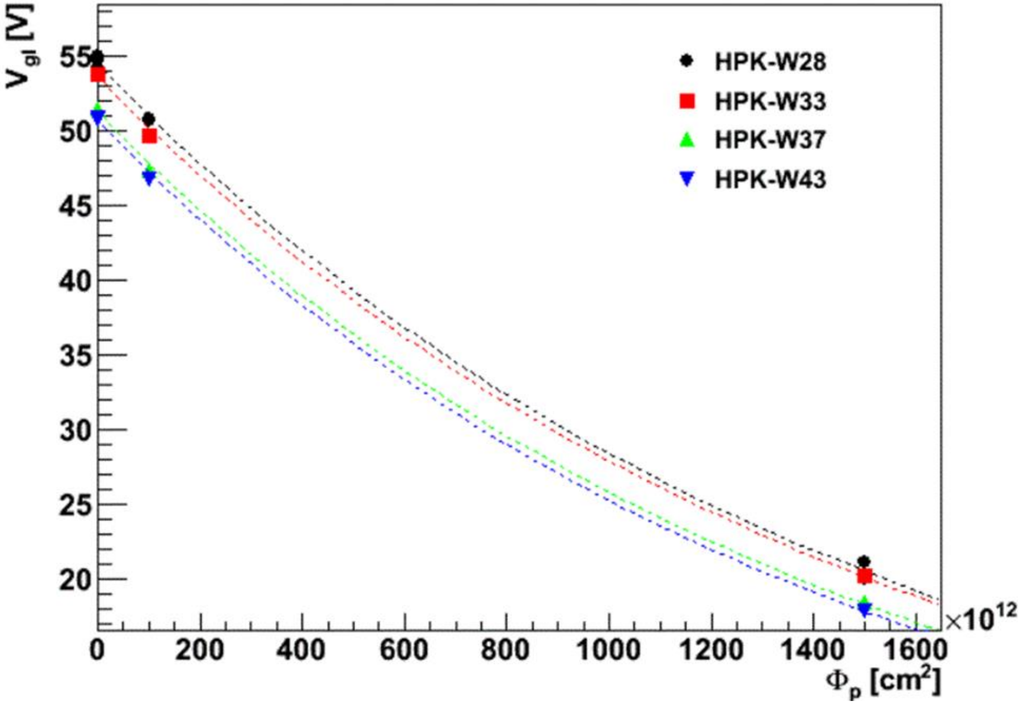


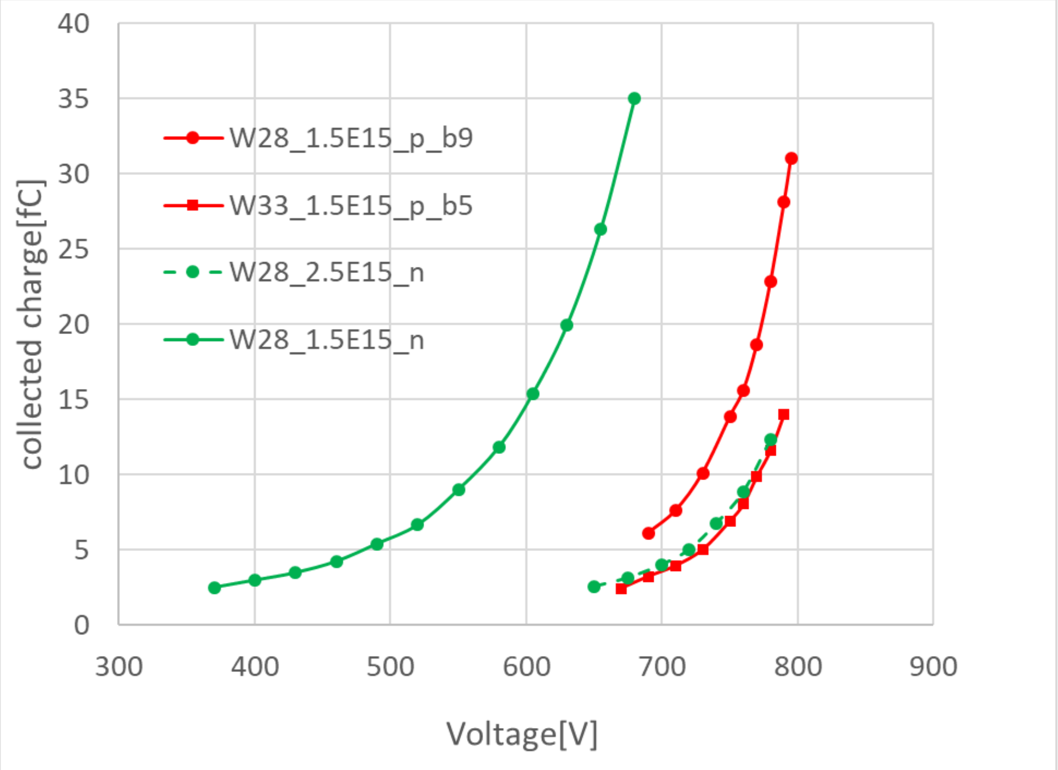






HPK-P2 – 70 MeV proton irradiated





Wafer	c [10^{-16} cm^{-2}]
28	6.51
33	6.53
37	6.87
43	6.96

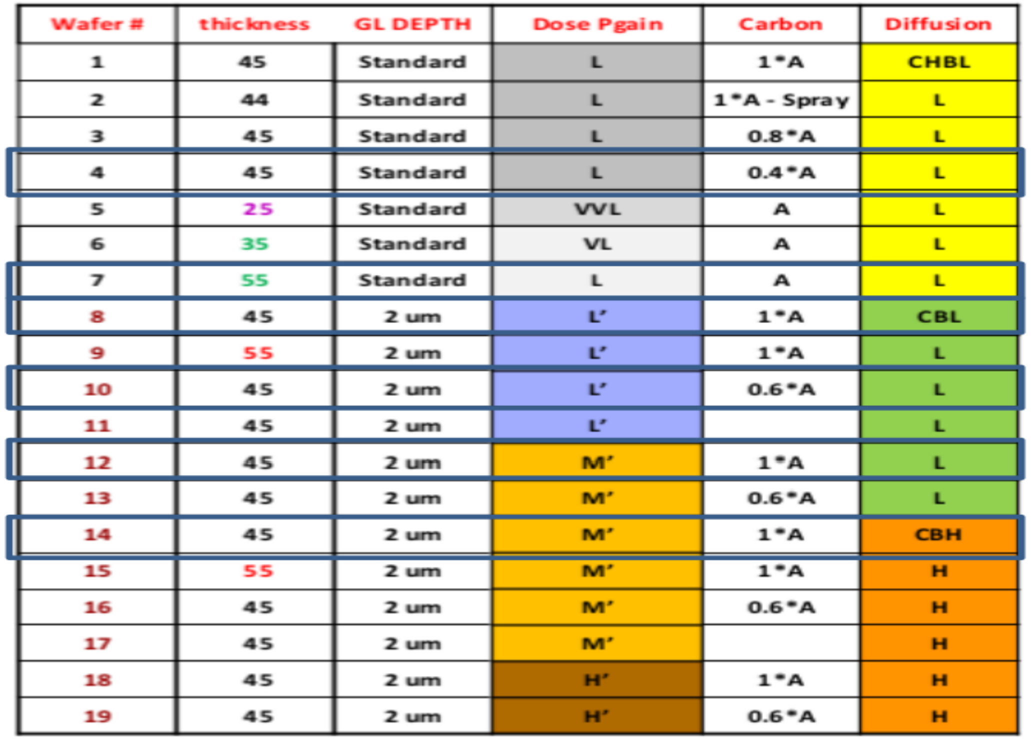
c_p/c_n~1.5-1.6

similar to previous measurements

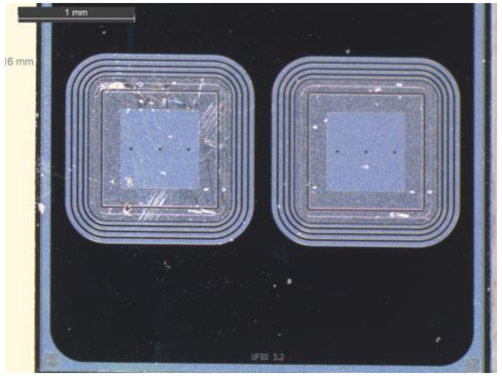
- 2 fluences [1e14, 15e14]
- Ratio between neutron and proton damage c_p/c_n is nicely reflected in CC measurements – similar charge vs. voltage plot for 1.5e15 p and 2.5e15 n.

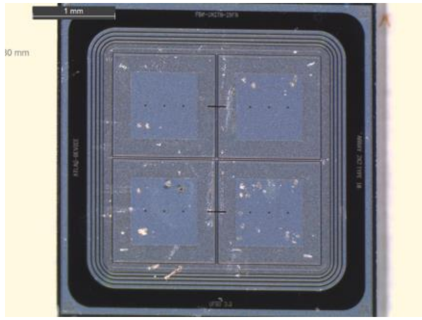
FBK UFSD3.2 run

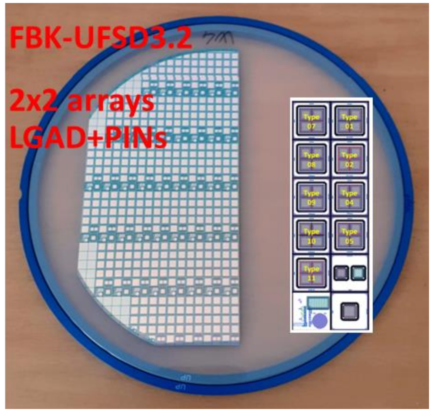
- Purpose of the run to find optimum gain layer doping layer parameters
    - Carbon dose
    - Boron dose
    - Depth of implantation
    - Thermal budget during activation
- Irradiated in two batches:
    - Batch 1: Wafers 4, 7, 8, 10, 12, 14
    - Batch 2 : Wafers 13, 18, 19
- 5 fluences [1e13(batch1)/1e14(batch2), 4e14, 8e14, 15e14, 25e14]



Wafer #	thickness	GL DEPTH	Dose Pgain	Carbon	Diffusion
1	45	Standard	L	1*A	CHBL
2	44	Standard	L	1*A - Spray	L
3	45	Standard	L	0.8*A	L
4	45	Standard	L	0.4*A	L
5	25	Standard	VVL	A	L
6	35	Standard	VL	A	L
7	55	Standard	L	A	L
8	45	2 um	L’	1*A	CBL
9	55	2 um	L’	1*A	L
10	45	2 um	L’	0.6*A	L
11	45	2 um	L’		L
12	45	2 um	M’	1*A	L
13	45	2 um	M’	0.6*A	L
14	45	2 um	M’	1*A	CBH
15	55	2 um	M’	1*A	H
16	45	2 um	M’	0.6*A	H
17	45	2 um	M’		H
18	45	2 um	H’	1*A	H
19	45	2 um	H’	0.6*A	H







FBK UFSD3.2 – V_{gl} vs fluence

preliminary

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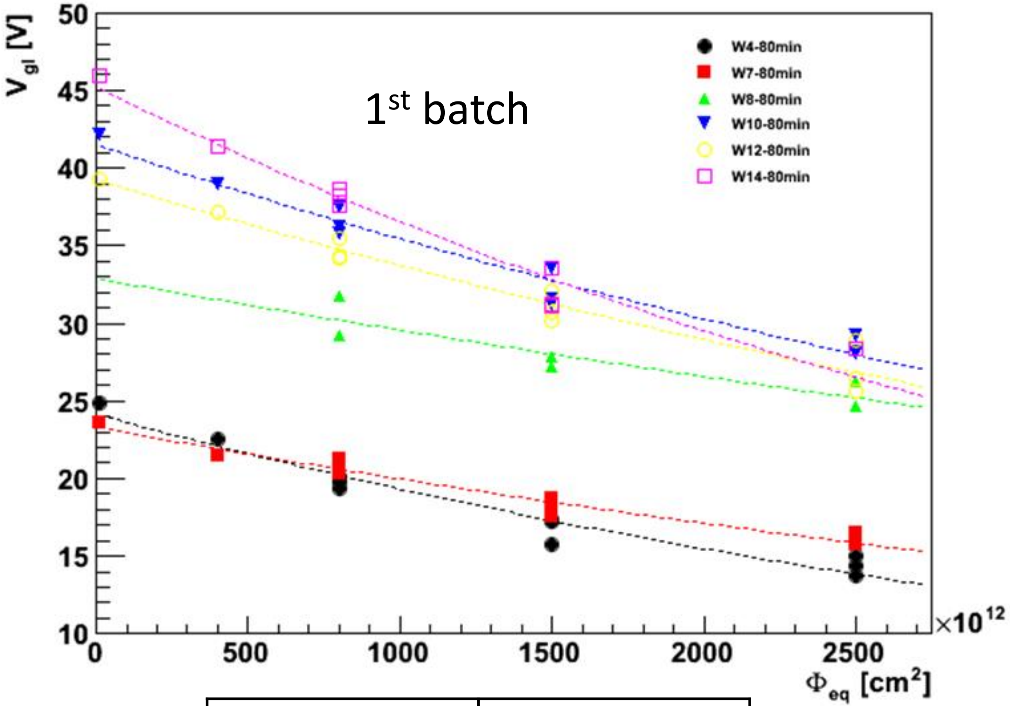

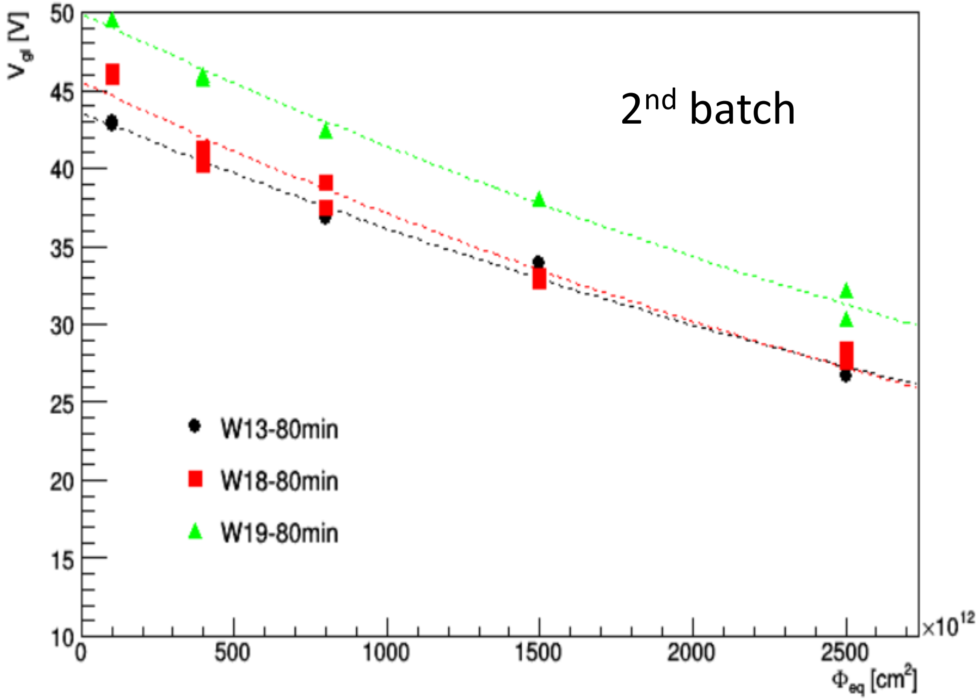

Wafer	c [10^{-16} cm^{-2}]
4	2.23
7	1.55
8	1.07
10	1.58
12	1.52
14	2.13

Large uncertainties in measured c – use them only as guidance!

Wafer	c [10^{-16} cm^{-2}]
13	1.87
18	2.06
19	1.87

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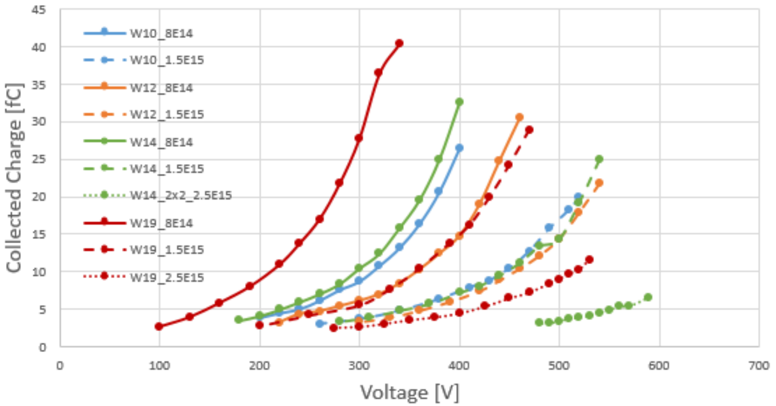
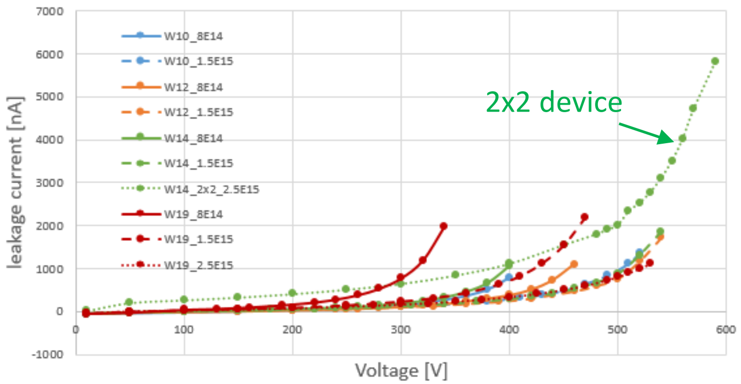
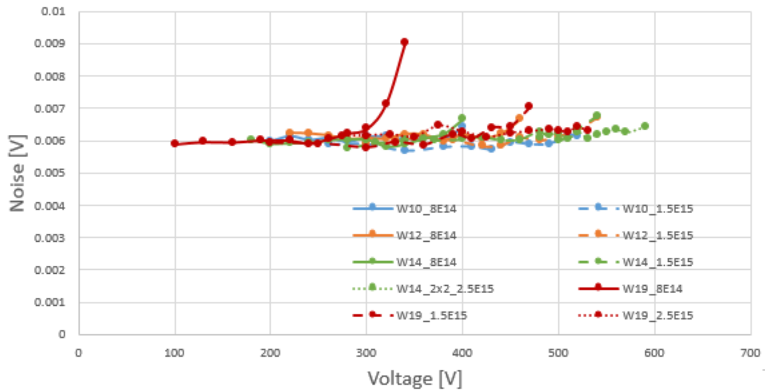
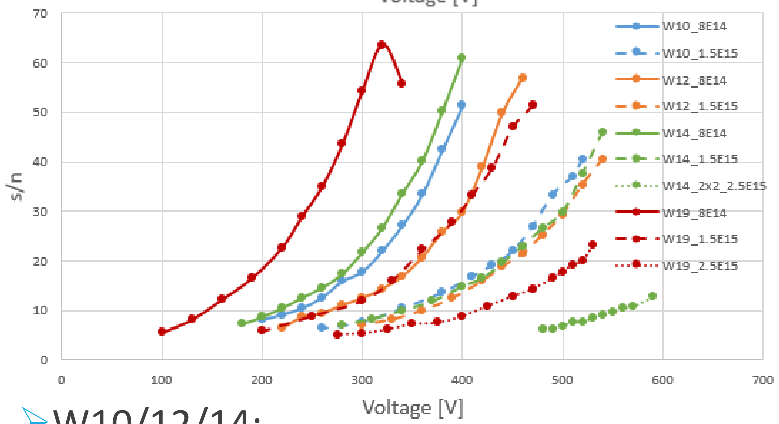
FBK UFSD3.2 – Timing/CC

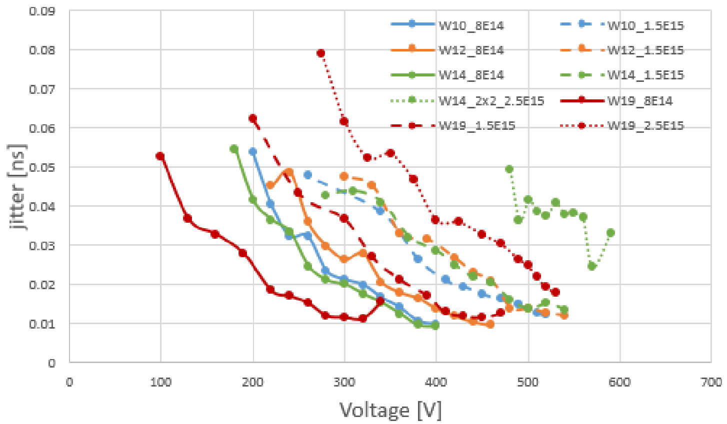
preliminary

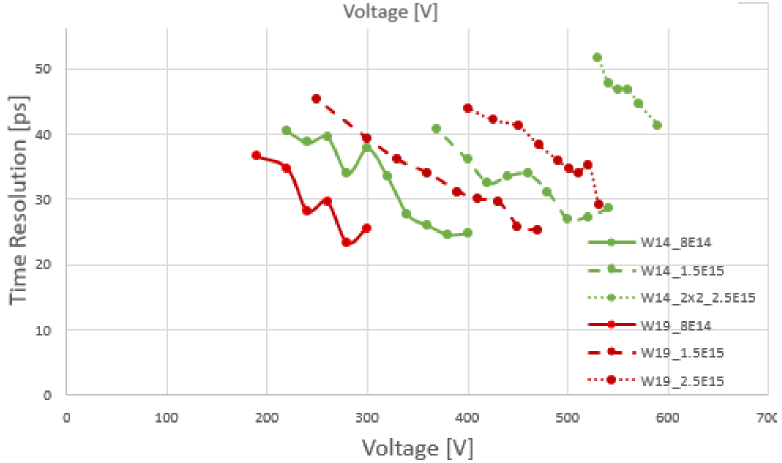








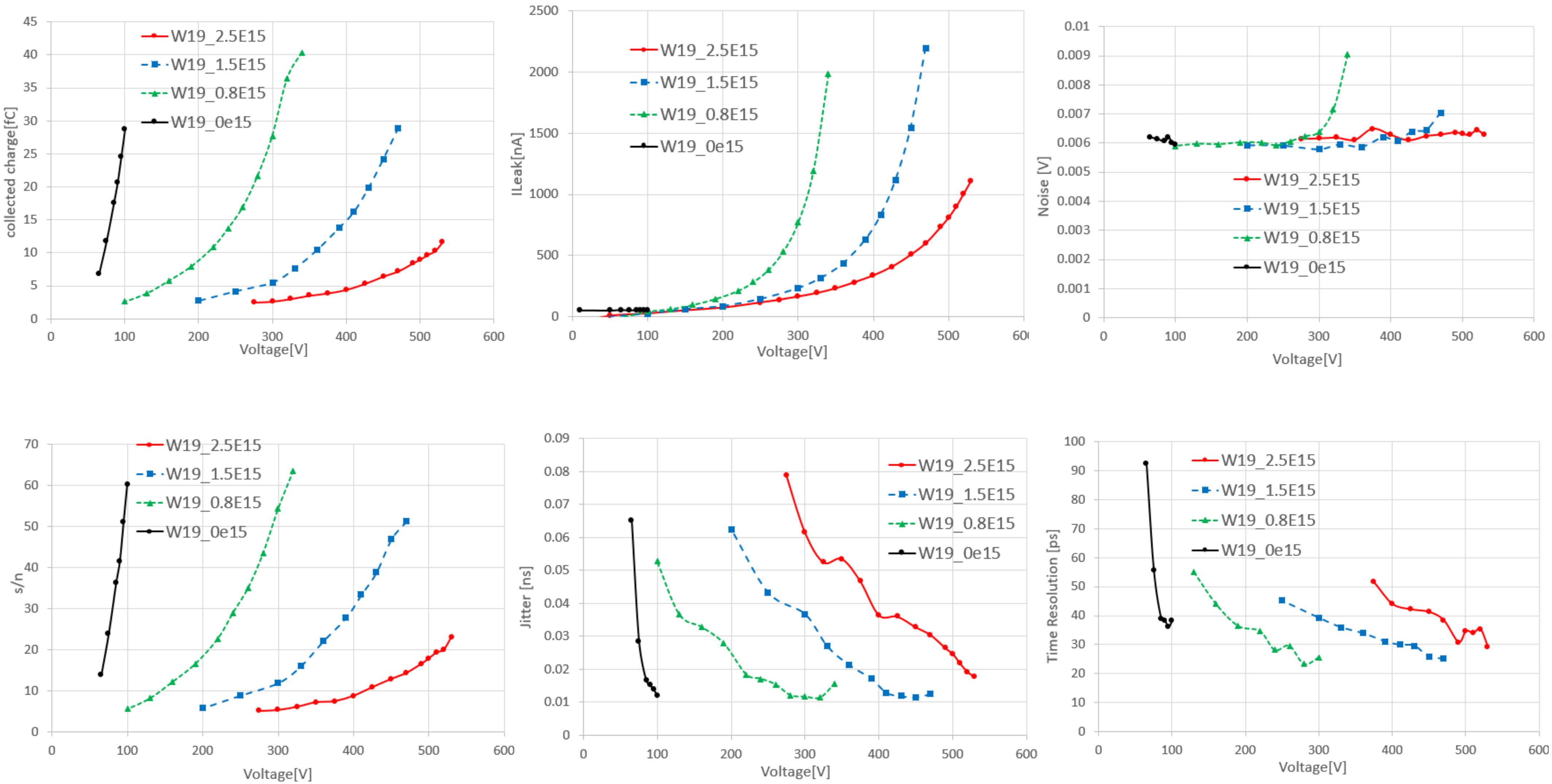




- W10/12/14:
  - Good results for 1.5e15cm^{-2}(all perform similarly), but early breakdown at < 600V doesn't allow exploitation of beneficial gain layer properties at 2.5e15 cm^{-2}.
  - ΔV(5fC)~200 V between 1.5&2.5e15, which corresponds roughly to ΔV_{GL} ~8 V for GL depth of ~2 μm. Measured ΔV_{GL}~6 V .

- W19:
  - much lower V_{op} – **most radiation hard LGAD seen so far!**
  - ΔV(5fC)~130 V between W19 & W14(2.5e15), which corresponds roughly to ΔV_{GL} ~5 V for GL depth of ~2 μm. Measured ΔV_{GL}~4 V .

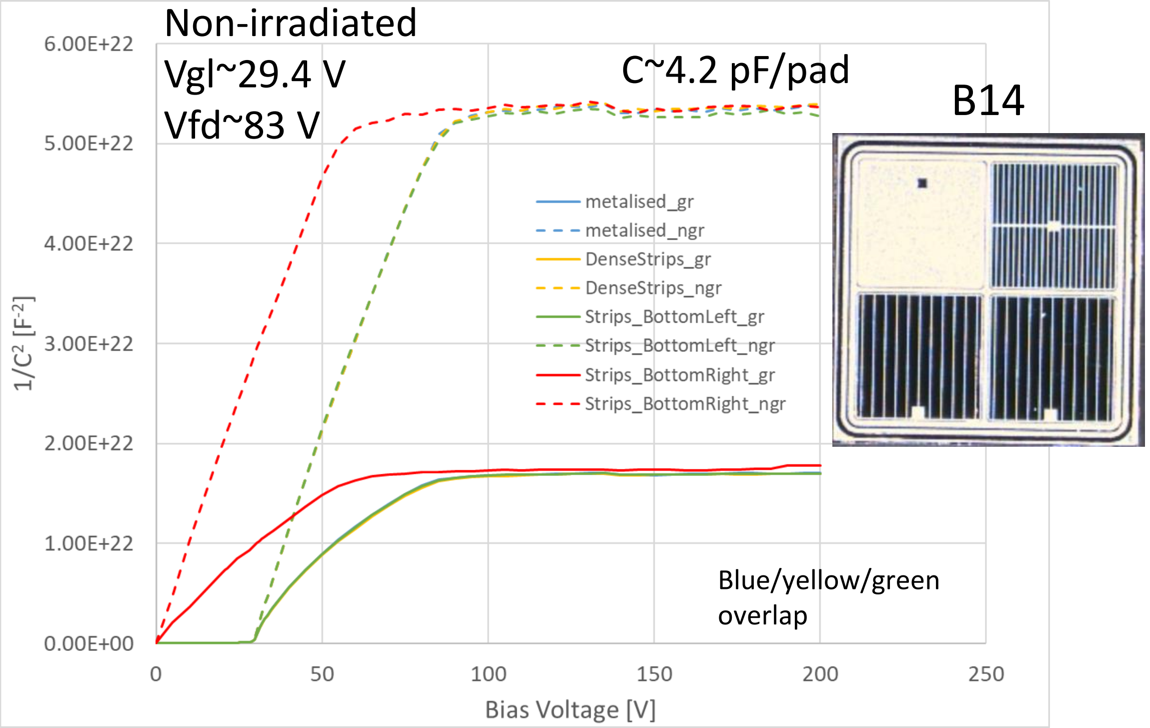
FBK UFSD3.2 – Timing/CC (W19)



- Excellent CC and time resolution
- Satisfies HGTD requirements and possibly extends the fluence range beyond required – **no need for inner ring replacements**

NDLv3 – CV

- 50 μm thick


Non-irradiated

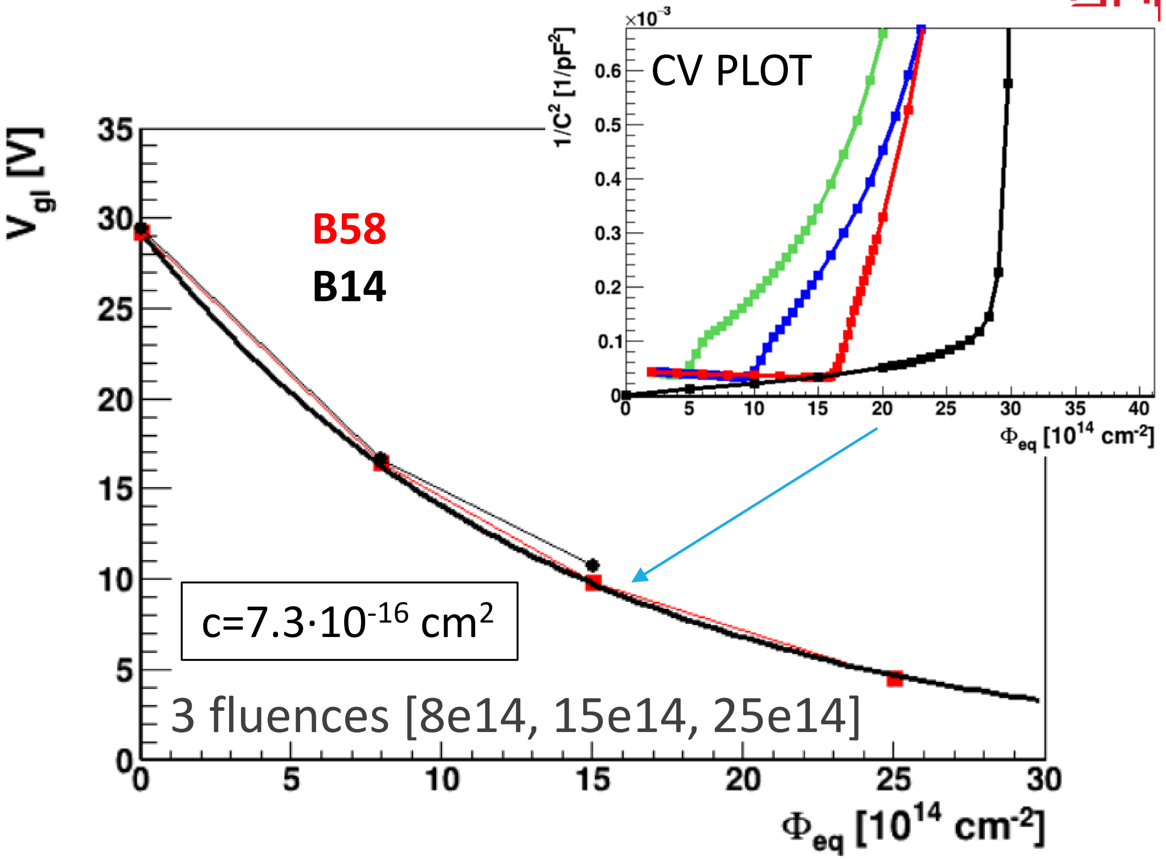
Vgl~29.4 V

Vfd~83 V

C~4.2 pF/pad

B14

Blue/yellow/green overlap


B58

B14

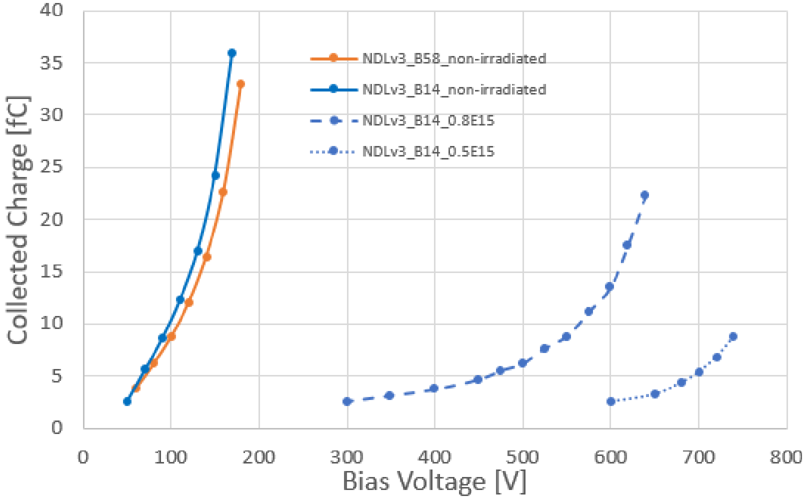
c=$7.3\cdot10^{-16}$ cm^2

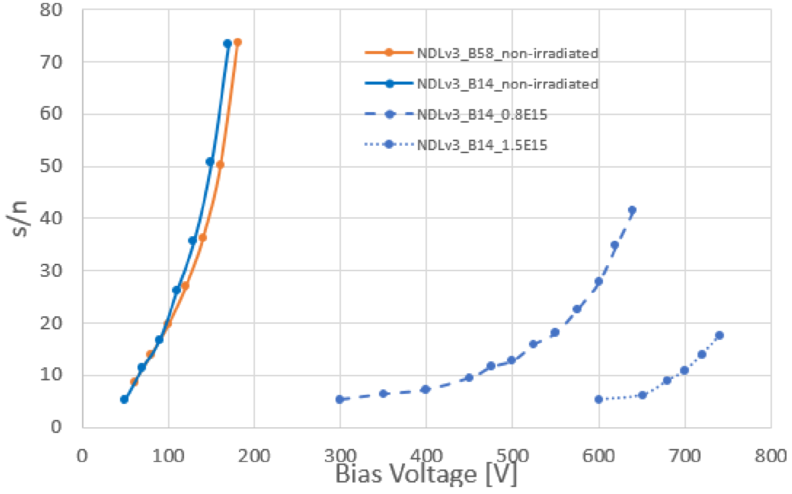
3 fluences [8e14, 15e14, 25e14]

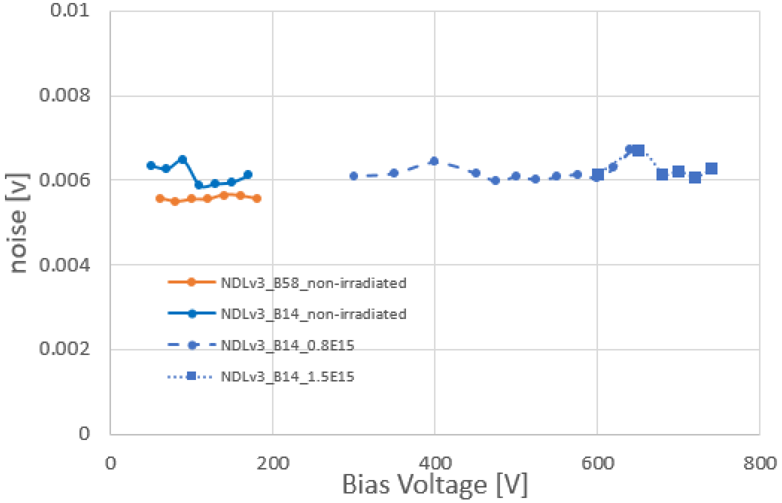
CV PLOT

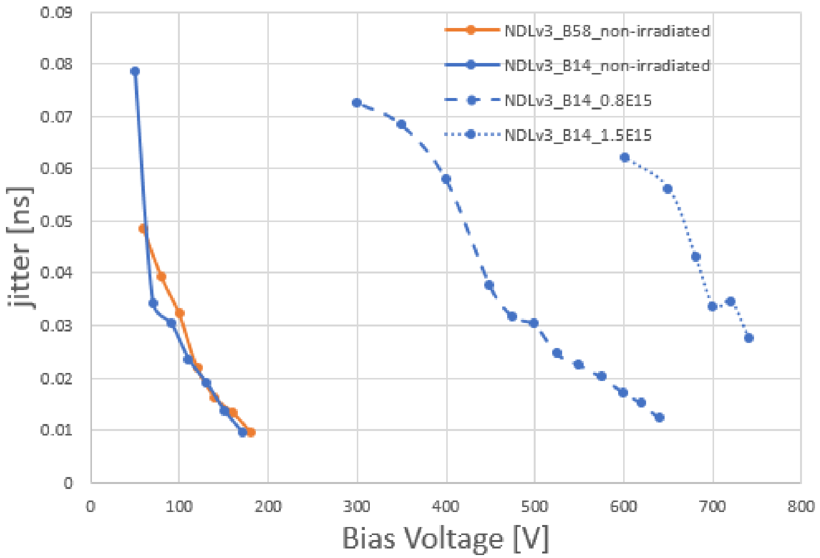
- Leakage current very small – on the level of hundreds of pA – no break down up to 200 V.
- Small resistivity of the wafer – V_{fd} ~ 83 V

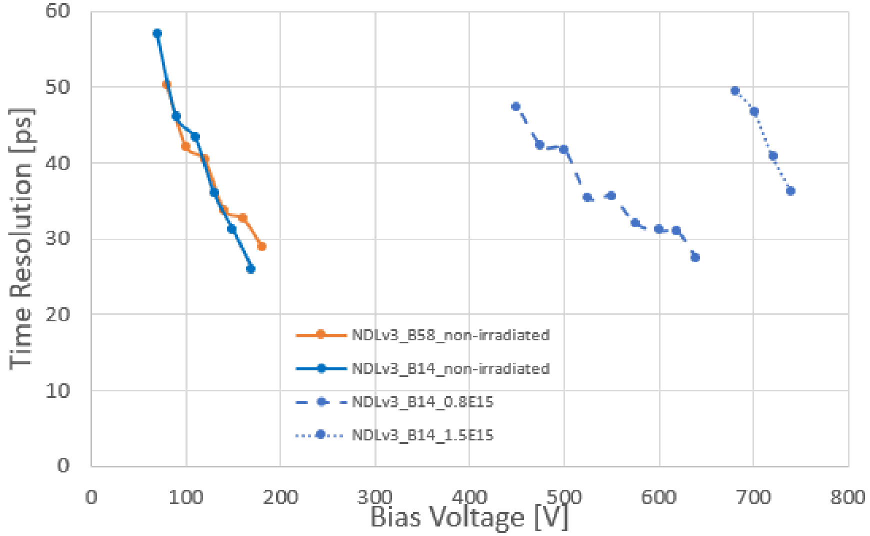
NDLv3 – CC & timing





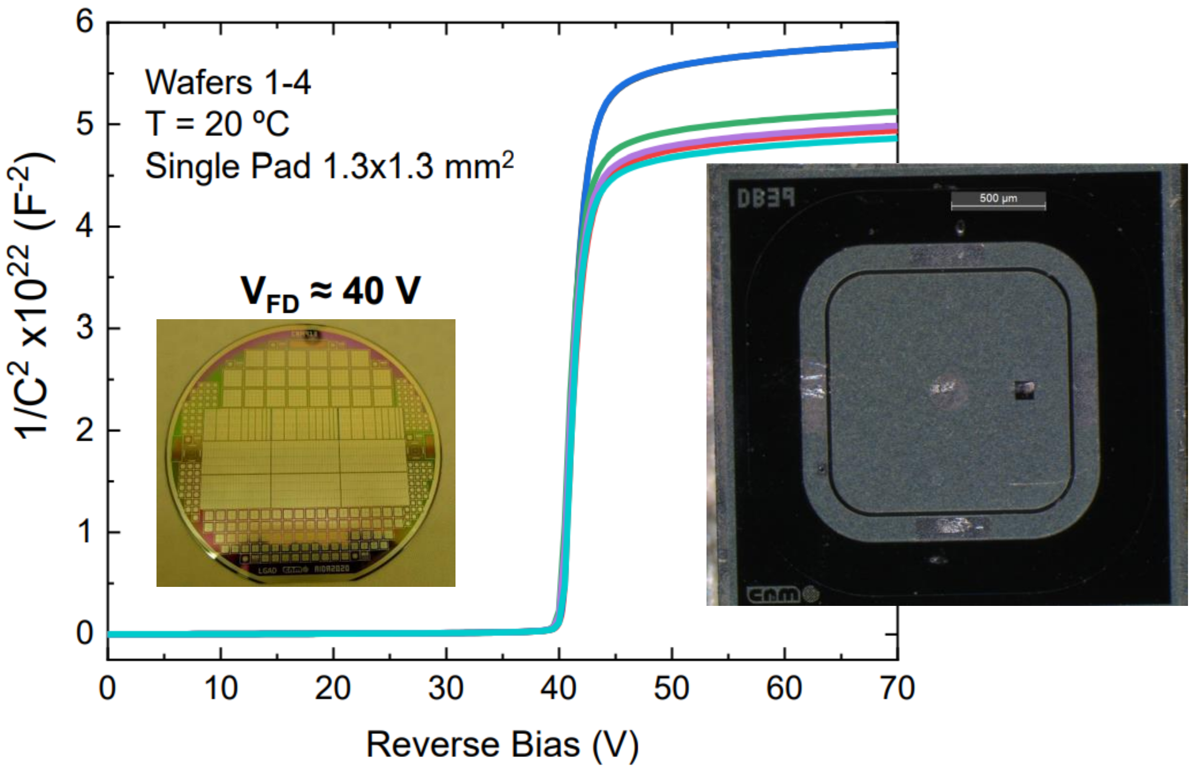


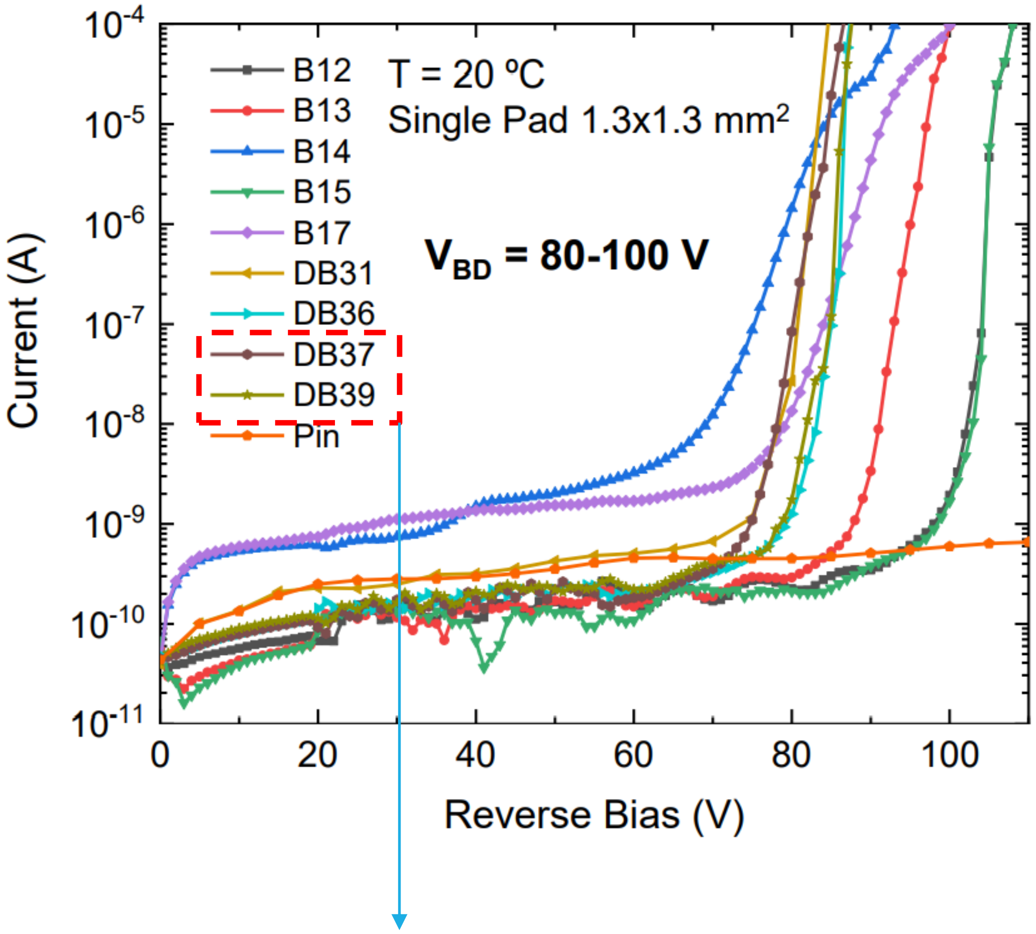




- Non-irradiated: Good charge collection, S/N and noise – similar for both device types
- Devices are functional
- Gain layer degradation is too large
  - devices can not be operated at 2.5e15 cm^{-2} , breakdown at 710 V

CNM – AIDA2020v2 (R12916)



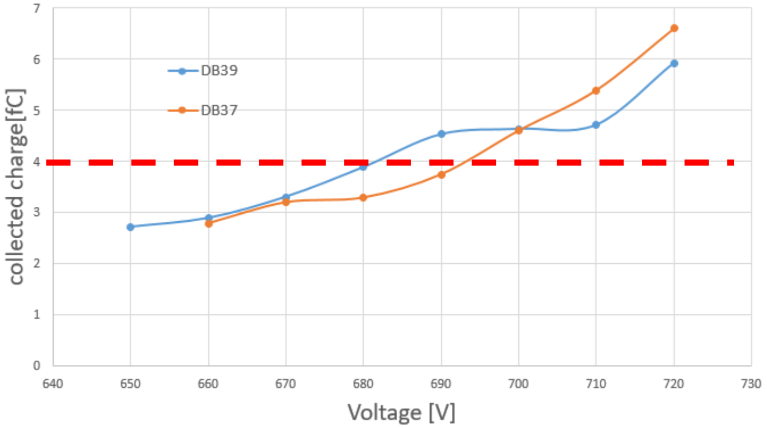


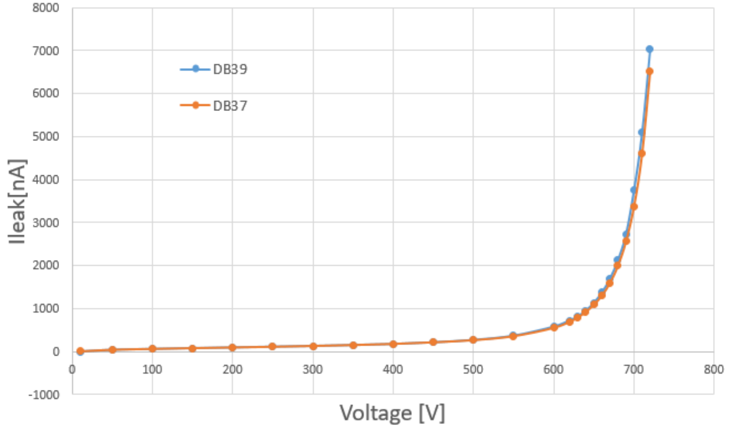
Wafer	Thickness (µm)	Dose (at/cm²)	Energy (keV)
1-4	50	Medium	Low

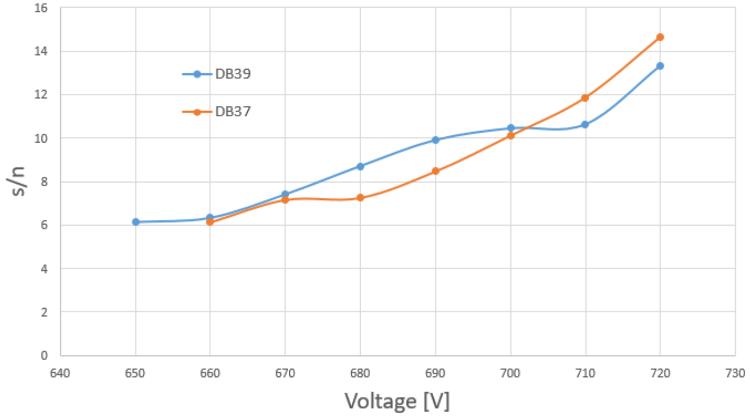
these two used in tests: irradiated to 2.5e15 cm^{-2}

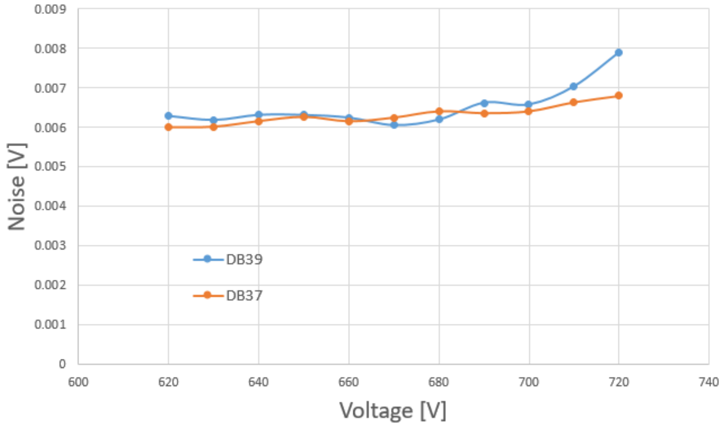
Narrow and highly doped implant, but also shallow

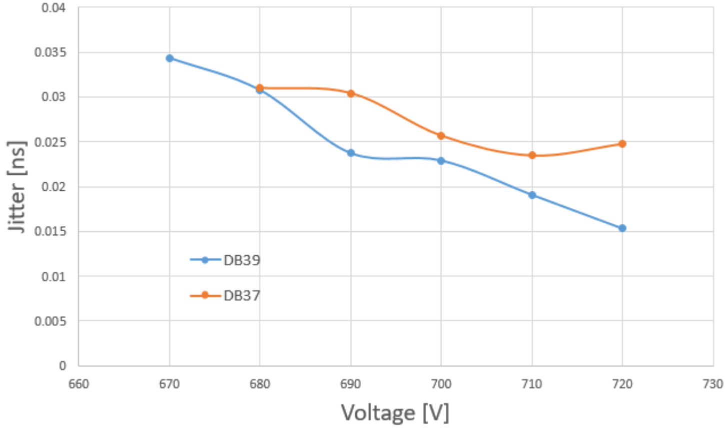
CNM – Timing/CC

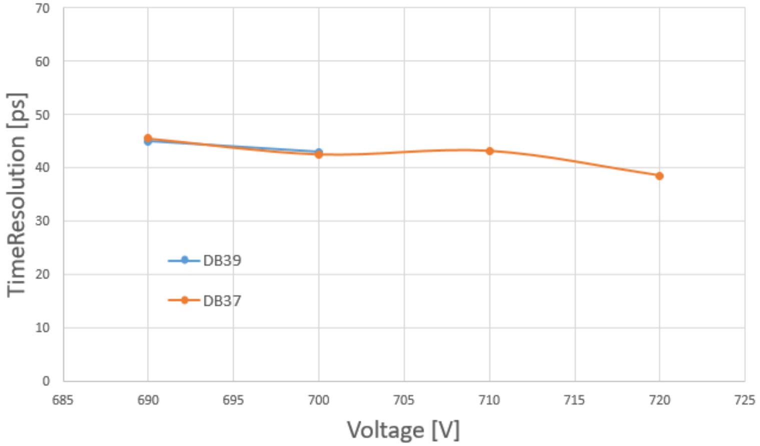






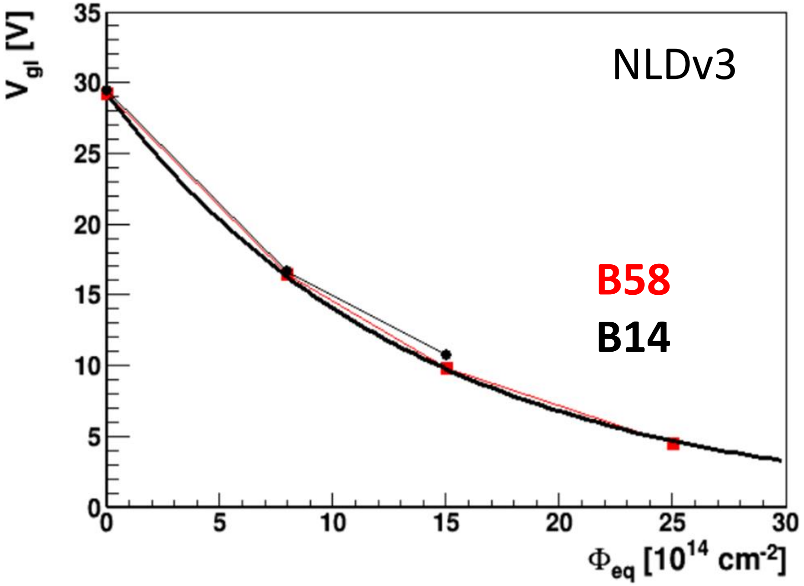






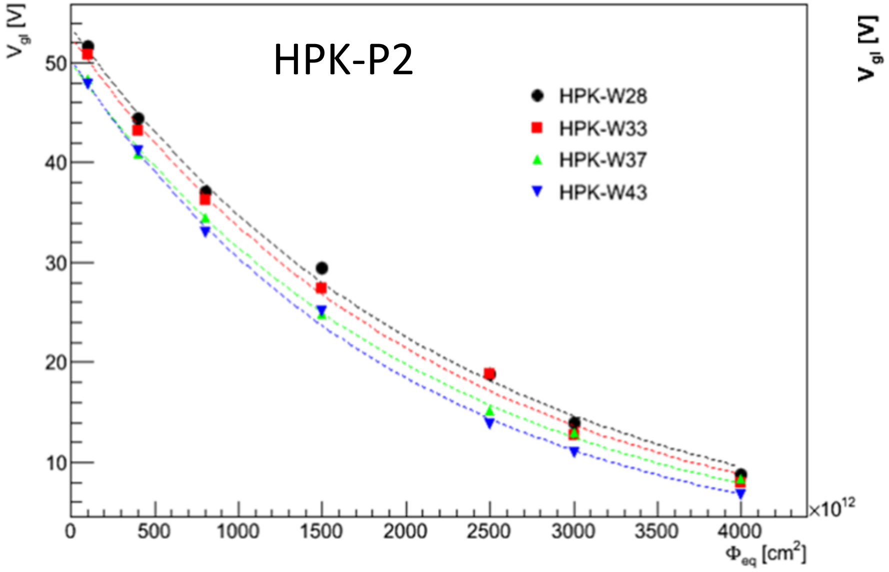
- Both irradiated to 2.5e15

Comparison of V_{gl} vs Fluence



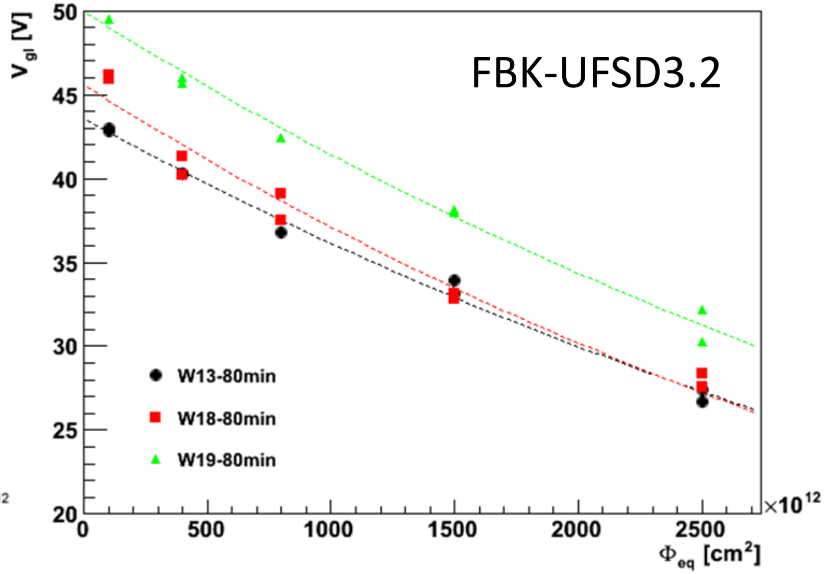
Shallow & narrow highly doped implant

Wafer	c [10^{-16} cm^{-2}]
B58/14	7.3



Deep & narrow highly doped implant

Wafer	c [10^{-16} cm^{-2}]
28	4.3
33	4.5
37	4.6
43	5

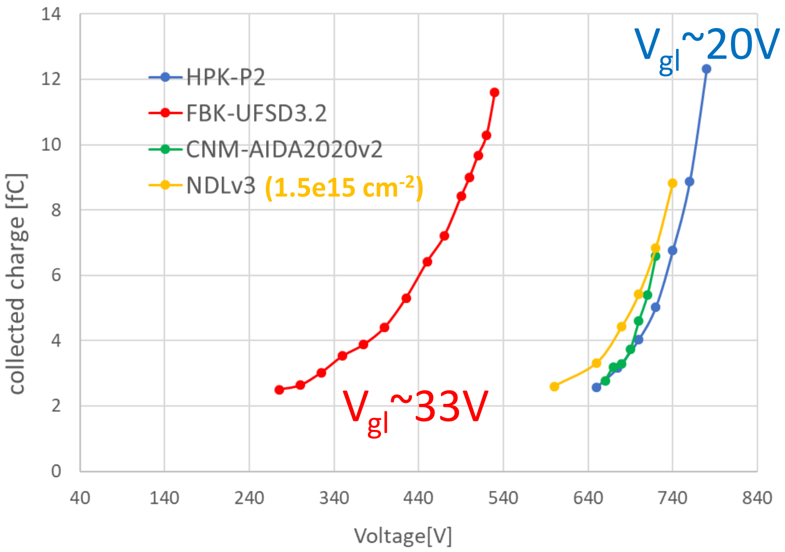


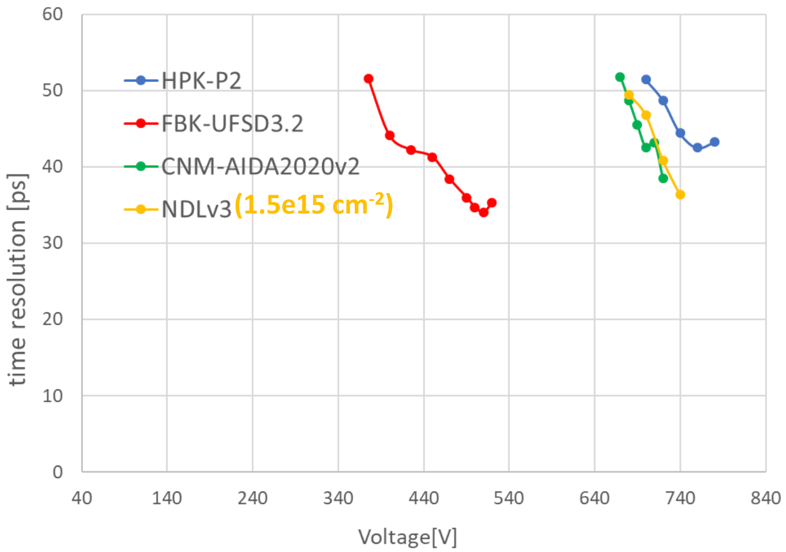
Deep & highly doped C enriched implant

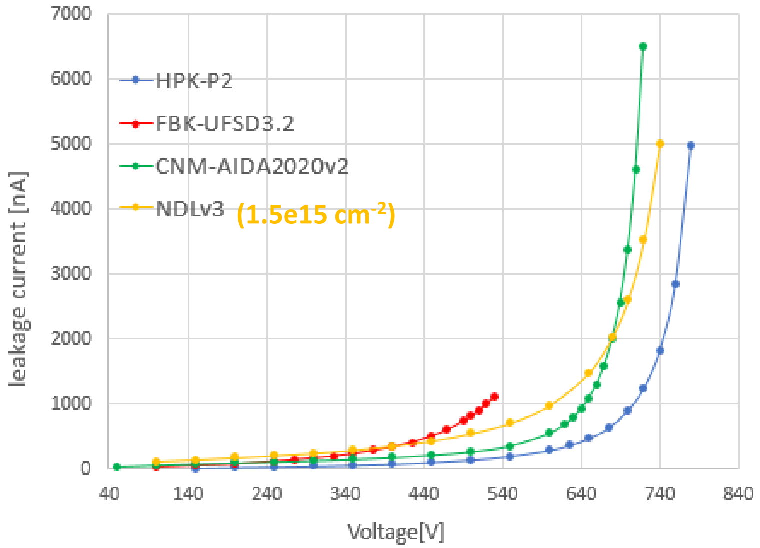
Wafer	c [10^{-16} cm^{-2}]
13	1.9
18	2
19	1.9

- Much lower *c* for FBK – carbon enrichment of gain layer significantly improves the radiation hardness.

Comparison at 2.5e15 cm^{-2}







- The most radiation hard wafers (FBK/HPK) and both NDLv3 and CNM-AIDA2020v2 compared!
- The performance of FBK seems to be comparable to HPK at voltages that are 300 V lower – significant improvement.
  - ΔV_{bias}=300 V for 50 μm thick detector means ΔE=6 V/μm. Assuming 2 μm thick gain layer that results in ΔV_{gl}~12 V. Measured ΔV_{gl}~12V.
- FBK UFSD3.2 is clearly most radiation hard, but we see some problems with sensors breaking down at >600V.

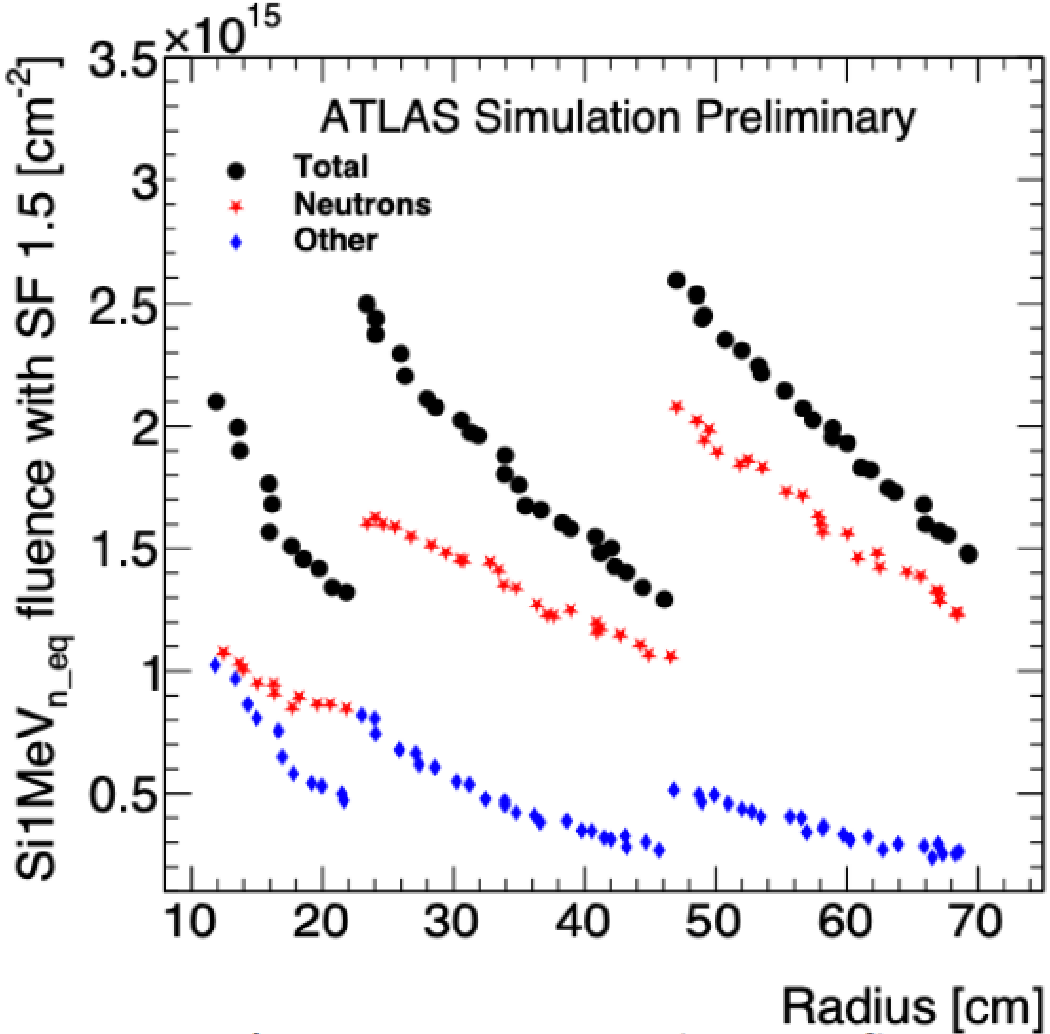
Conclusions and future work

- HPK meets radiation hardness requirement needed for HGTD
  - Behave well and have shown they can produce working full size sensors.
  - This will be the best we get from HPK – they will not do any C implantation
- FBK has also shown they can withstand high irradiation
  - Excellent GL design; C implantation significantly improves radiation hardness
  - V_{op} way below any other vendors
  - But need to show can perform equally well with full size sensors
  - Also need to fix breakdown problem
- CNM just reaches required radiation hardness
  - Future runs include C implantation
  - Also need to show can maintain performance with full size sensors
- NDL produced a sensor that works, but still in early phase of development
  - Need to improve radiation hardness by modifying GL

All future runs will be qualified in the same way as those presented here

Backup: c_p/c_n

- In HGTD inner ring, neutron/charge hadron mix is ~50/50, goes to ~75/25 in outer ring.
- Can use the c_p/c_n ratio during neutron irradiations, irradiating to higher fluence to take into account extra damage charged hadrons would cause.



HGTD's requirement on the NIEL fluence