Status report on the radiation tolerance assessment of CNM AIDA2020v2 and HPK-P2 LGADs

IFCA:

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CERN:

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Michael Moll, Marcos Fernandez, Julian Boell

UZH:

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Contents

1) Summary of **electrical characterizations** of non-irradiated and irradiated diodes of both, **HPK2** and **CNM AIDA2020 v2** productions, performed by 3 different institutes (CERN-SSD, IFCA, UZH).

2) **Algorithm** for IV measurement analysis:
   1) Automatic extraction of breakdown voltages
   2) Extraction of depletion voltage of gain layer from IV measurements
   3) Acceptor removal fits (IV vs CV)

3) **Timing** characterization of irradiated HPK2 samples

Samples and measurement campaign

CNM-AIDAv2 samples

4×4” wafers, same dose/energy parameters:

- 50 μm thick, dose medium, energy low
- 2 samples/fluence

HPK2 samples

4 different doping profile “splits”

W25-S1, W31-S2, W36-S3, W42-S4

50 μm thick

1 detector/split (W42: 2 detector/split)

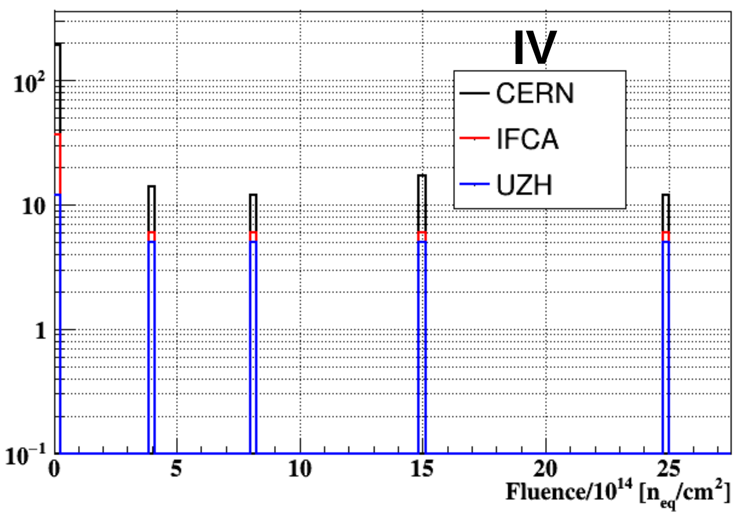
2 splits/fluence

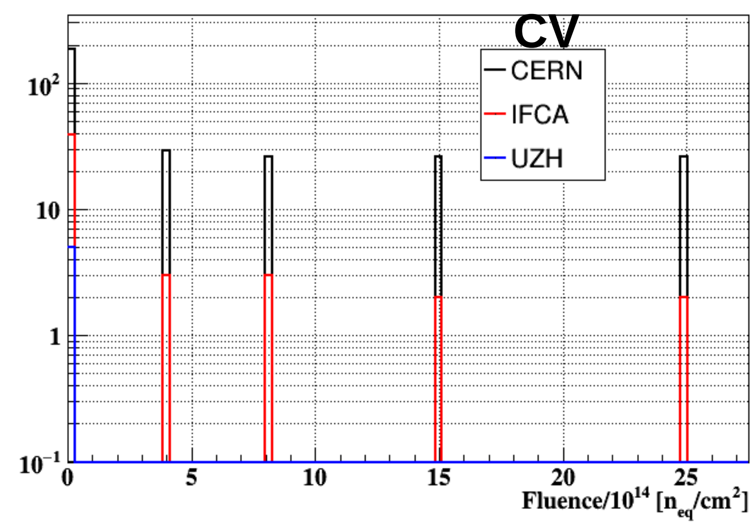
Common to both:

Measured structures: Single pads (PINs and LGADs): 1.3×1.3 mm^2

Characterized both non-irradiated and irradiated with neutrons (Lbj) at: 4e14, 8e14, 1.5e15, 2.5e15 neq/cm2

Measurement campaign:





IV Temp

	CERN	IFCA	UZH
Non-irrad:	20	(-20,22)	25
Irradiated:	(-30,-20,-10)	-20	-20

CV Temp

	CERN	IFCA	UZH
Non-irrad:	(0,20)	(20,22)	20
Irradiated:	(-30,-20,-10,0,20)	10	0

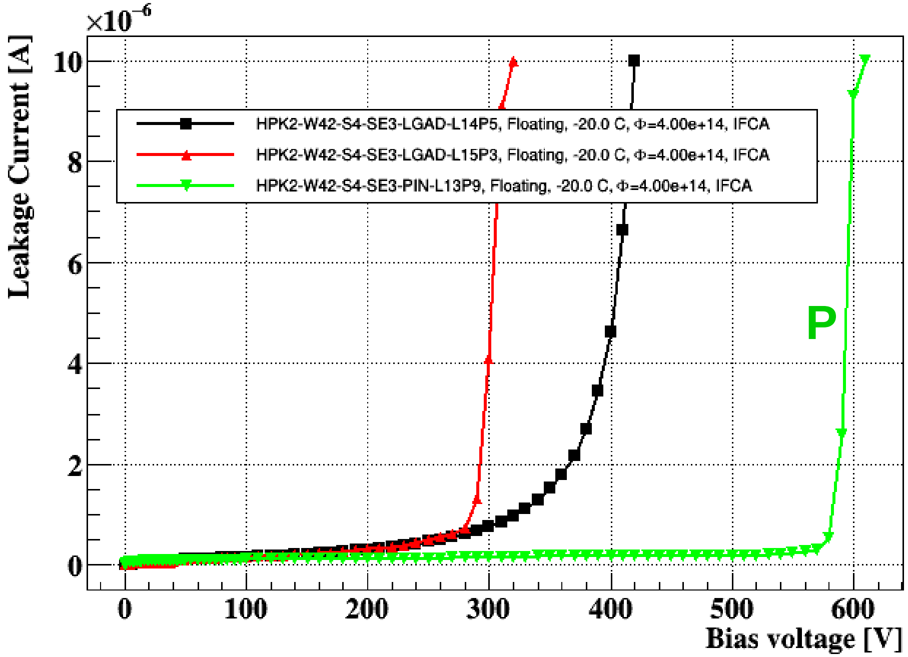
IV GR

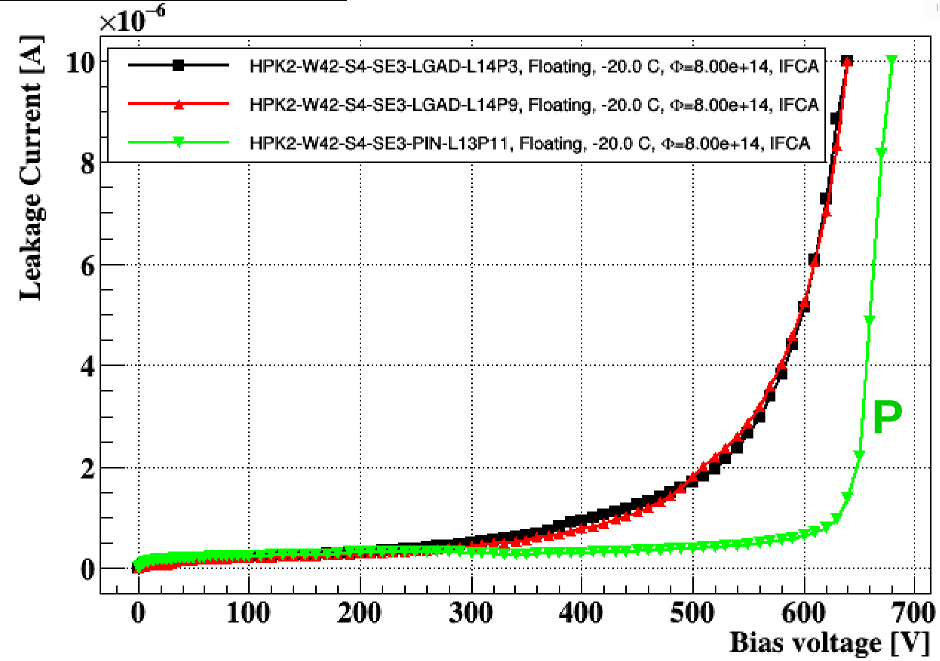
	CERN	IFCA	UZH
Non-irrad:	Floating	HV	Floating
Irradiated:	GND	Floating&HV	Floating

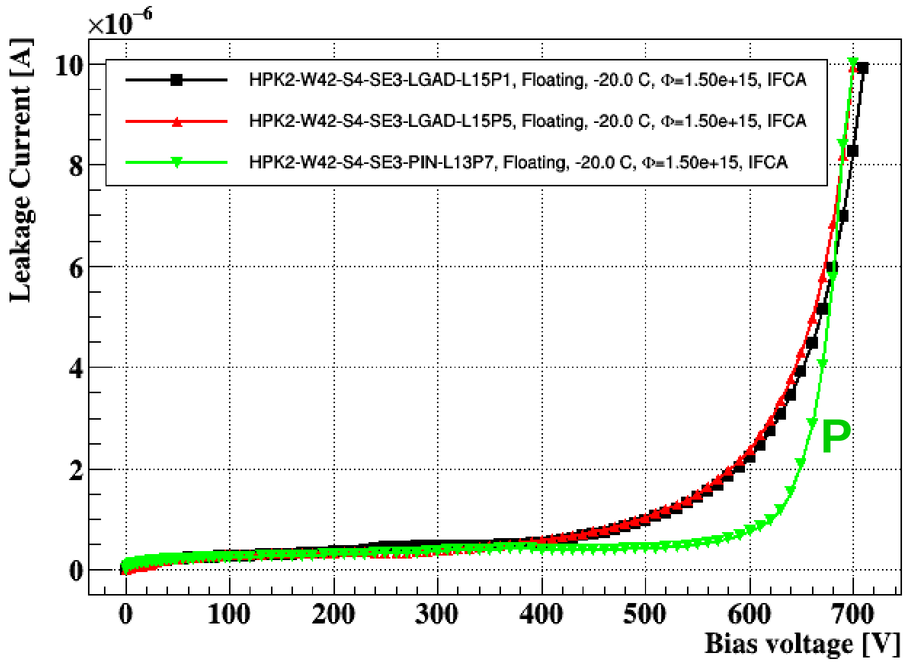
CV GR

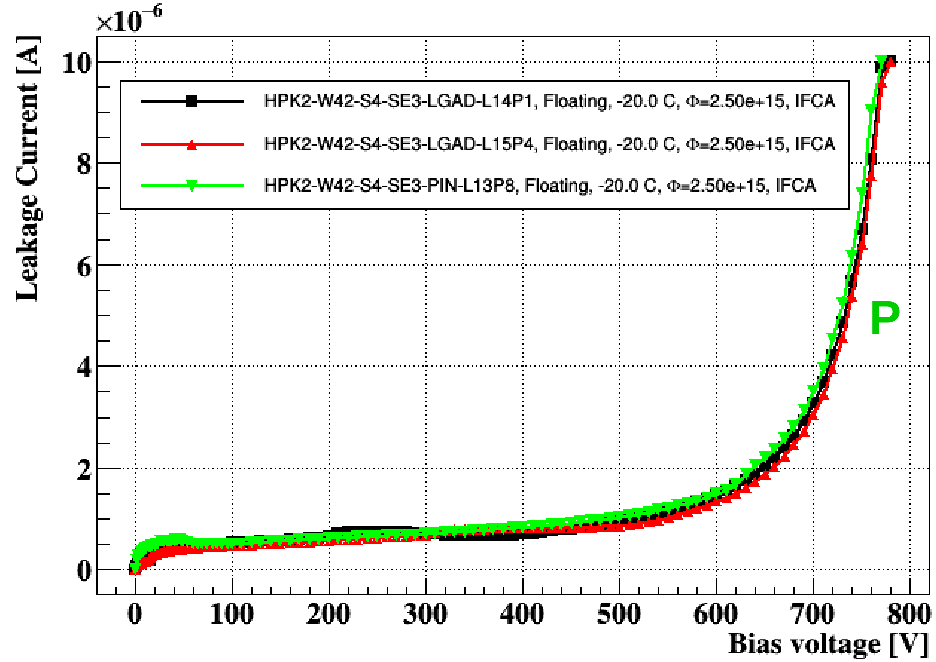
	CERN	IFCA	UZH
Non-irrad:	GND	HV	Floating
Irradiated:	GND	GND	--

HPK2-W42: LGADs and PINs









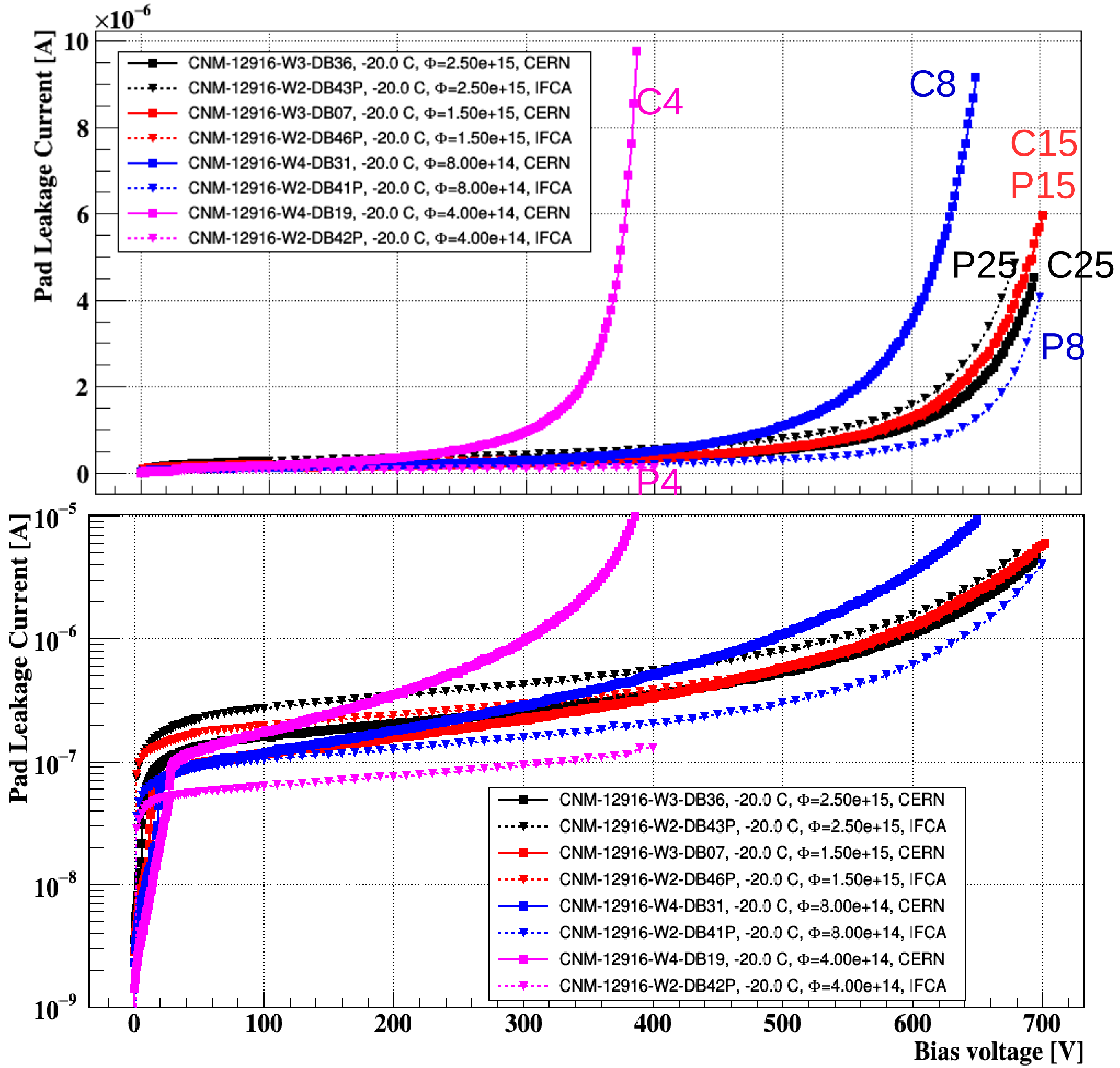
1) By comparison with HPK-W42-PIN, gain still well visible until 1.5e15 n_{eq}/cm^2
Gain disappeared at 2.5e15 n_{eq}/cm^2

CNM-AIDAv2 All Fluences

All PINs behave similar with breakdowns around 620V, for all fluences

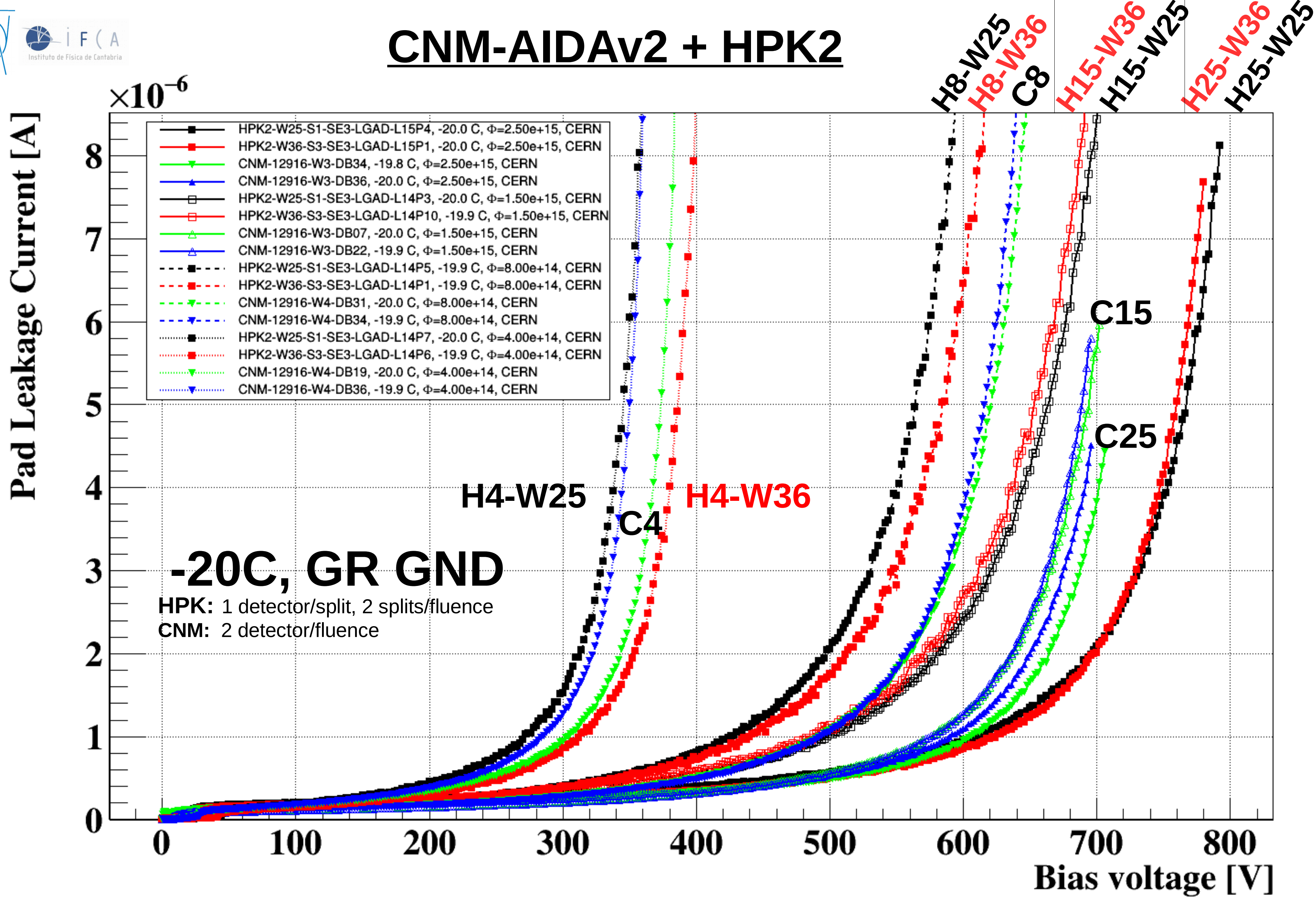
LGADs 4e14, 8e14:
Clear difference from their PINs, pointing at existence of gain at these fluences.

LGADs 1.5e15, 2.5e15:
LGAD are very PIN similar, probably no gain at this fluences.
Similar breakdown voltage for LGAD and PIN.



Notation:
PX = PIN irradiated to Xe14
CX = CNM LGAD irradiated to Xe14
HX = HPK2 LGAD irraduated to Xe14

CNM-AIDAv2 + HPK2



HPKs:

W25 (split 1, highest gain) breaks ~40 V **earlier** than **W36** (split 3) at 4e14 and 8e14 neq.

For $\Phi \geq$ 1.5e15, **W25**(split1) breaks slightly **after W36**.

PINs (not shown) measured up to 200V for HPK2

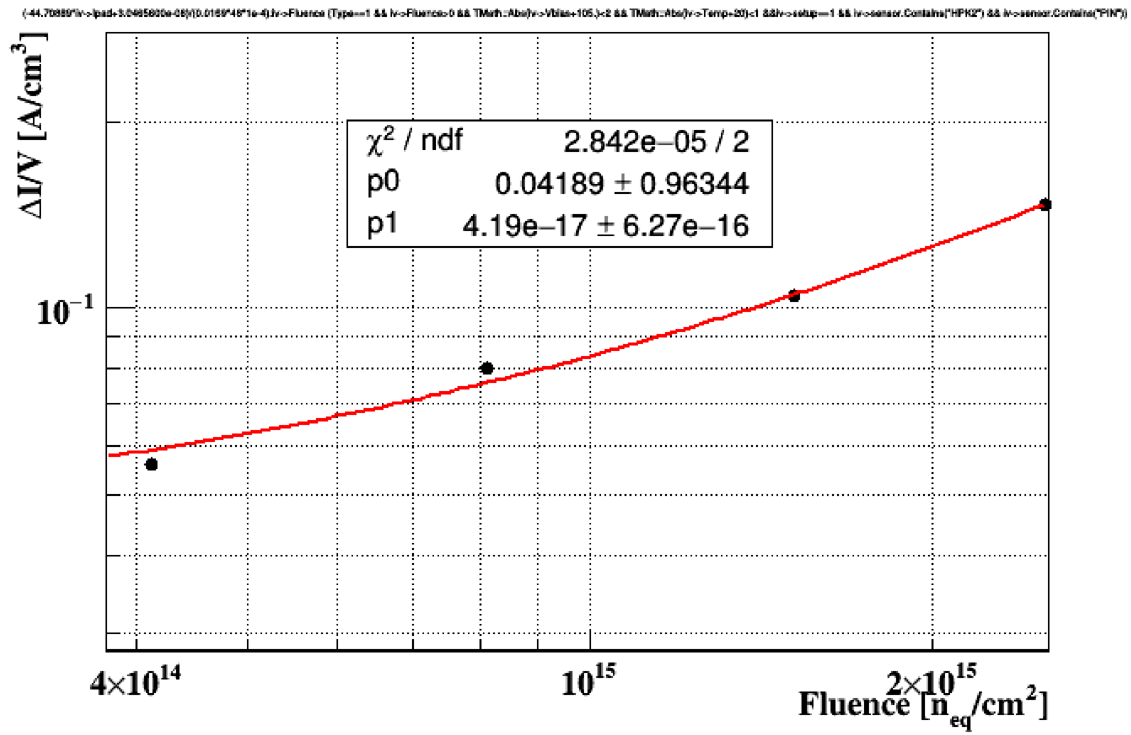
CNM:

CNM 8e14 and 1.5e15 have higher breakdown than HPK2 at same fluence

CNM 2.5e15 breaks earlier than HPK2

Uniform behavior

Leakage current scaling with fluence



Nominal in Moll's thesis~4×10^{-17} A/cm

CERN HPK2 W25 and W36 PINs

Calculated at Vbias=105 V and scaled to T_R=20C

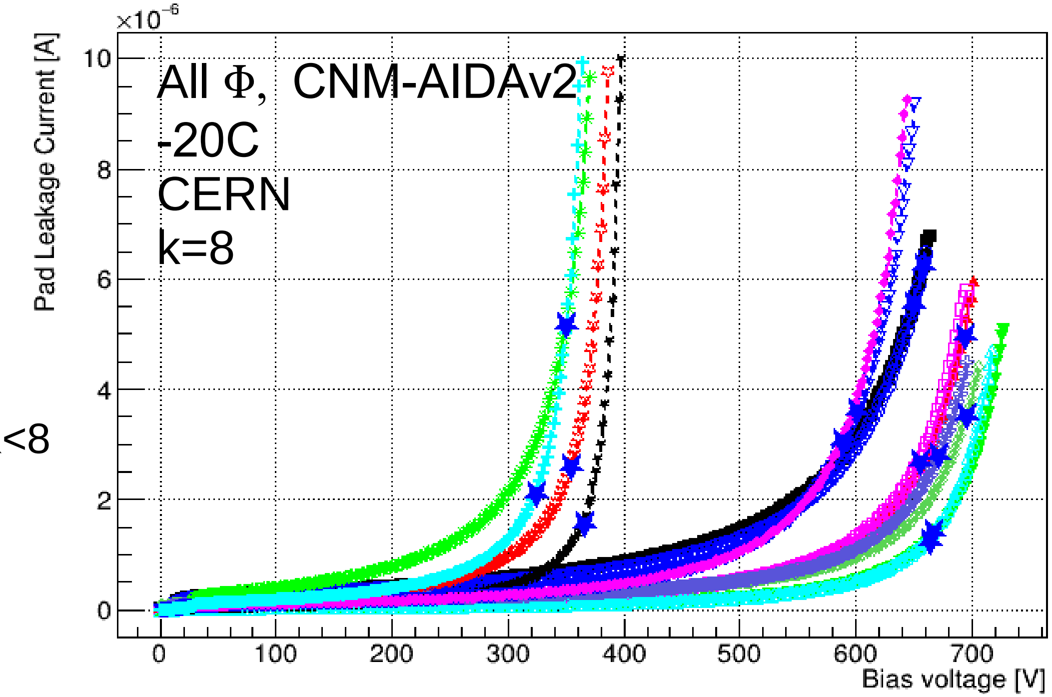
Breakdown voltage calculation

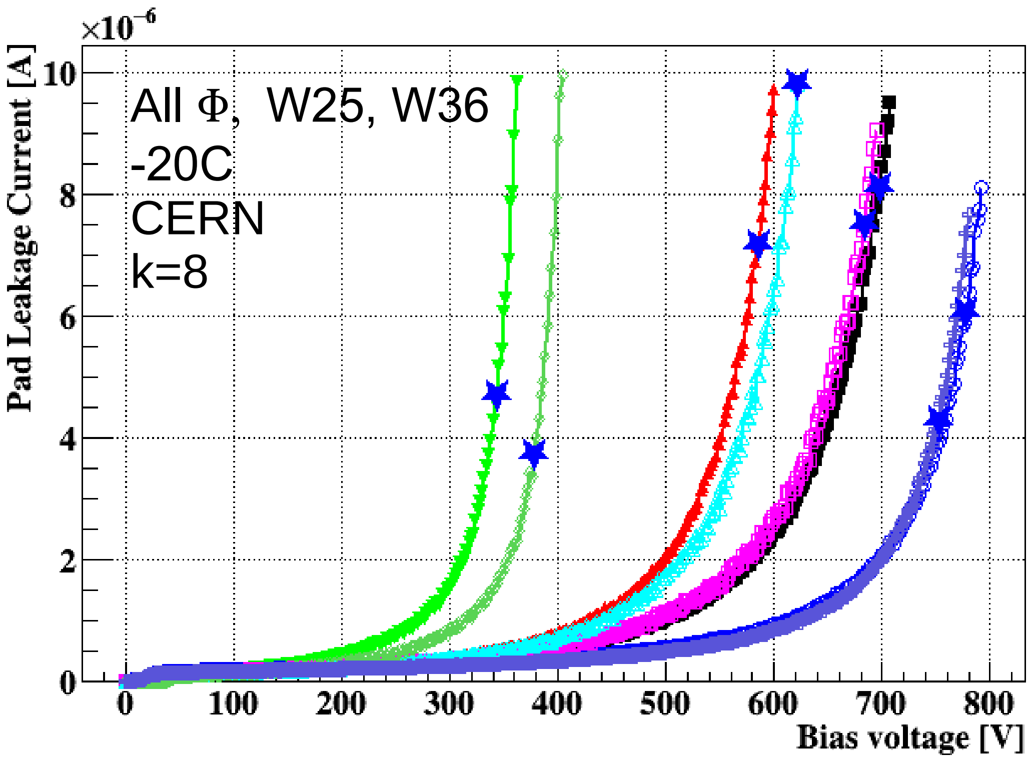
Breakdown can be calculated automatically using the “K” variable [1]:

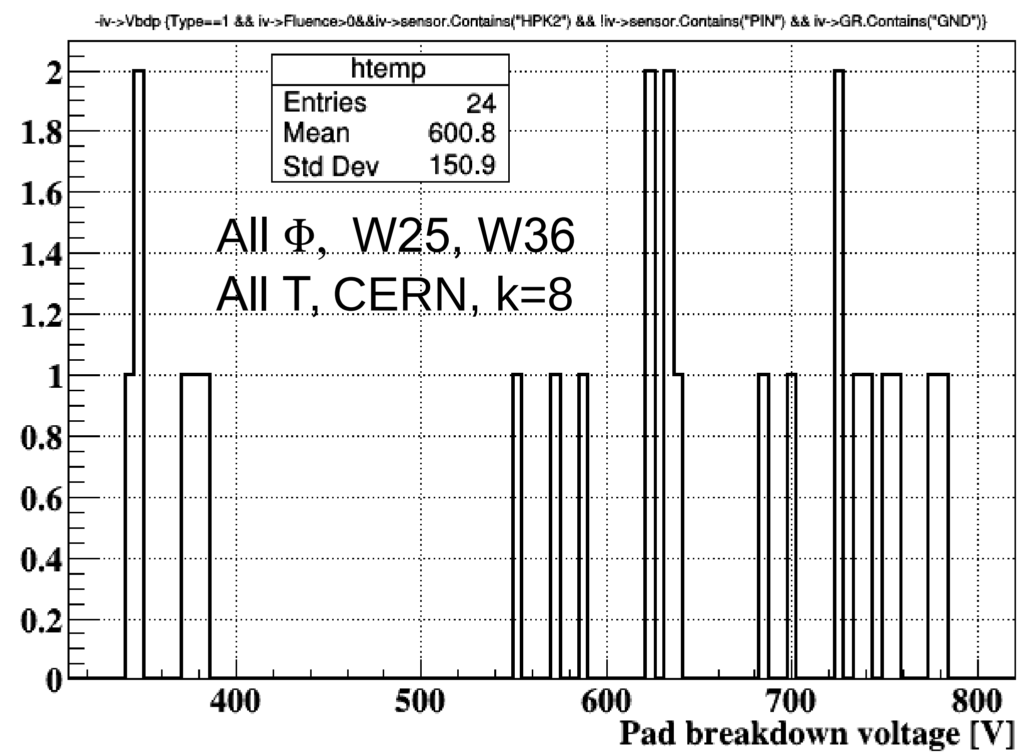
$$K(I,V)=\frac{\Delta I}{\Delta V}\frac{V}{I}$$

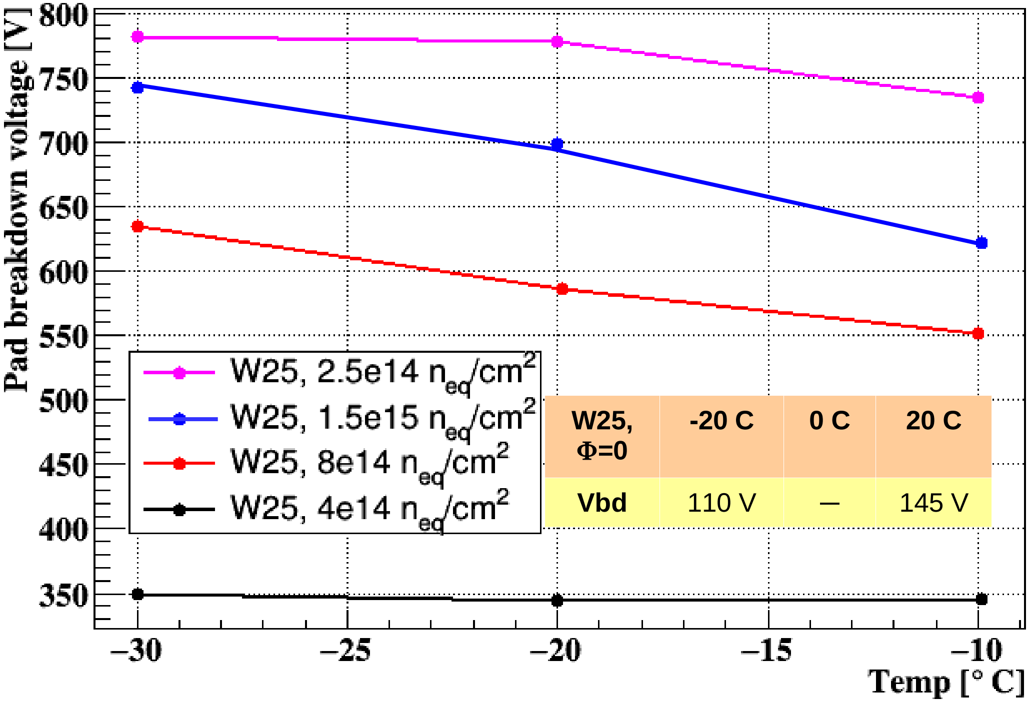
- K~1 Ohmic resistor
- V_{BD} defined as last bias at which K<8

[1] N. Bachetta et al.
https://doi.org/10.1016/S0168-9002(00)01207-9









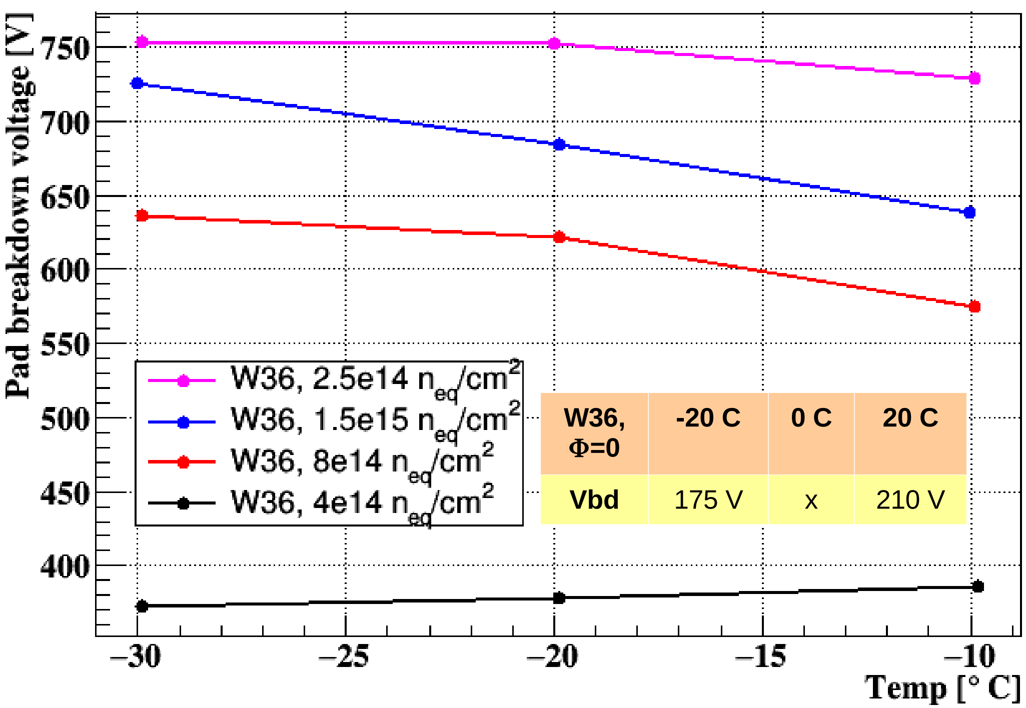
W25, Φ=0	-20 C	0 C	20 C
Vbd	110 V	—	145 V

Breakdown voltage vs Temperature for irradiated HPK2 and CNM AIDAv2:

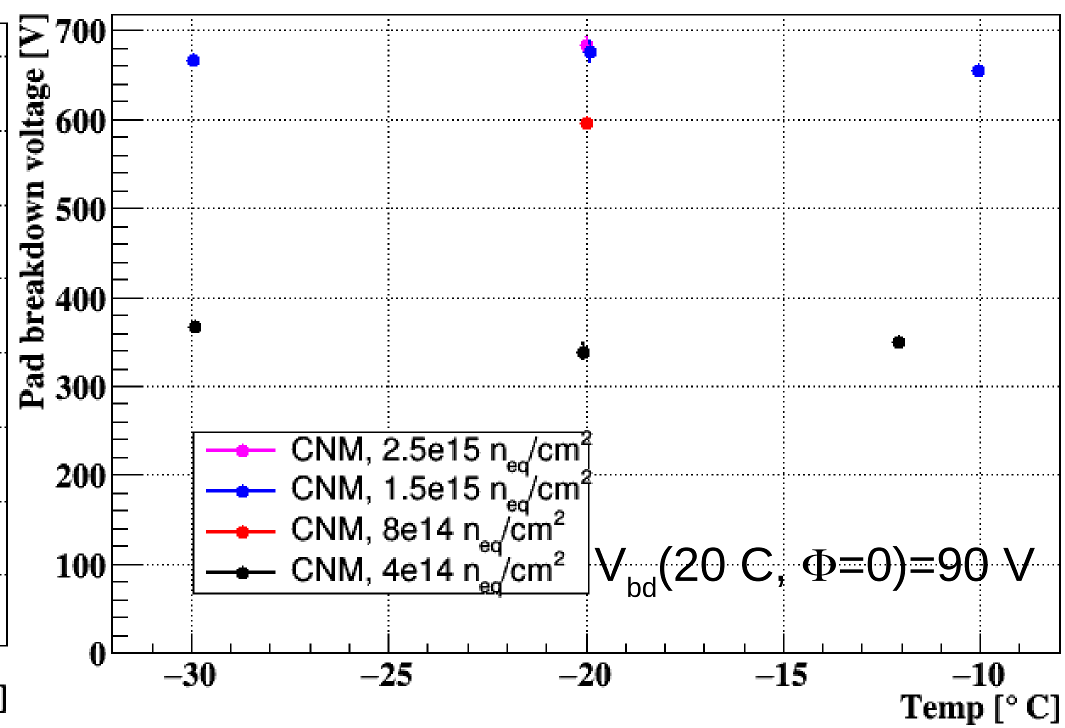
Beneficial effects of fluence and temperature on breakdown voltage:

1) The higher the fluence, the higher the breakdown voltage (substrate resistivity increase?)

2) The lower the Temperature, the higher the breakdown voltage .



W36, Φ=0	-20 C	0 C	20 C
Vbd	175 V	x	210 V



Gain layer depletion calculation

The characteristic foot on $1/C^2$ vs V of LGADs is interpreted as the depletion voltage of the gain layer. The position of the foot:

1) depends on fluence, it doesn't seem to depend on frequency (if you take care of zooming in)

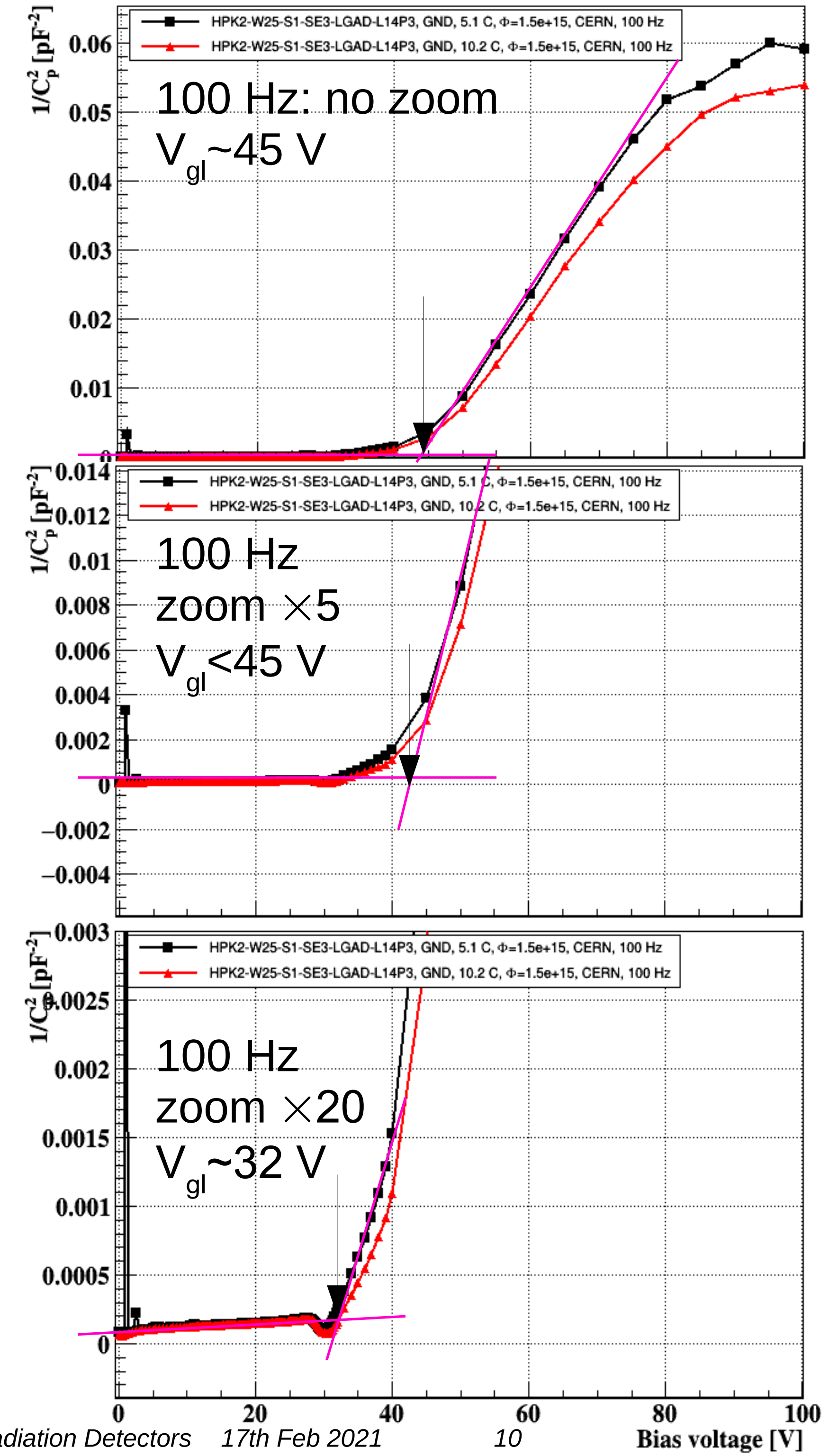
2) has little variation with Temperature

Double linear fit of $1/C^2$ can be:

1) Disturbed by "bumps" near the foot

2) Usually done by hand: different slopes in the raising part or zoom levels can turn fit subjective.

We propose another method to calculate the gain depletion voltage, **based on the measurement of the leakage current.**



Gain layer depletion calculation

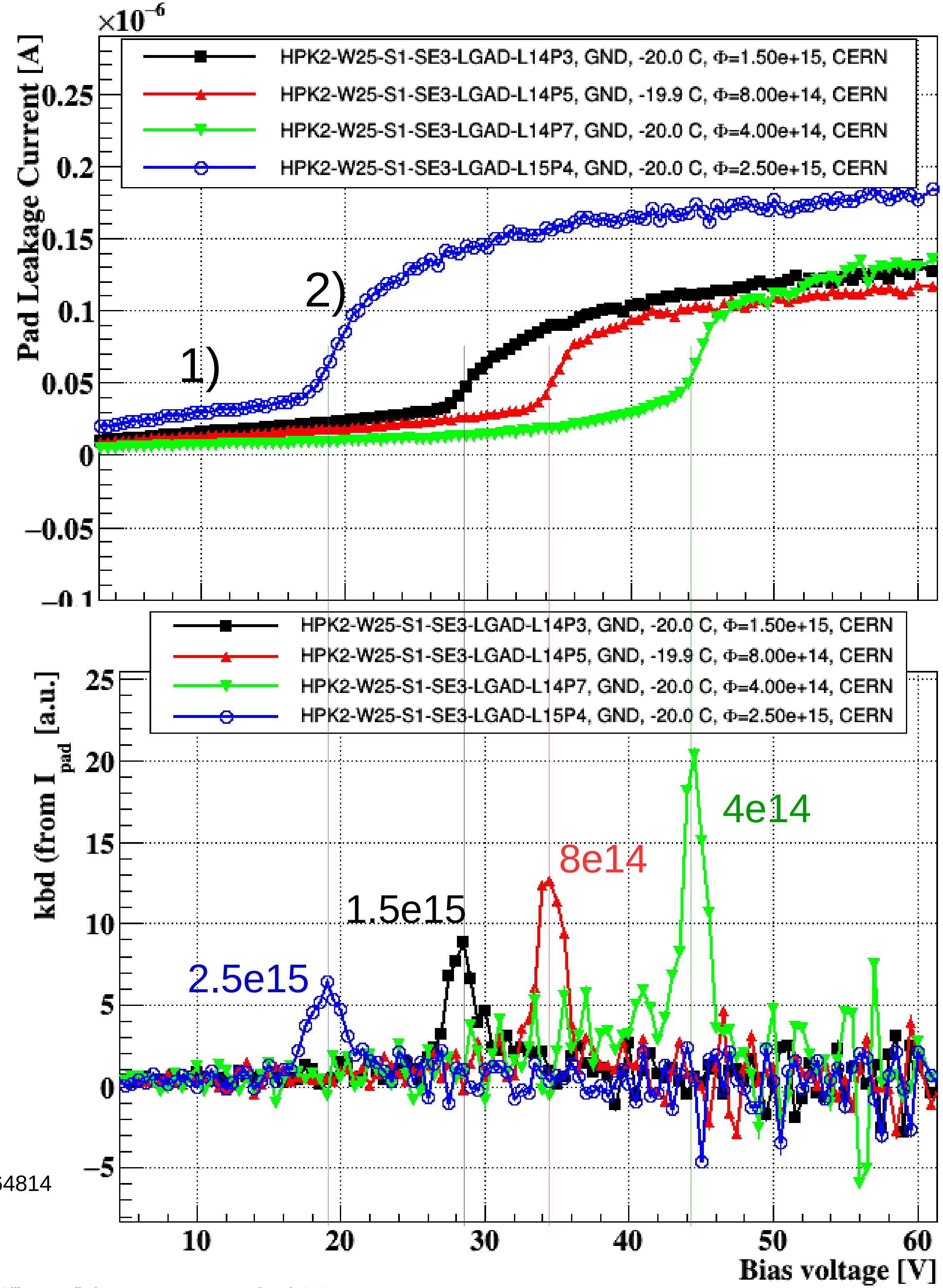
Leakage current of LGADs shows a distinct **kink [1]**:

1) at low bias → leakage current increase by multiplication in gain layer.

2) Then abrupt increase (kink position depends on Fluence) when field extends quickly into bulk

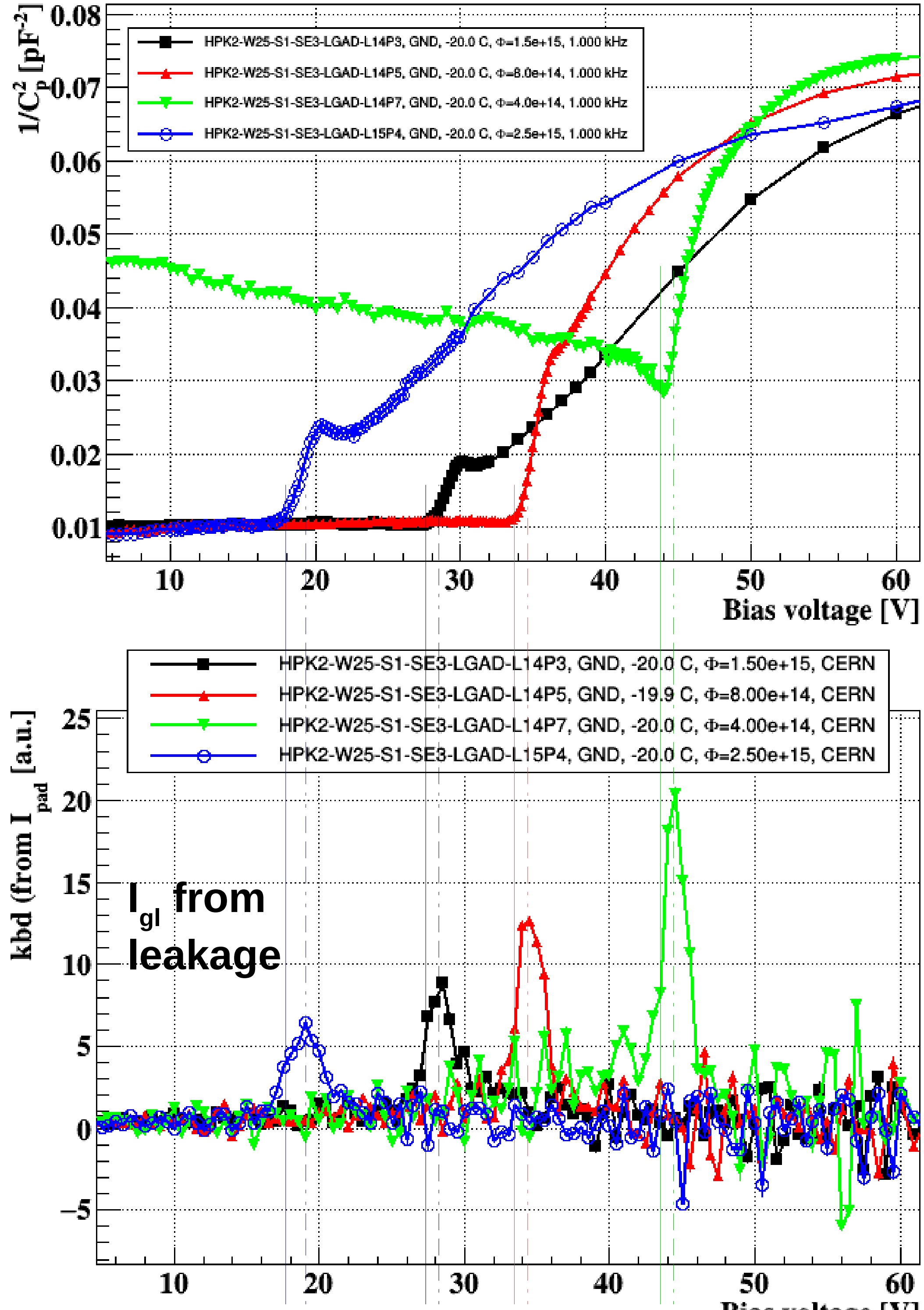
The formerly introduced K-variable is also very sensitive to the kink in leakage current.

In this case **it does not indicate a breakdown** but a transition.



[1] M. Wiehe, Nuclear Inst. and Methods in Physics Research, A 986 (2021) 164814
https://doi.org/10.1016/j.nima.2020.164814

Comparison of Vgl from IV and CV



Kink in **IV coincides with kink in 1/C²** **(at 1 kHz, -20 C)**

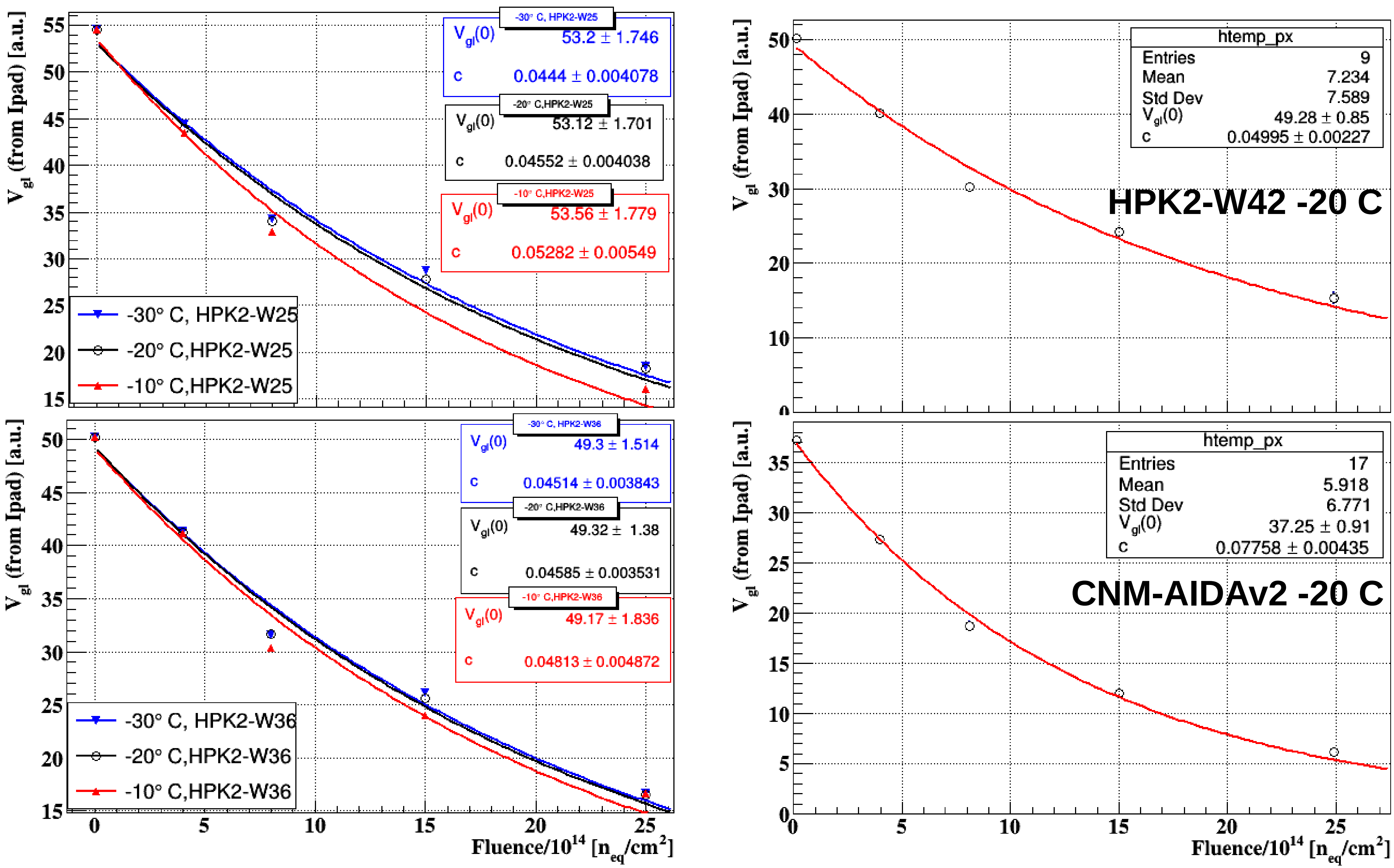
K(V) fitted with a gaussian.

The gain layer depletion voltage calculated from IV as **μ-0.5σ** coincides best with Vgl from CV

Gain layer: removal constant (from IV)

- Dependence of gain layer depletion with Fluence for different temperatures

Fitting: $V_{gl}(\Phi)=V_{gl}(\Phi=0)\times\exp(-c\Phi)$

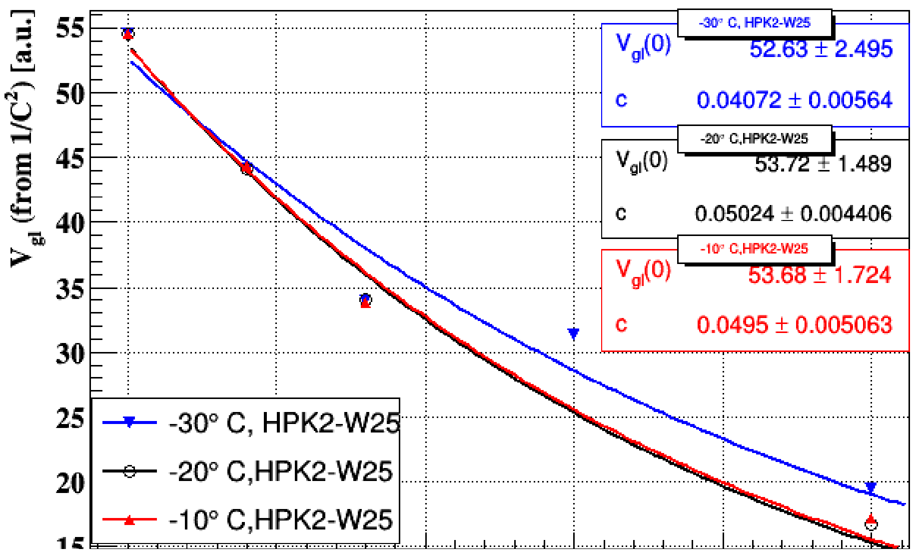


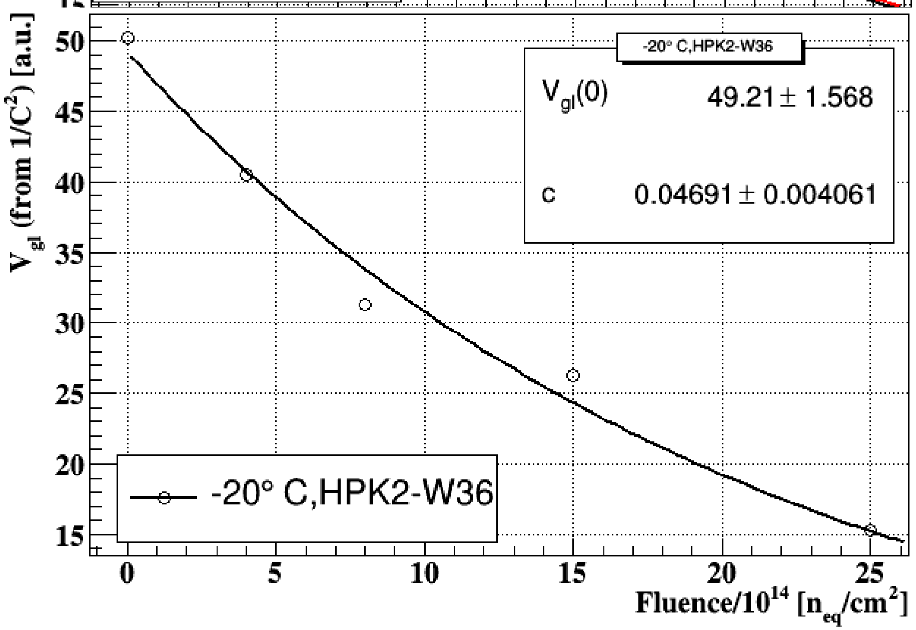
- Note that HPK2 and CNM-AIDAv2 have very different Gain Layer implementations

Gain layer: removal constant (from 1/C²)

- Dependence of gain layer depletion with Fluence for different temperatures.

Fitting: $V_{gl}(\Phi)=V_{gl}(\Phi=0)\times\exp(-c\Phi)$

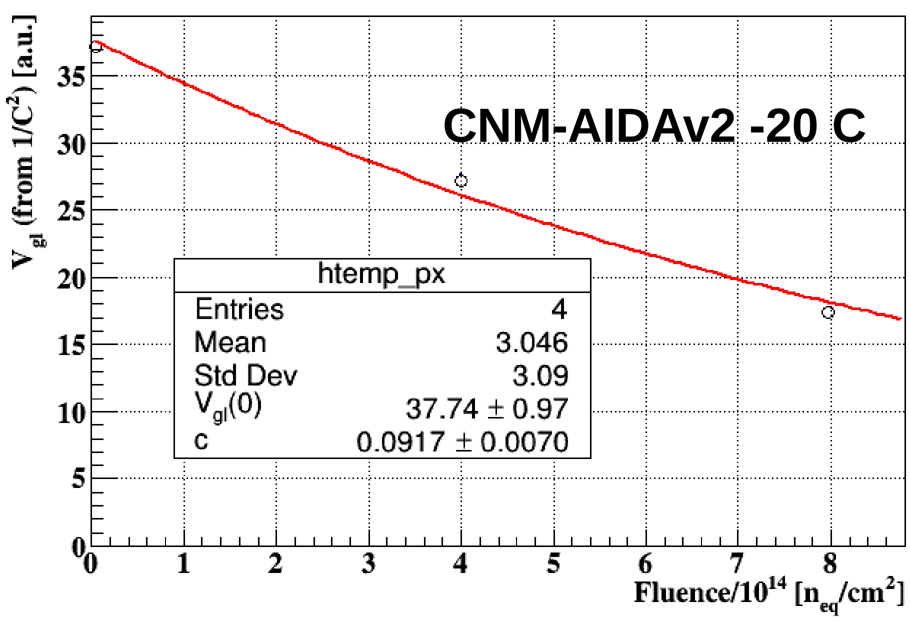




c [10^{-16} cm²]

	S1	S2	S3	S4
Vgl (Lbj, 1/C²,10 kHz,20 C)	4.3	4.5	4.6	5.0
Vgl (1/C²,1 kHz, -20C)	5.0	–	4.7	–
Vgl from IV	4.6	–	4.6	5.0

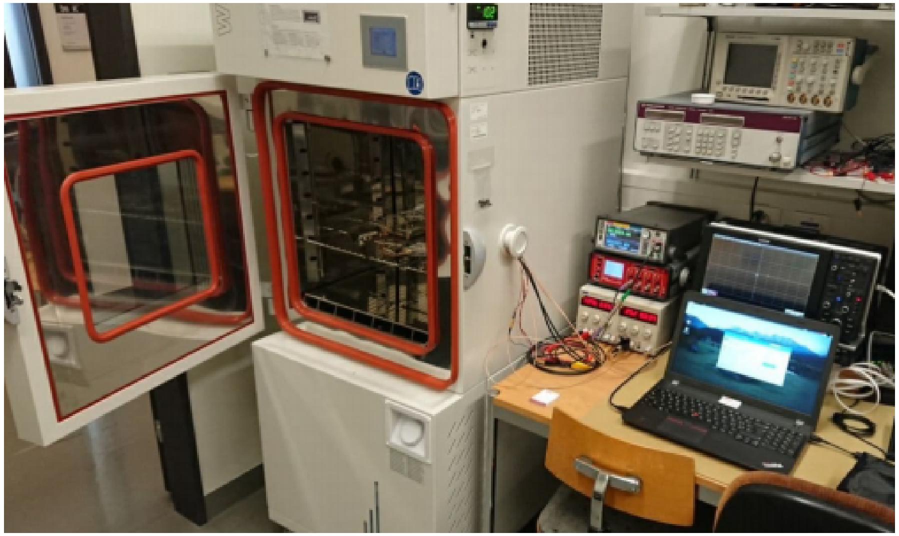
This talk {Vgl (1/C²,1 kHz, -20C); Vgl from IV}

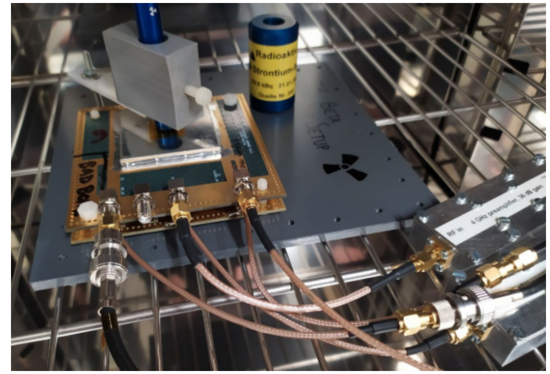


- Note that HPK2 and CNM-AIDAv2 have very different Gain Layer implementations

Timing measurements

UZH:





Temperature control: climate chamber(-20°C)

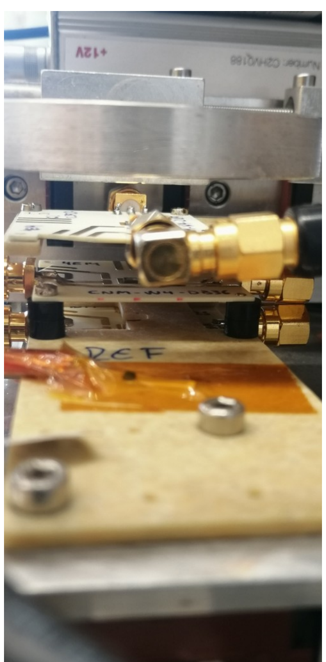
Reference sensor: LGAD AIDA-2020 run
(35 µm, medium doping)

Beta source: Sr90 radioactive source

Readout boards: UCSC v1.1 ROB

Amplifiers: fast amplifiers (in-house design)
(4 Ghz, 36 dB)

CERN-SSD:



New: 3 sensor stack for
calibration of 3 samples/run.

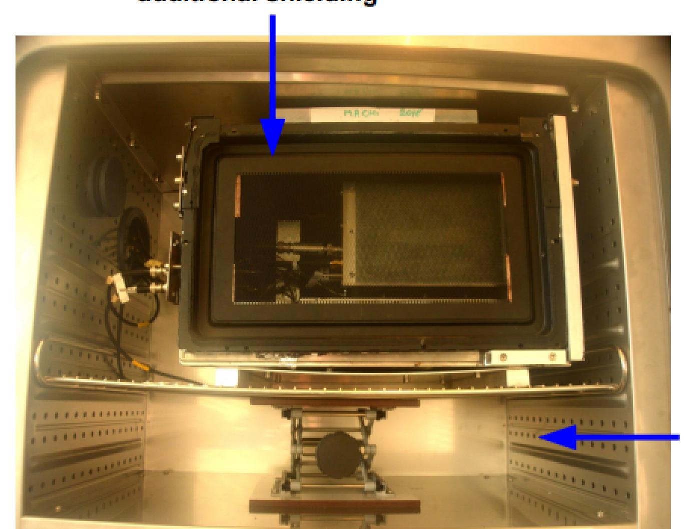
1st layer
2nd layer
3rd layer

Sensor stack inside Binder MKT 115T
climatic chamber, range: [-70,+180] C

Amplifiers: Cividec 2 GHz, 40 dB

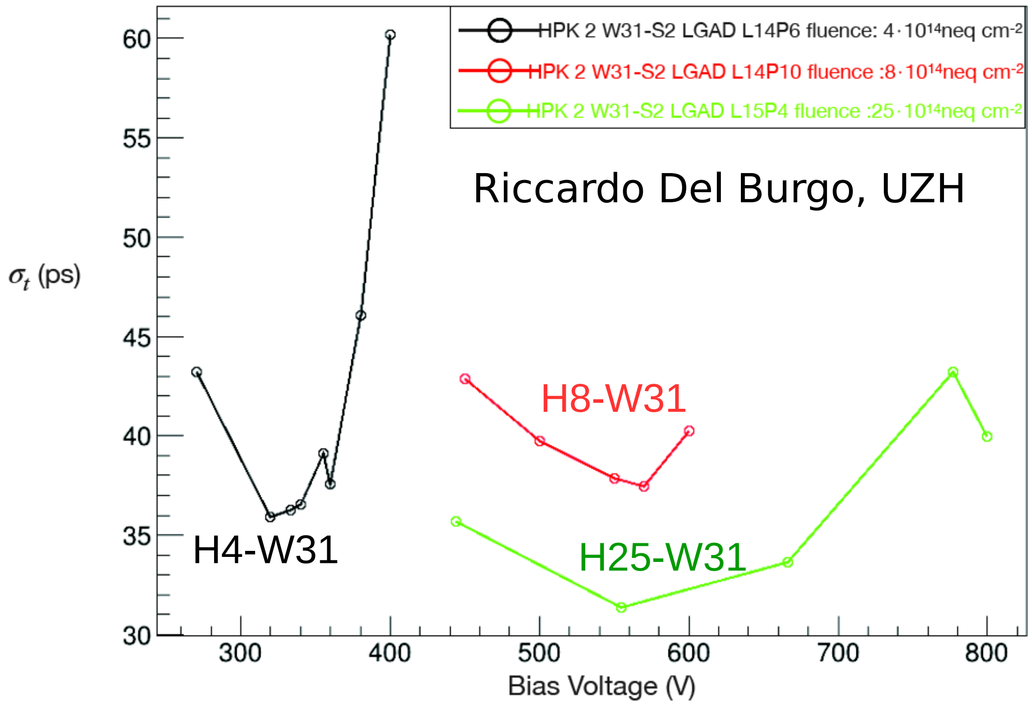
See J. Boell, 37th RD50 meeting for CERN-SSD HW details

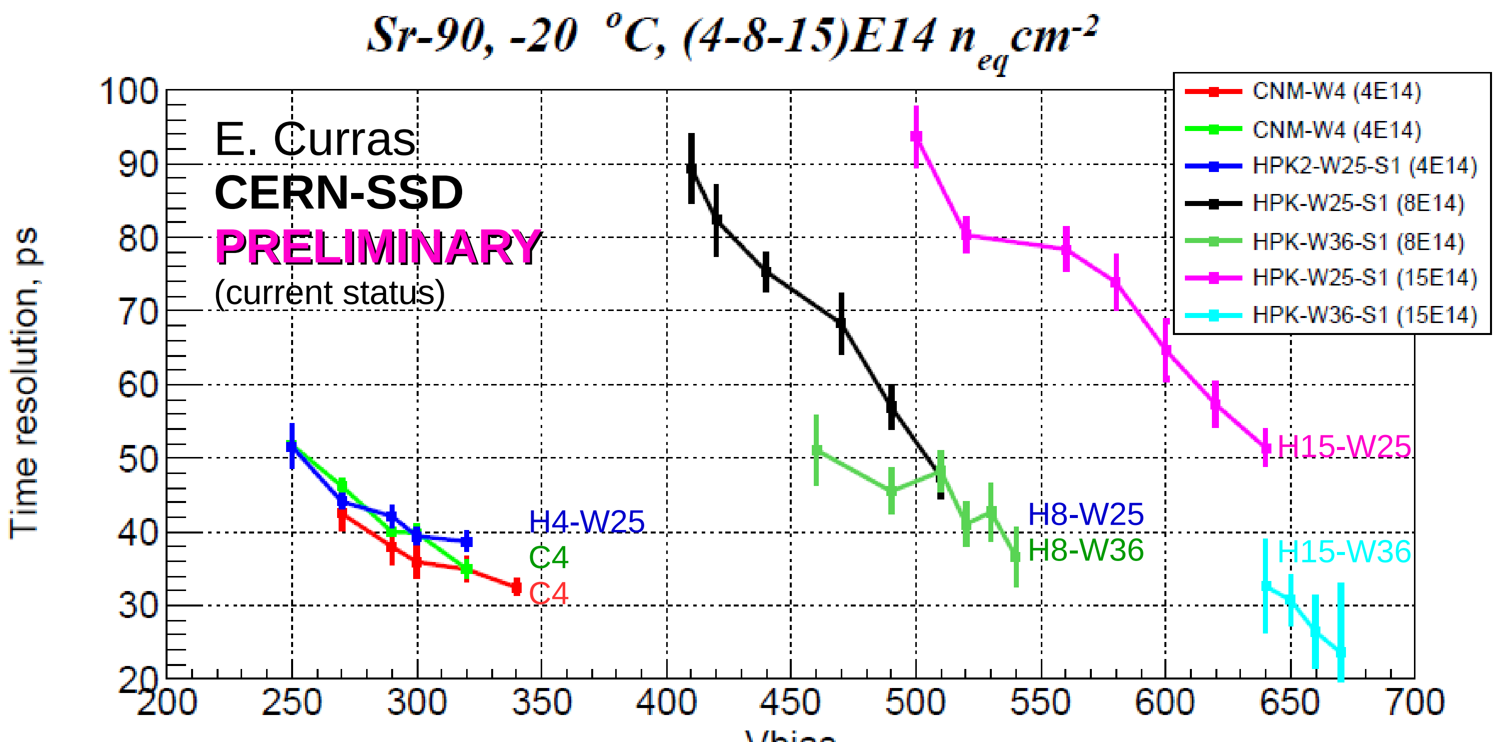
Modified microwave oven used for additional shielding



Climate chamber

Timing measurements





Conclusions

Electrical characterization campaign of CNM AIDAv2 and HPK2 devices, within the framework of the CMS-ETL project, conducted by 3 different institutions.

Comparison between irradiated LGADs to PINs at the same fluences indicate that:

1) HPK2 devices still hold gain until ~1.5e15 n_{eq}/cm^2.
2) CNM AIDAv2 devices exhibit gain at 4e14 and 8e14 n_{eq}/cm^2

Breakdown voltages calculation can be accomplished by using the “K variable” which uses the current derivative weighted by the current over voltage. A value of K=8 was used in this talk.

1) Vbd found to increase with fluence and with lower temperature

Pad current characteristics of LGADs show a distinct kink that marks the transition between the gain layer depletion to the bulk depletion.

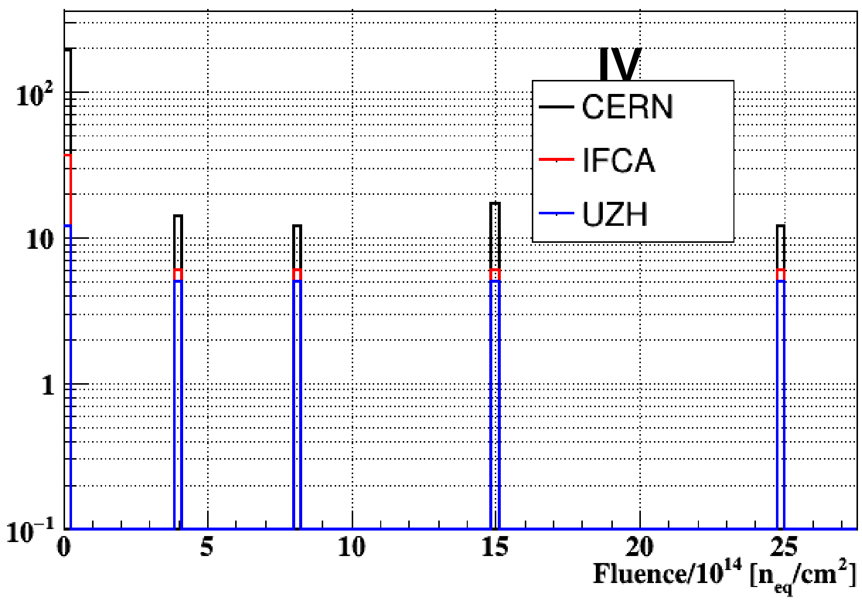
1) This kink was used to estimate Vgl without using CV information
2) Results show very good agreement with our $1/C^2$ measurements and measurements from other groups.

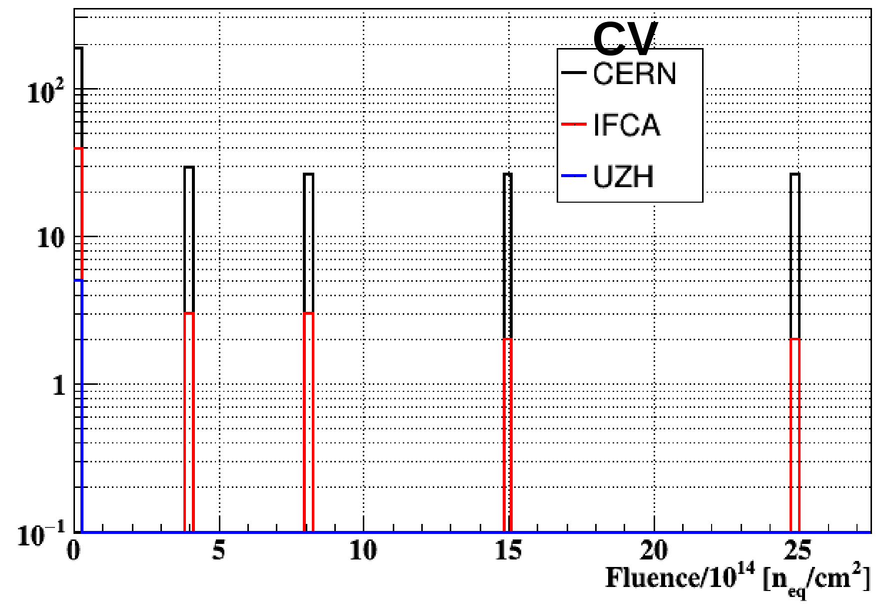
First timing measurements just started by UZH and CERN-SSD showing that a time resolution of ~30 ps can be reached for both CNM AIDAv2 and HPK2 devices at the tested fluences (measurements ongoing)

BACKUP

Measurements performed

Common: 50 um thick detectors. Pads and LGADs available





Different configurations across different institutes. Comparisons can be done "knowing what you do"

IV number of measurements

	CERN	IFCA	UZH
Non-irrad:	193	37	12
Irradiated:	55	24	20

CV number of measurements

	CERN	IFCA	UZH
Non-irrad:	185	39	5
Irradiated:	107	10	0

IV Temp

	CERN	IFCA	UZH
Non-irrad:	20	(-20,22)	25
Irradiated:	(-30,-20,-10)	-20	-20

CV Temp

	CERN	IFCA	UZH
Non-irrad:	(0,20)	(20,22)	20
Irradiated:	(-30,-20,-10,0,20)	10	0

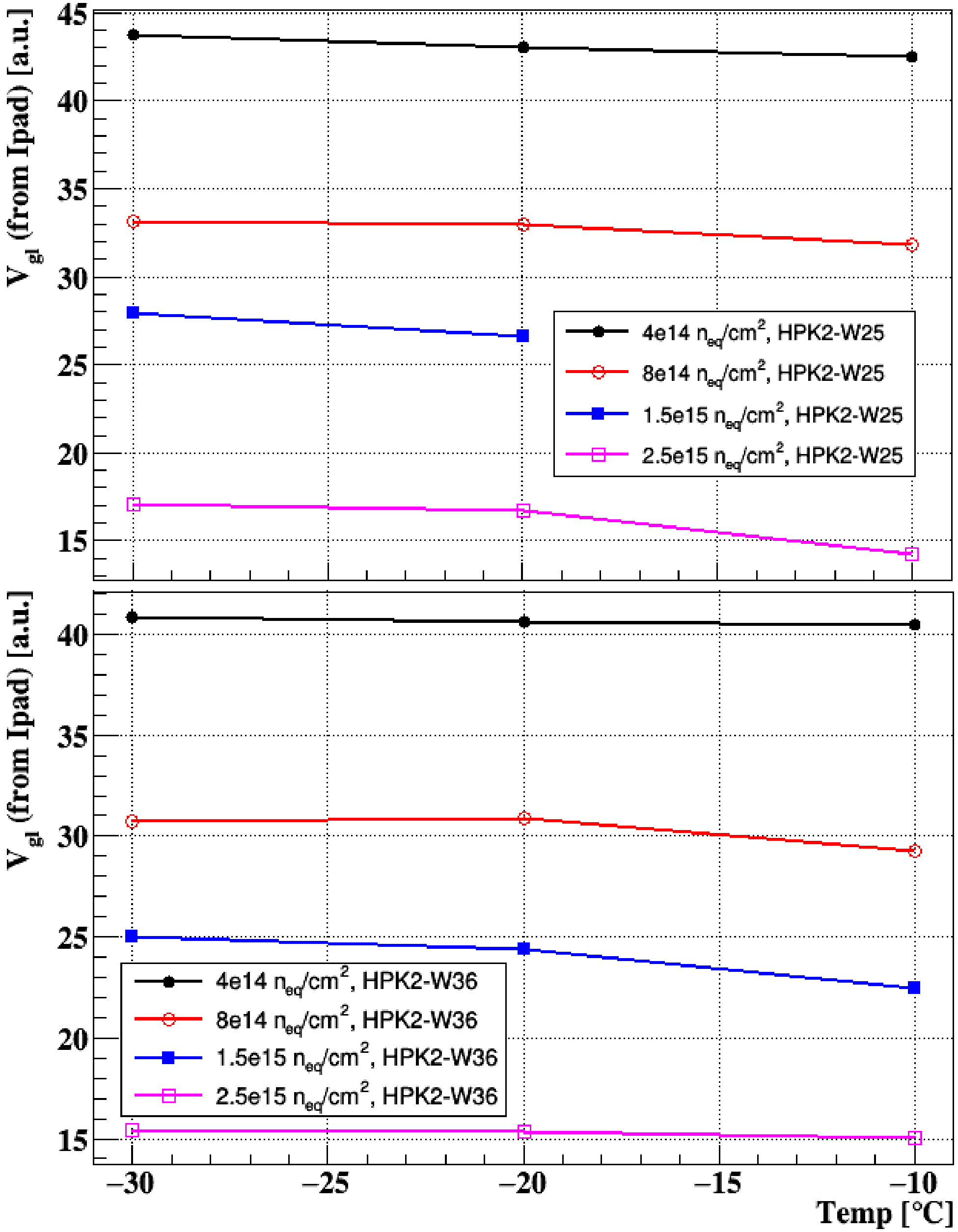
IV GR

	CERN	IFCA	UZH
Non-irrad:	Floating	HV	Floating
Irradiated:	GND	Floating	Floating

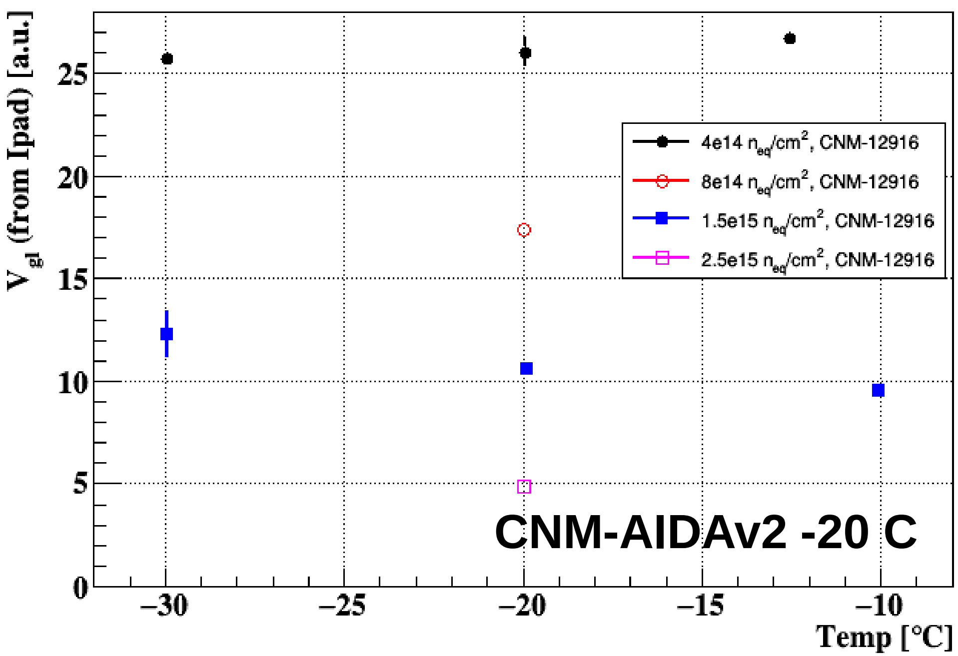
CV GR

	CERN	IFCA	UZH
Non-irrad:	GND	HV	Floating
Irradiated:	GND	GND	--

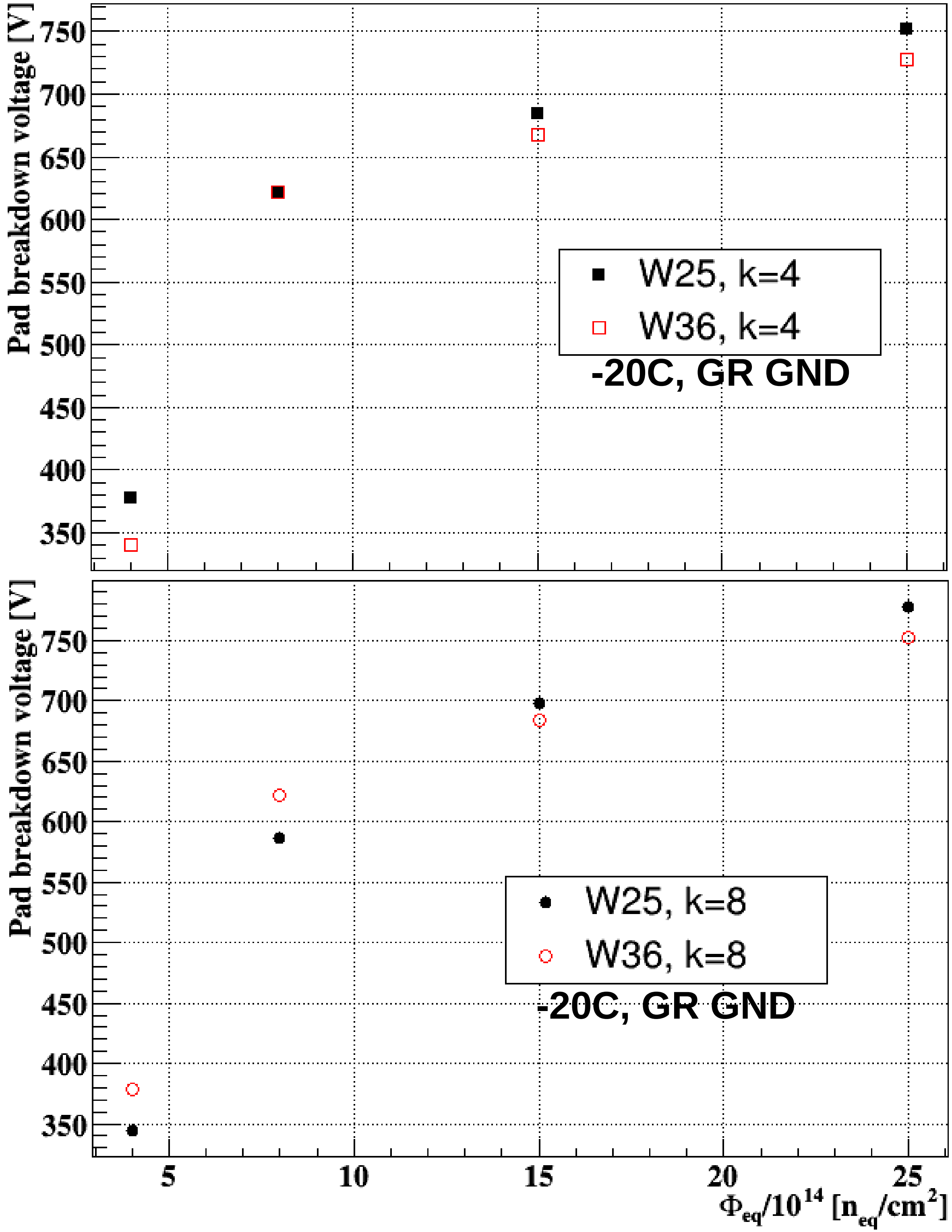
Gain layer: Temperature and Fluence dependence



- As expected, voltage needed to deplete the gain layer decreases with fluence
- Soft dependence of Vgl with Temperature

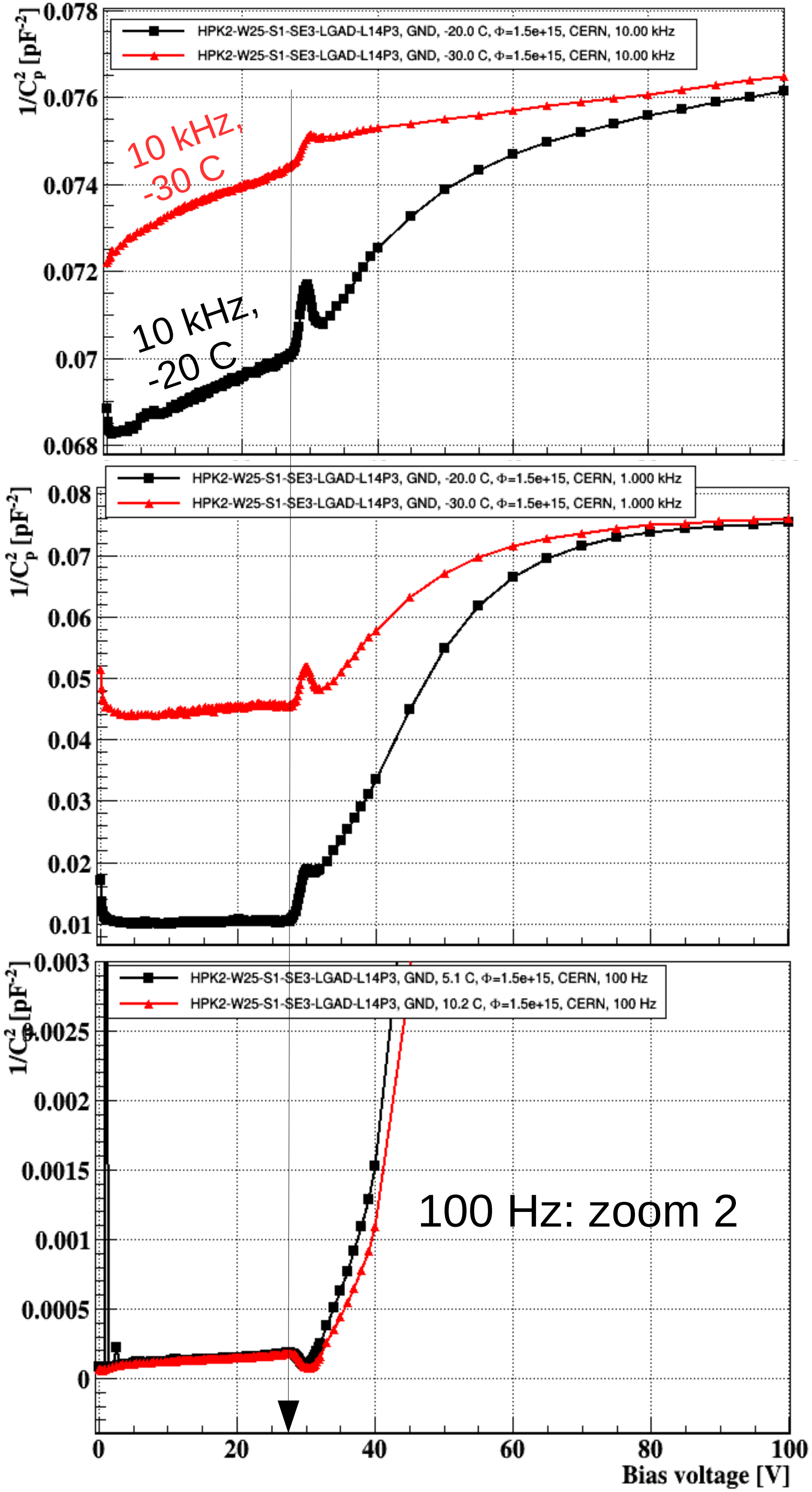


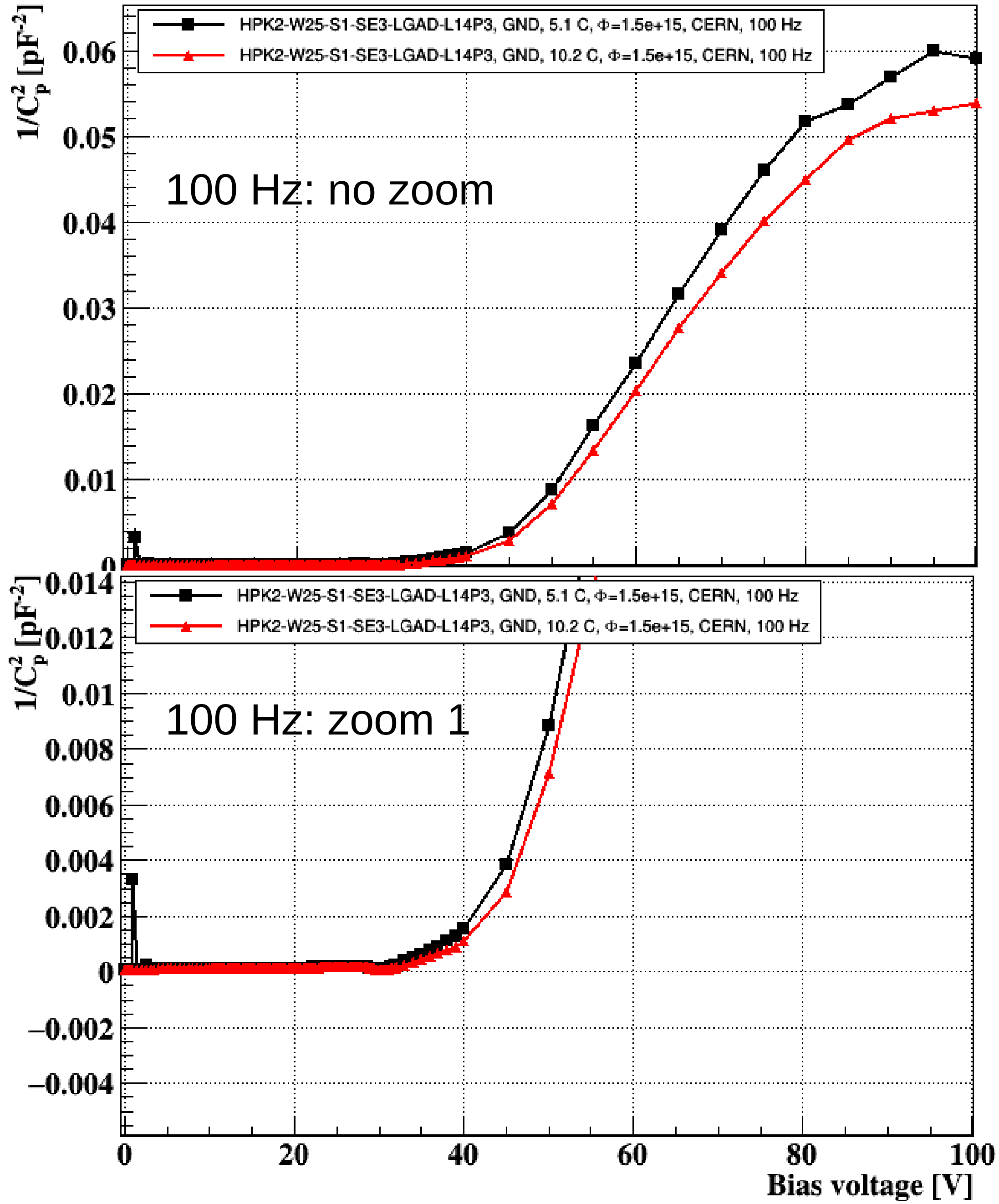
Choice of k value

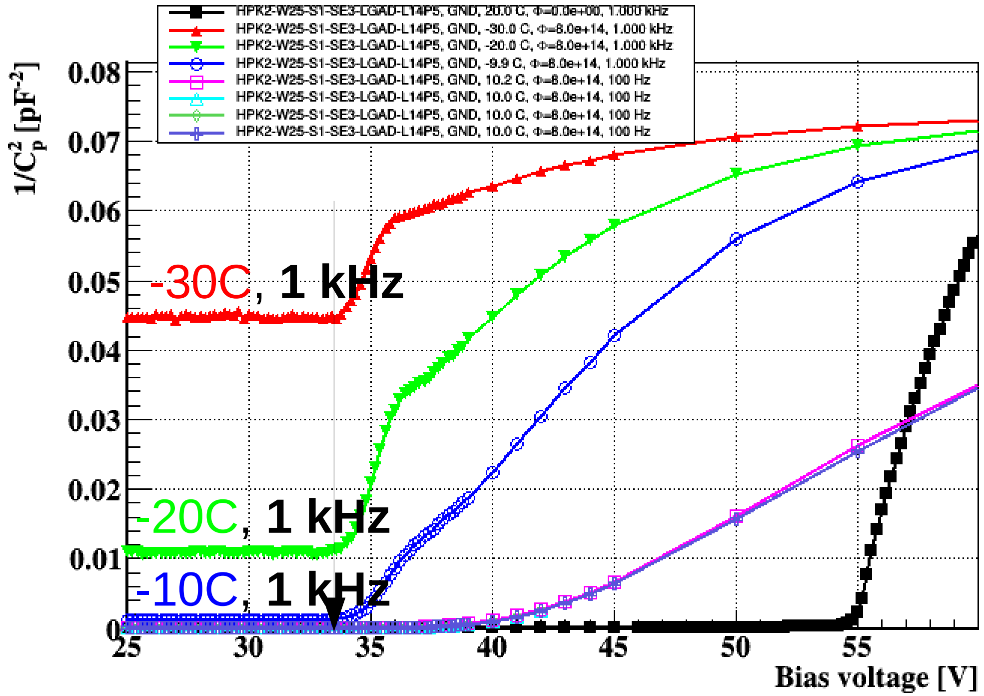


W25 (split 1, highest gain) breaks ~40 V earlier than **W36** (split 3) at 4e14 and 8e14 neq.
After 1.5e15 (included) **W25**(split1) breaks slightly after **W36**.

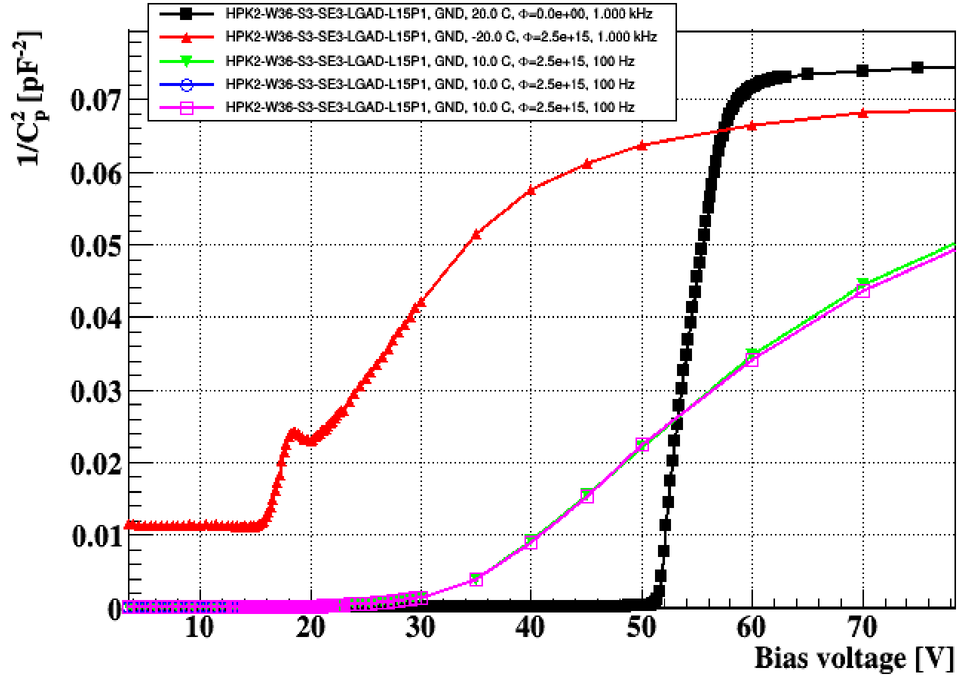
CV foot position and frequency



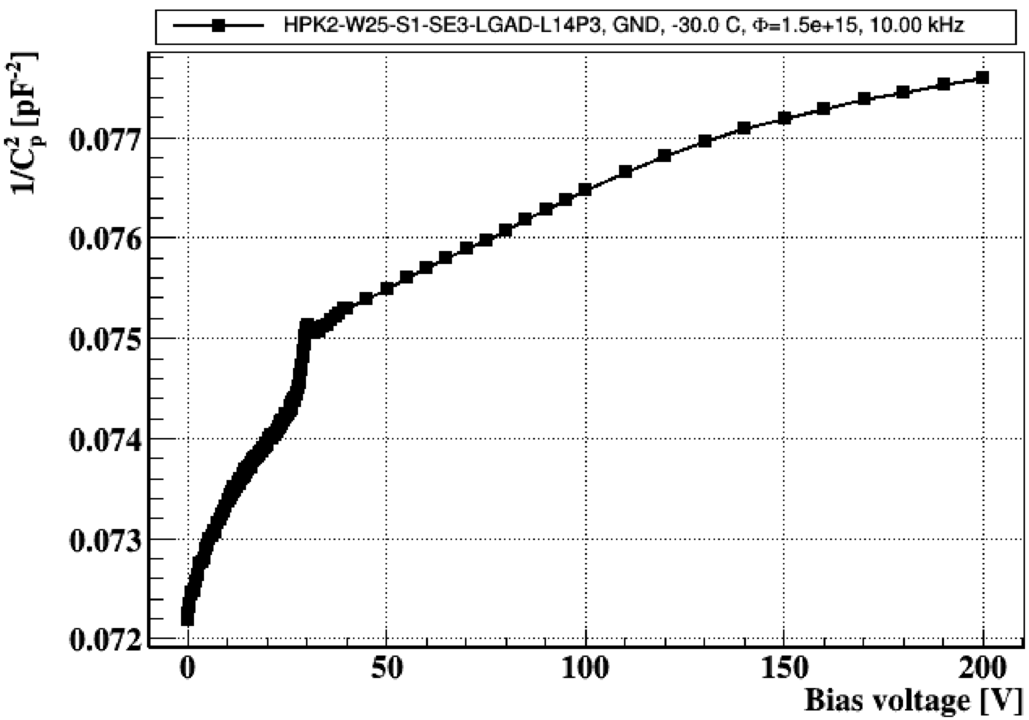




HPK2-W25-S1-SE3-LGAD-L14P5, GND, 20.0 C, Φ=0.0e+00, 1.000 kHz
HPK2-W25-S1-SE3-LGAD-L14P5, GND, -30.0 C, Φ=8.0e+14, 1.000 kHz
HPK2-W25-S1-SE3-LGAD-L14P5, GND, -20.0 C, Φ=8.0e+14, 1.000 kHz
HPK2-W25-S1-SE3-LGAD-L14P5, GND, -9.9 C, Φ=8.0e+14, 1.000 kHz
HPK2-W25-S1-SE3-LGAD-L14P5, GND, 10.2 C, Φ=8.0e+14, 100 Hz
HPK2-W25-S1-SE3-LGAD-L14P5, GND, 10.0 C, Φ=8.0e+14, 100 Hz
HPK2-W25-S1-SE3-LGAD-L14P5, GND, 10.0 C, Φ=8.0e+14, 100 Hz
HPK2-W25-S1-SE3-LGAD-L14P5, GND, 10.0 C, Φ=8.0e+14, 100 Hz
-30C, 1 kHz
-20C, 1 kHz
-10C, 1 kHz
1/C$_p^2$ [pF^{-2}]
Bias voltage [V]

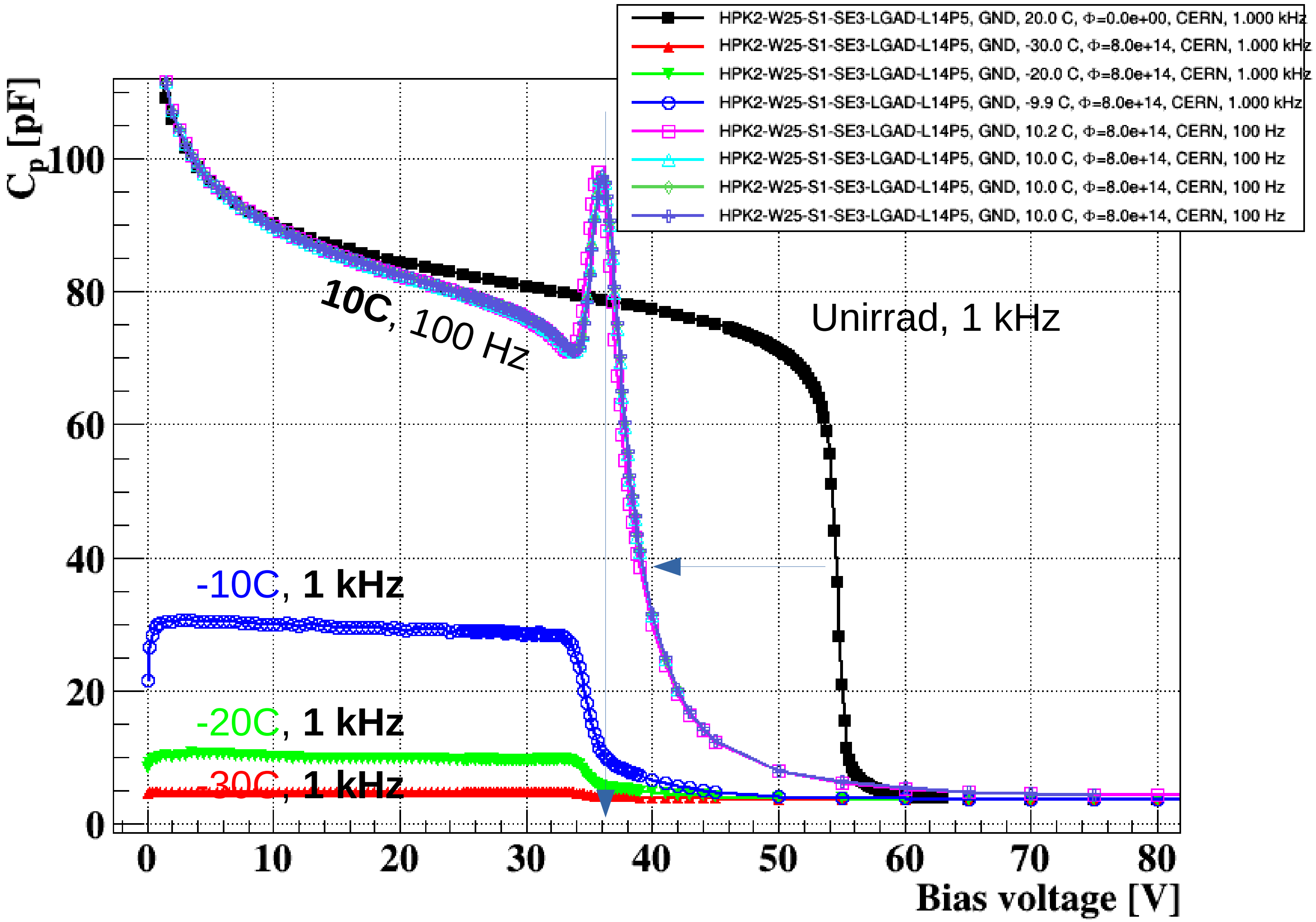


HPK2-W36-S3-SE3-LGAD-L15P1, GND, 20.0 C, Φ=0.0e+00, 1.000 kHz
HPK2-W36-S3-SE3-LGAD-L15P1, GND, -20.0 C, Φ=2.5e+15, 1.000 kHz
HPK2-W36-S3-SE3-LGAD-L15P1, GND, 10.0 C, Φ=2.5e+15, 100 Hz
HPK2-W36-S3-SE3-LGAD-L15P1, GND, 10.0 C, Φ=2.5e+15, 100 Hz
HPK2-W36-S3-SE3-LGAD-L15P1, GND, 10.0 C, Φ=2.5e+15, 100 Hz
1/C$_p^2$ [pF^{-2}]
Bias voltage [V]



HPK2-W25-S1-SE3-LGAD-L14P3, GND, -30.0 C, Φ=1.5e+15, 10.00 kHz
1/C$_p^2$ [pF^{-2}]
Bias voltage [V]

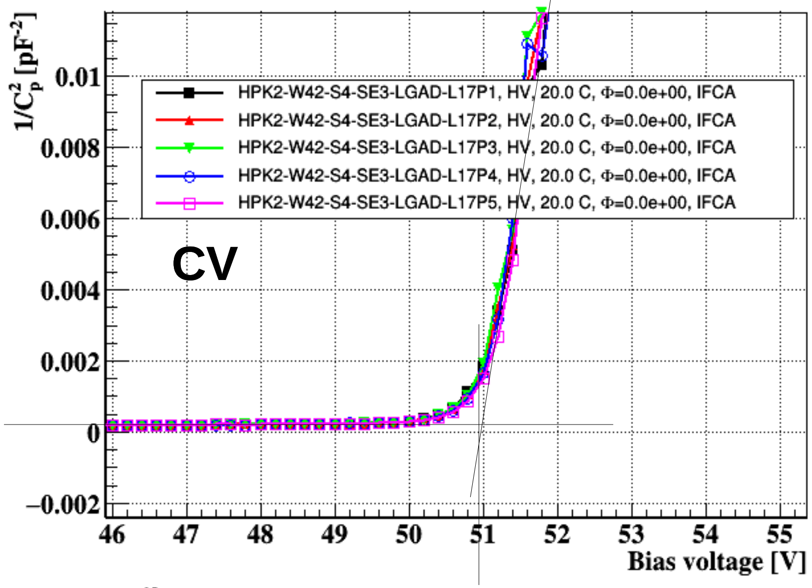
HPK2-W25, 8e14, CV at different freq and temperatures

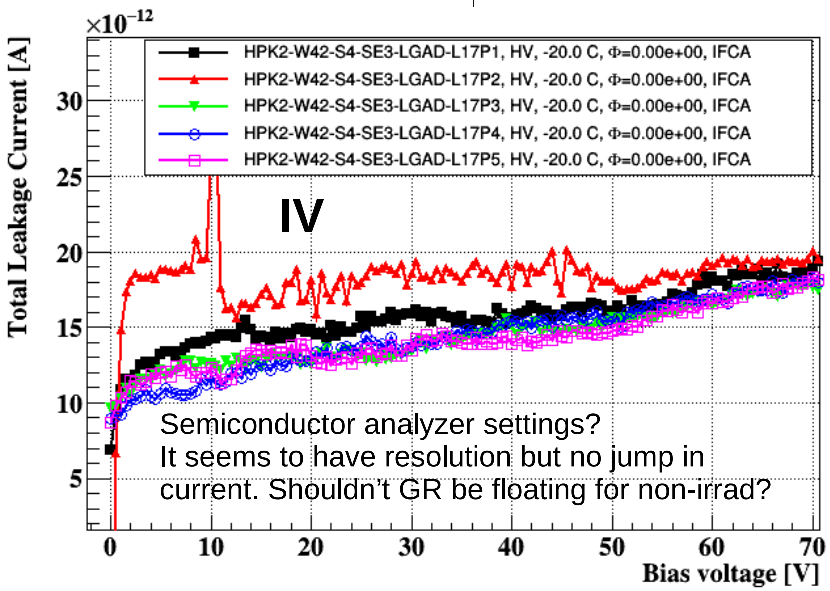


C(1 kHz, Φ=0, 20C ; 0V)=C(100 Hz, 8e14, 10C : 0V)

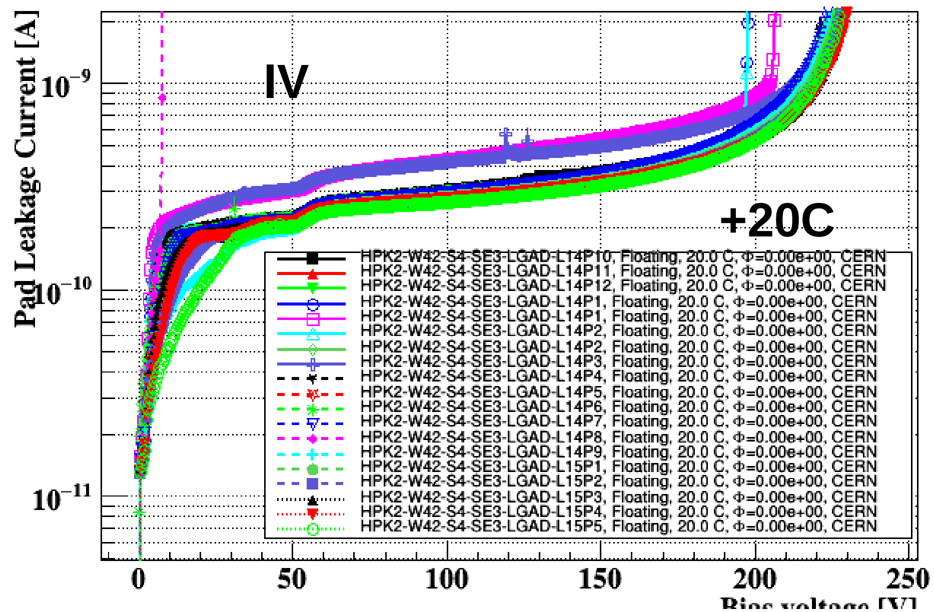
Cp(1 kHz, 0V) depends on T

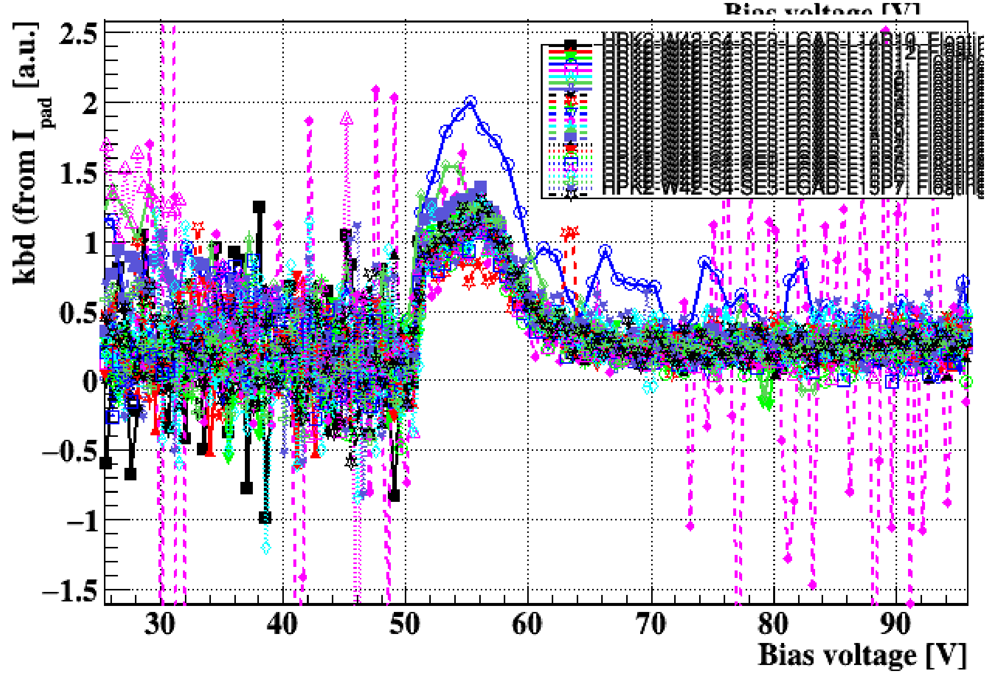
W42-IFCA



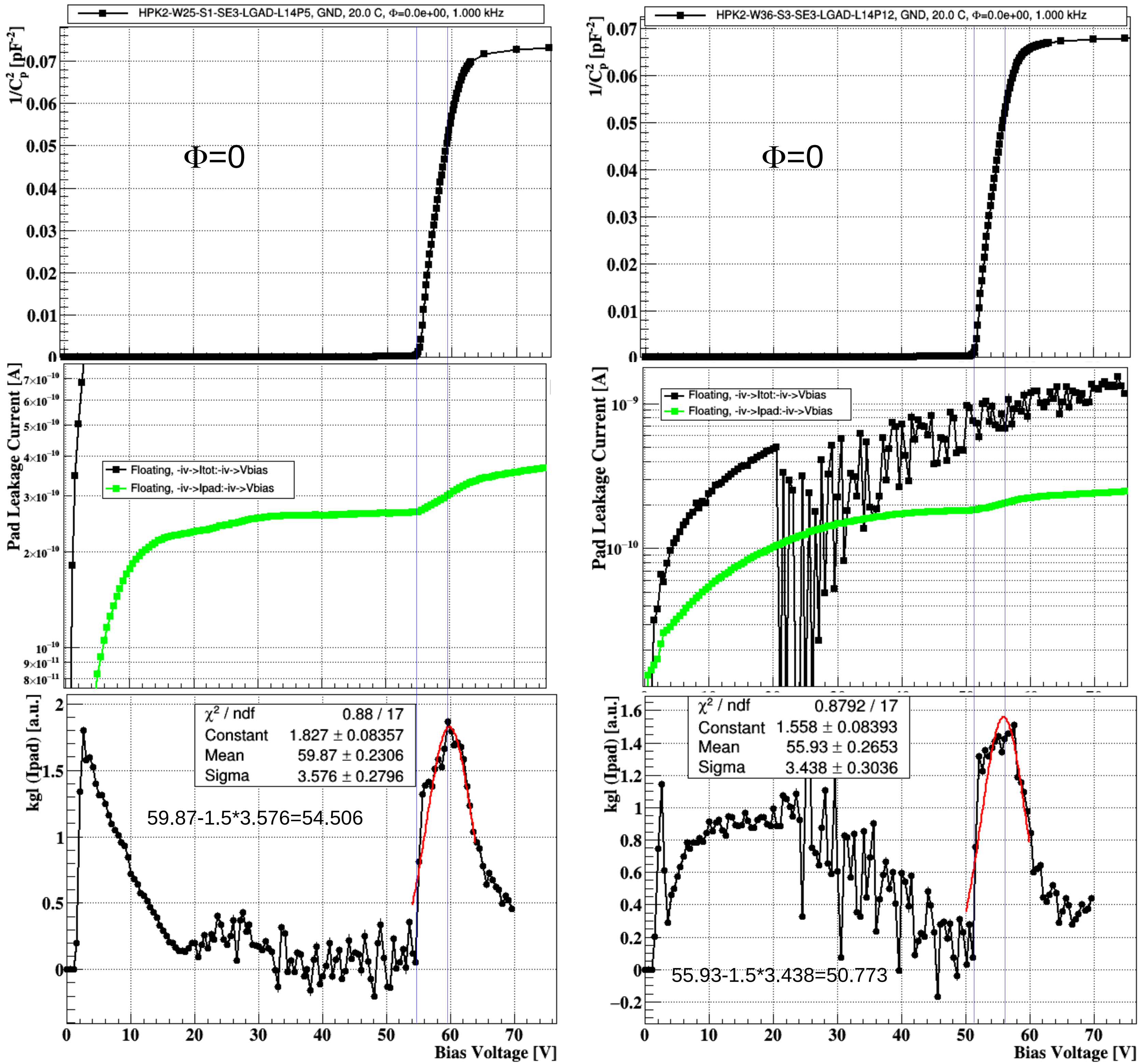


W42-CERN

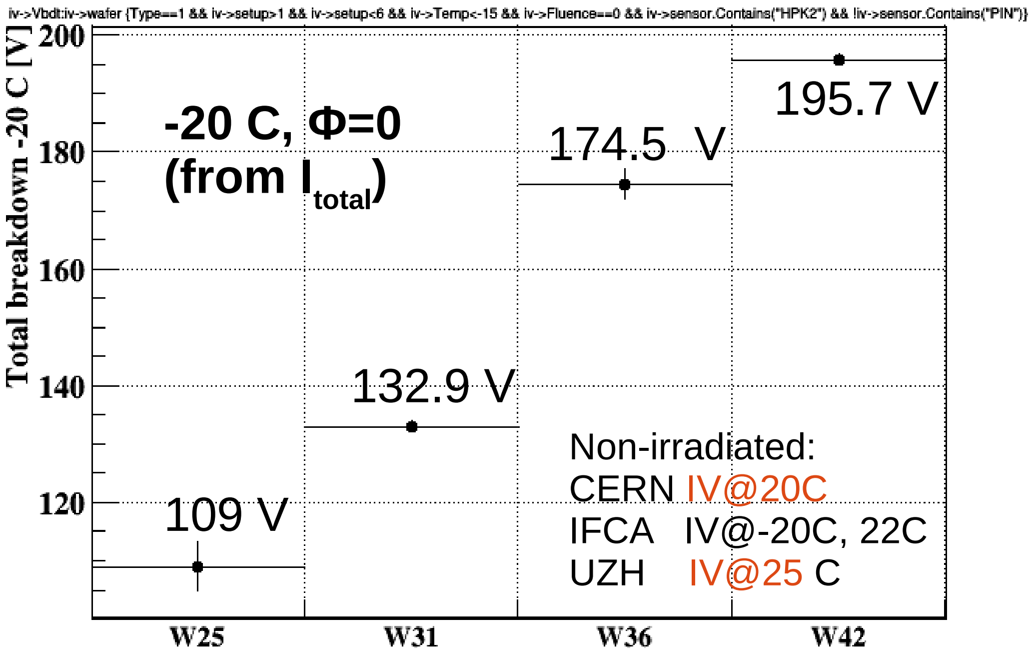


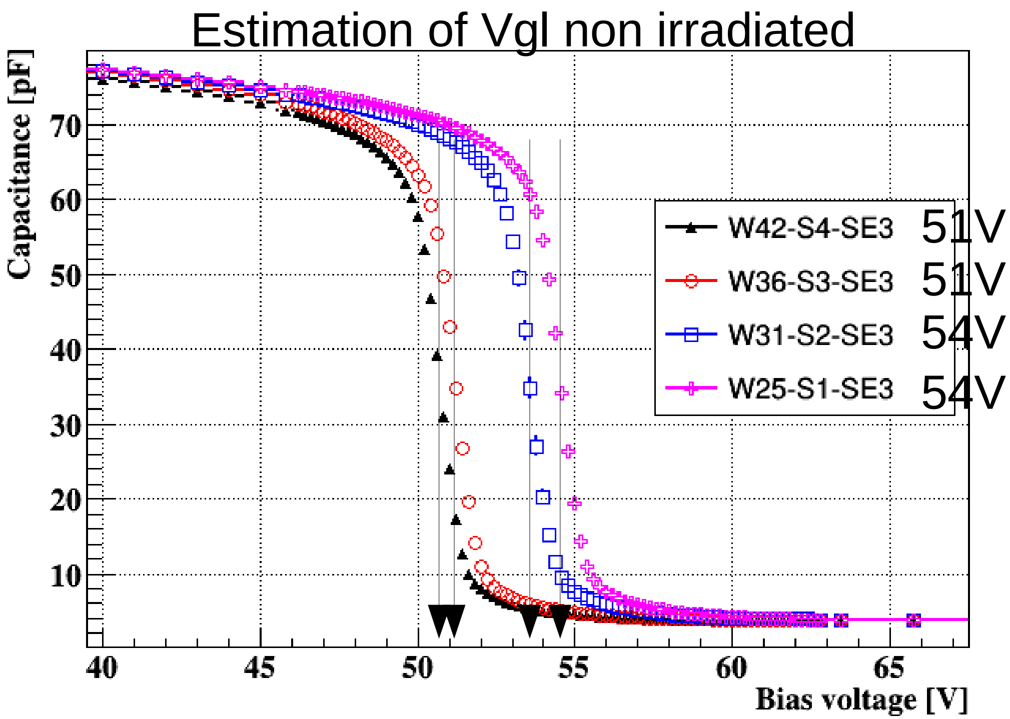


K-algorithm probably better at (+20C,non-irradiated). At -20C we probably measure more surface current instead of bulk current



HPK2-W25-S1-SE3-LGAD-L14P5, GND, 20.0 C, Φ=0.0e+00, 1.000 kHz
HPK2-W36-S3-SE3-LGAD-L14P12, GND, 20.0 C, Φ=0.0e+00, 1.000 kHz
Φ=0
Φ=0
1/C$_p^2$ [pF^{-2}]
Pad Leakage Current [A]
Floating, -iv->Itot:-iv->Vbias
Floating, -iv->Ipad:-iv->Vbias
kgl (Ipad) [a.u.]
χ^2 / ndf 0.88 / 17
Constant 1.827 ± 0.08357
Mean 59.87 ± 0.2306
Sigma 3.576 ± 0.2796
59.87-1.5*3.576=54.506
χ^2 / ndf 0.8792 / 17
Constant 1.558 ± 0.08393
Mean 55.93 ± 0.2653
Sigma 3.438 ± 0.3036
55.93-1.5*3.438=50.773
Bias Voltage [V]
Bias Voltage [V]


iv->Vbdt:iv->wafer {Type==1 && iv->setup>1 && iv->setup<6 && iv->Temp<-15 && iv->Fluence==0 && iv->sensor.Contains("HPK2") && !iv->sensor.Contains("PIN")}
Total breakdown -20 C [V]
-20 C, Φ=0
(from I total)
195.7 V
174.5 V
132.9 V
109 V
Non-irradiated:
CERN IV@20C
IFCA IV@-20C, 22C
UZH IV@25 C
W25
W31
W36
W42


Estimation of Vgl non irradiated
Capacitance [pF]
Bias voltage [V]
W42-S4-SE3 51V
W36-S3-SE3 51V
W31-S2-SE3 54V
W25-S1-SE3 54V