Characterization with a β-source setup of the UFSD3.2 production manufactured at FBK

16th "Trento" Workshop on Advanced Silicon Radiation Detectors,

2.18.2021

Siviero F., Arcidiacono R., Cartiglia N., Costa M., Ferrero M., Mandurrino M., Menzio L., Milanesio M., Sola V., Staiano A., Tornago M., Borghi G., Boscardin M., Dalla Betta G-F., Ficorella F., Pancheri L., Paternoster G., Centis Vignali M.

Outline

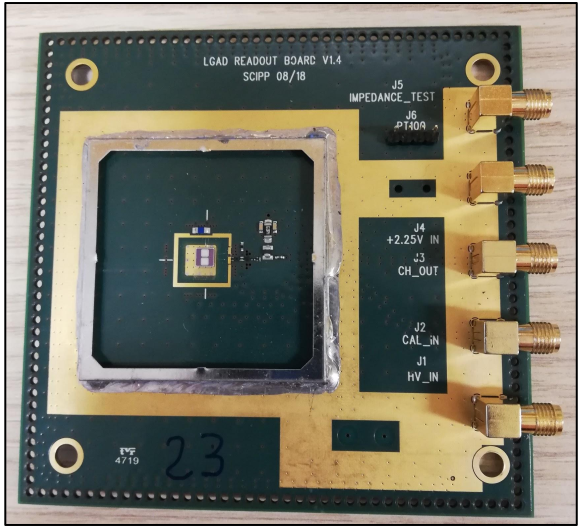
- FBK UFSD3.2 → 3 different Gain Layer designs
- Performance of pre-rad sensors
- Performance of irradiated sensors
- V_{irrad}(10fC) & DV(10fC)
- A study on the noise of tested sensors

Outline

- ➢ FBK UFSD3.2 → 3 different Gain Layer designs
- ➢ Performance of pre-rad sensors
- ➢ Performance of irradiated sensors
- ➢ V_{irrad}(10fC) & DV(10fC)
- ➢ A study on the noise of tested sensors

FBK UFSD3.2

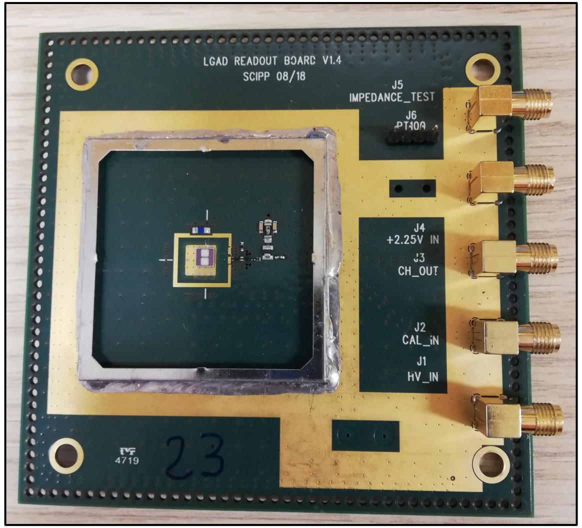
- Latest LGAD production at FBK → aim at studying different Gain Layer (GL) designs
- Tested sensors are 1.3x1.3 mm^2 single pads with 45 μm active thickness
- Gain implants of tested devices are enriched with carbon → more on M.Ferrero's talk
- Read-out with "Santa-Cruz" board



A UFSD3.2 sensor mounted on a "Santa-Cruz" board

FBK UFSD3.2

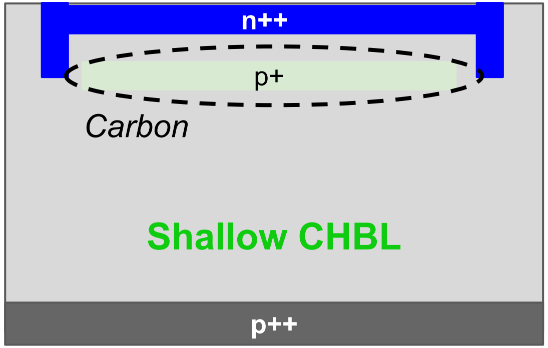
- Latest LGAD production at FBK → aim at studying different Gain Layer (GL) designs
- Tested sensors are 1.3x1.3 mm^2 single pads with 45 μm active thickness
- Gain implants of tested devices are enriched with carbon → more on M.Ferrero's talk
- Read-out with "Santa-Cruz" board



A UFSD3.2 sensor mounted on a "Santa-Cruz" board

Goal of this talk is to discuss the characteristics of the 3 GL designs implemented in this production

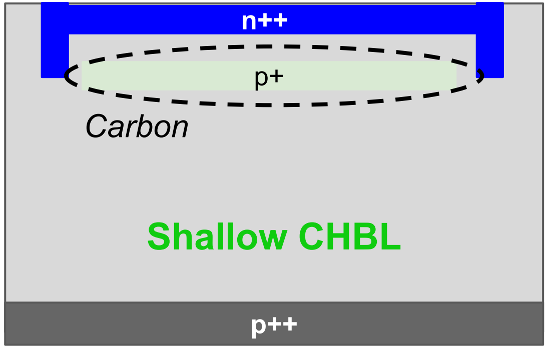
Gain Layer designs

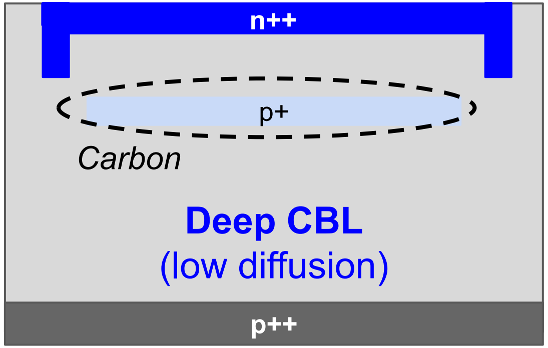


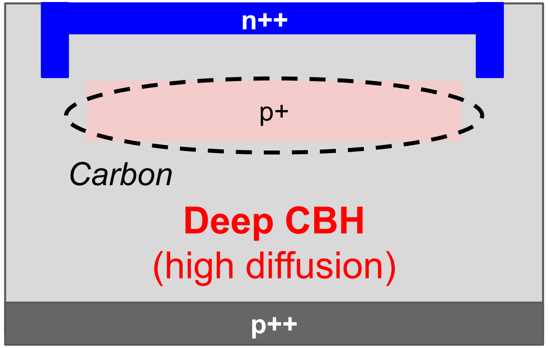
Shallow gain implant
(standard implant as previous UFSD productions)

- W3, W7

Gain Layer designs







Shallow gain implant (standard implant as previous UFSD productions)

- W3, W7

Deep CBL: diffusion at low thermal load, narrow implant

- W10, W12, W13

Deep CBH: diffusion at high thermal load, broad implant

- W14, W19

Deep gain implants improves the recovering power of VBias in irradiated sensors (see N.Cartiglia's talk at 34th RD50 workshop)

G … ble

shallow

deep CBL
2 Pgain doses
2 carbon doses

deep CBH
2 Pgain doses
2 carbon doses

Wafer	Thickness	GL depth	Pgain dose	Carbon dose	Diffusion
1	45 µm	standard	standard	A	CHBL
3	45 µm	standard	standard	0.8*A	CHBL
7	55 µm	standard	standard	A	CHBL
10	45 µm	deep	1	0.6*A	CBL
12	45 µm	deep	2	A	CBL
13	45 µm	deep	2	0.6*A	CBL
14	45 µm	deep	2	A	CBH
15	55 µm	deep	2	A	CBH
18	45 µm	deep	3	A	CBH
19	45 µm	deep	3	0.6*A	CBH

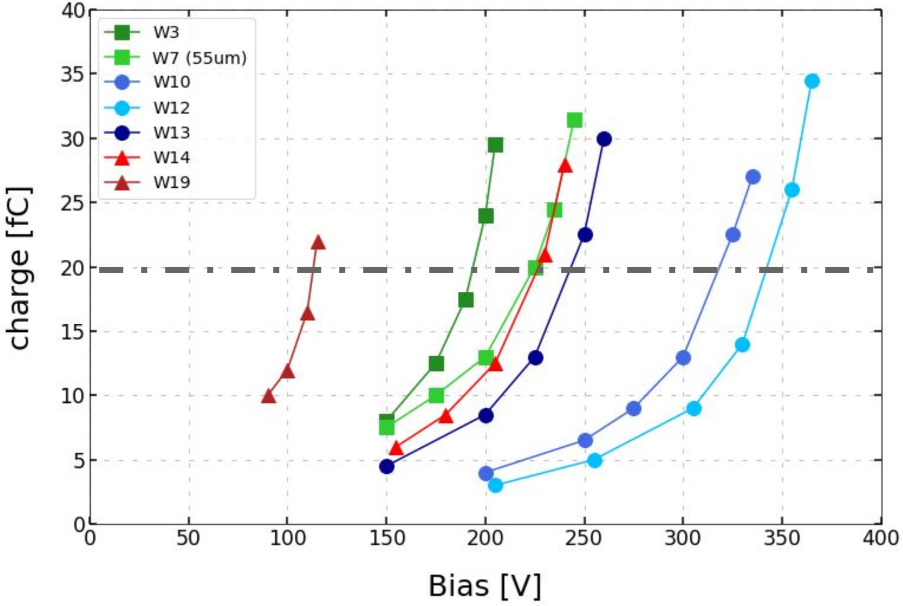
increasing dose

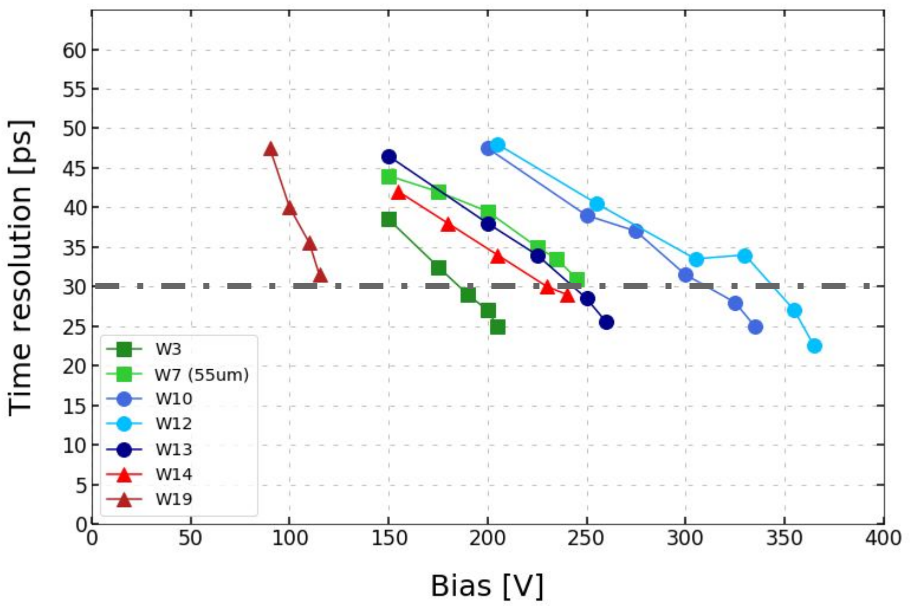
Outline

- FBK UFSD3.2 → 3 different Gain Layer designs
- Performance of pre-rad sensors
- Performance of irradiated sensors
- V_{irrad}(10fC) & DV(10fC)
- A study on the noise of tested sensors

Performances of pre-rad sensors

measurements performed at -25 °C

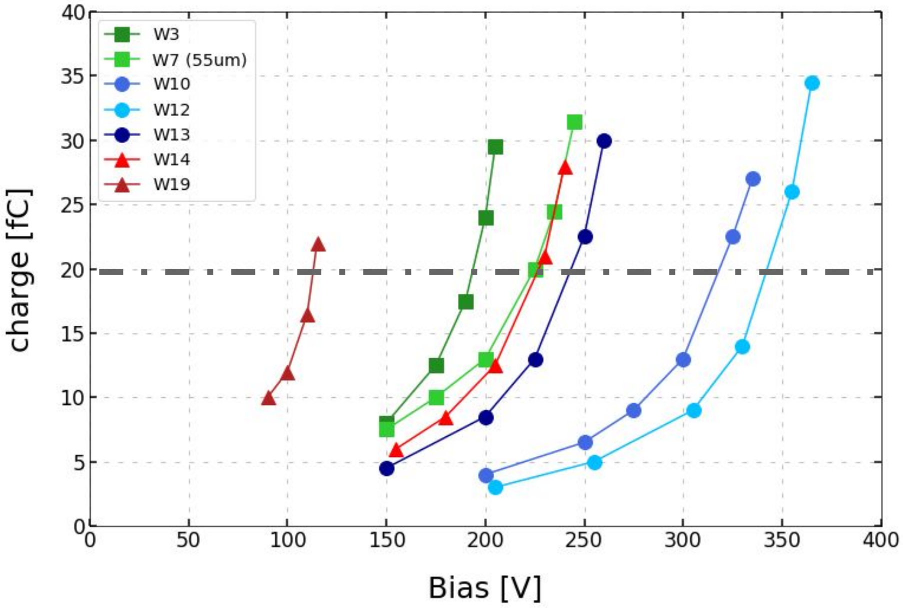


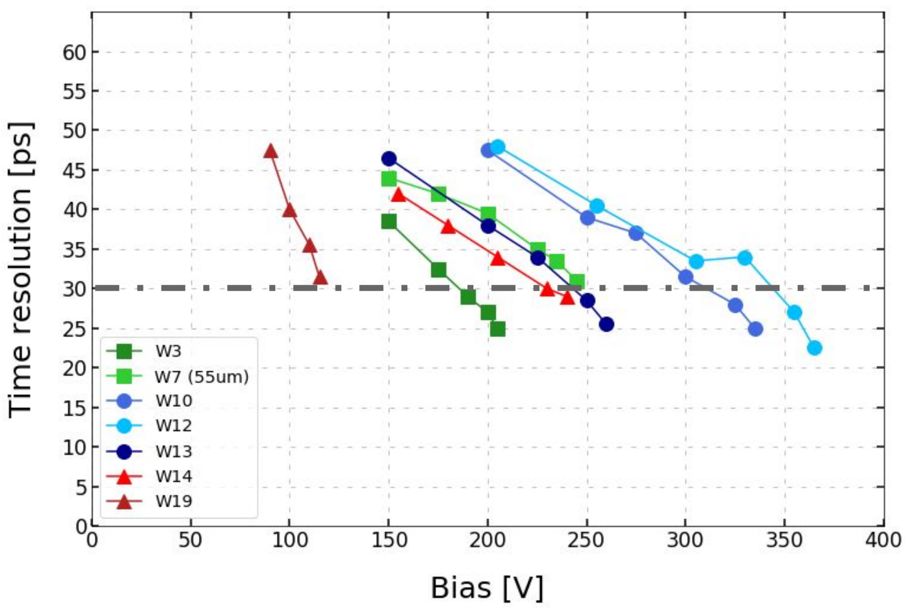


- Excellent performances of all sensors:
  - Delivered charge > 20fC
  - Time resolution ~ 30ps

Performances of pre-rad sensors

measurements performed at -25 °C



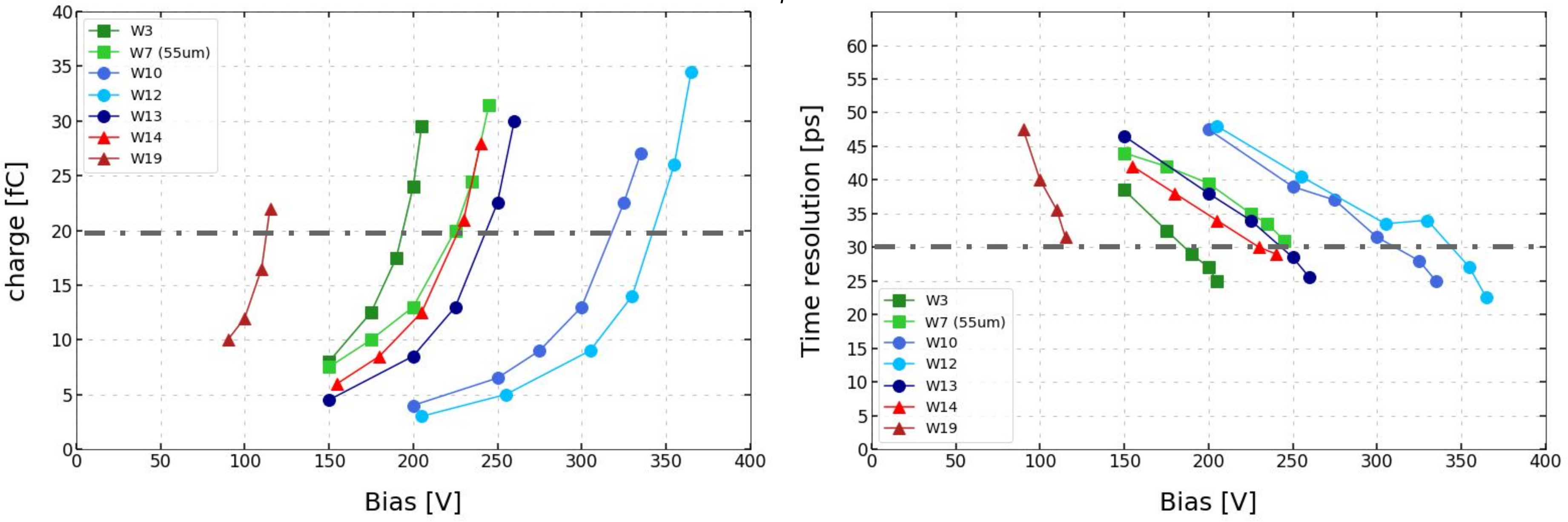


- Excellent performances of all sensors:
  - Delivered charge > 20fC
  - Time resolution ~ 30ps

→ **are they all equivalent?**

Performances of pre-rad sensors

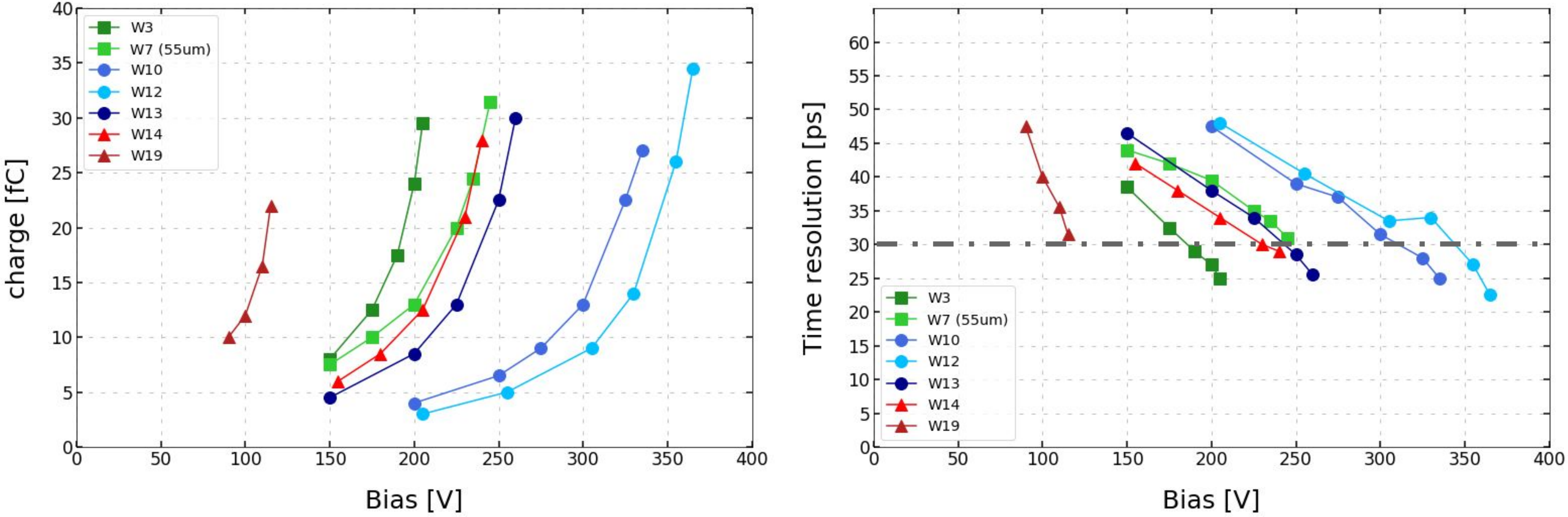
measurements performed at -25 °C



- We assess the performances of UFSD designs by looking at the collected charge and time resolution → but **all these sensors have very similar performances**, although they are not equal
- In the following, I will show what is the best way to discriminate between these designs

Performances of pre-rad sensors

measurements performed at -25 °C

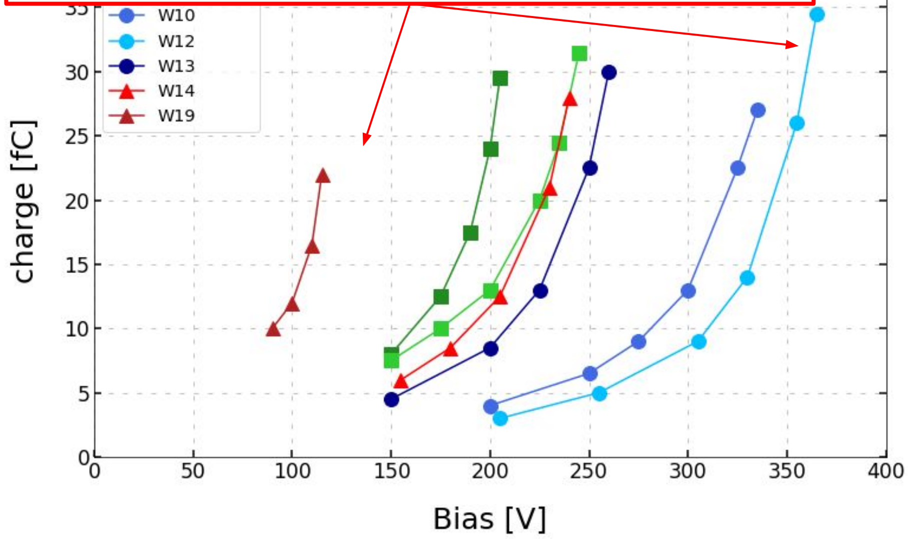


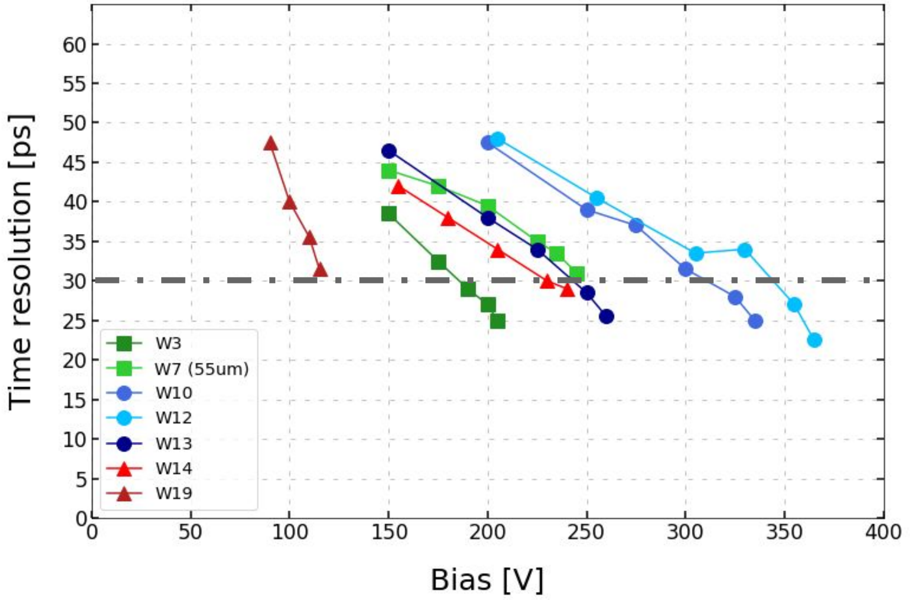
- For pre-rad sensors, the figures of merit can be the operating voltage and the steepness of the gain curve
  - High operating voltage → Carriers drift velocity saturated
  - Smooth gain curve → non uniformities between sensors affect performances less

Performances of pre-rad sensors

These two aspects are related: sensors with low breakdown voltage have steep curves

...urements performed at -25 °C

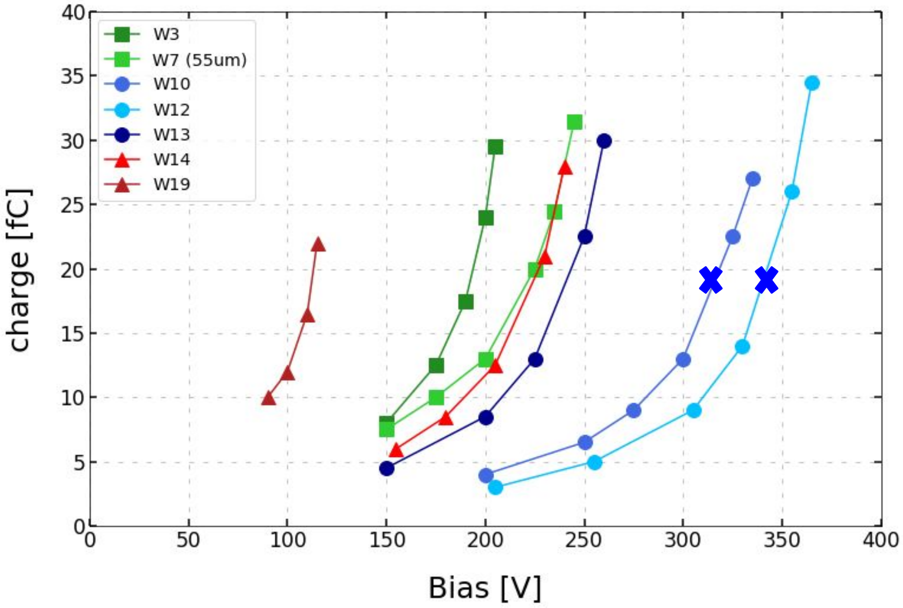


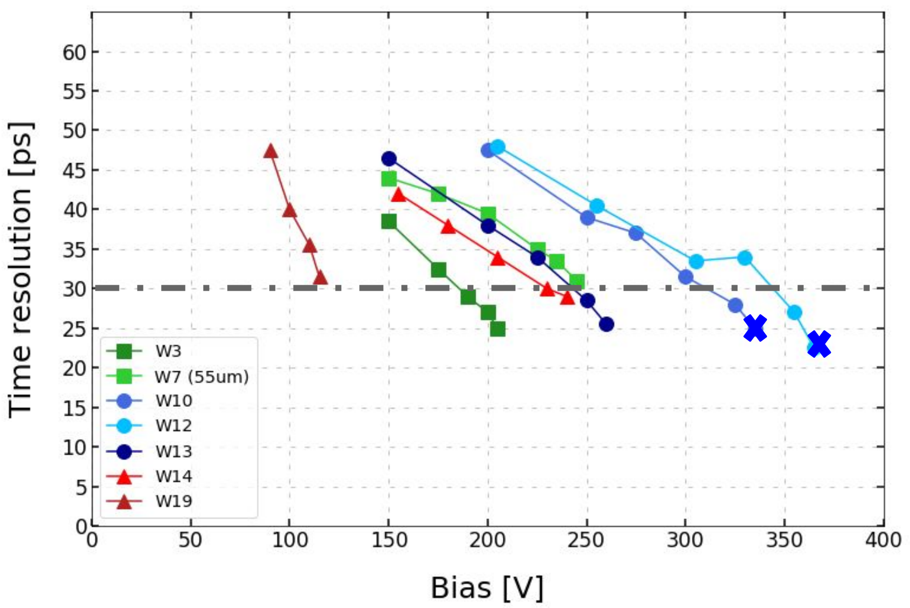


- For pre-rad sensors, the <u>figures of merit can be the operating voltage and the steepness of the gain curve</u>
  - High operating voltage → Carriers drift velocity saturated
  - Smooth gain curve → non uniformities between sensors affect performances less

Performances of pre-rad sensors

measurements performed at -25 °C

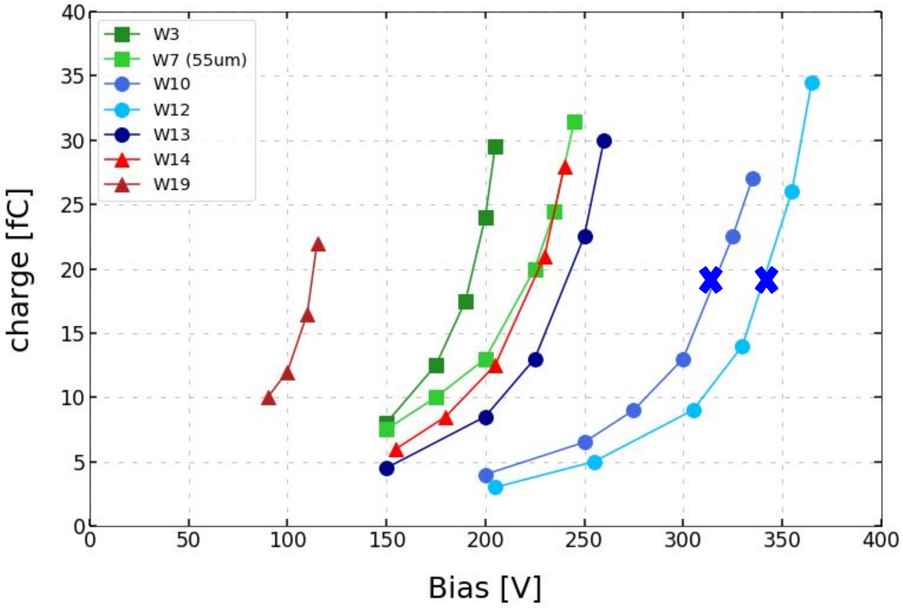


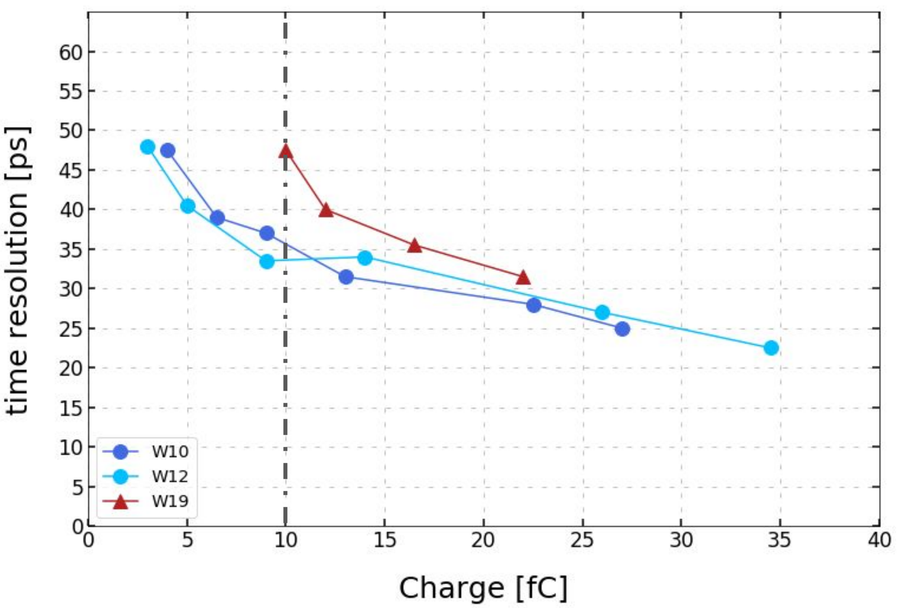


- **W10, W12 (CBL) ideal when new → <u>low Pgain dose</u>**

Performances of pre-rad sensors

measurements performed at -25 °C

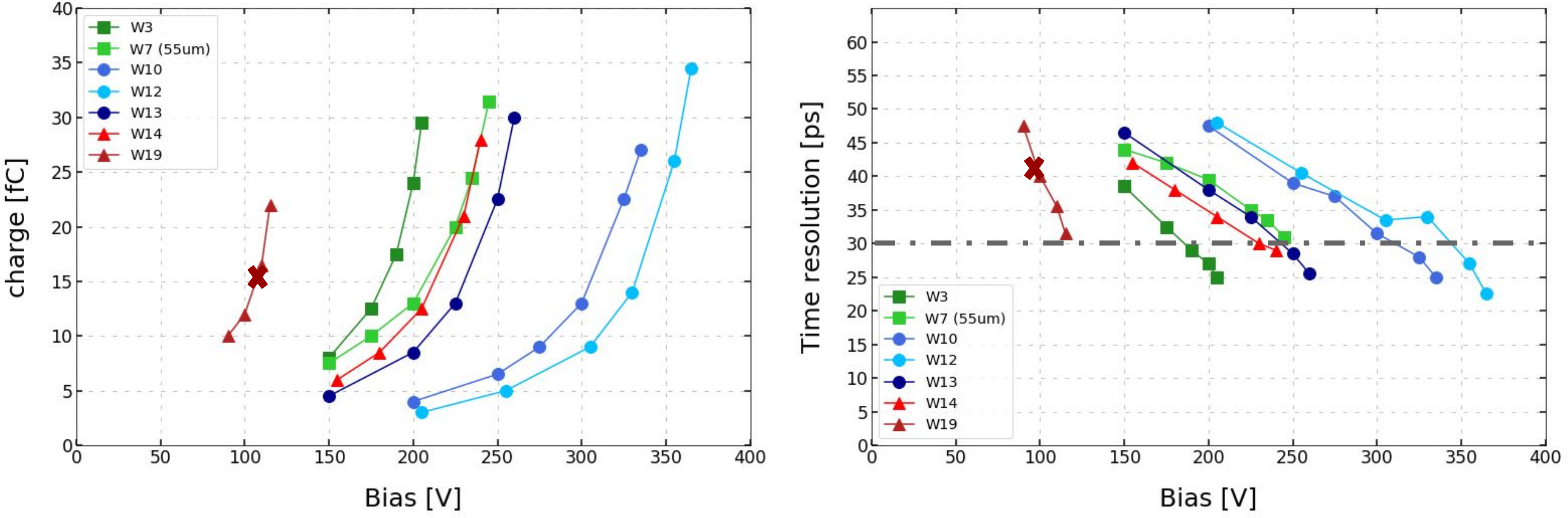




- **W10, W12 (CBL) ideal when new → <u>low Pgain dose</u>**
    - For a given gain/charge → the higher Vbias, the better the time resolution is

Performances of pre-rad sensors

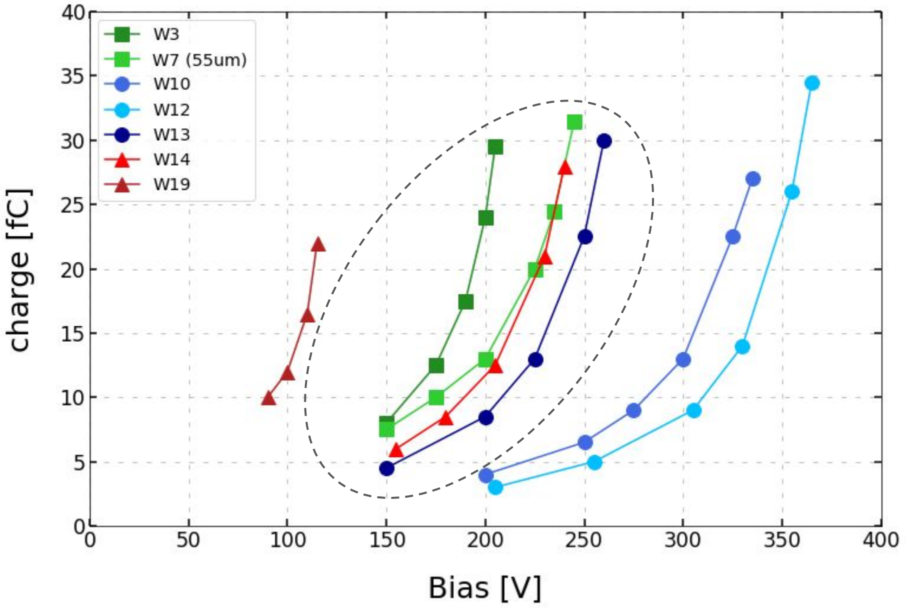
measurements performed at -25 °C

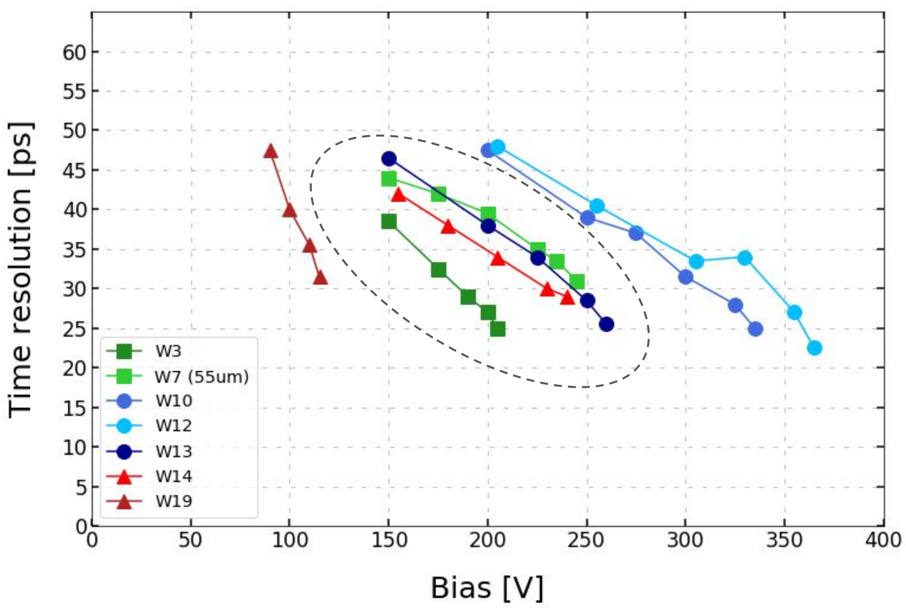


- **W19 (CBH) has very high doping, not the best pick when new**
  - Steep gain curve → hard to operate several sensors with same performances
  - Carriers drift velocity not saturated (or just close to saturation) → can barely reach 30ps

Performances of pre-rad sensors

measurements performed at -25 °C





- **W 3, 7, 13, 14 in between → work well when new, although not the best**

Outline

- FBK UFSD3.2 → 3 different Gain Layer designs
- Performance of pre-rad sensors
- Performance of irradiated sensors
- V_{irrad}(10fC) & DV(10fC)
- A study on the noise of tested sensors

Irradiated sensors

All wafers have been irradiated at JSI TRIGA reactor → fluences: 8e14, 1.5e15, 2.5e15 n_{eq}/cm^2

c : inverse of the fluence after which the GL initial acceptor density is reduced by a factor *e*

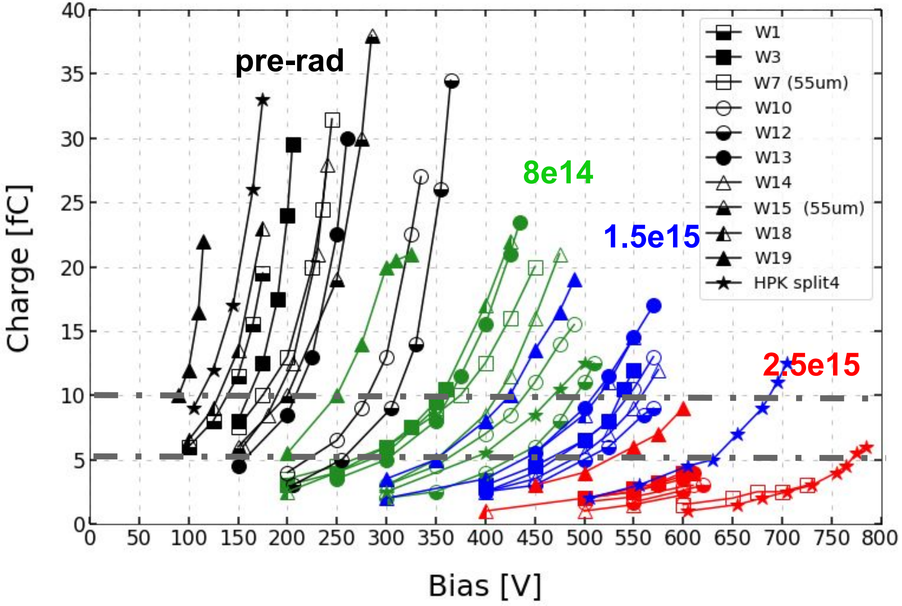
Wafer	Pgain dose	Carbon dose	*c* coeff. $[10^{-16}\ cm^2]$	
3	std	A	1,48	shallow
7	std	A	1,91	shallow
10	1	0.6*A	2,16	deep CBL
12	2	A	2,06	deep CBL
13	2	0.6*A	1,63	deep CBL
14	2	A	2,45	deep CBH
19	3	0.6*A	1,9	deep CBH

Details on UFSD3.2 radiation resistance in M.Ferrero's talk

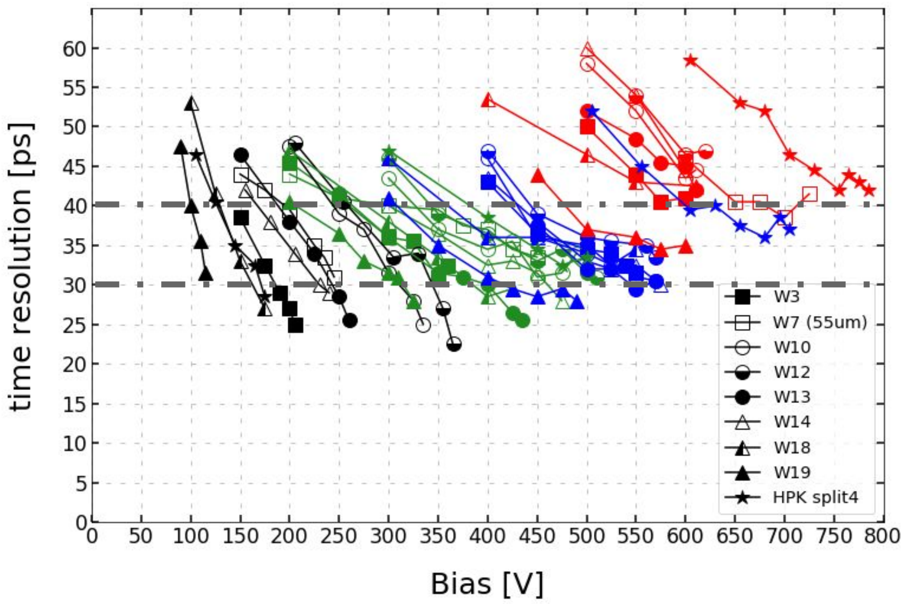
Performances of irradiated sensors

measurements performed at -25 °C

Charge vs Bias



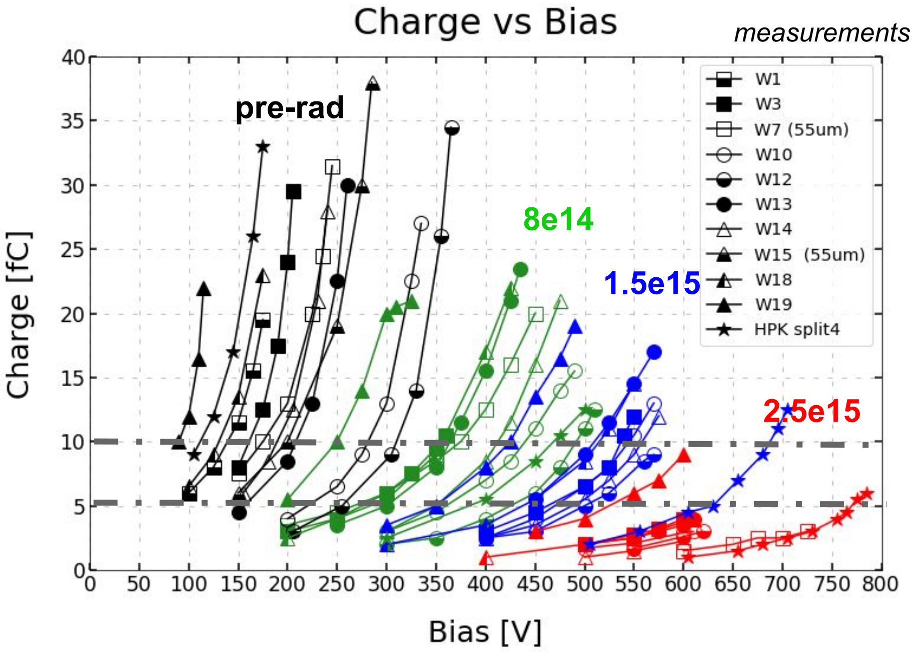
Time resolution vs Bias

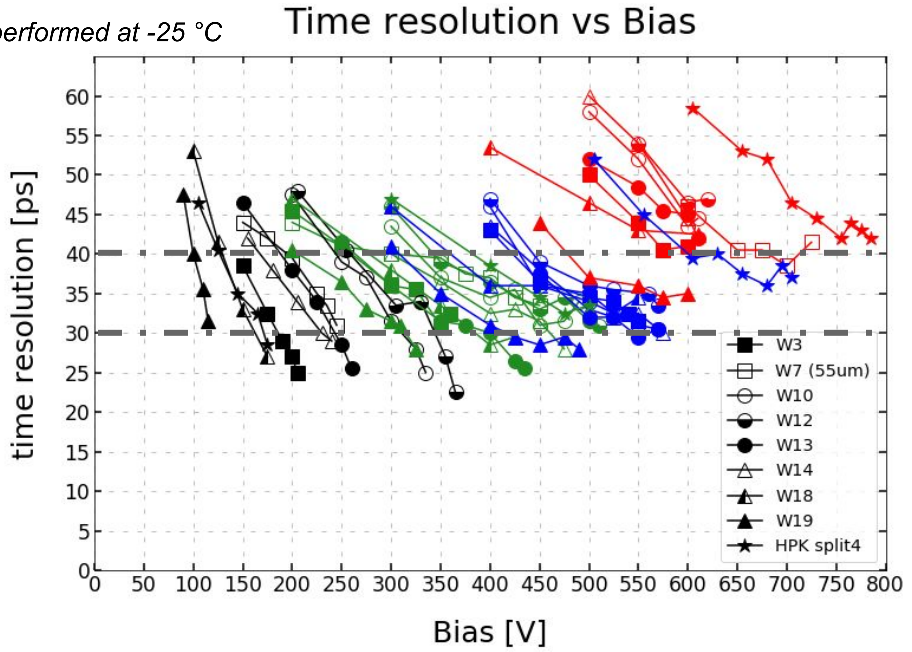


- All sensors deliver ≥ 10 fC up to 1.5e15 n_{eq}/cm^2 (~ 5 fC at 2.5e15)
- **30 ps are reached by all tested sensors up to 1.5e15** (~40 ps at 2.5e15)

Performances of irradiated sensors

measurements performed at -25 °C





- All sensors deliver ≥ 10 fC up to 1.5e15 n_{eq}/cm^2 (~ 5 fC at 2.5e15)
- **30 ps are reached by all tested sensors up to 1.5e15** (~40 ps at 2.5e15)

all sensors fulfill the desired criteria → need to define new figures of merit to discriminate between them

Outline

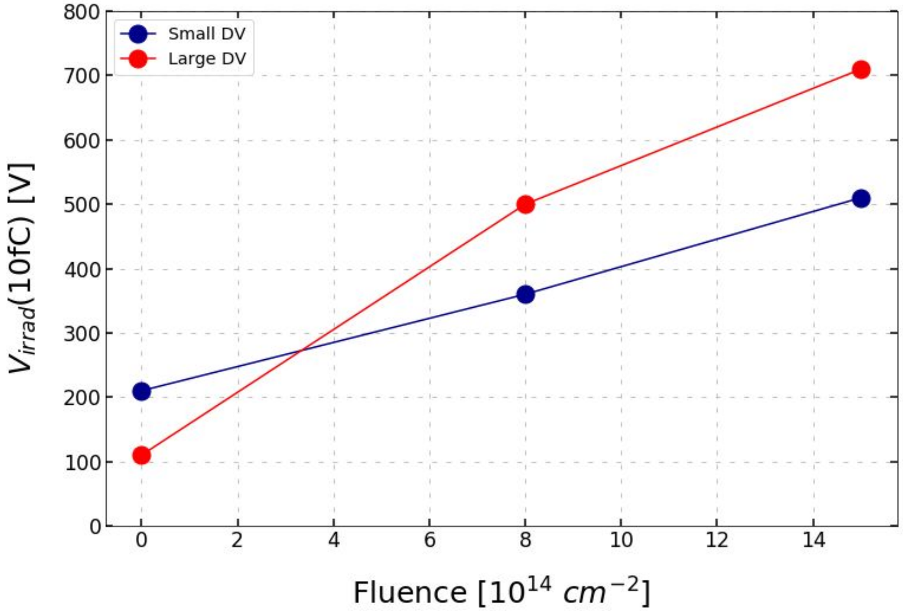
- ➢ FBK UFSD3.2 → 3 different Gain Layer designs
- ➢ Performance of pre-rad sensors
- ➢ Performance of irradiated sensors
- ➢ V_{irrad}(10fC) & DV(10fC)
- ➢ A study on the noise of tested sensors

V_{irrad}(10fC) & DV(10fC)

- What do we look for in an irradiated sensor? (provided it achieves the desired resolution)
  - **Operation at low VBias**
  - **VBias increase to compensate radiation effects as low as possible**
- We can introduce two additional useful parameters to evaluate irradiated sensors:
  - **VBias required to deliver 10fC at a given fluence → V_{irrad}(10fC)**
  - **VBias increase wrt pre-rad condition → DV(10fC)** = V_{irrad}(10fC) - $V_{pre\text{-}rad}$(10fC)
- The smaller such parameters, the better the GL design

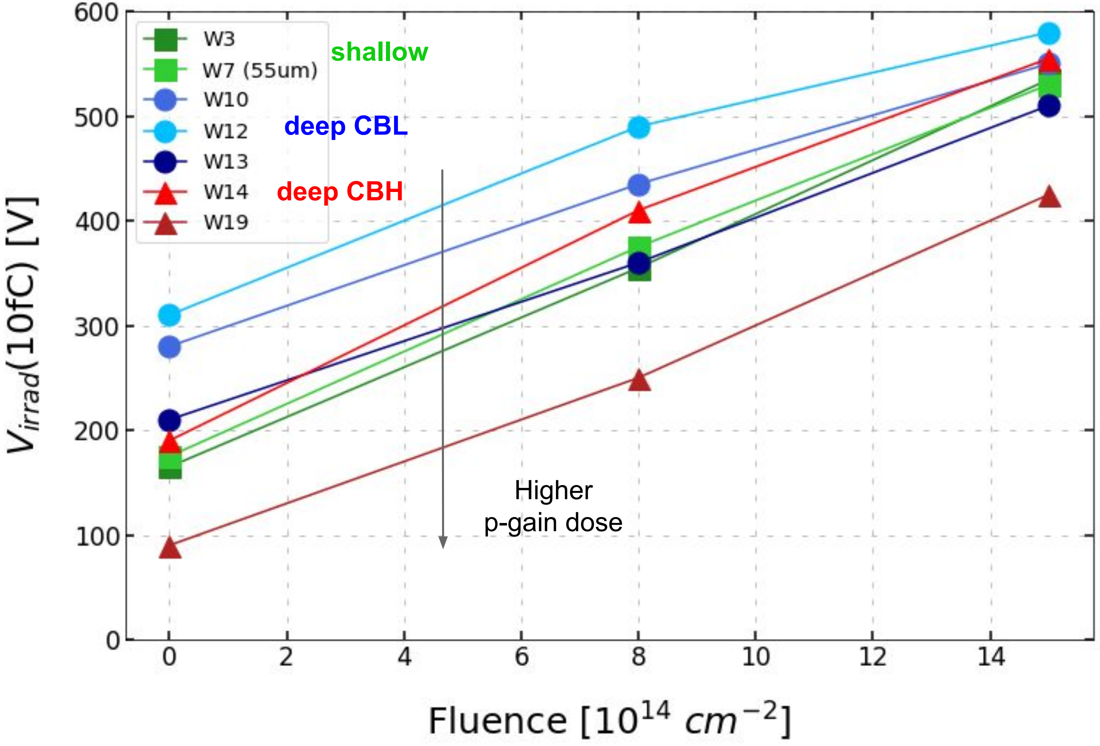
V_{irrad}(10fC) & DV(10fC)

- Small V_{irrad}(10fC) = low power consumption, safe operation of the device
- Small DV(10fC) = less affected by non-uniform irradiation → VBias shift to compensate a variation in fluence is smaller in sensors with small DV



V_{irrad}(10fC)

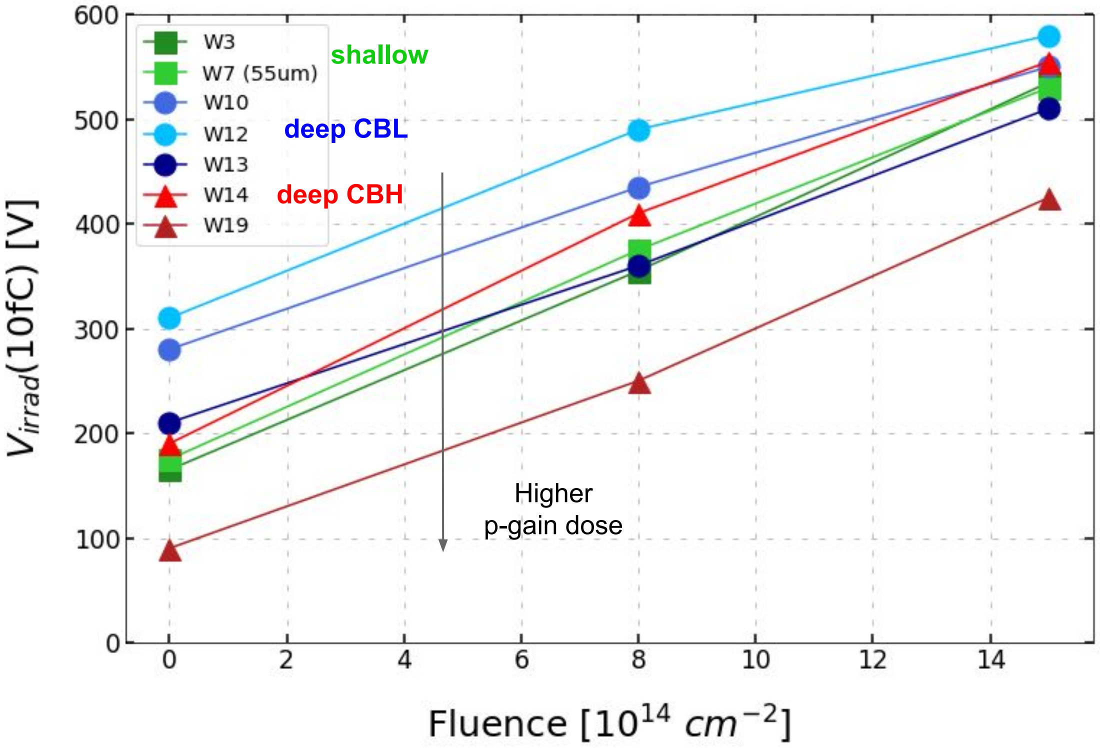
measurements performed at -25 °C



- The higher the initial doping, the lower V_{irrad}(10fC)
- W19 (deep CBH) has the lowest V_{irrad} but poor performance when new
- W13 (deep CBL) has higher V_{irrad} but works well when new

V_{irrad}(10fC)

measurements performed at -25 °C

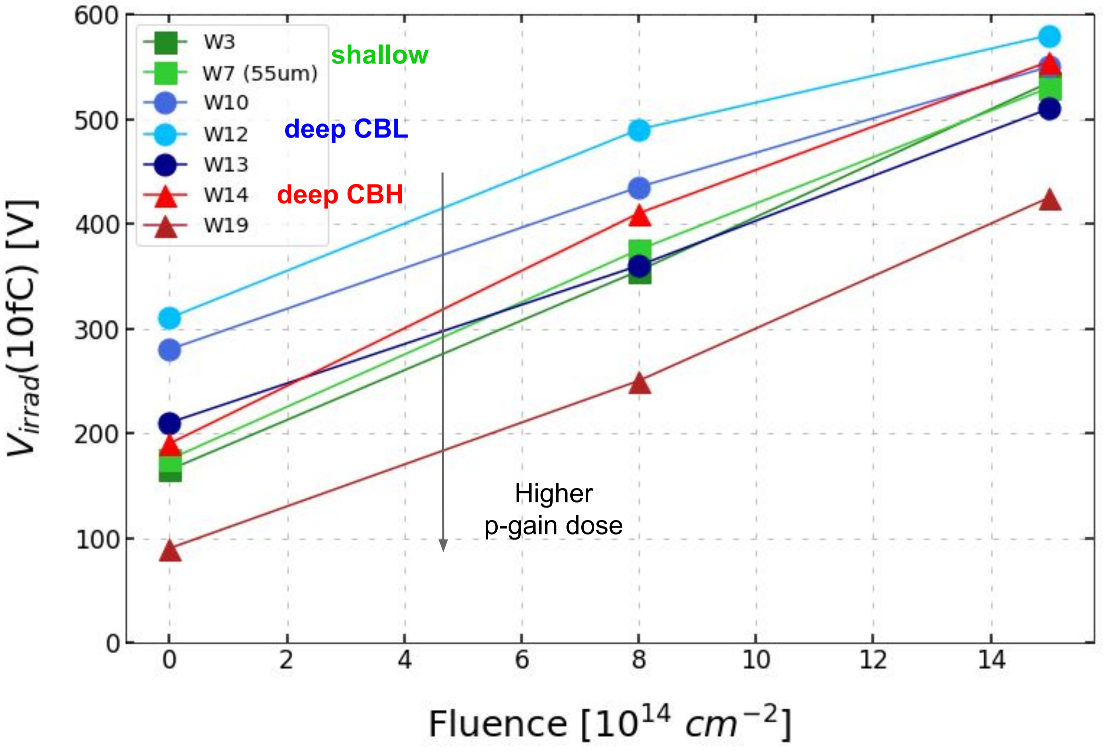


- The higher the initial doping, the lower V_{irrad}(10fC)
- W19 (deep CBH) has the lowest V_{irrad} but poor performance when new
- W13 (deep CBL) has higher V_{irrad} but works well when new

→ **High doping + deep implants provide the best V_{irrad}(10fC)**

V_{irrad}(10fC)

measurements performed at -25 °C

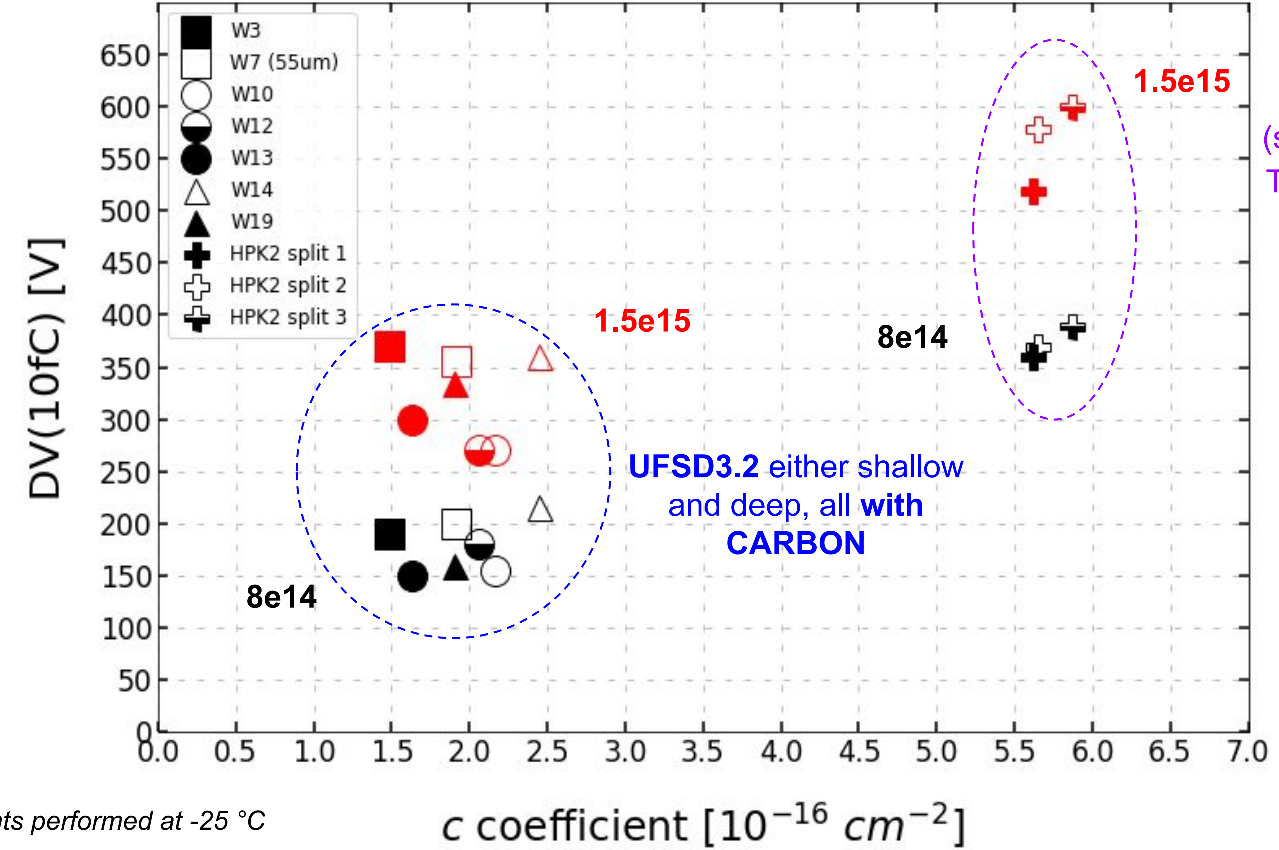


- The higher the initial doping, the lower V_{irrad}(10fC)
- W19 (deep CBH) has the lowest V_{irrad} but poor performance when new
- W13 (deep CBL) has higher V_{irrad} but works well when new

→ High doping + deep implants provide the best V_{irrad}(10fC)

→ a too high doping affect the performances when new

DV(10fC)

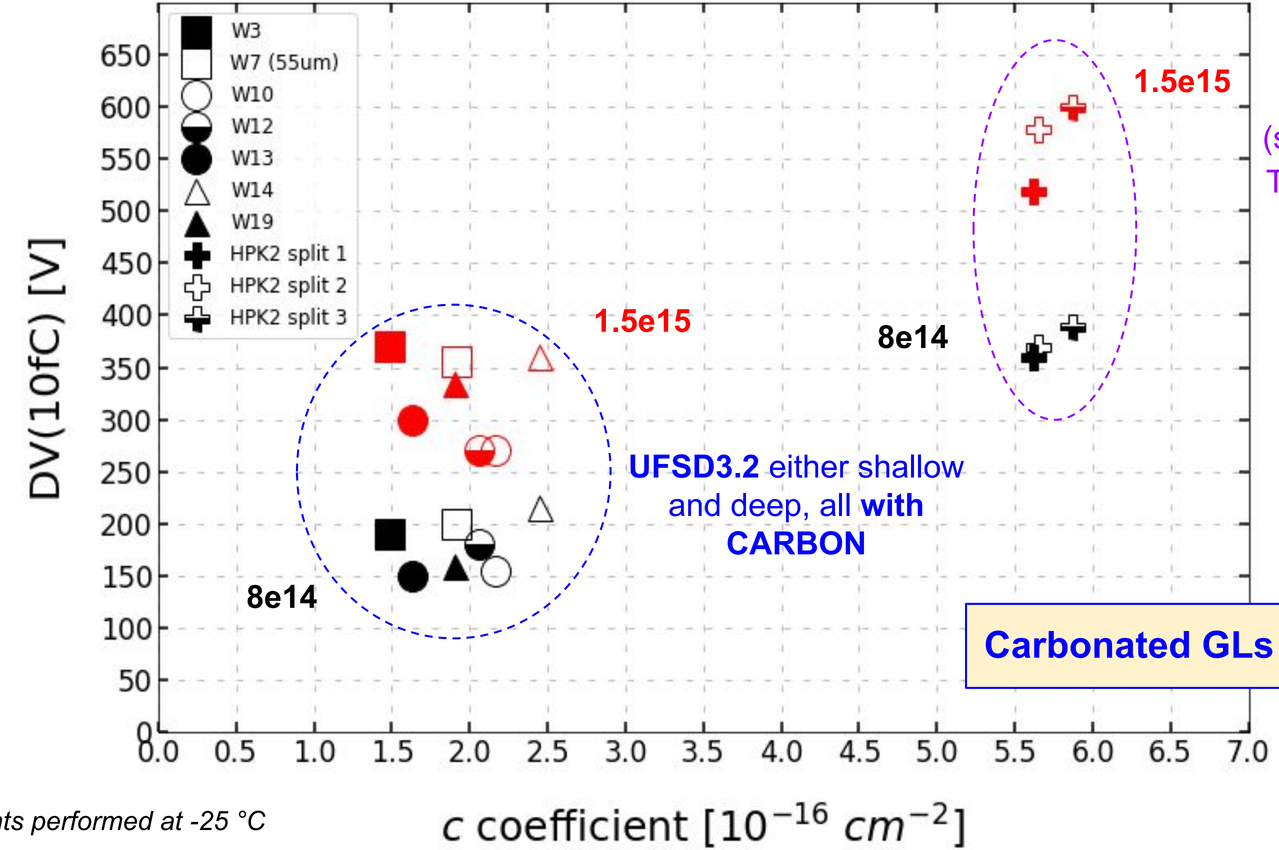


UFSD3.2 either shallow and deep, all **with CARBON**

HPK2 sensors
(shown for comparison)
They feature deep GLs
but **NO CARBON**

measurements performed at -25 °C

DV(10fC)



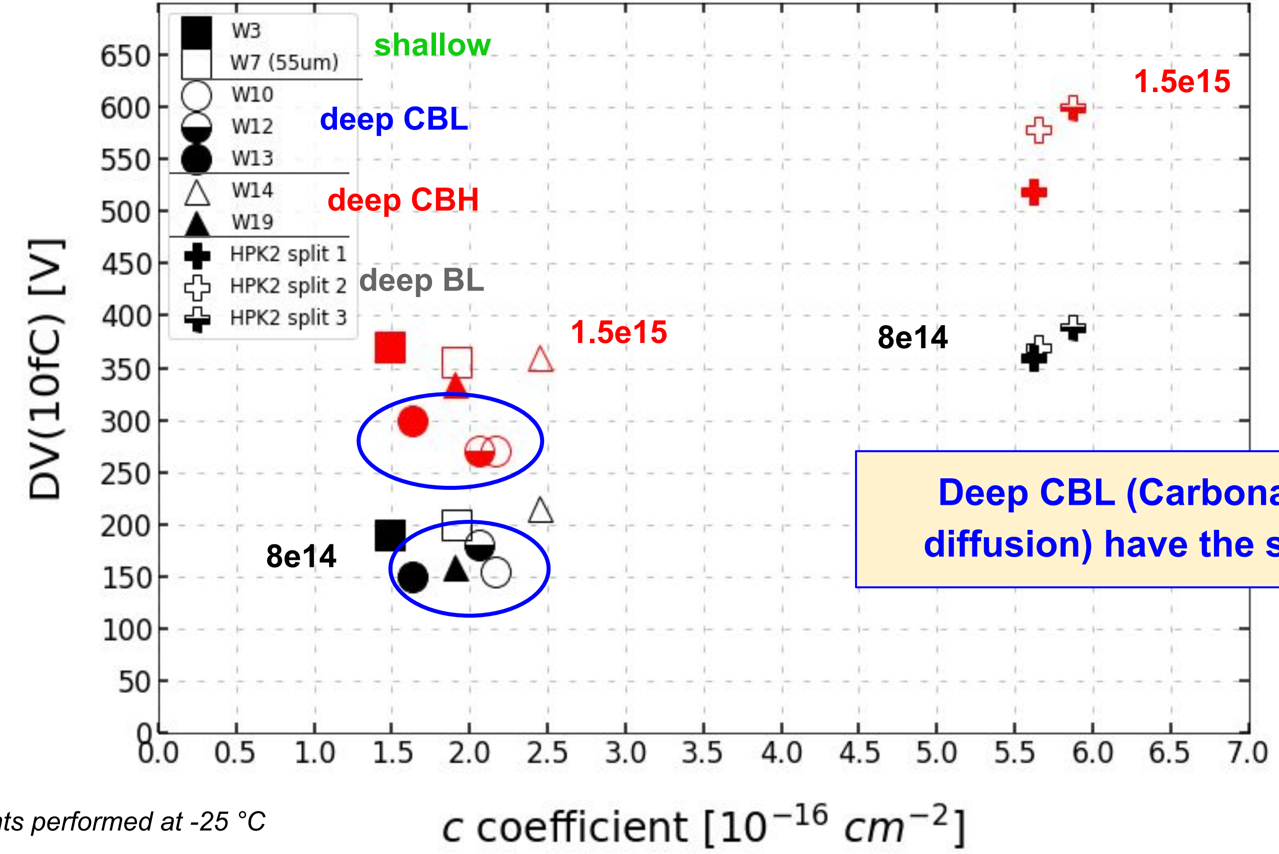
UFSD3.2 either shallow and deep, all **with CARBON**

HPK2 sensors (shown for comparison) They feature deep GLs but **NO CARBON**

Carbonated GLs have lower DV

measurements performed at -25 °C

DV(10fC)



Deep CBL (Carbonated + Low diffusion) have the smallest DV

measurements performed at -25 °C

Most radiation resistant design

- All UFSD3.2 sensors have very good radiation hardness and reach 30-40 ps up to high fluences
- V_{irrad}(10fC) and DV(10fC) are effective figures of merit:
    - Deep and highly doped implants have the lowest V_{irrad}(10fC)
    - Carbonated GL have much lower DV than not-carbonated
    - Deep implants have lower DV than shallow
    - Deep Low diffusion implants have lower DV than High diffusion ones

Most radiation resistant design

- All UFSD3.2 sensors have very good radiation hardness and reach 30-40 ps up to high fluences
- V_{irrad}(10fC) and DV(10fC) are effective figures of merit:
  - Deep and highly doped implants have the lowest V_{irrad}(10fC)
  - Carbonated GL have much lower DV than not-carbonated
  - Deep implants have lower DV than shallow
  - Deep Low diffusion implants have lower DV than High diffusion ones
- Summing up the above points → we conclude that the **Carbonated deep Gain Layer with low diffusion (CBL) is the most radiation resistant design in the UFSD3.2 production**

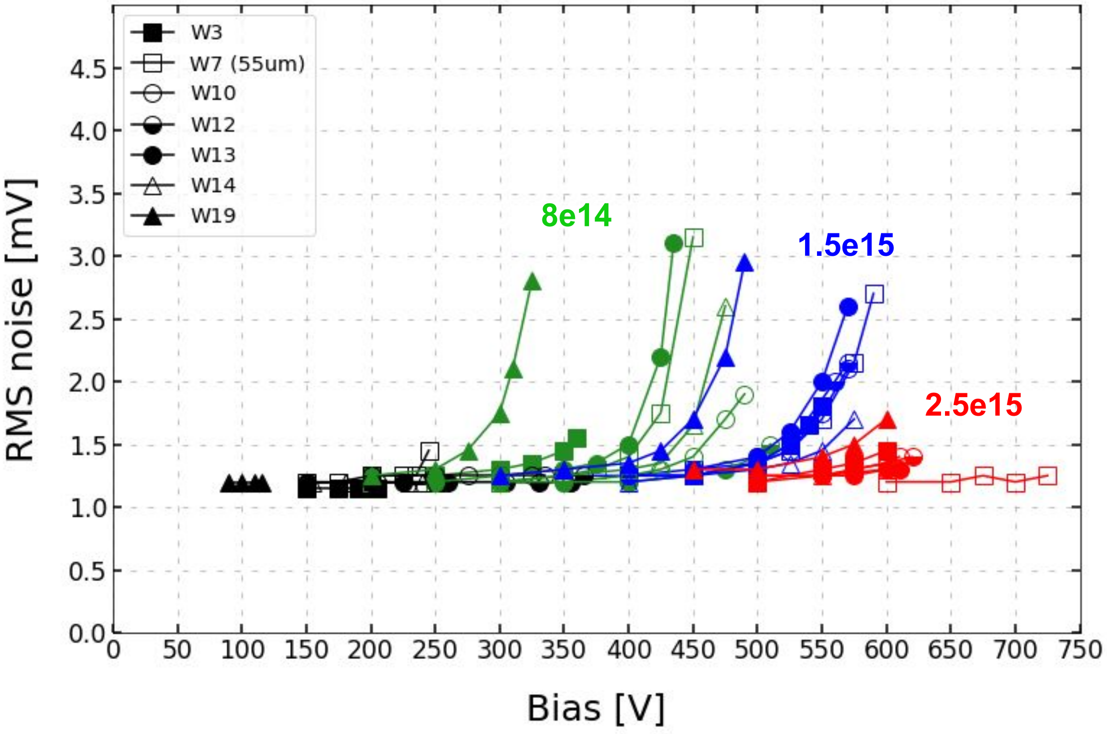
Outline

- ➢ FBK UFSD3.2 → 3 different Gain Layer designs
- ➢ Performance of pre-rad sensors
- ➢ Performance of irradiated sensors
- ➢ V_{irrad}(10fC) & DV(10fC)
- ➢ A study on the noise of tested sensors

Noise vs Bias: irradiated sensors

measurements performed at -25 °C

- “Santa-Cruz” read-out board noise ~ 1.2 mV
- High noise appears at high gain in irradiated devices



Noise vs Bias: irradiated sensors

measurements performed at -25 °C

- “Santa-Cruz” read-out board noise ~ 1.2 mV
- High noise appears at high gain in irradiated devices

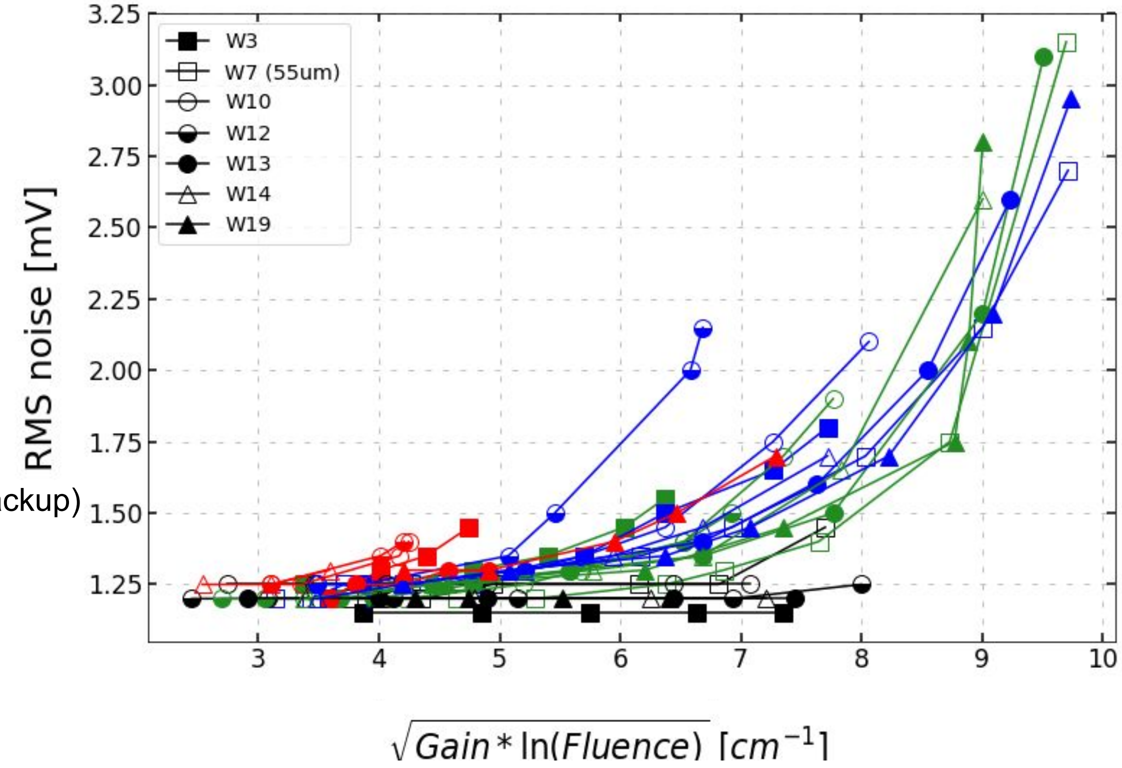
- There is a common trend when plotting

*noise vs sqrt(gain*ln(fluence))*

  - Noise ∝ sqrt(current)
  - current ∝ gain*ln(fluence)

→ noise does not depend significantly on the GL design

- *ln(fluence)* reproduces better than *fluence* (backup)



Noise vs Bias: irradiated sensors

measurements performed at -25 °C

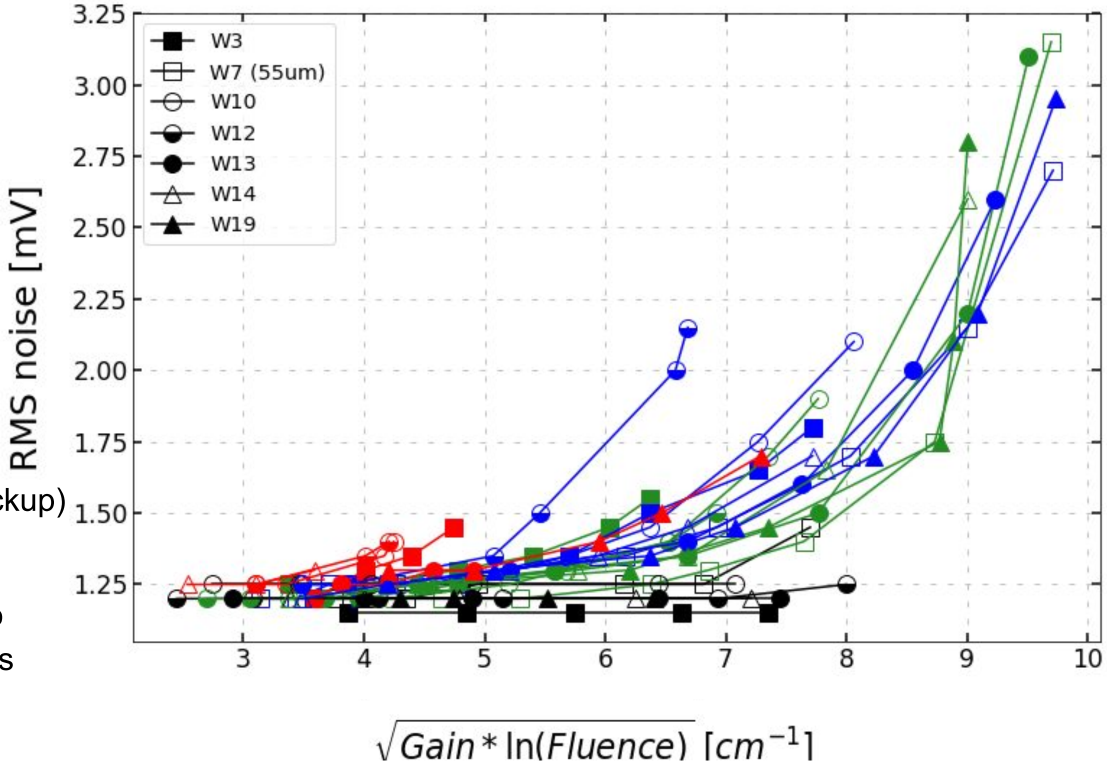
- “Santa-Cruz” read-out board noise ~ 1.2 mV
- High noise appears at high gain in irradiated devices

- There is a common trend when plotting *noise vs sqrt(gain*ln(fluence))*
  - Noise ∝ sqrt(current)
  - current ∝ gain*ln(fluence)

→ <u>noise does not depend significantly on the GL design</u>

- *ln(fluence)* reproduces better than *fluence* (backup)

- Noise > read-out noise when: *sqrt(gain*ln(fluence))* ≳ *5* → useful indication to prevent large noise when operating the sensors



Noise vs Bias: irradiated sensors

measurements performed at -25 °C

- “Santa-Cruz” read-out board noise ~ 1.2 mV
- High noise appears at high gain in irradiated devices

- There is a common trend when plotting

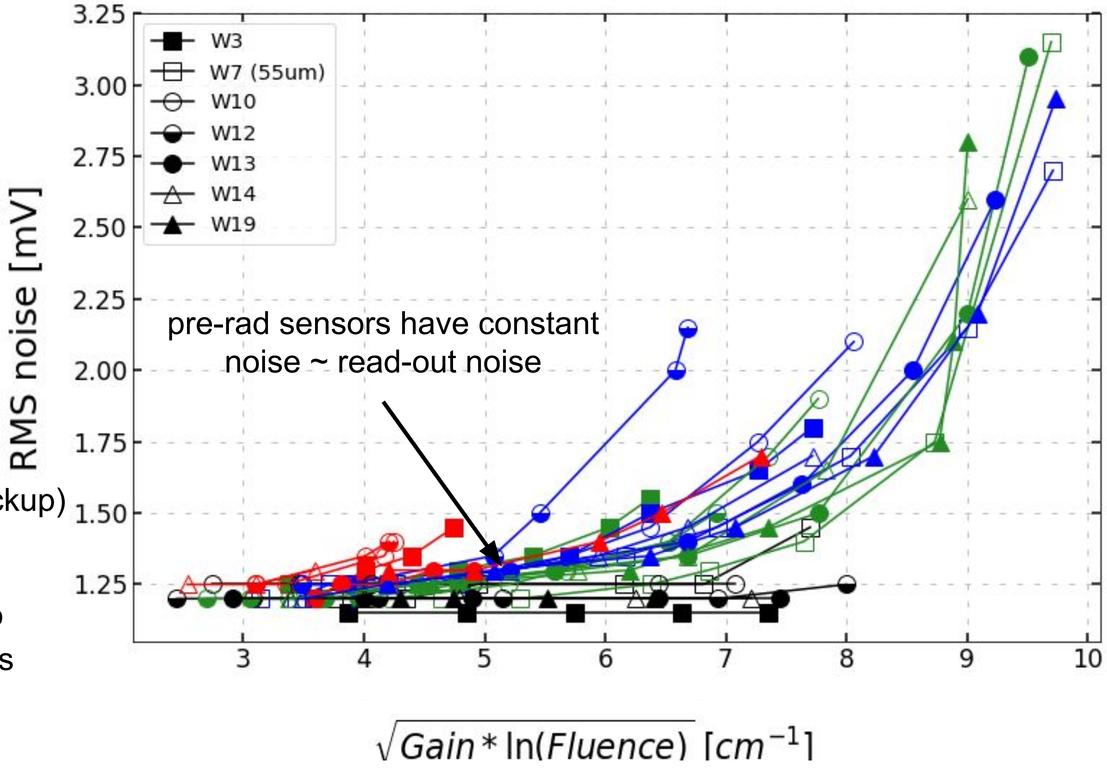
*noise vs sqrt(gain*ln(fluence))*

  - Noise ∝ sqrt(current)
  - current ∝ gain*ln(fluence)

<u>→ noise does not depend significantly on the GL design</u>

- *ln(fluence)* reproduces better than *fluence* (backup)

- Noise > read-out noise when: *sqrt(gain*ln(fluence))* ≳ *5* → useful indication to prevent large noise when operating the sensors



Noise vs Bias: irradiated sensors

measurements performed at -25 °C

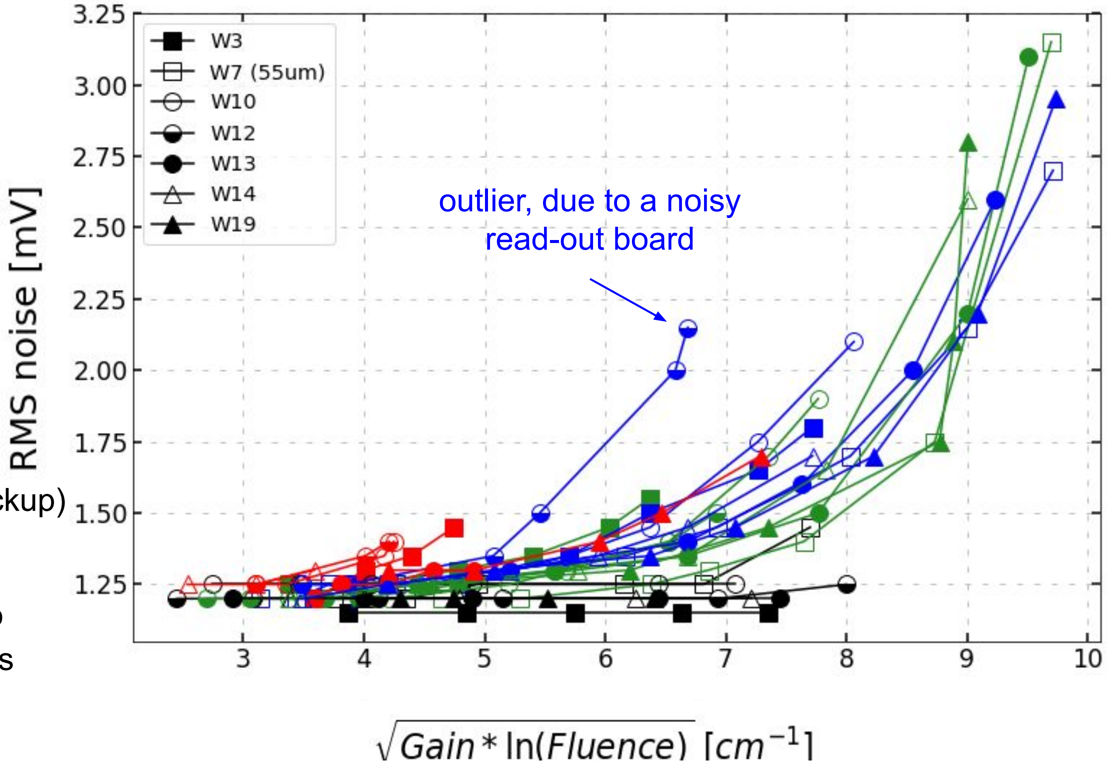
- “Santa-Cruz” read-out board noise ~ 1.2 mV
- High noise appears at high gain in irradiated devices

- There is a common trend when plotting
*noise vs sqrt(gain*ln(fluence))*
  - Noise ∝ sqrt(current)
  - current ∝ gain*ln(fluence)

<u>→ noise does not depend significantly on the GL design</u>

- *ln(fluence)* reproduces better than *fluence* (backup)

- Noise > read-out noise when:
*sqrt(gain*ln(fluence))* ≳ *5* → useful indication to prevent large noise when operating the sensors



Conclusions

- **The UFSD3.2 production features 3 different Gain Layer (GL) designs:**
  - Shallow (standard) carbonated GL
  - Deep carbonated GL with low diffusion → "CBL"
  - Deep carbonated GL with high diffusion → "CBH"

- **Key point: the gain layer design has to be tailored to the specific application** → no design fits all needs

- **Time resolution and radiation hardness are excellent for all sensors** → **30-40 ps up to 2.5e15 n_{eq}/cm^2**
  - Need to find the figures of merit to discriminate the various designs

- **Pre-rad sensors: look for operation at high voltage** (saturated fields, smooth gain curves) → low Pgain dose

- **Irradiated sensors:** Deep Carbonated GL with low diffusion (CBL) are presently the most radiation resistant design
  - Operated at the lowest VBias and require the smallest increase of voltage to compensate the effects of radiations

- Very high noise appears at high gain in irradiated sensors
  - It does not depend on the GL design
  - Seems to be a threshold effect depending on the sensor gain and log of the fluence

Thank You!

Acknowledgements

We kindly acknowledge the following funding agencies, collaborations:

- ▻ Horizon 2020, grant UFSD669529
- ▻ Horizon 2020, grant INFRAIA
- ▻ AIDA-2020, grant agreement no. 654168
- ▻ INFN, Gruppo V
- ▻ Ministero degli Affari Esteri, Italy, MAE, "Progetti di Grande Rilevanza Scientifica"
- ▻ MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)

➢ Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe

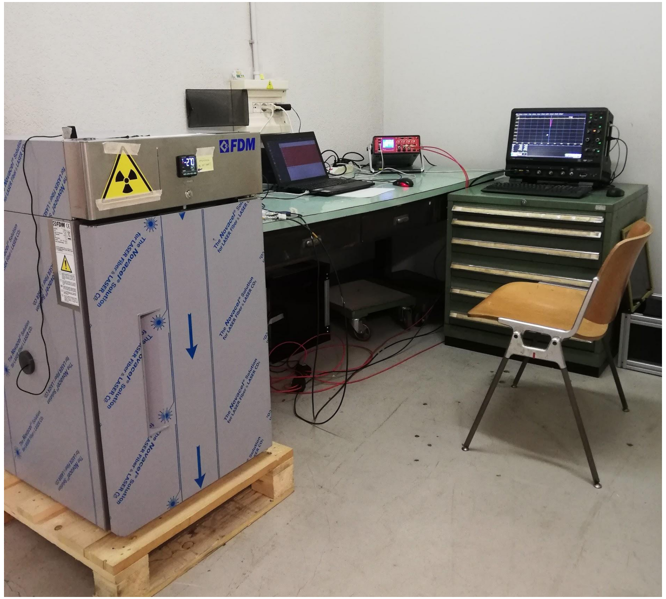
➢ Ministero della Ricerca, Italia, FARE, R165xr8frt_fare

We also kindly acknowledge FBK for providing sensors and support during the testing campaign

BACKUP

Torino β-source setup

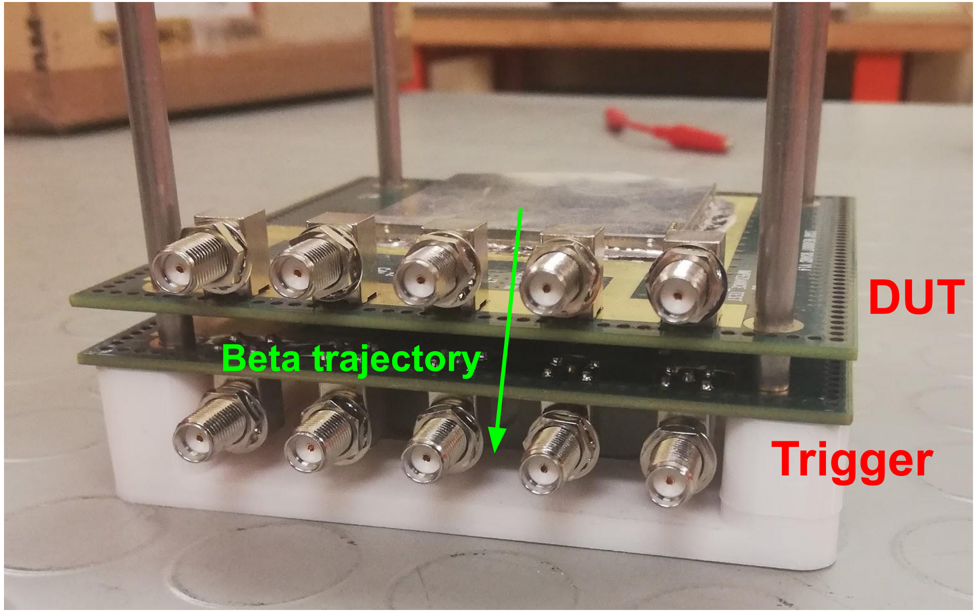
- DAQ and Analysis are fully automated
- Climate chamber
  - Can go down to -30°C with ± 0.1°C uncertainty
  - < 10% humidity



Torino β-source setup

- DAQ and Analysis are fully automated
- Climate chamber
  - Can go down to -30°C with ± 0.1°C uncertainty
  - < 10% humidity

- DUT + trigger Telescope, placed inside a specific structure (3d-printed) for alignment
- A trigger placed below the DUT ensures that we trigger only on MIPs
- Trigger: HPK1 1x3 mm^2 single pad
  - well known resolution
- ~1cm of air between DUT & trigger

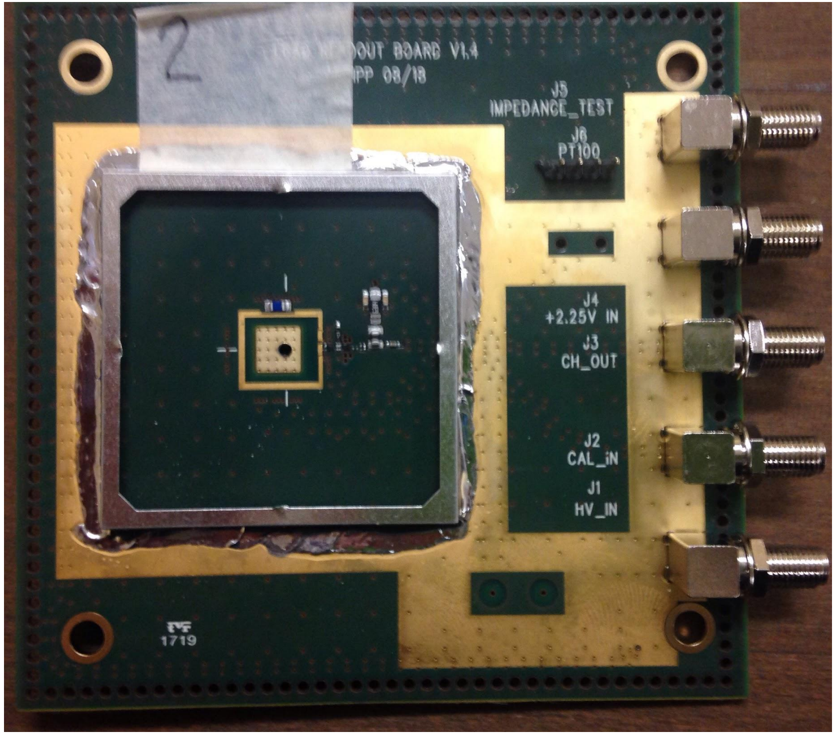


Torino β-source setup

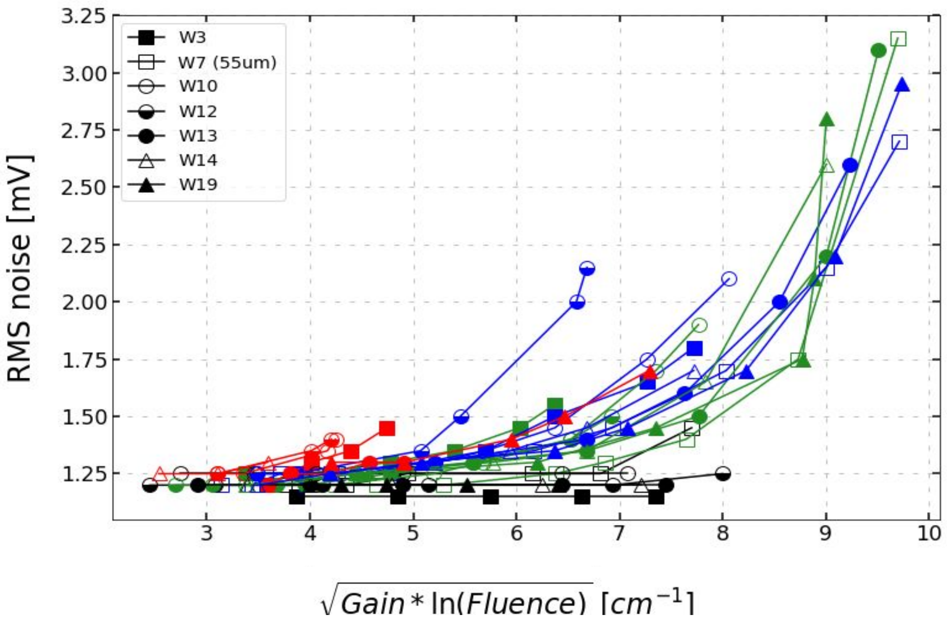
- DAQ and Analysis are fully automated
- Climate chamber
  - Can go down to -30°C with ± 0.1°C uncertainty
  - < 10% humidity

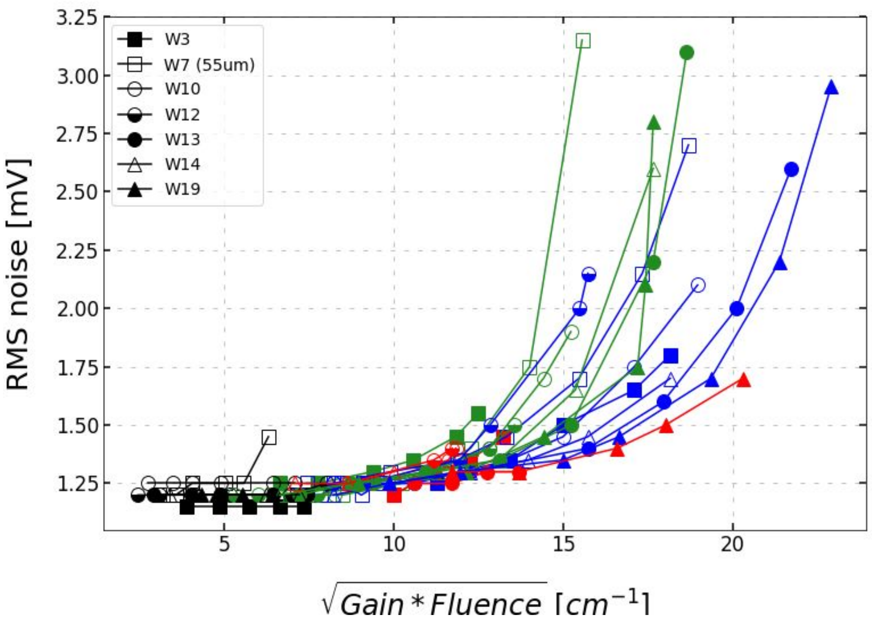
- DUT + trigger Telescope, placed inside a specific structure (3d-printed) for alignment
- A trigger placed below the DUT ensures that we trigger only on MIPs
- Trigger: HPK1 1x3 mm^2 single pad
  - well known resolution
- ~1cm of air between DUT & trigger

- "Santa Cruz" Read-out board made by Artel
  - single channel
  - x10 amplification (+ 20dB Cividec broadband amplifier)



Noise vs Bias: irradiated sensors





using *ln(fluence)* gives a better trend

Weightfield2 Simulation