Study on the effects of mixed-field irradiation on SiPM performance

Valentin Buchakchiev

Sofia, 19.06.2025

Study of the Effects of Ionizing Radiation in Silicon Photomultipliers

ESA Contract No. [illegible]

Radiation damage to SiPM

- Overview on Radiation Damage
- Setup and questions of interest
- Mixed field irradiation and static SiPM characteristics
- Mixed field irradiation and pulse shape effect
- Conclusions

Radiation damage to SiPM

- Radiation is a problem for all Silicon-based detectors, as the Silicon structure itself degrades with time (and dose).
- Numerous studies have been performed on SiPM radiation hardness, and there is active R&D by manufacturers aiming to mitigate the effects.
- Most SiPM manufacturers perform radiation studies on their own sensors, with the results freely available to users.
- The standard results observe increasing DCR and dark current after irradiation to ~10^8 [1MeV n_{eq}/cm^2]. Cooling the sensors seems to improve radiation hardness. Annealing seems capable of restoring their state to a degree.

About this study

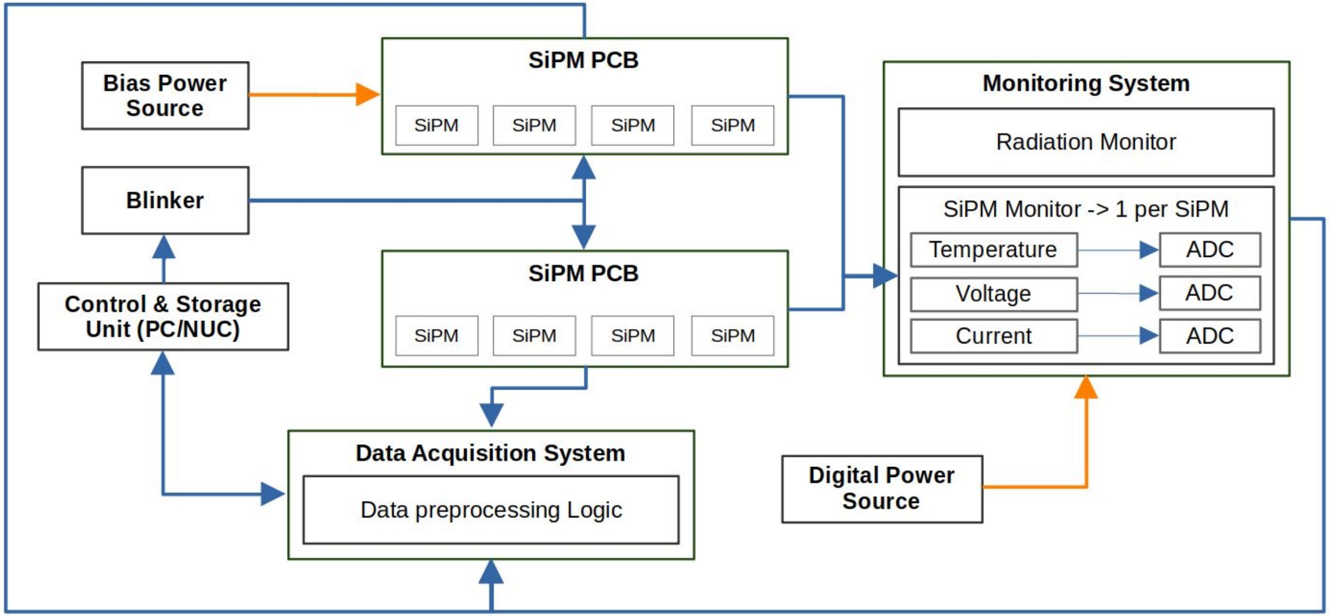
- This study is mainly interested in filling some holes in the methods usually employed in the SiPM studies, and comparing the performance of multiple types of SiPM after the irradiation.

- Studies in general tend to passively irradiate SiPM samples to pre-set doses, then let them anneal for a while, and a comparison is made between the SiPM responses before and after the irradiation.

- In this case, a few key differences are introduced:
  - Irradiation is not fully passive - with half the samples powered OFF, and half of them powered ON.
  - There is no wait and/or annealing before the measurement. Measurements are performed during the irradiation itself.
  - Aside from the standard evaluation on how each SiPM is affected, the additional aim of comparing differences in results between the powered ON and powered OFF devices is introduced.

- Annealing with time to be studied at a later stage (measurements after 4 months, 6 months, 1 year after the irradiation
  - Passive annealing planned.
  - Active annealing with temperature increase might be also studied at a later stage

Basic design

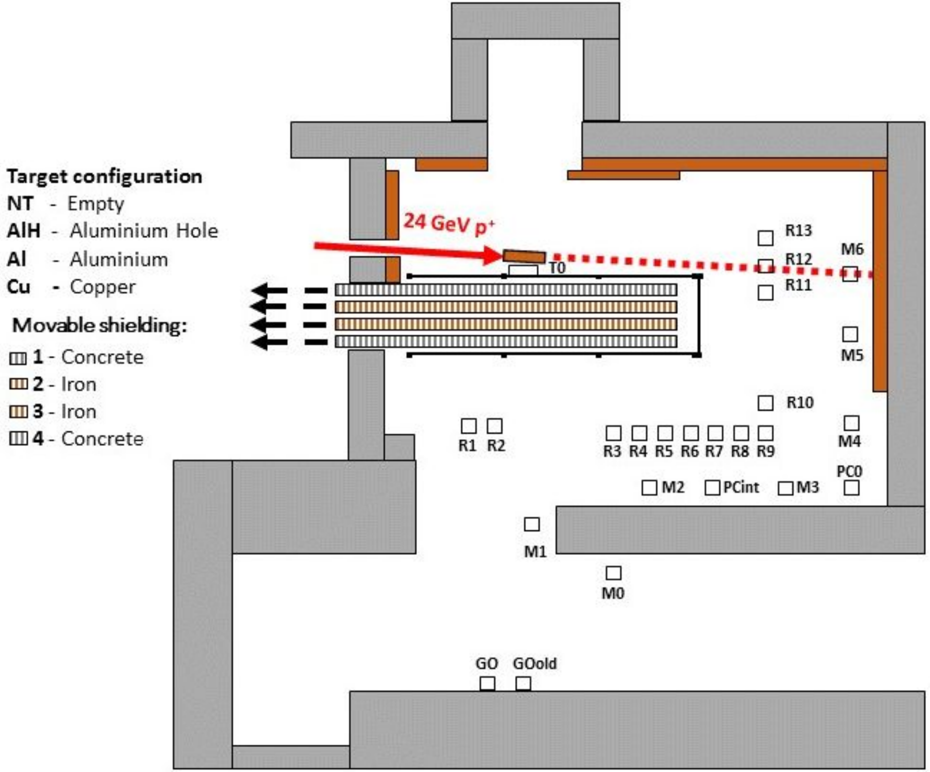


Main questions

- Which of the tested SiPM types perform best after heavy irradiation?
- How do the characteristics of SiPMs change with irradiation, for different SiPM types and technologies?
- Does powering the SiPMs affect the damage to their performance?
- How much irradiation can the different SiPMs handle?
- What damage mitigation strategies can be employed, while retaining the compactness of the devices?

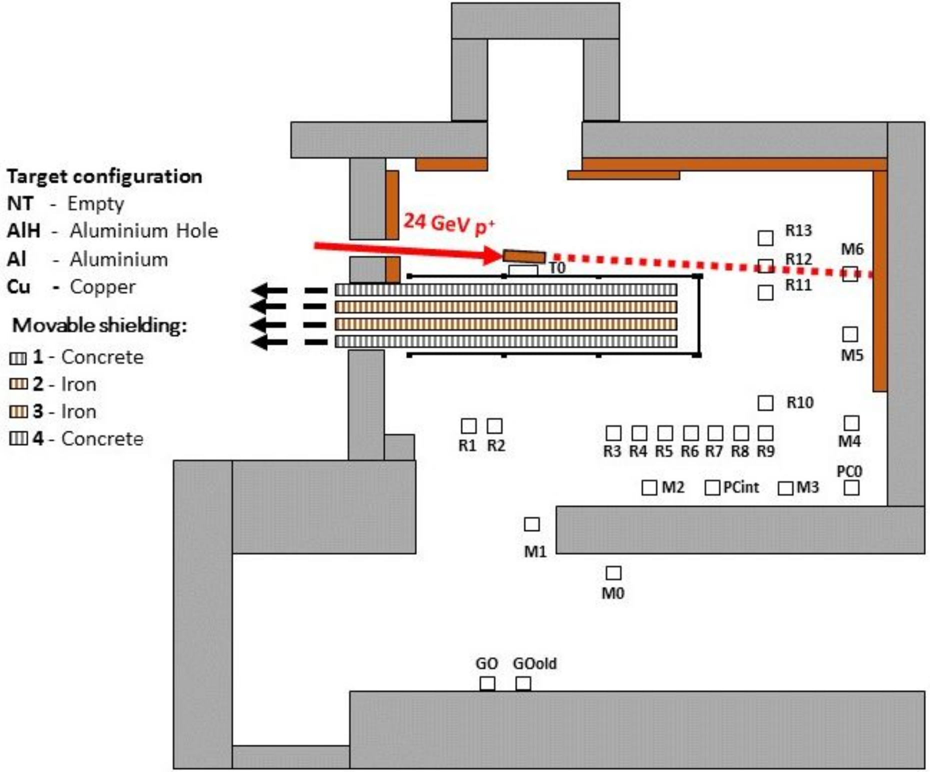
Test irradiation at CERN's CHARM facility

- CHARM is presented as a mixed-field facility:
  - An aluminium target is bombarded by a high energy proton beam, giving birth to multiple types of secondary particles for the irradiation.
- The proton beam is taken from the CERN PS:
  - Proton momentum is 24 GeV/c.
  - Beam intensity is ~5*10^{11} protons per spill.
  - Each spill lasts around 350 ms.
  - There are three spills per cycle, with each cycle being ~45 s long.



Test irradiation at CERN's CHARM facility

- Irradiation rate and levels are dependent on the position within the facility and the presence of configurable shielding.
- Highest irradiation levels are at the R11-R13 positions close to the beam axis.
    - TID achieved ~500 Gy.
    - Fluence achieved ~$3*10^{12}$ [1 MeV n_{eq}/cm^2].
- Weakest irradiation is at the G0 position:
    - TID achieved ~40 Gy.
    - Fluence achieved ~$7*10^{11}$ [1 MeV n_{eq}/cm^2].



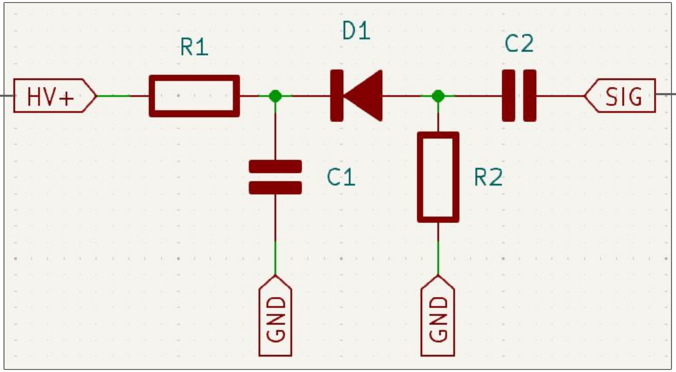
Irradiation setup

- Two boxes, put at different positions at CHARM - one at maximum dose, and one at minimum dose.
- In each box there are:
  - 2 FBK 4x4 mm^2 SiPM.
  - 2 FBK 3x3 mm^2 SiPM.
  - 2 ONS MicroFJ 3x3 mm^2 SiPM.
- For each SiPM pair, one is kept constantly powered, and one is irradiated passively.
- Box 1 (Lower total dose) is connected to the patch panel at the facility using 10m long coaxial cables.
- Box 2 (Higher total dose) is connected to the patch panel at the facility using 25m long coaxial cables.

SiPM readout

ISEG SHR 4020
Source Measure Unit

PC
Readout



R1 = 10 kOhm
R2 = 1 kOhm
C1 = 10 nF
C2 = 100 pF

R&S RTA4000
Oscilloscope

Save to
USB

Measurements

- Measurement were performed periodically during the irradiation without stopping the beam or removing the mixed-field target.

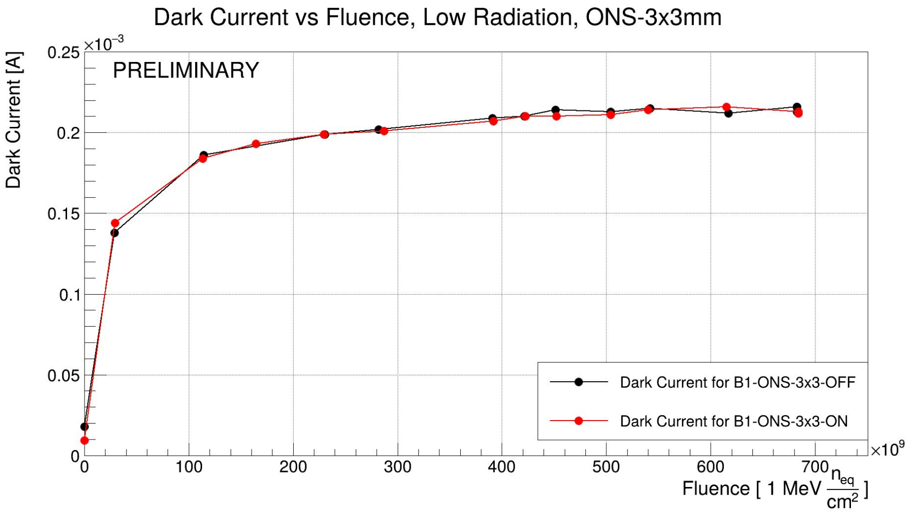
- IV curves were saved for each SiPM during each measurement.
  - Measurement would be started at around 5V below V_{BR}, and voltage would be raised to around 3V above V_{BR}.

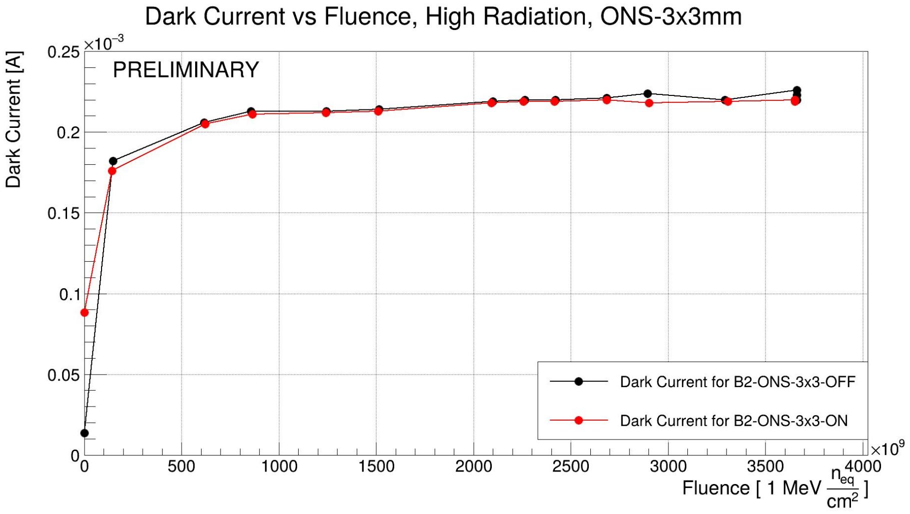
- The signals produced by the SiPMs were saved as waveforms during each measurement period.
  - Diodes connected to a generator allowed for pulse illumination of the SiPMs for signal shape detection.
  - A number of single-probe waveforms were saved for each SiPM, along with averaged signal shapes.

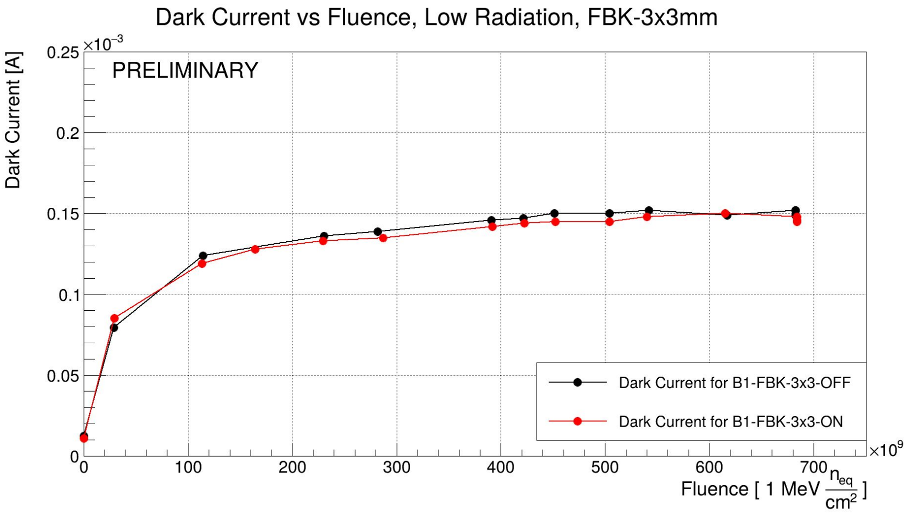
- Measurements timeline is as follows:
  - 1 measurement for each SiPM before any irradiation.
  - 11 measurements for each SiPM during the irradiation period.
  - 3 measurements after direct irradiation is stopped, but before removal (the facility itself is still rather radioactive).

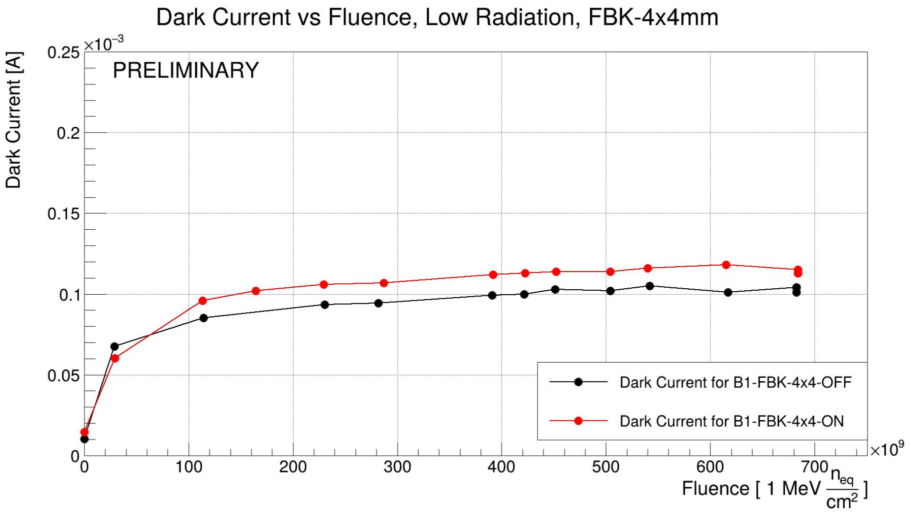
Dark current vs fluence

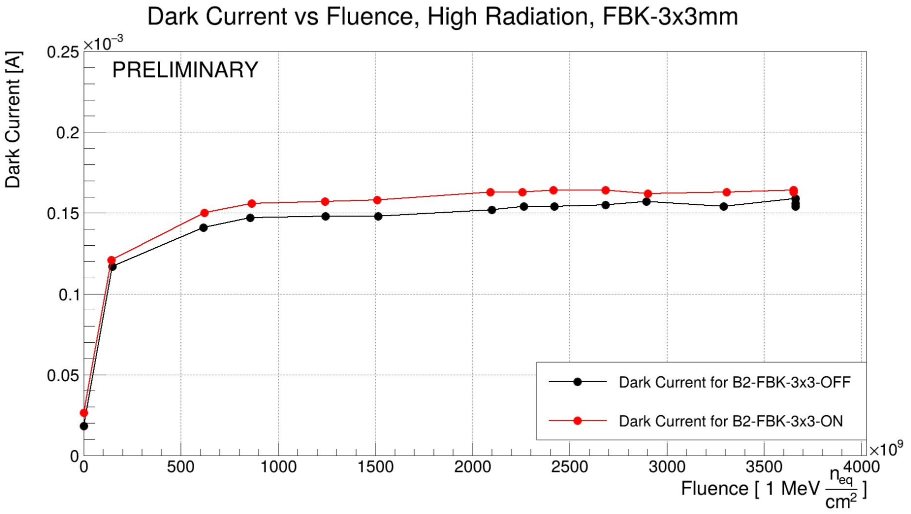
- Dark current rises ~10 times from before the irradiation.
- Dark current seems to plateau after fluence hits ~10^{12} [1 MeV n_{eq}/cm^2].
- There doesn’t seem to be a large discrepancy between the current rise for the ON and OFF state SiPM.

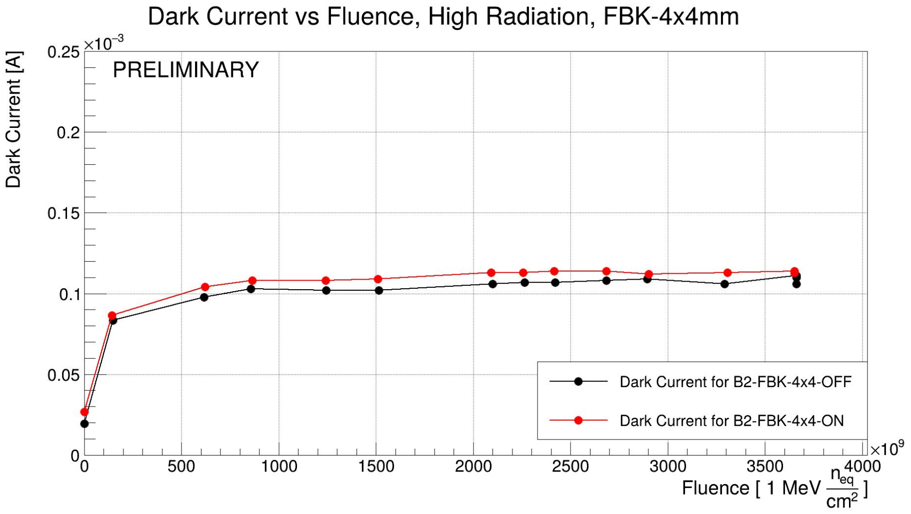





Dark Current vs Fluence, Low Radiation, FBK-3x3mm
PRELIMINARY
Dark Current [A]
×10^-3
Fluence [1 MeV n_eq/cm^2]
×10^9
Dark Current for B1-FBK-3x3-OFF
Dark Current for B1-FBK-3x3-ON


Dark Current vs Fluence, Low Radiation, FBK-4x4mm
PRELIMINARY
Dark Current [A]
×10^-3
Fluence [1 MeV n_eq/cm^2]
×10^9
Dark Current for B1-FBK-4x4-OFF
Dark Current for B1-FBK-4x4-ON

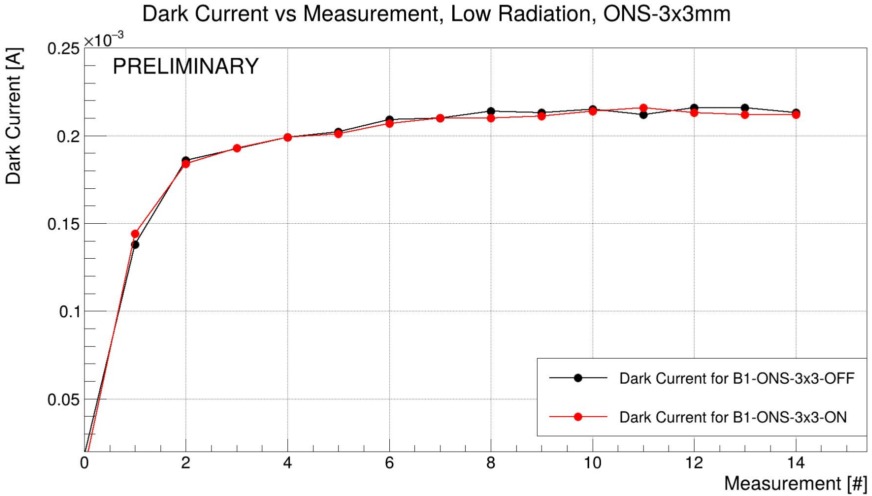

Dark Current vs Fluence, High Radiation, FBK-3x3mm
PRELIMINARY
Dark Current [A]
×10^-3
Fluence [1 MeV n_eq/cm^2]
×10^9
Dark Current for B2-FBK-3x3-OFF
Dark Current for B2-FBK-3x3-ON

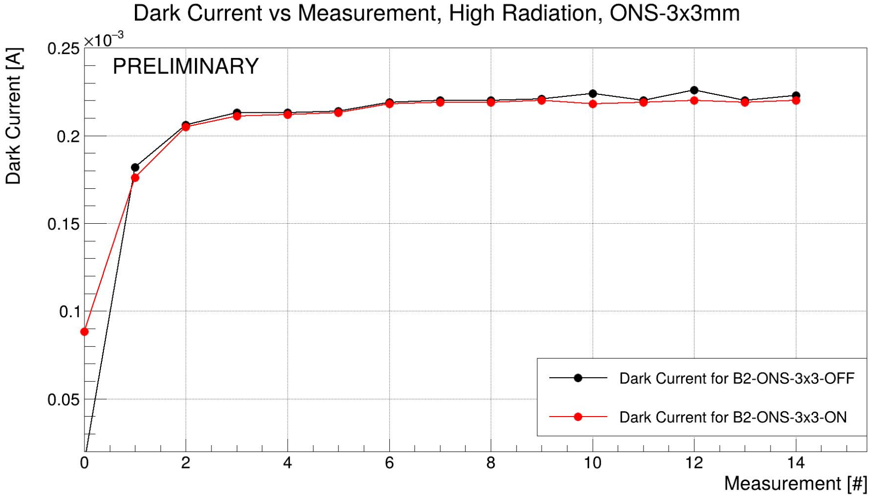

Dark Current vs Fluence, High Radiation, FBK-4x4mm
PRELIMINARY
Dark Current [A]
×10^-3
Fluence [1 MeV n_eq/cm^2]
×10^9
Dark Current for B2-FBK-4x4-OFF
Dark Current for B2-FBK-4x4-ON

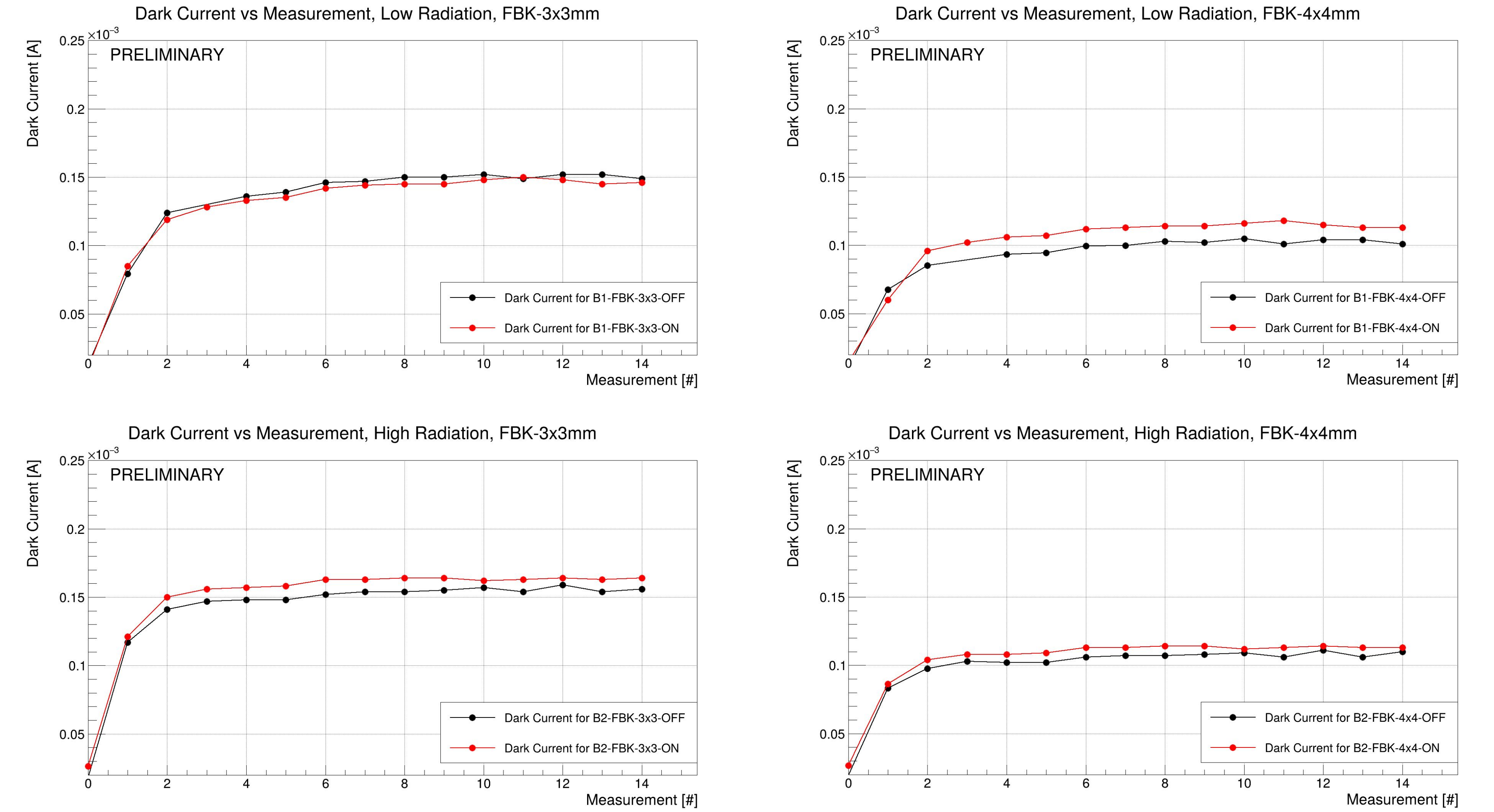
Dark current vs measurement

- Errors estimated to be of the order of 10 uA (5% for the plateau) for all SiPM, using the spread (RMS) in final three points (performed after switching off the beam)

- Differences in final currents consistent within error and offset of “No dose” point for the ON and OFF SiPM.






Dark Current vs Measurement, Low Radiation, FBK-3x3mm
Dark Current [A]
×10^-3
PRELIMINARY
Measurement [#]
Dark Current for B1-FBK-3x3-OFF
Dark Current for B1-FBK-3x3-ON
Dark Current vs Measurement, Low Radiation, FBK-4x4mm
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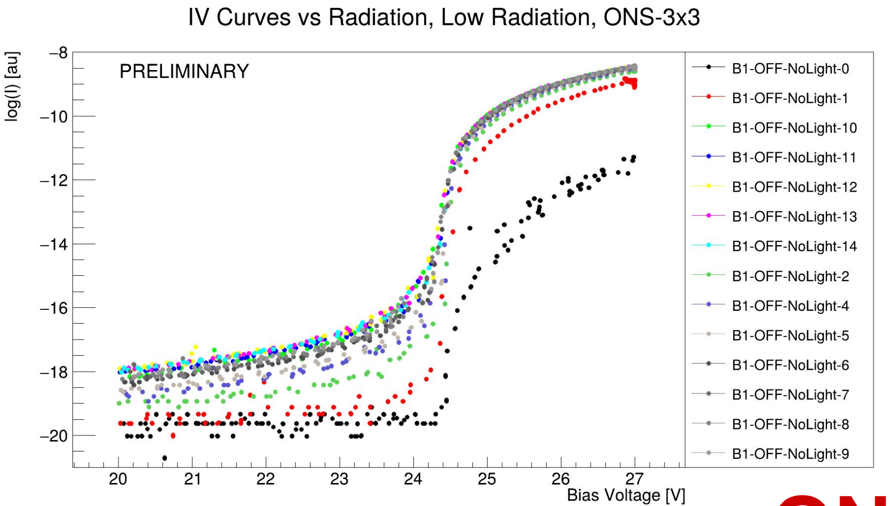
×10^-3
PRELIMINARY
Measurement [#]
Dark Current for B2-FBK-4x4-OFF
Dark Current for B2-FBK-4x4-ON

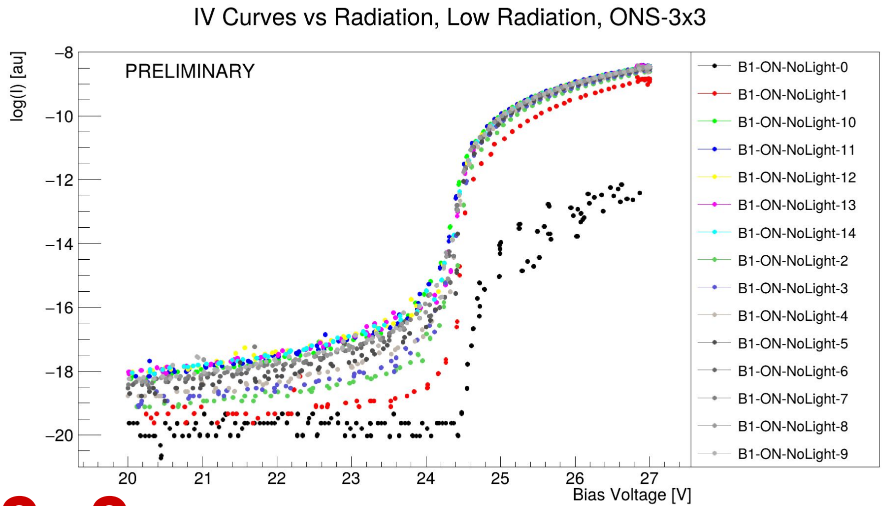
I-V curves vs irradiation

- Changes in the sensors' IV curves with irradiation were recorded.

- The curves show some standard results - increases in the currents both before V_{BR}, and after.

- Another result is a slow "shift" of the curve "knee" to the left, indicating a change in V_{BR} with irradiation. Important result, as this would also mean a change in the gain of the SiPMs during the procedure.
    - Most studies on radiation hardness assume no change in gain.


IV Curves vs Radiation, Low Radiation, ONS-3x3
PRELIMINARY
log(I) [au]
Bias Voltage [V]
B1-OFF-NoLight-0
B1-OFF-NoLight-1
B1-OFF-NoLight-10
B1-OFF-NoLight-11
B1-OFF-NoLight-12
B1-OFF-NoLight-13
B1-OFF-NoLight-14
B1-OFF-NoLight-2
B1-OFF-NoLight-4
B1-OFF-NoLight-5
B1-OFF-NoLight-6
B1-OFF-NoLight-7
B1-OFF-NoLight-8
B1-OFF-NoLight-9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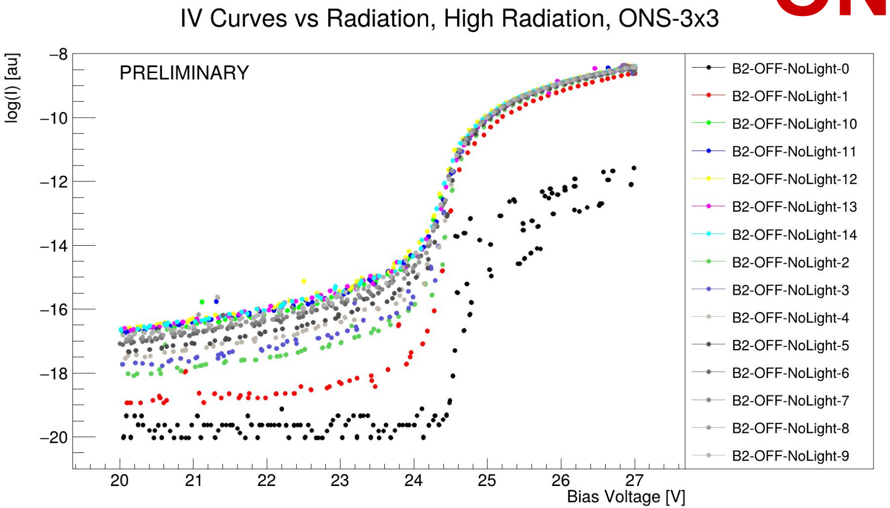
B1-ON-NoLight-2
B1-ON-NoLight-3
B1-ON-NoLight-4
B1-ON-NoLight-5
B1-ON-NoLight-6
B1-ON-NoLight-7
B1-ON-NoLight-8
B1-ON-NoLight-9

ONS 3x3


IV Curves vs Radiation, High Radiation, ONS-3x3
PRELIMINARY
log(I) [au]
Bias Voltage [V]
B2-OFF-NoLight-0
B2-OFF-NoLight-1
B2-OFF-NoLight-10
B2-OFF-NoLight-11
B2-OFF-NoLight-12
B2-OFF-NoLight-13
B2-OFF-NoLight-14
B2-OFF-NoLight-2
B2-OFF-NoLight-3
B2-OFF-NoLight-4
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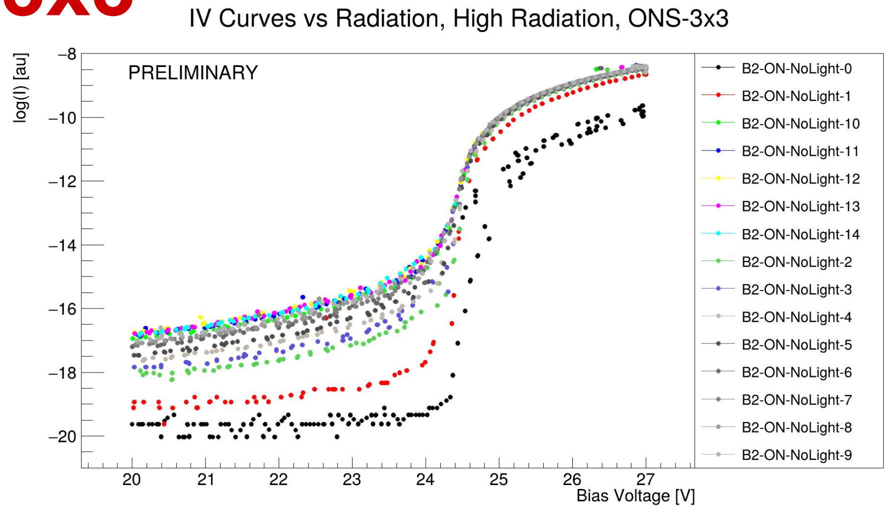
B2-OFF-NoLight-8
B2-OFF-NoLight-9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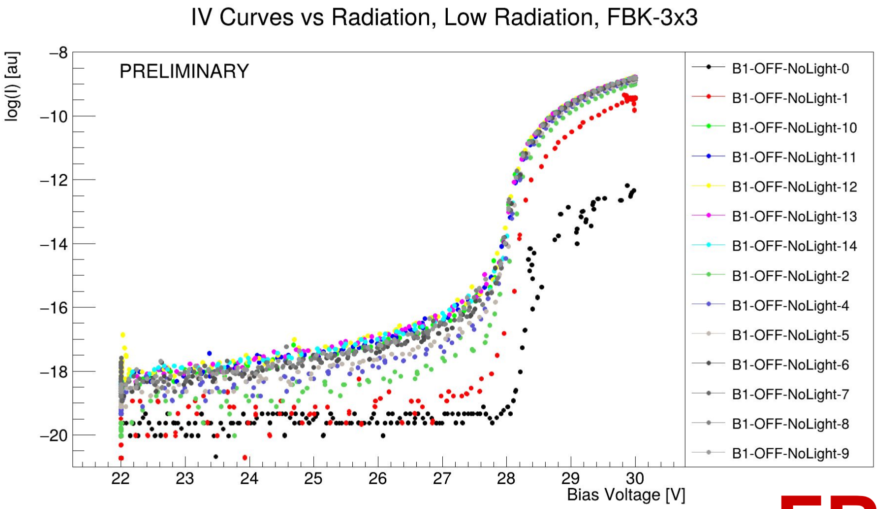
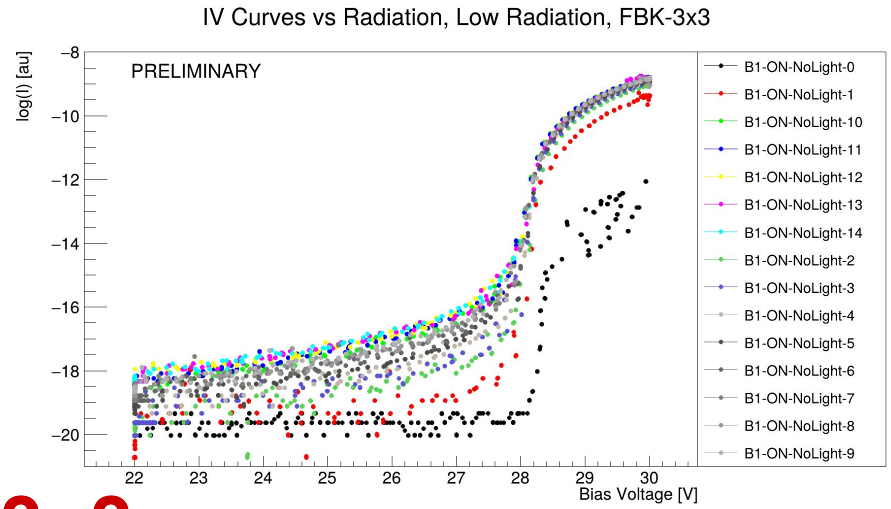
B2-ON-NoLight-14
B2-ON-NoLight-2
B2-ON-NoLight-3
B2-ON-NoLight-4
B2-ON-NoLight-5
B2-ON-NoLight-6
B2-ON-NoLight-7
B2-ON-NoLight-8
B2-ON-NoLight-9

FBK 3x3



IV Curves vs Radiation, Low Radiation, FBK-3x3
PRELIMINARY
log(I) [au]
−8
−10
−12
−14
−16
−18
−20
22
23
24
25
26
27
28
29
30
Bias Voltage [V]
B1-OFF-NoLight-0
B1-OFF-NoLight-1
B1-OFF-NoLight-10
B1-OFF-NoLight-11
B1-OFF-NoLight-12
B1-OFF-NoLight-13
B1-OFF-NoLight-14
B1-OFF-NoLight-2
B1-OFF-NoLight-4
B1-OFF-NoLight-5
B1-OFF-NoLight-6
B1-OFF-NoLight-7
B1-OFF-NoLight-8
B1-OFF-NoLight-9



IV Curves vs Radiation, Low Radiation, FBK-3x3
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B1-ON-NoLight-13
B1-ON-NoLight-14
B1-ON-NoLight-2
B1-ON-NoLight-3
B1-ON-NoLight-4
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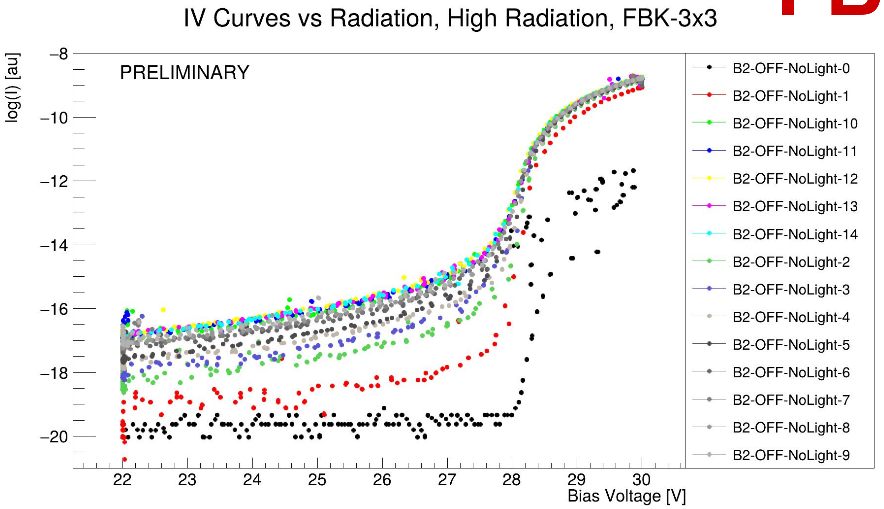
B1-ON-NoLight-9



IV Curves vs Radiation, High Radiation, FBK-3x3
PRELIMINARY
log(I) [au]
−8
−10
−12
−14
−16
−18
−20
22
23
24
25
26
27
28
29
30
Bias Voltage [V]
B2-OFF-NoLight-0
B2-OFF-NoLight-1
B2-OFF-NoLight-10
B2-OFF-NoLight-11
B2-OFF-NoLight-12
B2-OFF-NoLight-13
B2-OFF-NoLight-14
B2-OFF-NoLight-2
B2-OFF-NoLight-3
B2-OFF-NoLight-4
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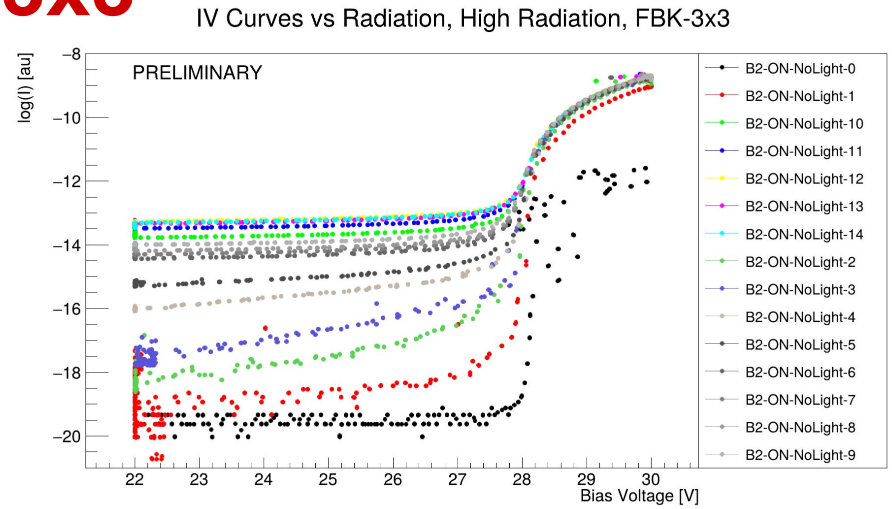
B2-OFF-NoLight-9



IV Curves vs Radiation, High Radiation, FBK-3x3
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−8
−10
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−14
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22
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24
25
26
27
28
29
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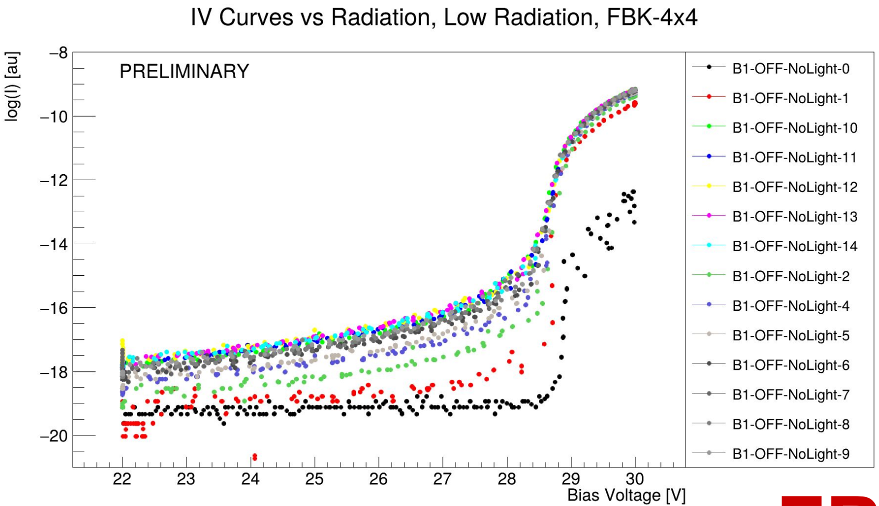
Bias Voltage [V]
B2-ON-NoLight-0
B2-ON-NoLight-1
B2-ON-NoLight-10
B2-ON-NoLight-11
B2-ON-NoLight-12
B2-ON-NoLight-13
B2-ON-NoLight-14
B2-ON-NoLight-2
B2-ON-NoLight-3
B2-ON-NoLight-4
B2-ON-NoLight-5
B2-ON-NoLight-6
B2-ON-NoLight-7
B2-ON-NoLight-8
B2-ON-NoLight-9

FBK 4x4


IV Curves vs Radiation, Low Radiation, FBK-4x4
PRELIMINARY
log(I) [au]
Bias Voltage [V]
B1-OFF-NoLight-0
B1-OFF-NoLight-1
B1-OFF-NoLight-10
B1-OFF-NoLight-11
B1-OFF-NoLight-12
B1-OFF-NoLight-13
B1-OFF-NoLight-14
B1-OFF-NoLight-2
B1-OFF-NoLight-4
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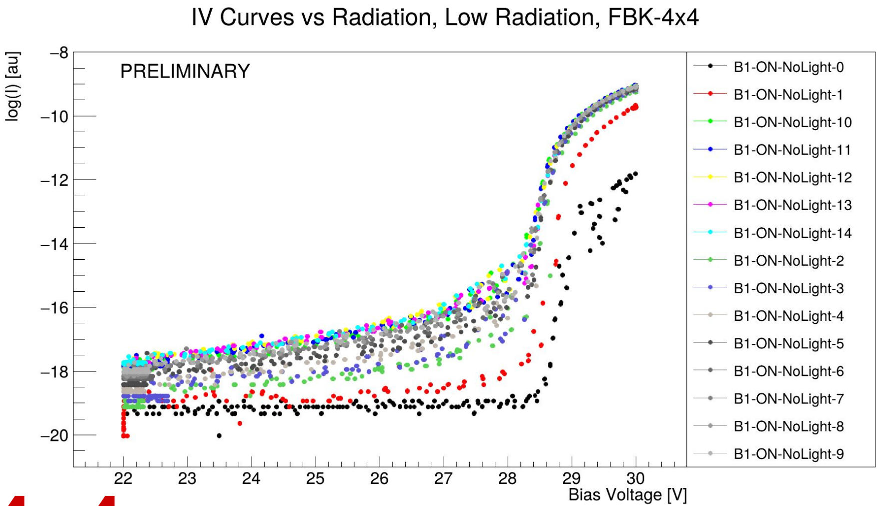
B1-OFF-NoLight-9


IV Curves vs Radiation, Low Radiation, FBK-4x4
PRELIMINARY
log(I) [au]
Bias Voltage [V]
B1-ON-NoLight-0
B1-ON-NoLight-1
B1-ON-NoLight-10
B1-ON-NoLight-11
B1-ON-NoLight-12
B1-ON-NoLight-13
B1-ON-NoLight-14
B1-ON-NoLight-2
B1-ON-NoLight-3
B1-ON-NoLight-4
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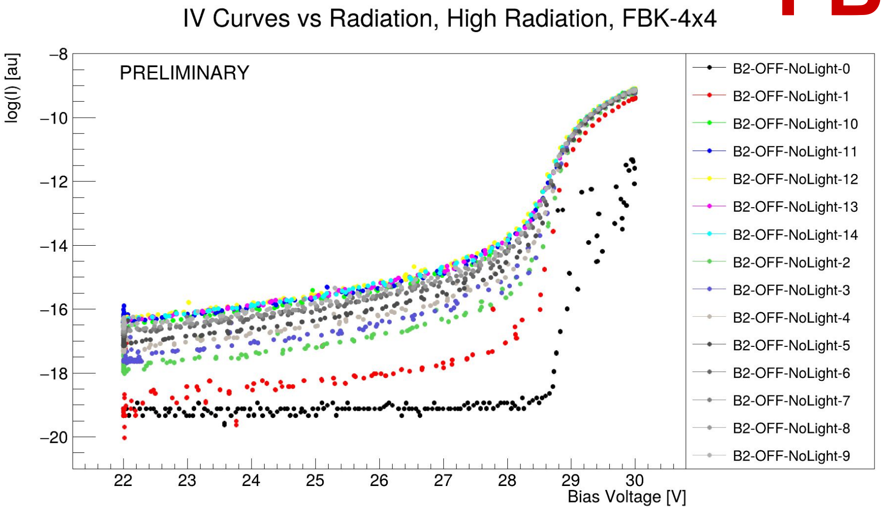
B1-ON-NoLight-9


IV Curves vs Radiation, High Radiation, FBK-4x4
PRELIMINARY
log(I) [au]
Bias Voltage [V]
B2-OFF-NoLight-0
B2-OFF-NoLight-1
B2-OFF-NoLight-10
B2-OFF-NoLight-11
B2-OFF-NoLight-12
B2-OFF-NoLight-13
B2-OFF-NoLight-14
B2-OFF-NoLight-2
B2-OFF-NoLight-3
B2-OFF-NoLight-4
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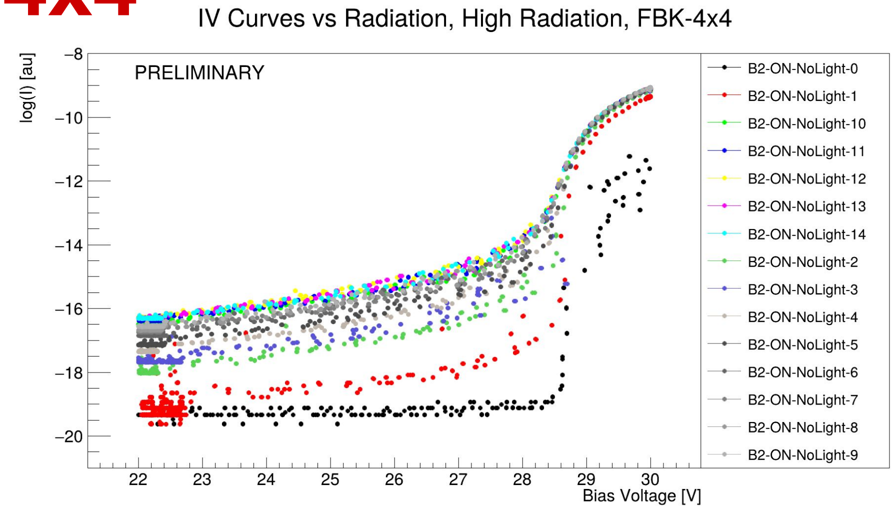
B2-OFF-NoLight-8
B2-OFF-NoLight-9


IV Curves vs Radiation, High Radiation, FBK-4x4
PRELIMINARY
log(I) [au]
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B2-ON-NoLight-0
B2-ON-NoLight-1
B2-ON-NoLight-10
B2-ON-NoLight-11
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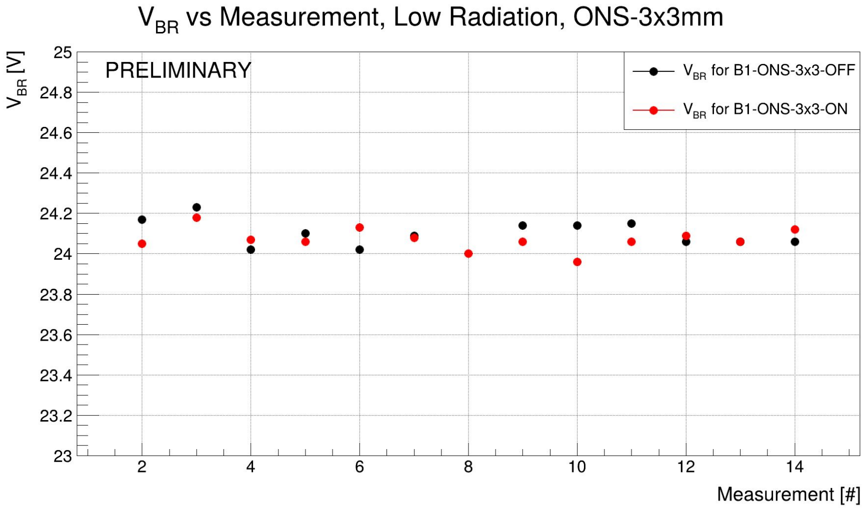
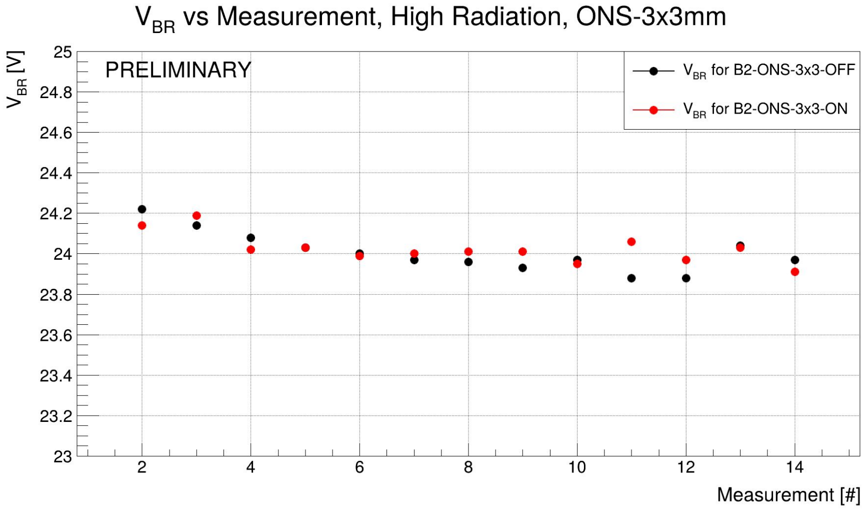
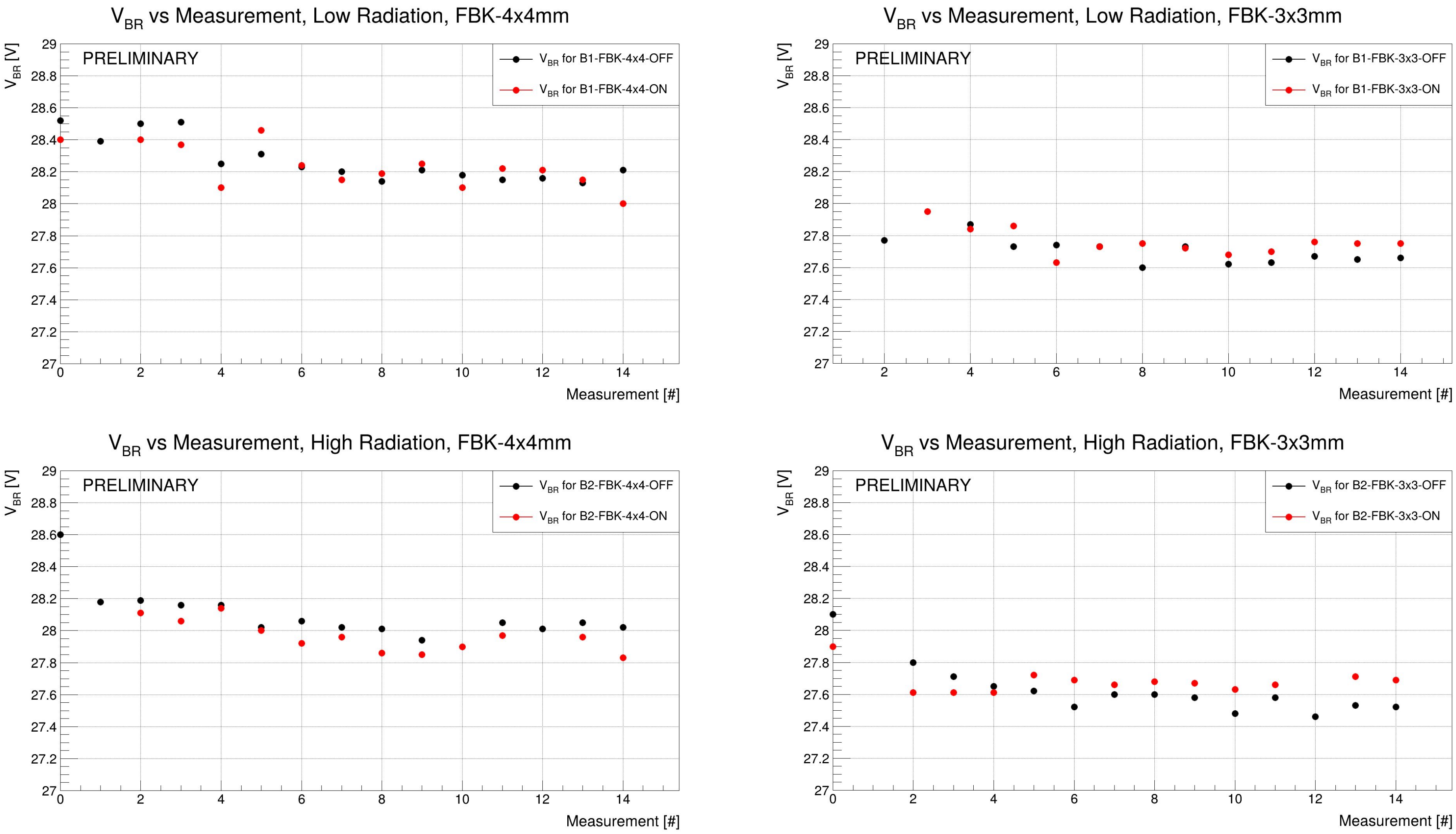
B2-ON-NoLight-14
B2-ON-NoLight-2
B2-ON-NoLight-3
B2-ON-NoLight-4
B2-ON-NoLight-5
B2-ON-NoLight-6
B2-ON-NoLight-7
B2-ON-NoLight-8
B2-ON-NoLight-9

Breakdown voltage

- Data on whether V_{BR} is affected by irradiation is rather inconclusive.
- One can argue for a drop in V_{BR}, especially noticeable on graphs which have the “No dose” point.
- Data is unfortunately noisy, so more robust methods need to be employed.
- Using final 3 points, errors can be estimated to about:
  - 0.1 V for ONS-3x3.
  - 0.2 V for FBK-3x3.
- When “No dose” point is taken into account, this error does not account for the drop observed.





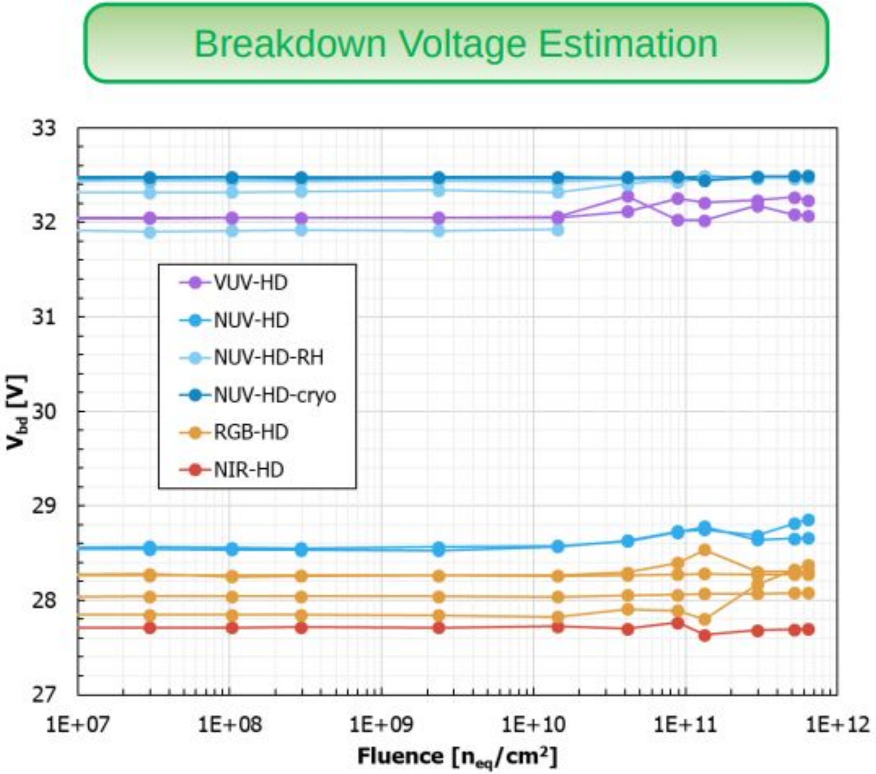


V_BR vs Measurement, Low Radiation, FBK-4x4mm
PRELIMINARY
V_BR for B1-FBK-4x4-OFF
V_BR for B1-FBK-4x4-ON
V_BR [V]
Measurement [#]
V_BR vs Measurement, Low Radiation, FBK-3x3mm
PRELIMINARY
V_BR for B1-FBK-3x3-OFF
V_BR for B1-FBK-3x3-ON
V_BR [V]
Measurement [#]
V_BR vs Measurement, High Radiation, FBK-4x4mm
PRELIMINARY
V_BR for B2-FBK-4x4-OFF
V_BR for B2-FBK-4x4-ON
V_BR [V]
Measurement [#]
V_BR vs Measurement, High Radiation, FBK-3x3mm
PRELIMINARY
V_BR for B2-FBK-3x3-OFF
V_BR for B2-FBK-3x3-ON
V_BR [V]
Measurement [#]

Data vs literature

- FBK's private tests show no consistent change in V_{BR} - result needs to be further verified.

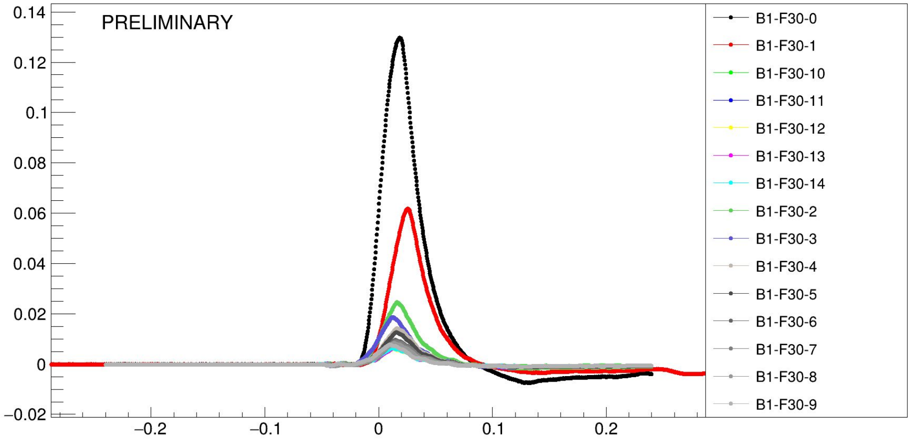
- The reason for the disagreement would need to be investigated.



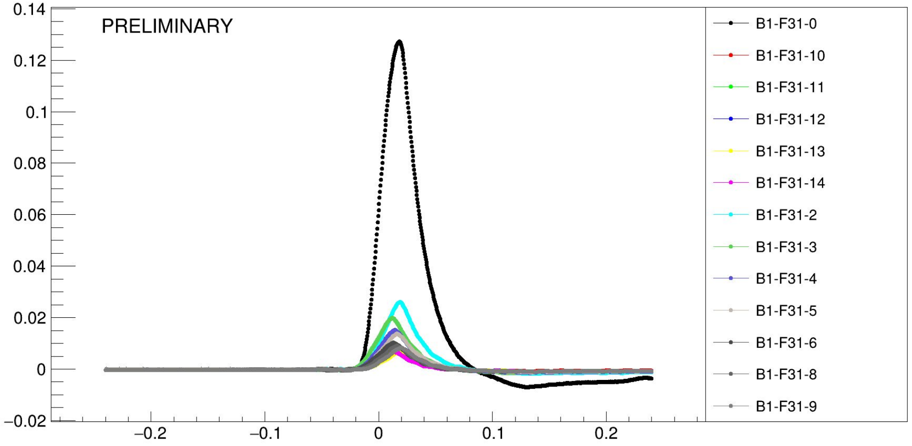
FBK Data on change of V_{BR} with irradiation. Source: https://indico.in2p3.fr/event/31710/contributions/138644/attachments/85123/127340/2024-06-03%20-%20Alberto%20Gola%20-%20SiPM%20roadmap%20-%20LPSC%202024.pdf

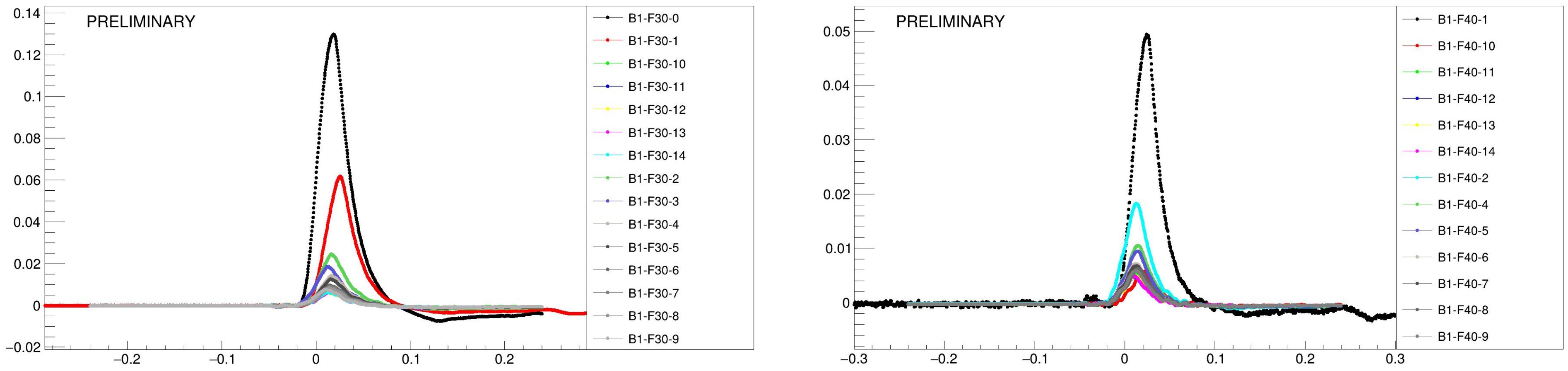
Signals

- Dose results in serious deformation in SiPM signals.
- SiPM amplitude drops by approximately an order of magnitude.
- SiPM signal shape gets distorted.
- For B2-FBK-3x3, difference between ON and OFF is clearly visible, but it is an isolated case.

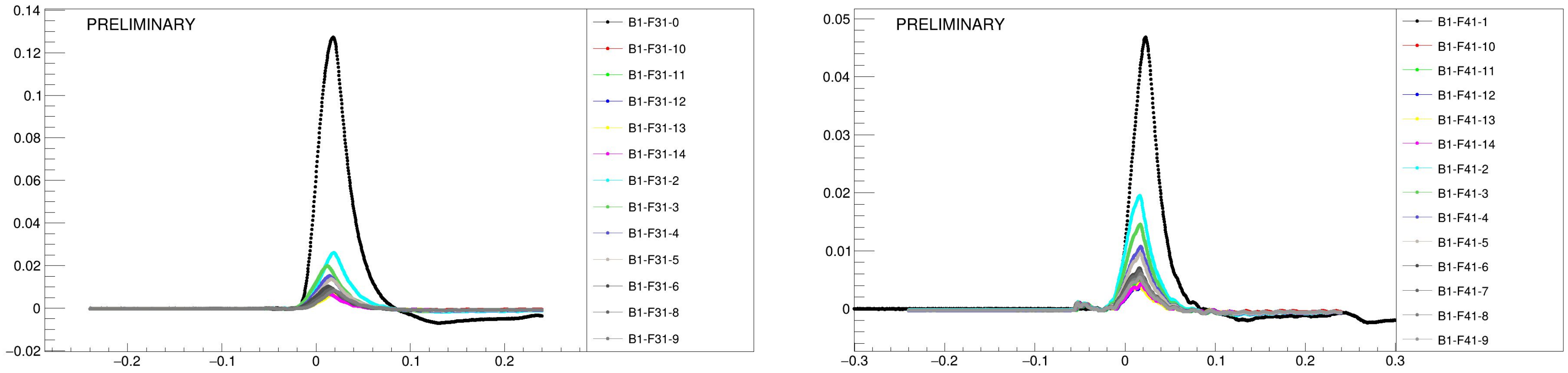


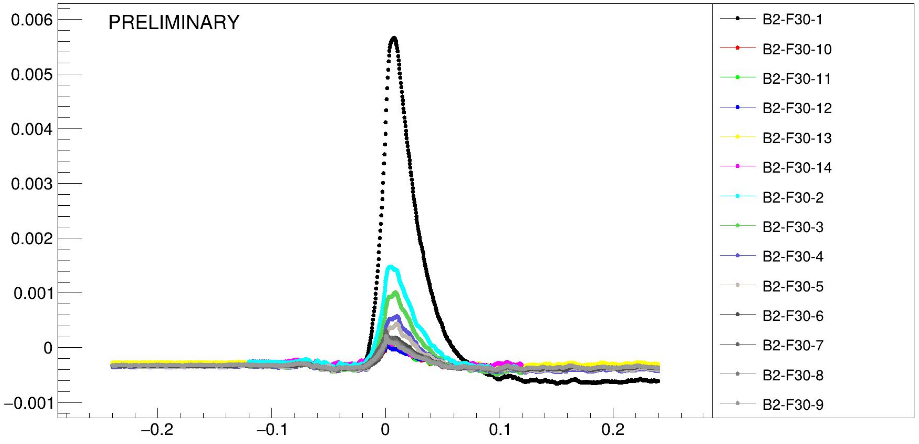
ONS Low irradiation

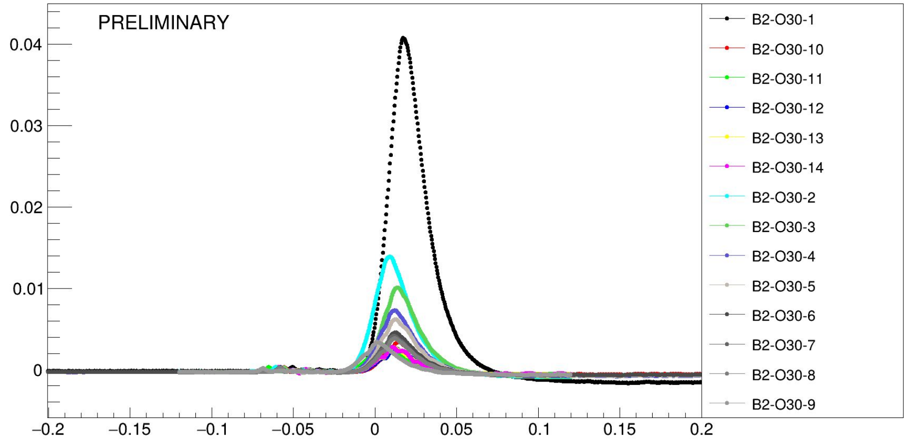




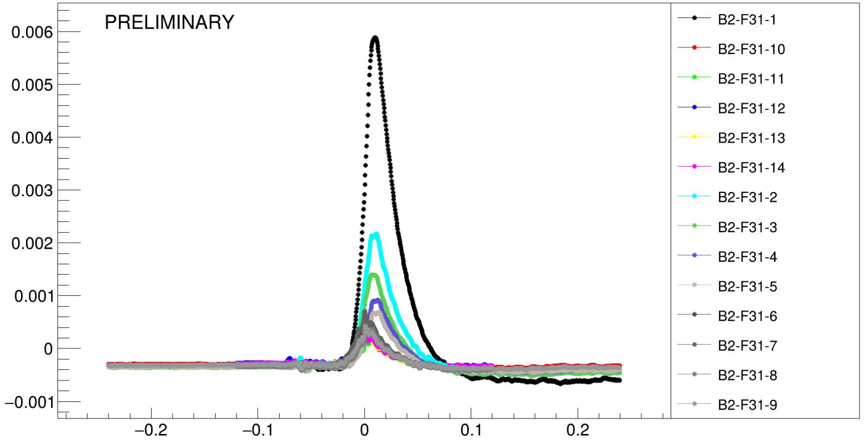
FBK Low irradiation

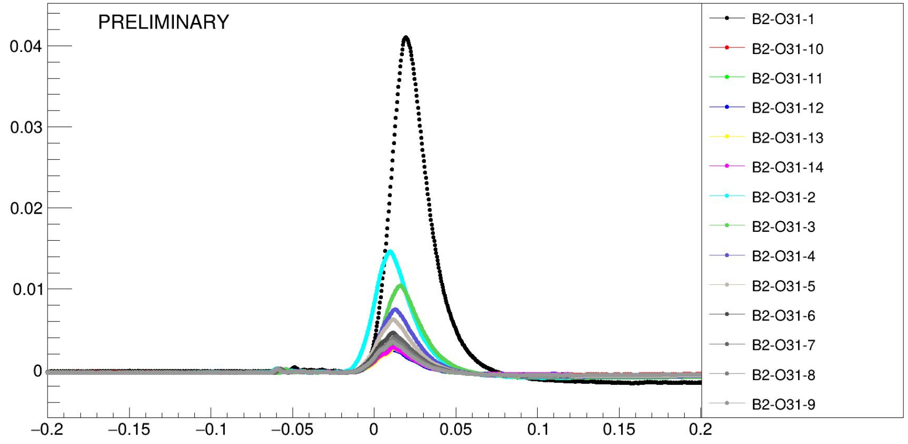






High irradiation





Future plans

- Employ simulations to support the data analysis, to disentangle effects of TID and TNID.
- Another irradiation campaign at CHARM planned for the late summer/early autumn.
- Perform tests with more SiPM samples and more varied and sensitive readout.
- Possible tests on effects of cooling during the irradiation.
- Possible Irradiation with Co-60 source to verify the TID-only.
- Tests with irradiation until destruction.
- Perform tests in the LHC tunnel.

Conclusions

- As expected from literature, dark currents increase with irradiation, but this increase seems to plateau after a point.

- There is little to no difference in damage relating to SiPM state during the irradiation - SiPMs that were powered ON, did not show significant disparity in results, compared to their powered OFF counterparts.

- There is an observed drop in V_{BR} with irradiation, potentially meaning that SiPM gain changes over time. Further analysis needed to minimise impact of errors.

- Further tests featuring more advanced (and varied) measurement procedures are in order.