Characterization of irradiated SiPM for the TOP detector at the Belle II experiment

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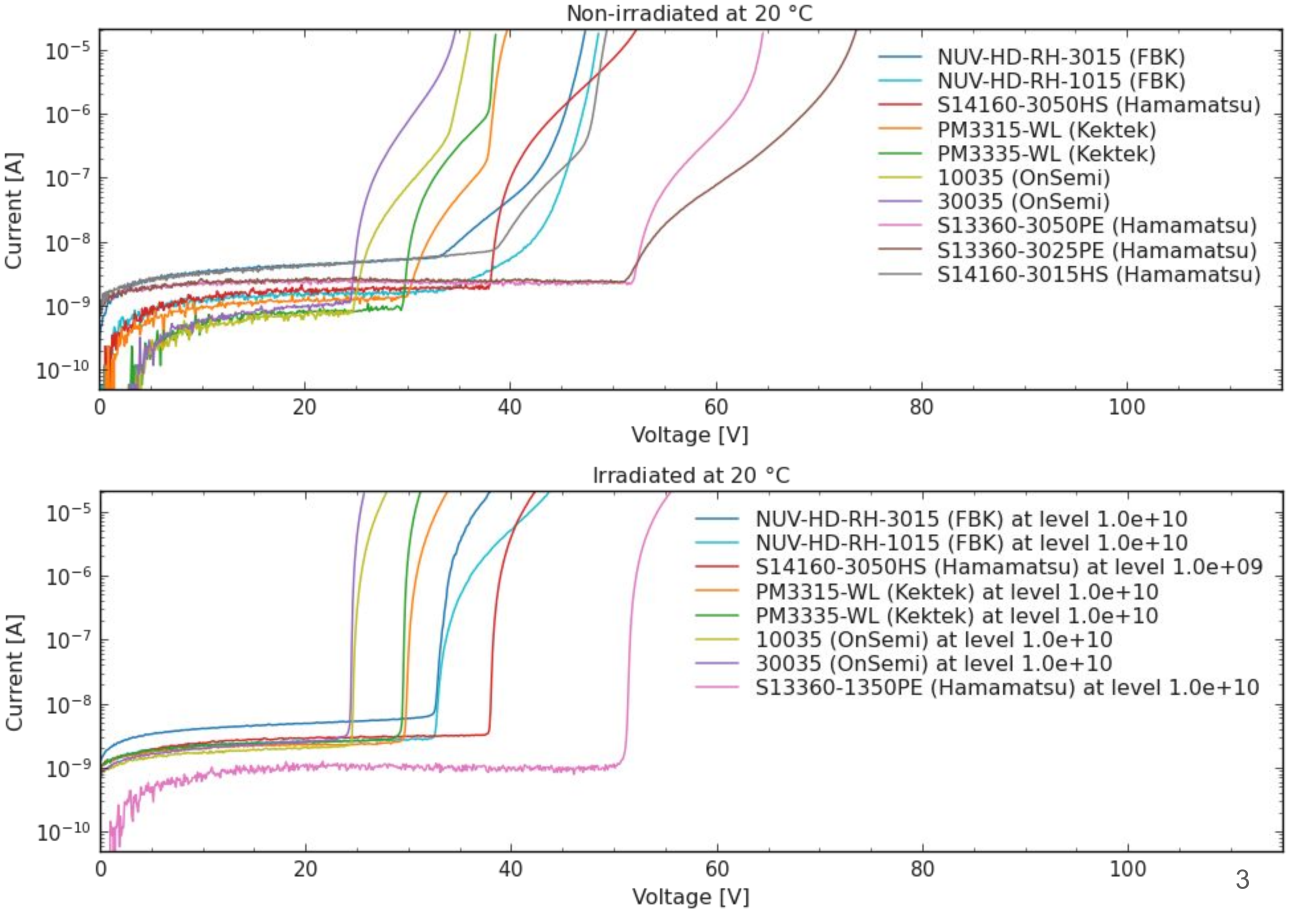
Tests with irradiated modules in Padova

- Eventually MCP-PMTs with extended lifetime can be replaced by SiPMs in next long shutdown.
- We irradiated 32 SiPM modules with different neutron fluxes in Legnaro, tested by laser, processed and analysed
- During analysis, we did:
    - Current voltage characteristics
    - Photon spectra fit using two different methods to extract maximum of photons
    - Extraction breakdown voltage using fitting of gain as function of bias voltage
    - Time resolution of single and two photon peak
    - Dark count rate measurement
- Data was analyzed before irradiation, after irradiation, after annealing (150 °C for 8 weeks) and after re-irradiation

Producer	Code	Index	Dimension [mm×mm]	Pitch [μm]	Irradiation	Re-irradiation
					Neutron 1 MeV eg/cm² fluence	
Hamamatsu	S13360-1350PE	0 - 7	1.3×1.3	50	$5.0{\cdot}10^{11}$ - $1.0{\cdot}10^{9}$	$1.0{\cdot}10^{10}$
FBK	NUV-HD-RH-3015	8 - 10	3×3	15	$1.0{\cdot}10^{10}$ - $1.0{\cdot}10^{9}$	$1.0{\cdot}10^{10}$
FBK	NUV-HD-RH-1015	11 - 14	1×1	15	$2.0{\cdot}10^{10}$ - $1.0{\cdot}10^{9}$	$1.0{\cdot}10^{10}$
Hamamatsu	S14160-3050HS	15, 30, 31	3×3	50	$1.0{\cdot}10^{9}$, $1.0{\cdot}10^{10}$	$1.0{\cdot}10^{10}$
Kektek	PM3315-WL	16, 17	3×3	15	$1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$	$1.0{\cdot}10^{10}$
Kektek	PM3335-WL	18, 19	3×3	35	$1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$	$1.0{\cdot}10^{10}$
OnSemi	10035	20, 21	1×1	35	$1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$	$1.0{\cdot}10^{10}$
OnSemi	30035	22, 23	3×3	35	$1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$	$1.0{\cdot}10^{10}$
Hamamatsu	S13360-3025PE	24, 25	3×3	25	$1.0{\cdot}10^{10}$	
Hamamatsu	S13360-3050PE	26, 27	3×3	50	$1.0{\cdot}10^{10}$	
Hamamatsu	S14160-3015PS	28, 29	3×3	15	$1.0{\cdot}10^{10}$	

Current-voltage characteristics

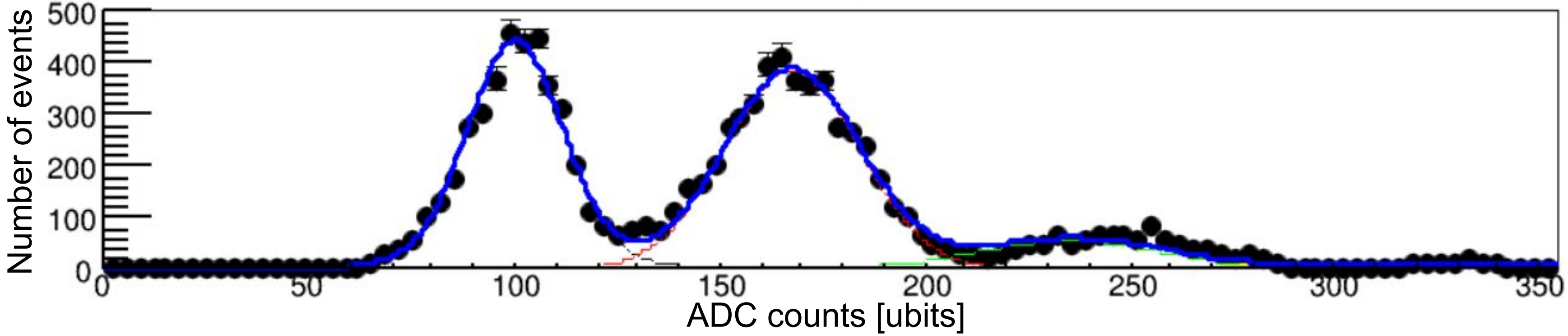
- Current-voltage characteristics have been checked for several modules
- For non-irradiated data current-voltage characteristics slightly change as function of temperature
- For modules produced by FBK, breakdown voltage changed about 6 to 10 V as function of temperature (backup)
- Current-voltage characteristics for irradiated data changed rapidly in comparison with non-irradiated data, but breakdown voltages are consistent with non-irradiated data.



Photon spectra and time resolution fits

- We are using two different methods for extraction of maximum of photons:
  - Standard algorithm
  - Background subtracting algorithm
- The photon spectra is fitted by poissonian distribution convoluted with gaussian(s)
- Time resolution is fitted twice with gaussian, in the second fit the fitting window is in range ($-5 \cdot$ sigma, sigma) of previous fit
- In high temperatures or with large detection area (highly irradiated) modules do not provide sufficient results for photon spectra fit.

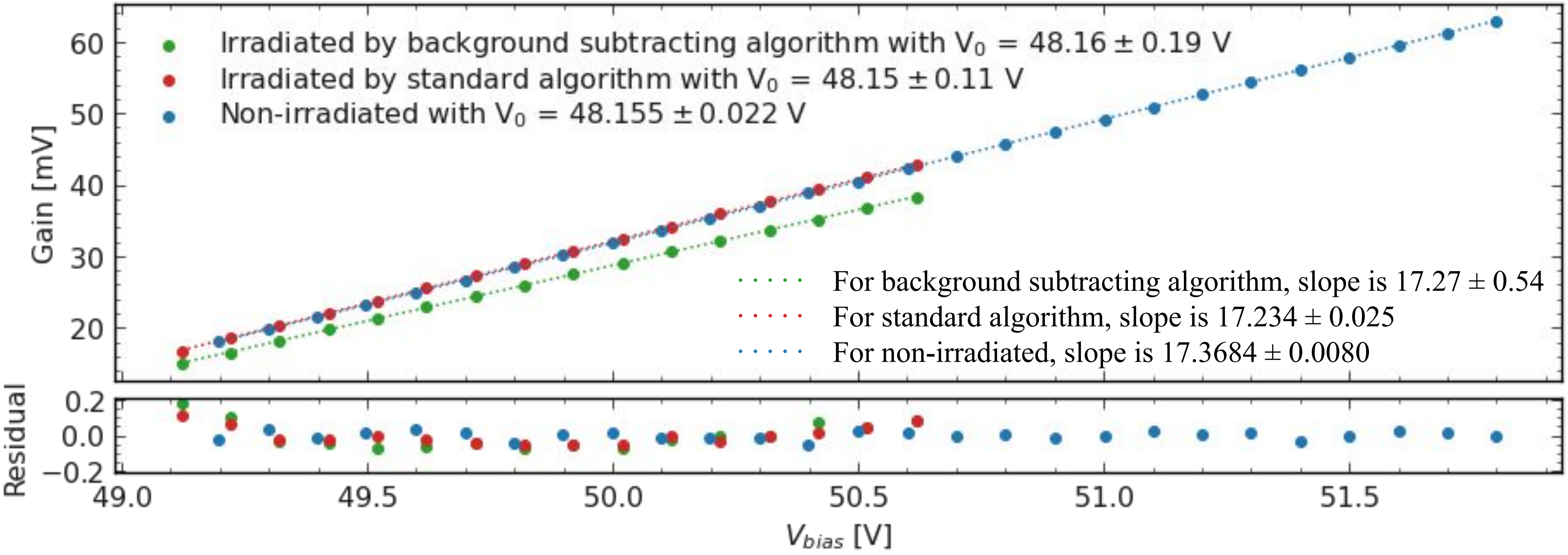
S13360-1350 by Hamamatsu (1.3 mm × 1.3 mm × 50 µm) at level $1 \cdot 10^{10}$ at -35 °C



Extraction breakdown voltage

- Breakdown voltage are extracted using linear fit of gains as function of bias voltage
- Extracted breakdown voltage after irradiation is consistent with results before irradiation
- Background subtracting algorithm provides less precise result than standard algorithm
- The slope of linear fit is less precise for background subtracting algorithm too.

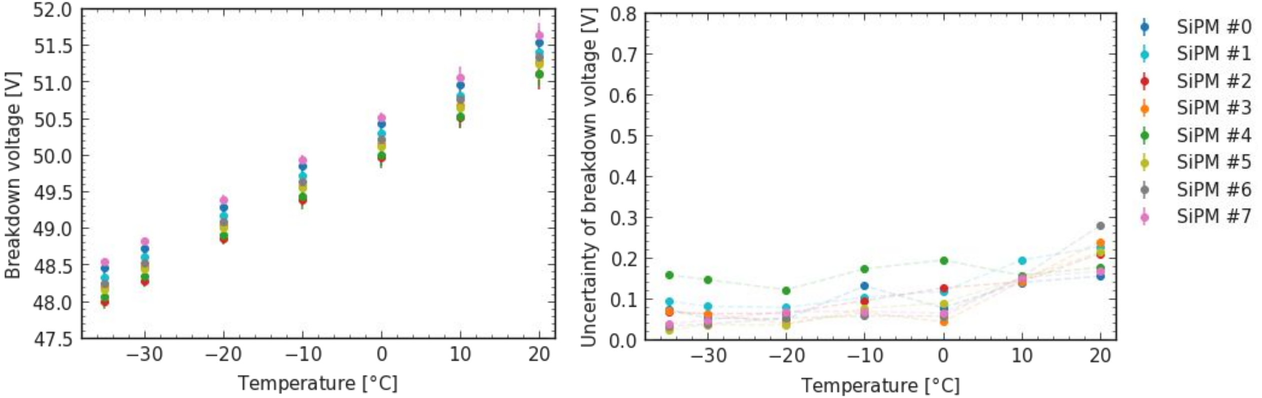
S13360-1350 by Hamamatsu (1.3 mm × 1.3 mm × 50 μm) at level $1 \cdot 10^{10}$ at -35 °C



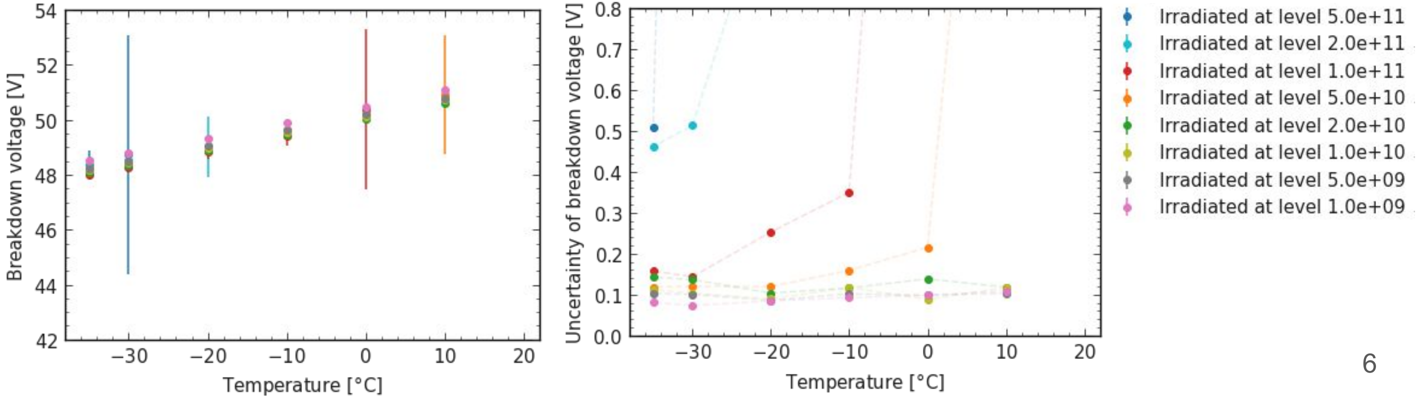
Breakdown voltage as function of temperature

- Breakdown voltages slightly decreasing as function of temperature, but it is not large as for FBK modules observed using current voltage characteristics
- For non-irradiated data, we can see the most precise breakdown voltage between -30 °C and -20 °C
- For high irradiations ($5 \cdot 10^{10}$ and more), the breakdown voltages are more precise for lower temperatures.

Before irradiation

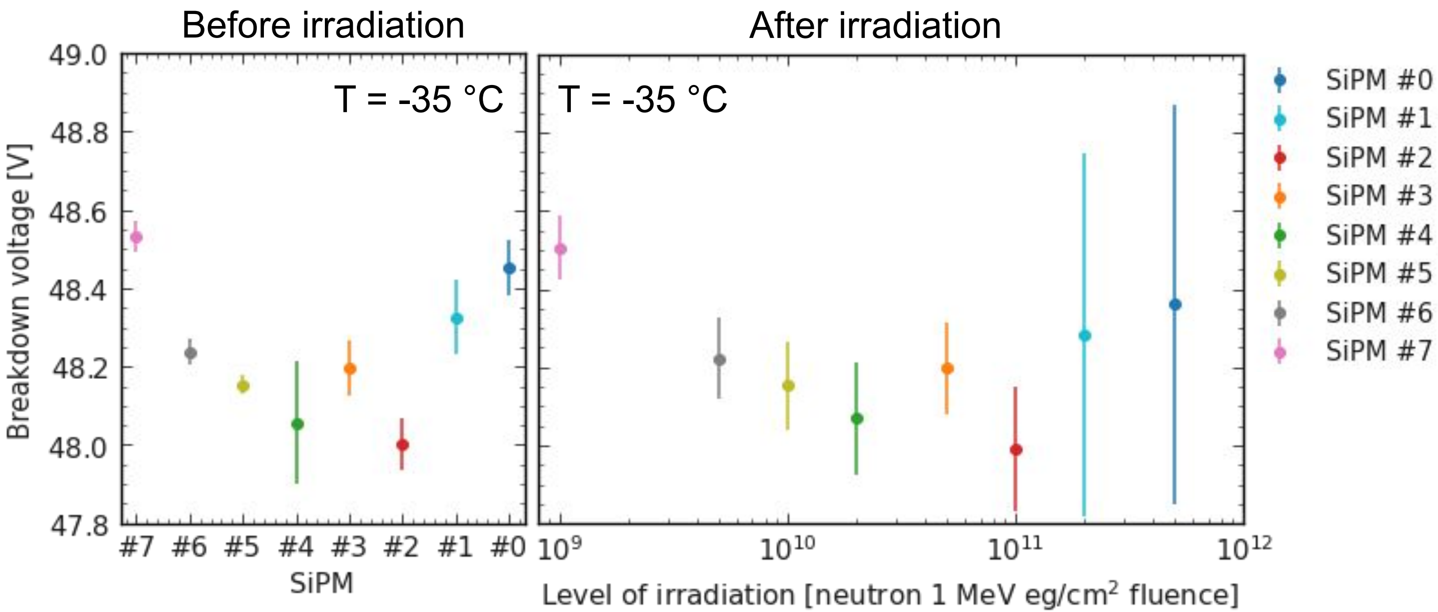


After irradiation



Breakdown voltage as function of irradiation

- Breakdown voltage as function of irradiation level does not show any discrepancy.
- Values of breakdown voltages look consistent with values before irradiation.
- Uncertainties of breakdown voltage are higher for high irradiation levels, where it is more difficult extract clear photon spectra than for less irradiated environment.

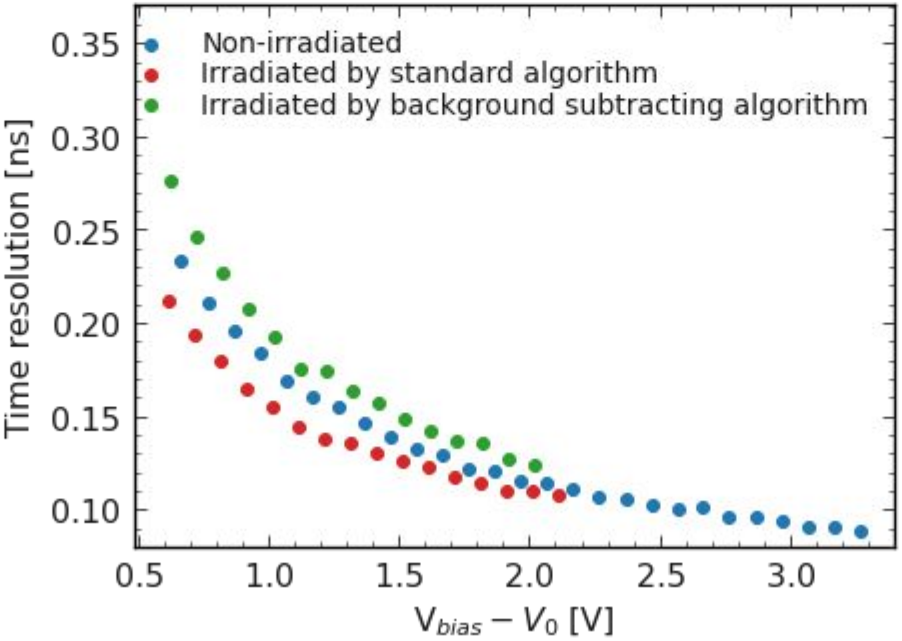


Time resolution

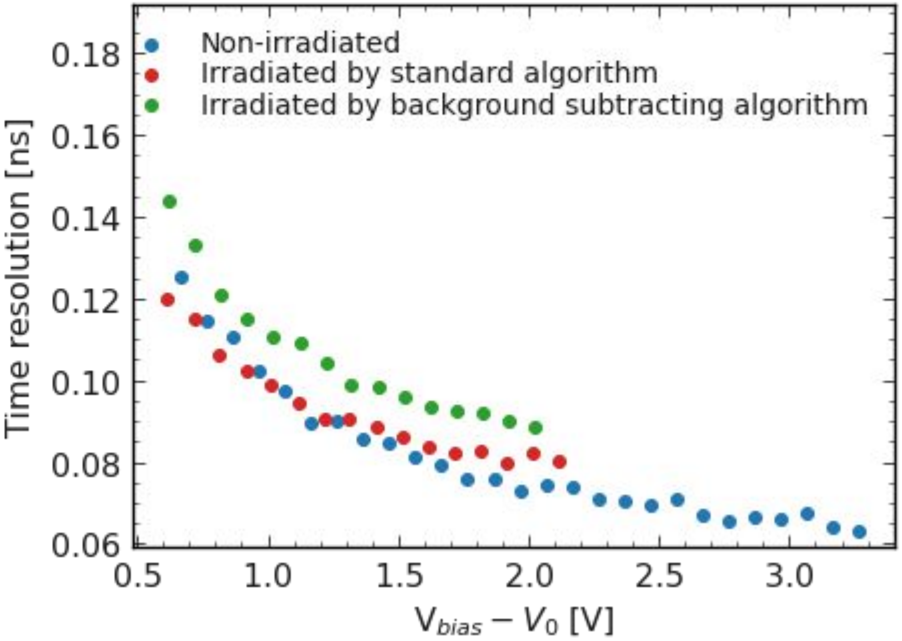
- Another check has been provided using time resolution of single and two photon peaks.
- Time resolutions as function of overvoltage demonstrate consistency results before and after irradiation.
- Both algorithms have similar results, but background subtracting algorithm is slightly worse.

S13360-1350 by Hamamatsu (1.3 mm × 1.3 mm × 50 µm) at level $1 \cdot 10^{10}$ at -35 °C

Single photon peak

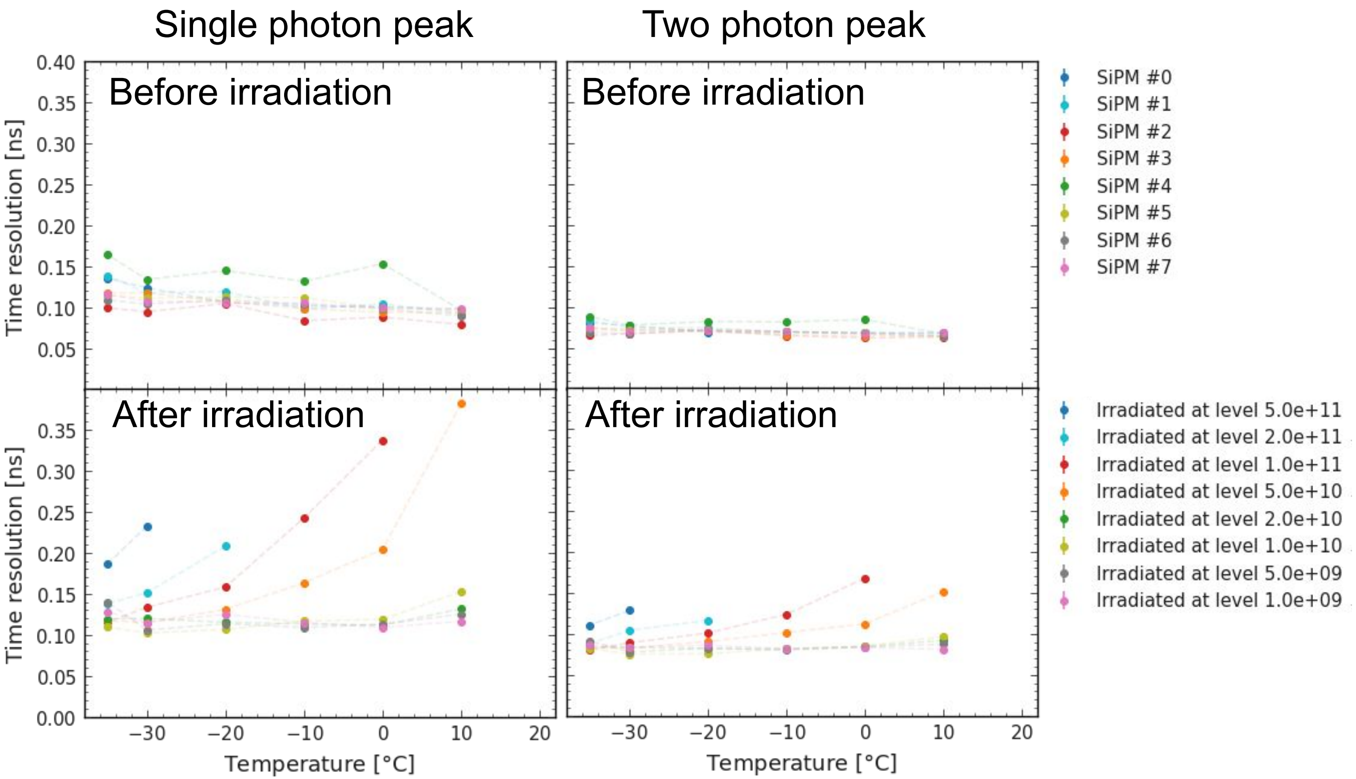


Two photon peak



Time resolution as function of temperature

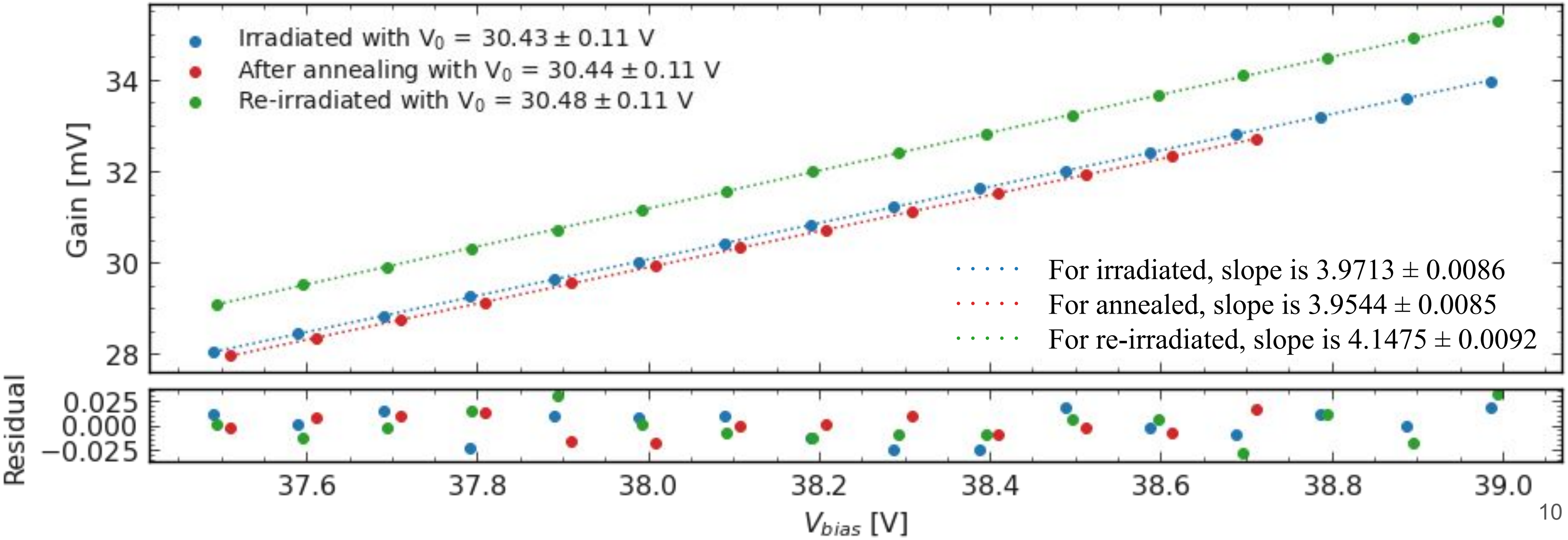
- Overvoltage set to 2 V
- For non-irradiated data, the most precise results can be observed between -30 °C and -20 °C.
- For high irradiation levels ($5 \cdot 10^{10}$ and more), time resolution is significantly dependent on temperature.
- Lower temperatures can improve time resolution, but not in case very high irradiation levels.



Photon spectra for annealing and re-irradiation

- Breakdown voltages have been check for annealed and re-irradiated data too.
- Level of re-irradiation is the same as level of irradiation.
- No significant difference between breakdown voltages extracted from irradiated, annealed and re-irradiated data.
- The major difference comes from significantly higher slope for re-irradiated data in compare to other data.

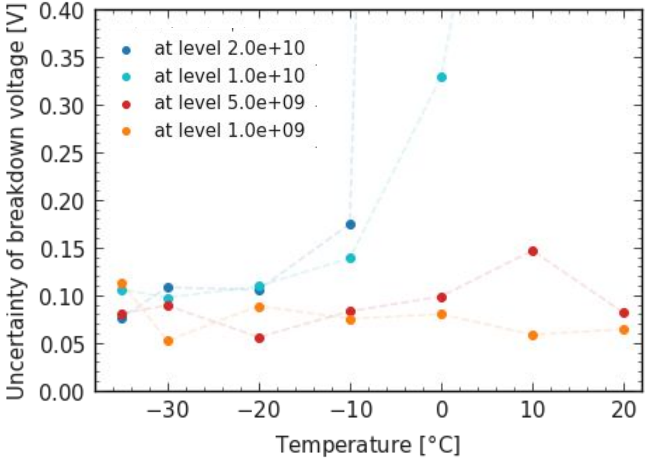
NUV-HD-RH-1015 by FBK (1 mm × 1 mm × 15 μm) at level $1 \cdot 10^{10}$ at -35 °C



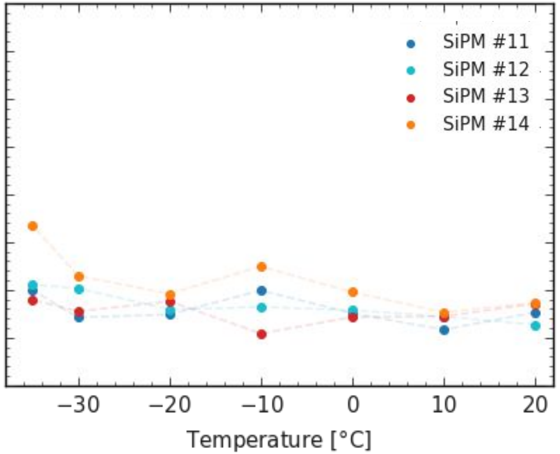
Breakdown voltage as function of temperature

- For irradiated FBK modules, we observed similar results as for irradiated Hamamatsu modules, where optimal candidates for operation temperature are -20 °C and -30 °C.
- Higher irradiation level moves optimal operation temperature to lower values (e.g. -35 °C for $2 \cdot 10^{10}$)
- Precision of higher temperature have been recovered by annealing and it is consistent with lower temperatures.
- For re-irradiated modules, uncertainty of breakdown voltages are consistent with irradiated results.
- Operation on the lower temperature allows to extract breakdown voltage precisely for irradiated, annealed and re-irradiated modules.

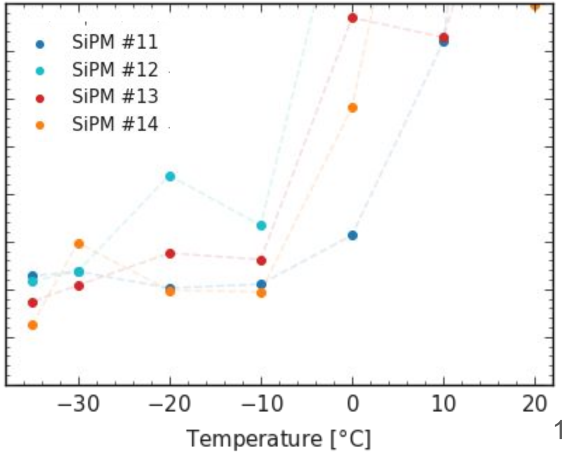
After irradiation



After annealing

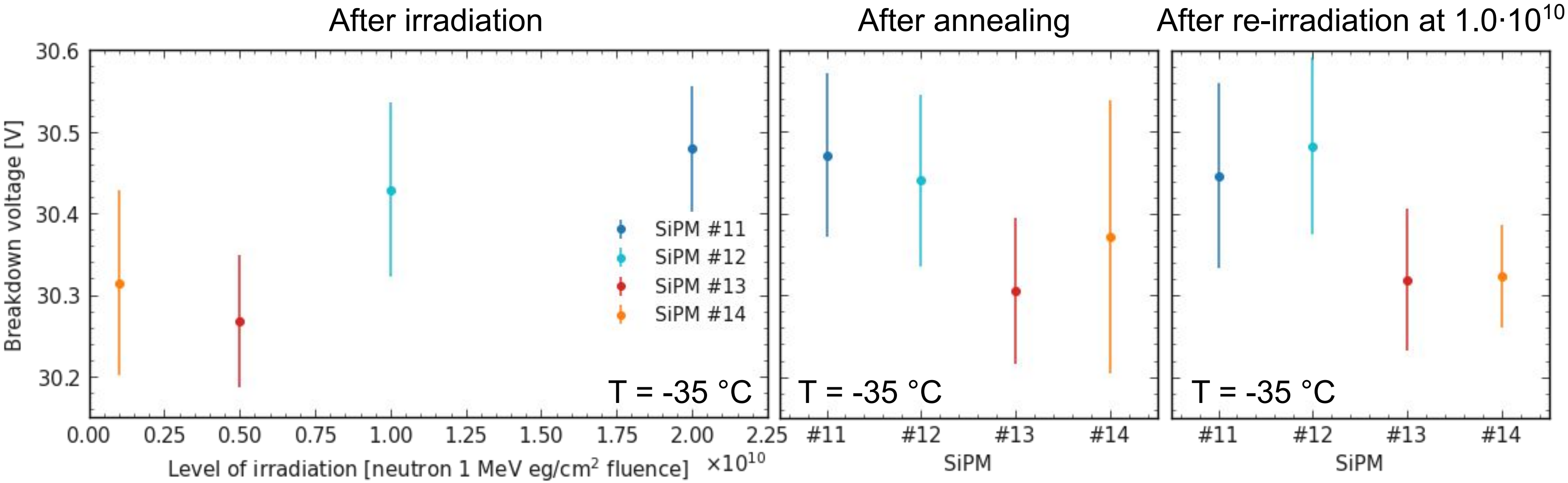


After re-irradiation at $1.0 \cdot 10^{10}$



Breakdown voltage as function of irradiation

- Breakdown voltage as function of irradiation level shows consistency for irradiated, annealed and re-irradiated data

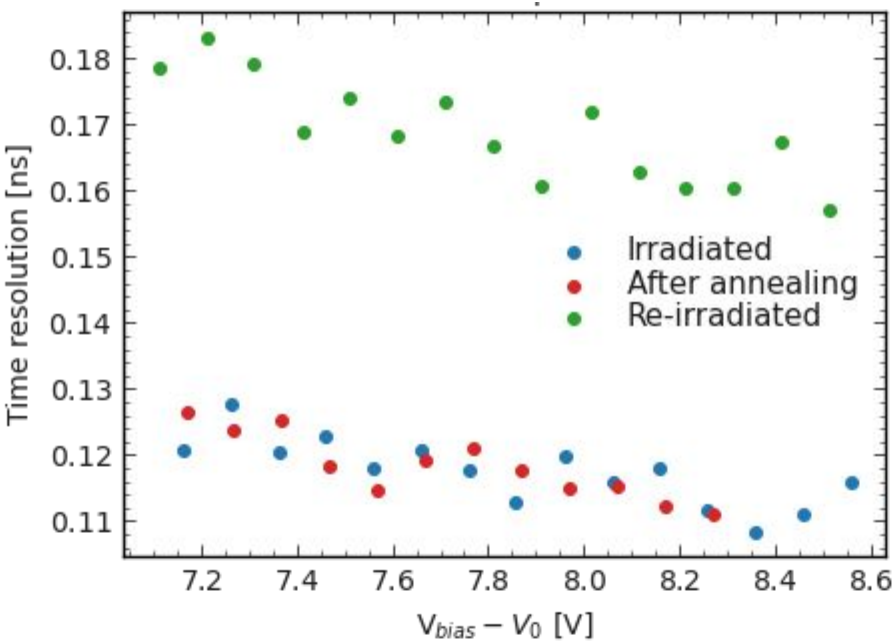


Time resolution for annealing and re-irradiation

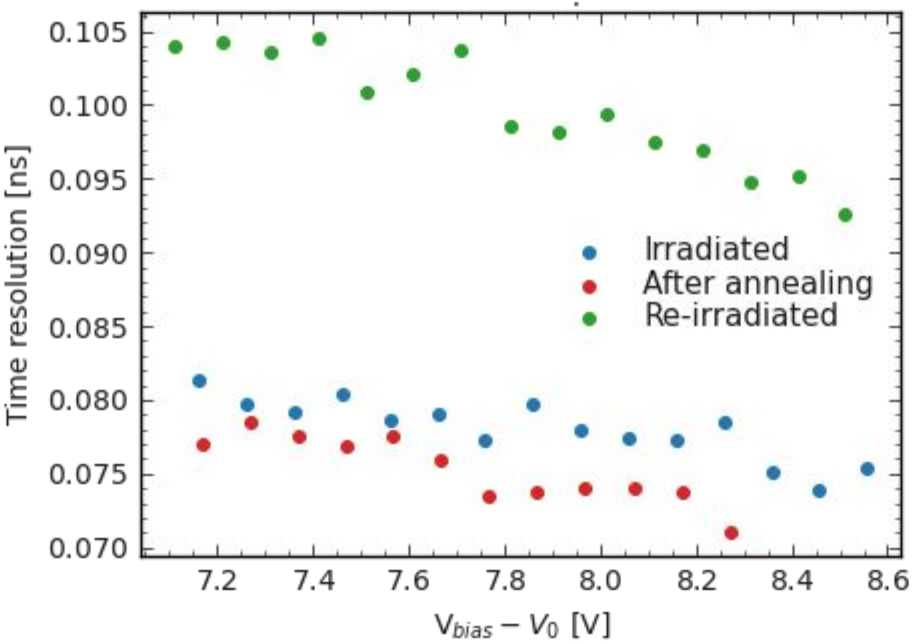
- Time resolution is consistent for irradiated and annealed data.
- We observed significant drop in time resolution between annealed and re-irradiated data about 60% of annealed value.

NUV-HD-RH-1015 by FBK (1 mm × 1 mm × 15 μm) at level $1 \cdot 10^{10}$ at -35 °C

Single photon peak

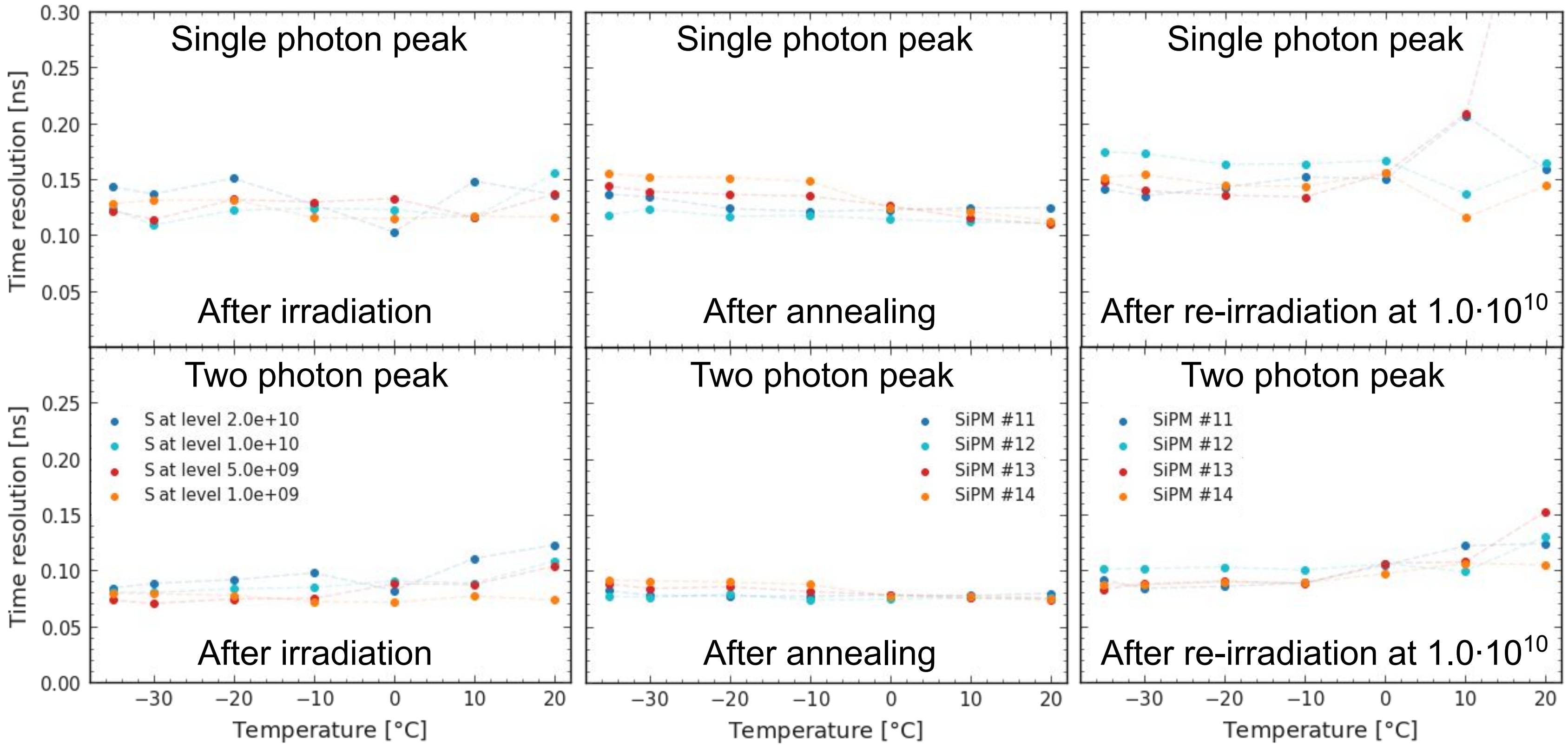


Two photon peak



Time resolution as function of temperature

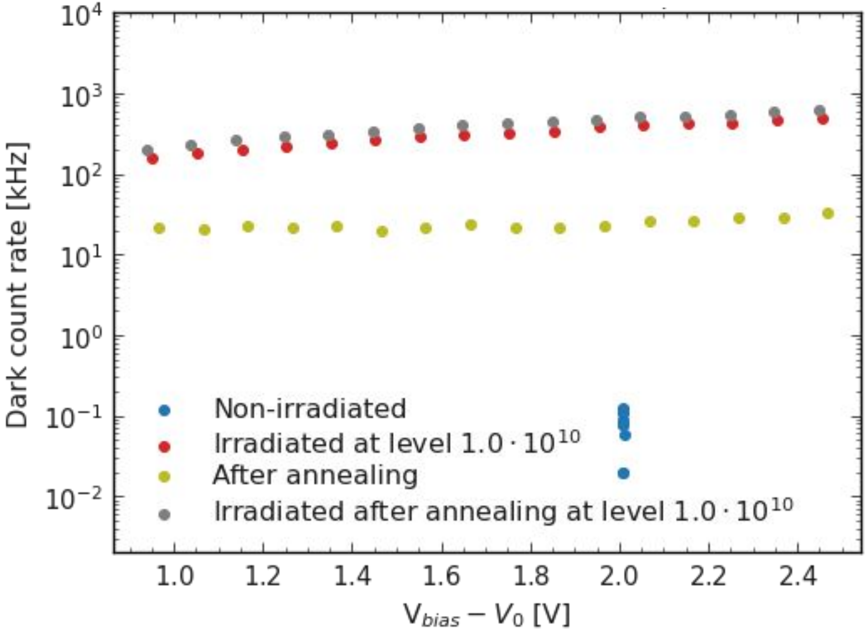
- Overvoltage set to 7.5 V
- Higher time resolution for high temperatures have been recovered by annealing.
- Drop between annealed and re-irradiated data is not significant for all studied modules.



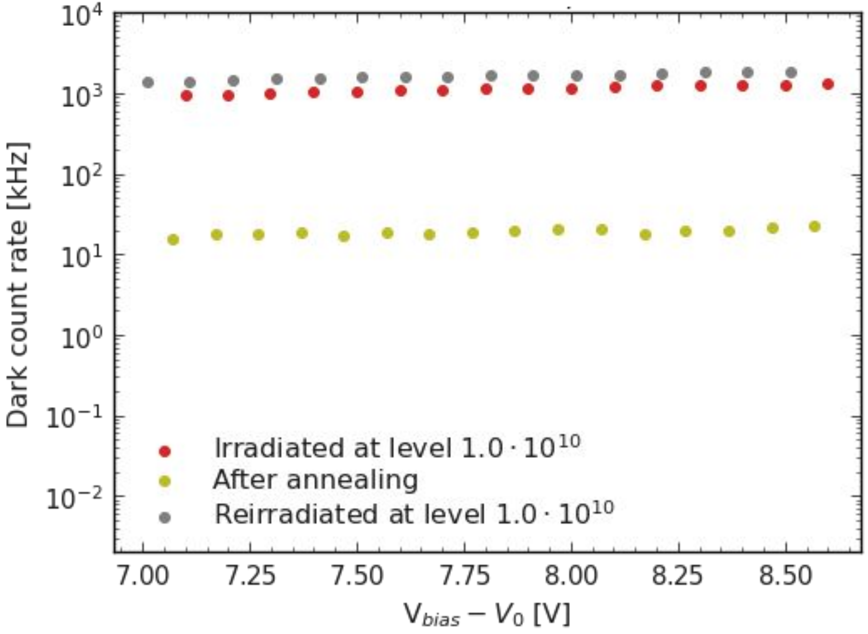
Dark count rates

- We provide dark count rate measurements using non-irradiated, irradiated, annealed data and re-irradiated for several modules.
- Annealing helps to reduce dark count rates on level of several magnitudes.
- Re-irradiated and irradiated results are nicely consistent.

S13360-1350 by Hamamatsu (1.3 mm × 1.3 mm × 50 μm)

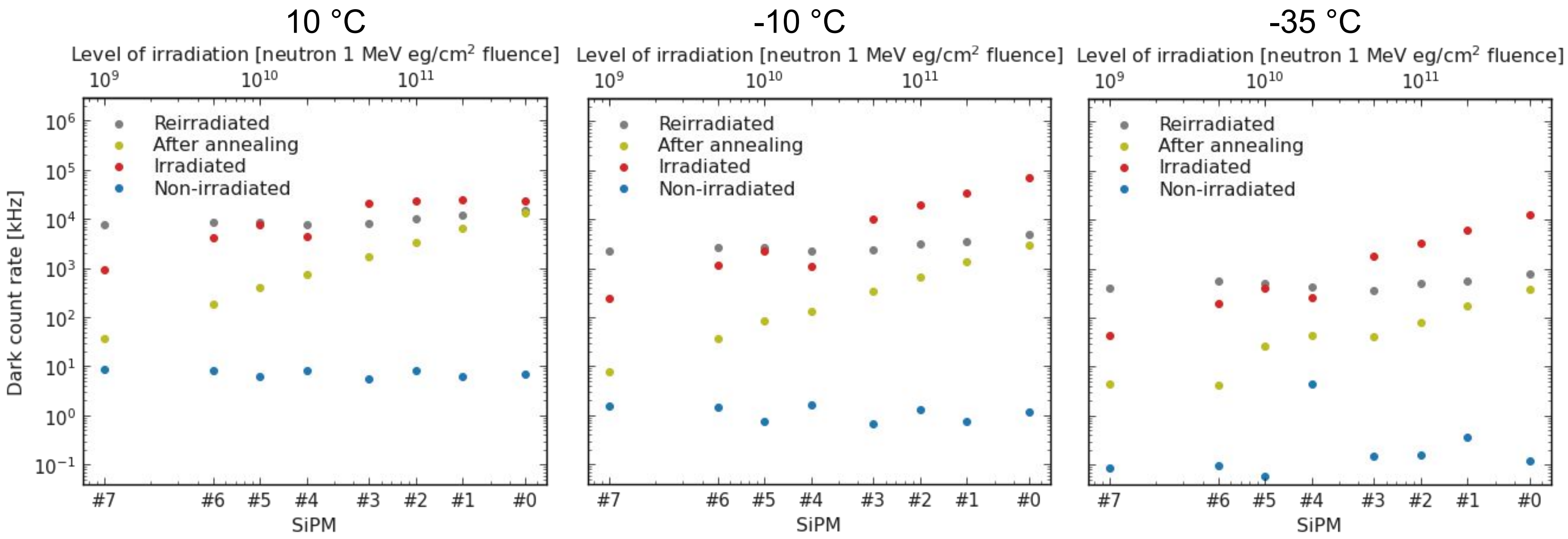


NUV-HD-RH-1015 by FBK (1 mm × 1 mm × 15 μm)



Dark count rates as function of irradiation level

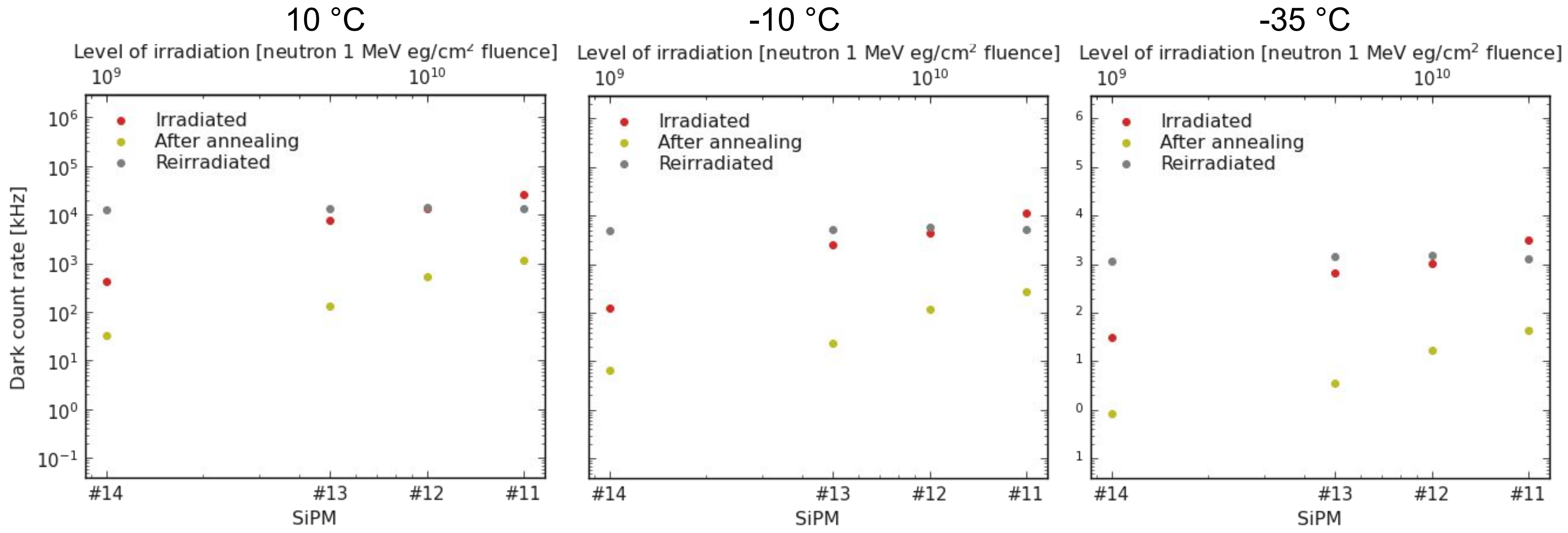
S13360-1350 by Hamamatsu (1.3 mm × 1.3 mm × 50 µm)



- Overvoltage set to 2 V
- Dark count rates can be recovered by annealing, but not to the level before irradiation.
- To remind the modules was re-irradiated at the same level results ($1.0 \cdot 10^{10}$)
- Re-irradiated results are nicely consistent with irradiated.

Dark count rates as function of irradiation level

NUV-HD-RH-1015 by FBK (1 mm × 1 mm × 15 µm)



- Overvoltage set to 7.5 V
- Dark count rates decreased for annealed data, but we can not compare with non-irradiated results.
- Re-irradiated results nicely consistent with irradiated.

Conclusions and outlook

- The 32 SiPM modules were irradiated with different neutron fluxes at Legnaro, tested by laser and analysed.
- Some of them have been annealed (at 150 °C for 8 weeks), processed, re-irradiated and processed again.
- For most of modules, the current-voltage characteristics do not introduce an bias over temperature, irradiation, ...
  - Significant shift of breakdown voltage as function of temperature observed for FBK modules.
- High temperatures, irradiation levels and large detection area does not allow to fit photon spectra in all modules.
- For most of modules:
  - Extracted breakdown voltages are consistent over temperature, irradiation levels and different datasets
  - Uncertainty of breakdown voltages is sensitive to:
    - Temperature (lower temperatures are more optimal)
    - Irradiation level after some value (depends on producer), where lower temperatures are optimal.
  - Background subtracting and standard algorithms for extracting maximum photons have very similar results.
  - Fitted time resolutions are consistent over temperature, irradiation levels and different datasets.
  - Time resolution is sensitive to irradiation level for some modules and lower temperature are optimal
  - Dark count measurements demonstrate
    - Annealing reduces rates, but not to level of non-irradiation.
    - Re-irradiation rate results are same to irradiation observations.
- There are couple of modules, which we need to test, processed and analysed.
- We are starting to writing a paper we would like to publish.

Backup

Tests with irradiated modules in Padova

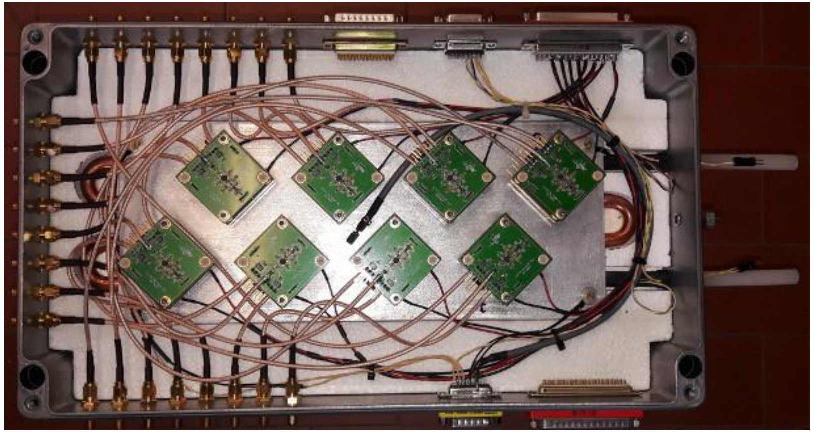
Producer	Code	Index	Non-irradiated	Irradiated	Annealed	Re-irradiated
Hamamatsu	S13360-1350PE[1]	0 - 7	Photon spectra Dark count	Photon spectra Dark count	Dark count	Dark count
FBK	NUV-HD-RH-3015[2]	8 - 10	Dark count	Dark count	Dark count	Dark count
FBK	NUV-HD-RH-1015[3]	11 - 14	Photon spectra Dark count	Photon spectra Dark count	Photon spectra Dark count	Photon spectra Dark count
Hamamatsu	S14160-3050HS[4,5]	15, 30, 31	Photon spectra Dark count	Photon spectra Dark count	Photon spectra Dark count	Photon spectra Dark count
Kektek	PM3315-WL[2]	16, 17	Dark count	Dark count	Dark count	Dark count
Kektek	PM3335-WL[6]	18, 19	Photon spectra Dark count	Dark count	Dark count	Dark count
OnSemi	10035	20, 21	Photon spectra Dark count	Photon spectra Dark count	Photon spectra Dark count	Photon spectra Dark count
OnSemi	30035[6]	22, 23	Photon spectra Dark count	Dark count	Dark count	Dark count
Hamamatsu	S13360-3025PE[7]	24, 25	Photon spectra Dark count			
Hamamatsu	S13360-3050PE[7]	26, 27	Photon spectra Dark count			
Hamamatsu	S14160-3015PS[7]	28, 29	Photon spectra Dark count			

[1] No annealing and re-irradiation data, because photon spectra readout device have been broken.
[2] No photon spectra data, because no peaks identified in spectra.
[3] Non-irradiated data is collected using different bias voltage range as others.
[4] For index 17, Non-irradiated data is collected using different bias voltage range as others.
[5] For indices 30 and 31, non-irradiated data is done and others is analysed now.
[6] Non-irradiated data was analysed, in others no peaks was found in photon spectra.
[7] Non-irradiated data is done and others is analysed now.

Experimental setup

- Measuring characteristics of several available SiPMs for different temperatures and level of irradiations
- Modules have been illuminated with picosecond laser with temperature range from 20 °C to -50 °C

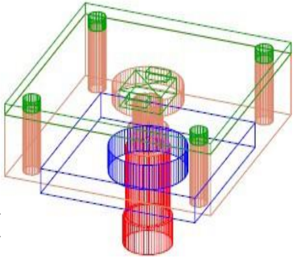
Dark box with SiPM blocks

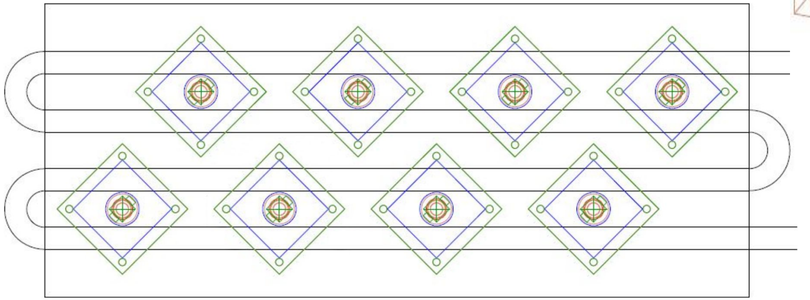


PCB - Amplifier

PCB - SiPM with T sensor

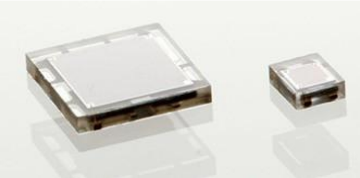
PCB - peltier





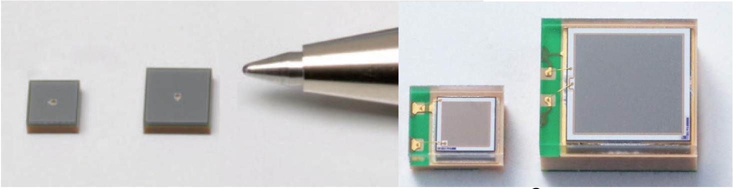
Cooling plate (glycolate water)

OnSemi (35μm)



$3{\times}3$ - $1{\times}1$ mm^2

Hamamatsu (15-25-50 μm)

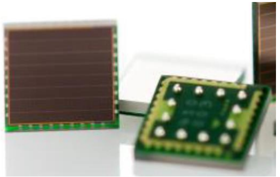


$1.3{\times}1.3$ - $3{\times}3$ mm^2

FBK (15μm)

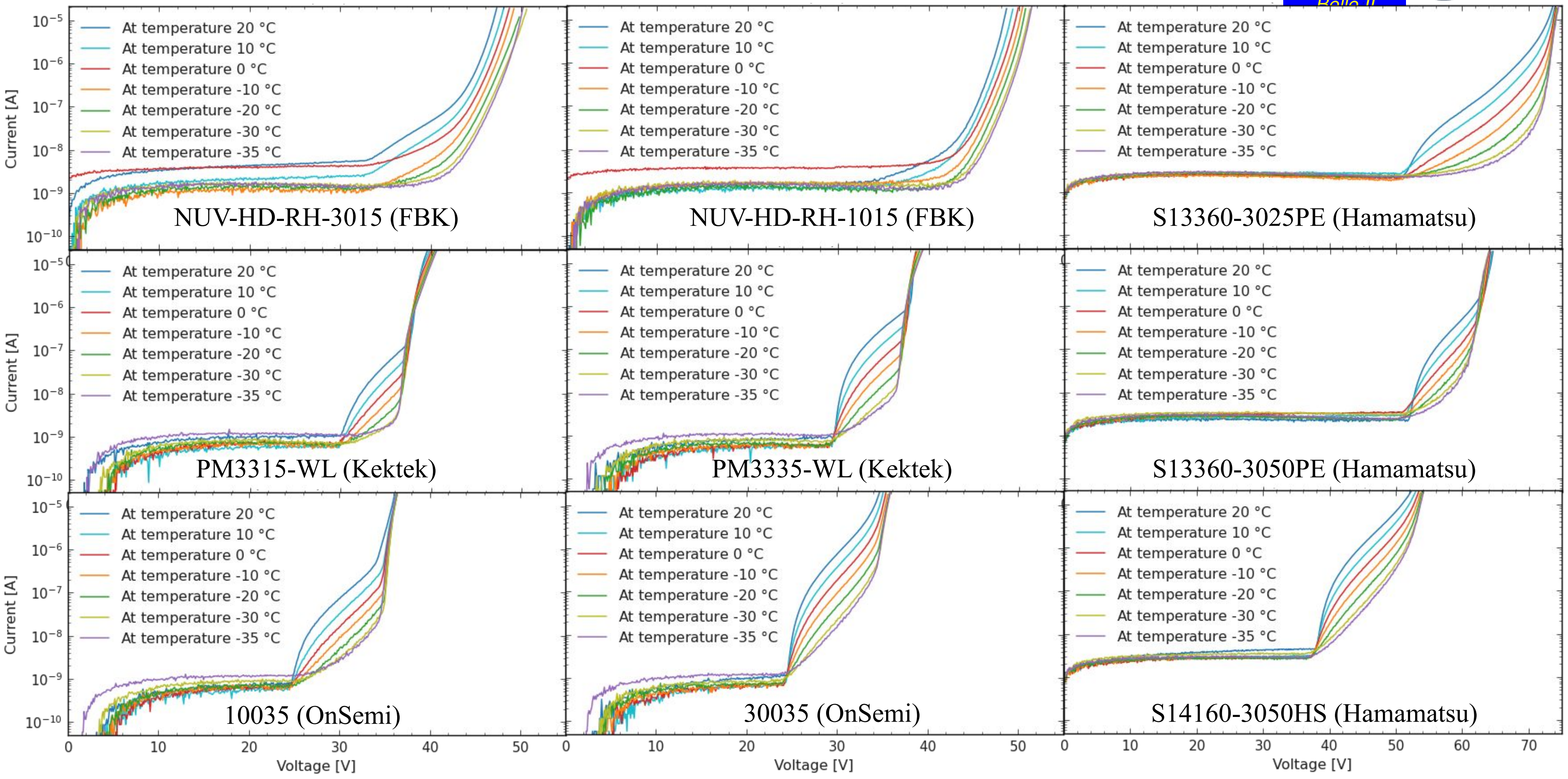
$1{\times}1$ - $3{\times}3$ mm^2

Ketek (15-35 μm)

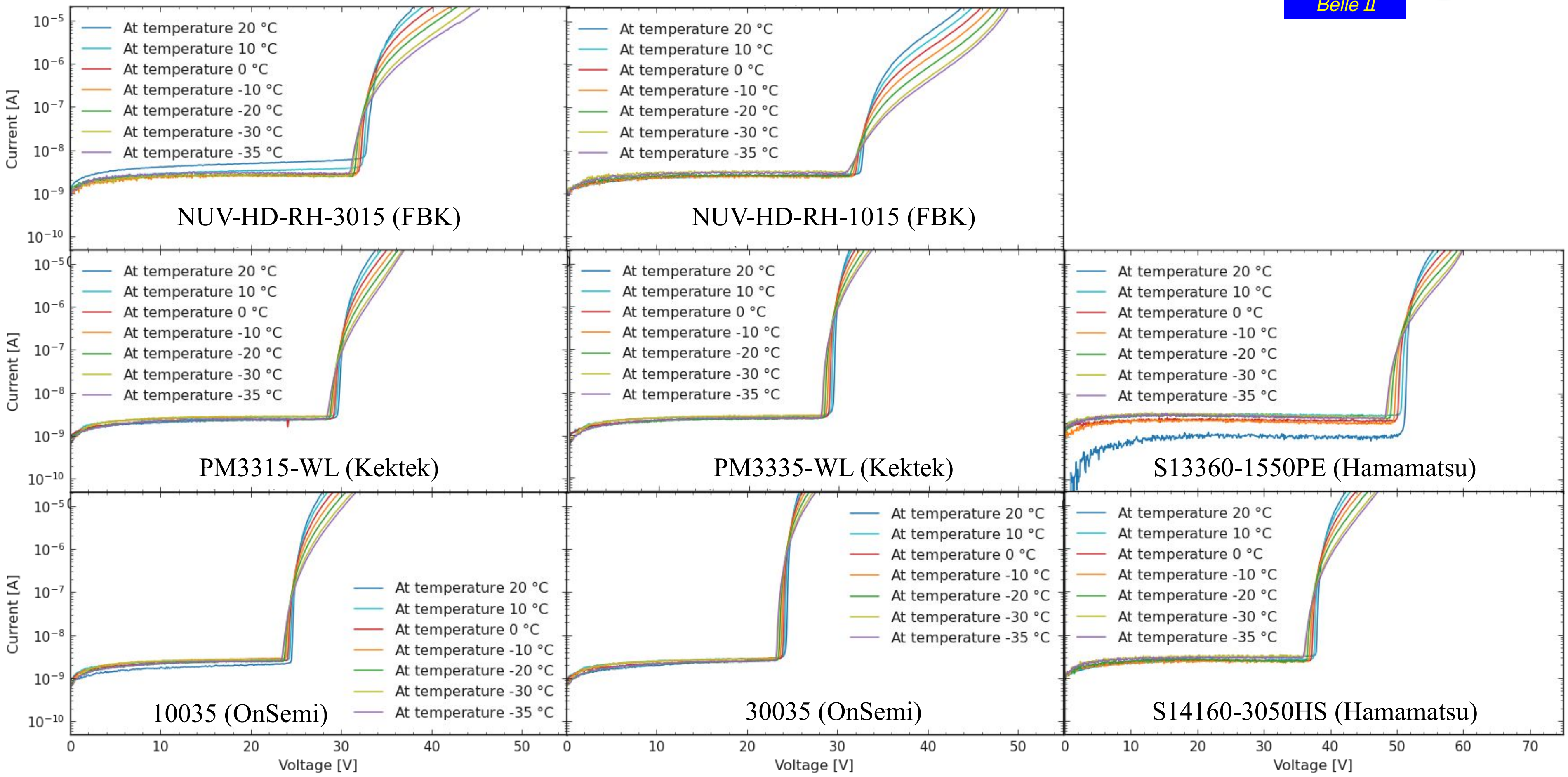


$3{\times}3$ mm^2

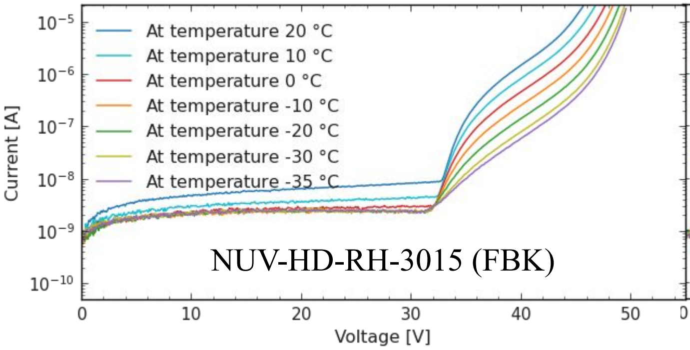
Current-voltage characteristics (non-irradiated)

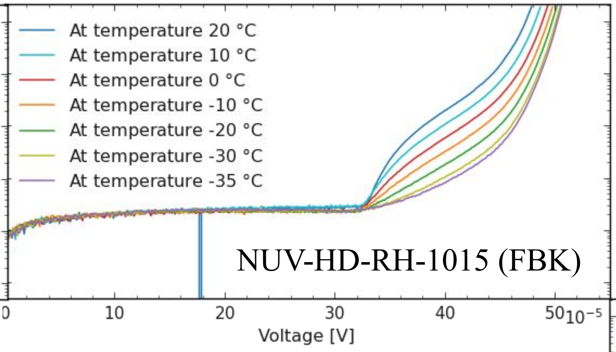


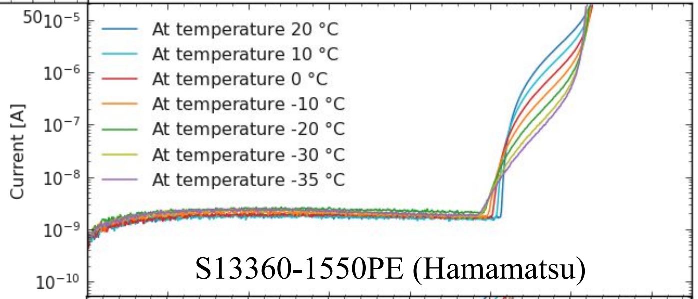
Current-voltage characteristics (irradiated)

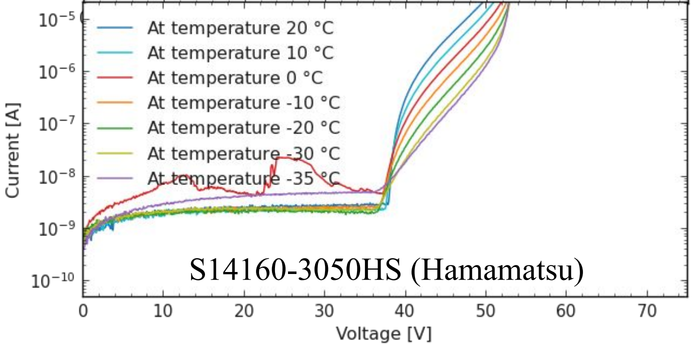


Current-voltage characteristics (annealed)

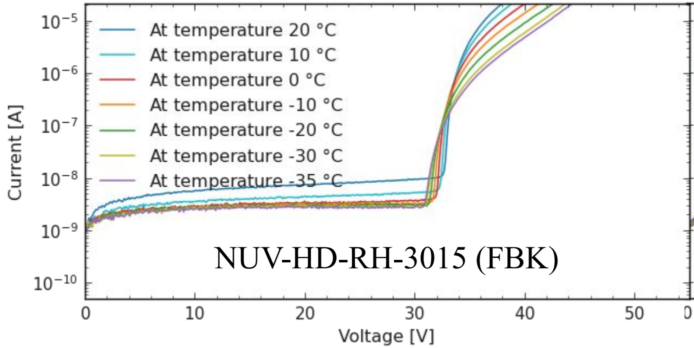


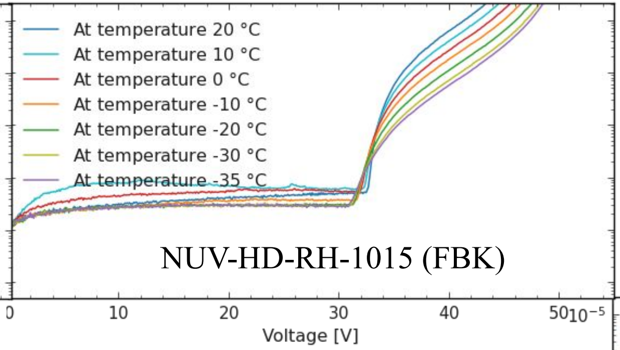


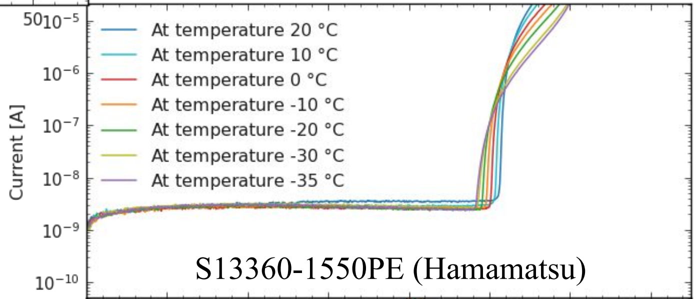


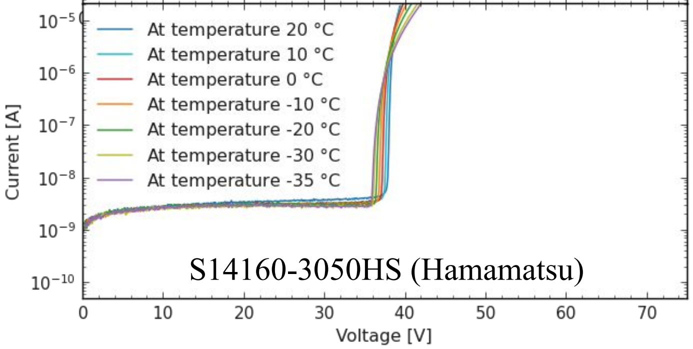


Current-voltage characteristics (re-irradiated)



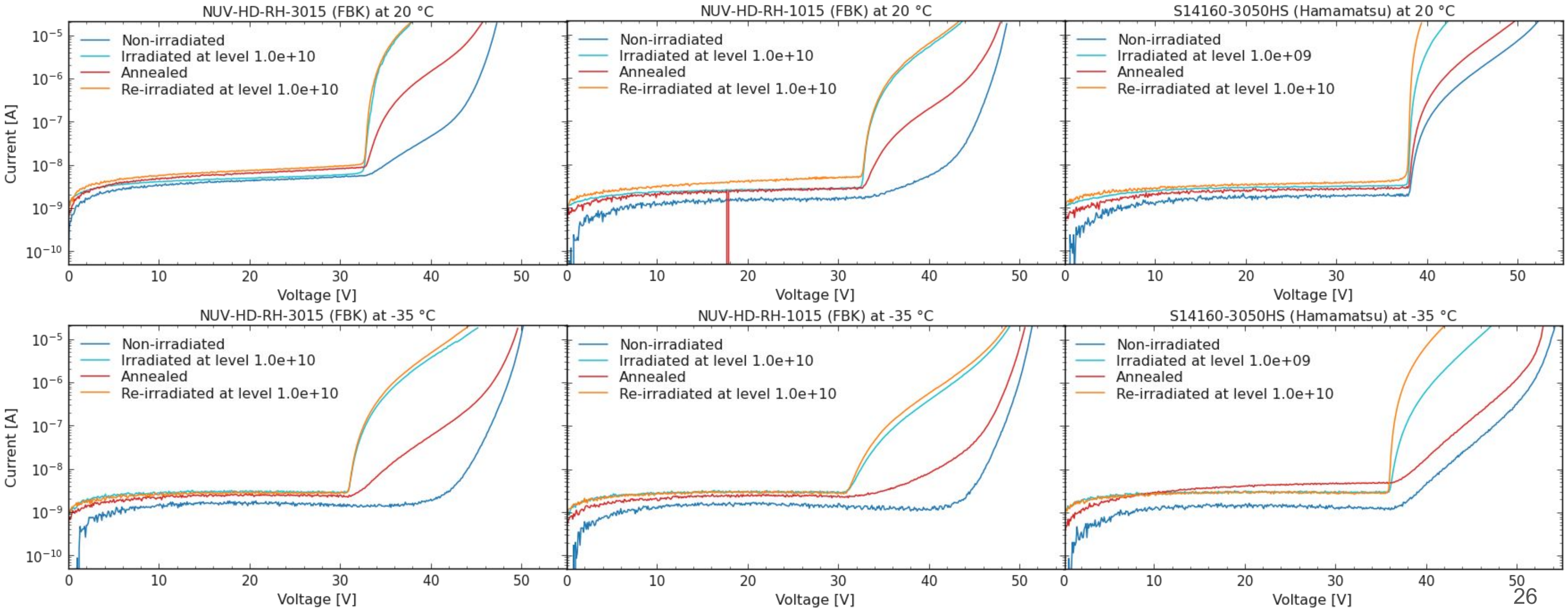






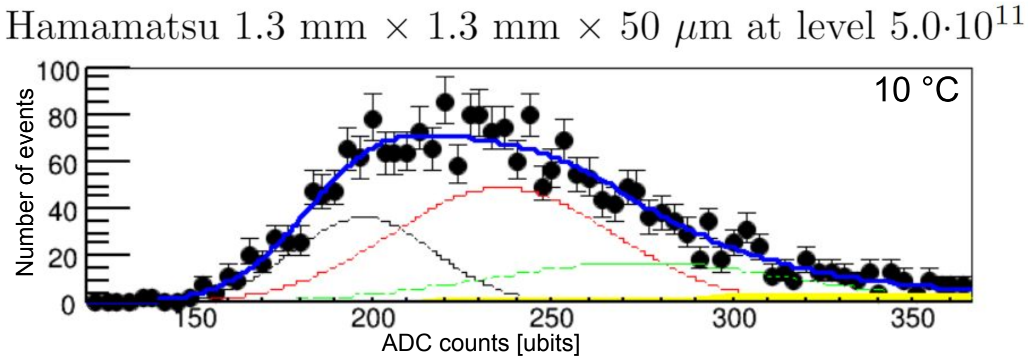
Current-voltage characteristics of FBK modules

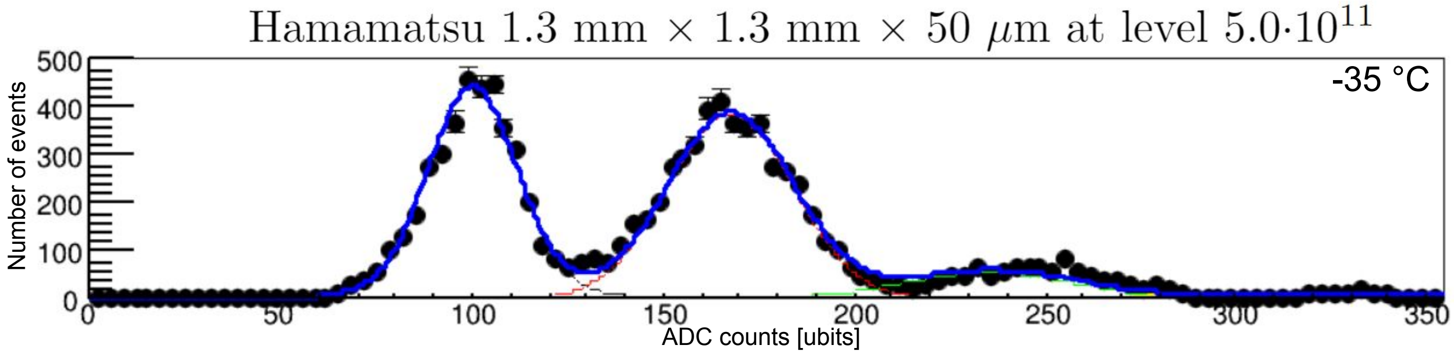
- For non-irradiated data current-voltage characteristics slightly change as function of temperature
- For FBK modules, breakdown voltage changed about 6 to 10 V as function of temperature for non-irradiated data.
- For irradiated data characteristics changed rapidly and partially recovered by annealing.



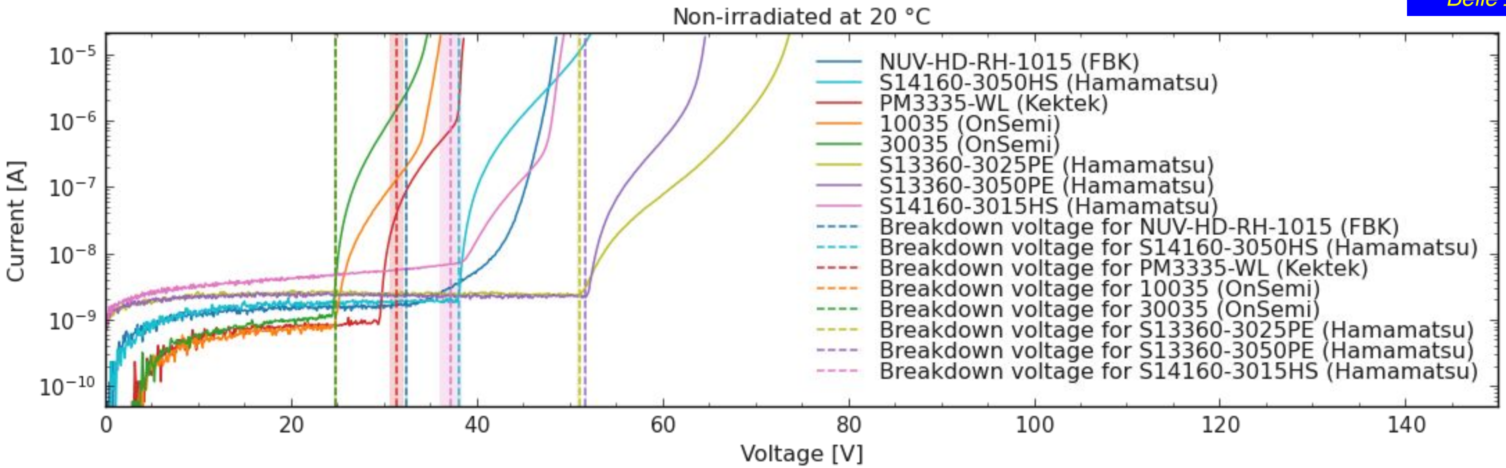
Photon spectra fits

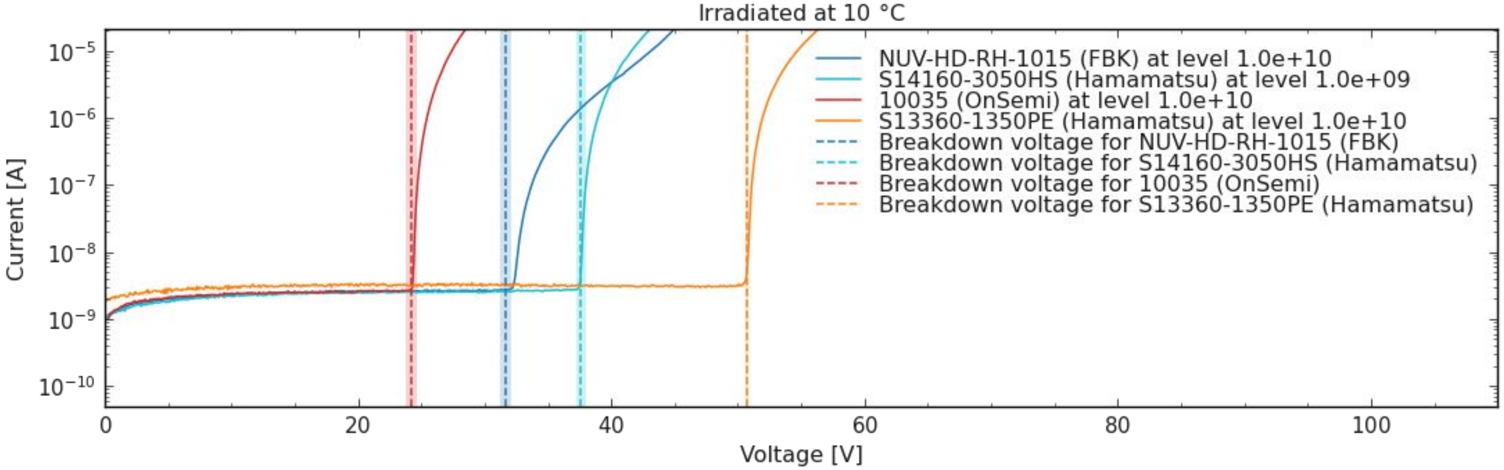
- We are using two different methods for extraction of maximum of photons:
  - Standard algorithm
  - Algorithm with background subtraction
- Algorithm with background subtraction allows us to provide photon spectra cleaner in harder environments
- Using highly irradiated modules in high temperatures or with large detection area it does not provide sufficient results for photon spectra fit.





Breakdown voltages and characteristics

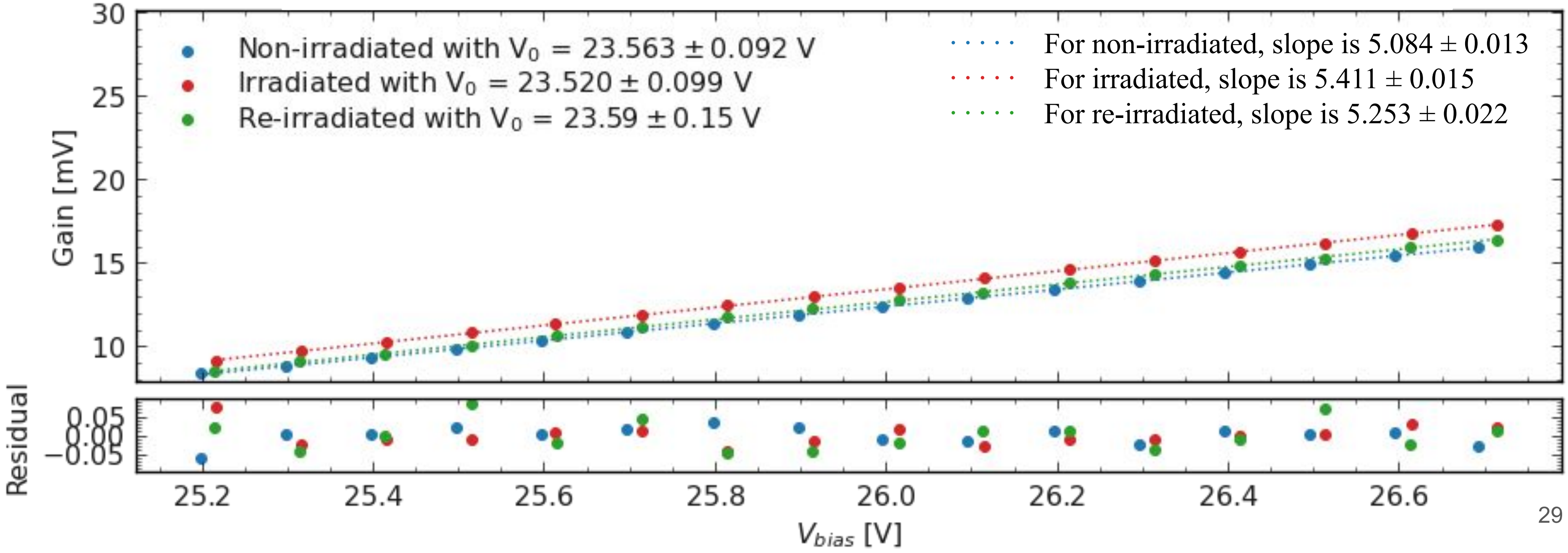




Photon spectra for 10035 (OnSemi) module

- For non-irradiated, irradiated and re-irradiated data, no significant difference between breakdown voltages.
- Slopes looks very similar too.

100035 by OnSemi (1 mm × 1 mm × 35 μm) irradiated to level $1 \cdot 10^9$ and re-irradiated to level $1.1 \cdot 10^{10}$ at -35 °C

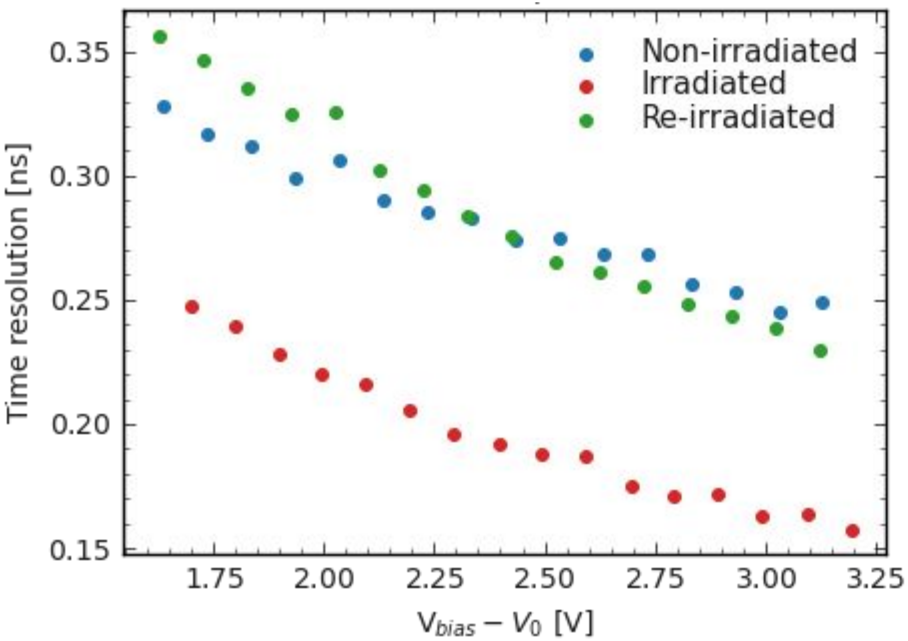


Time resolution for 10035 (OnSemi) module

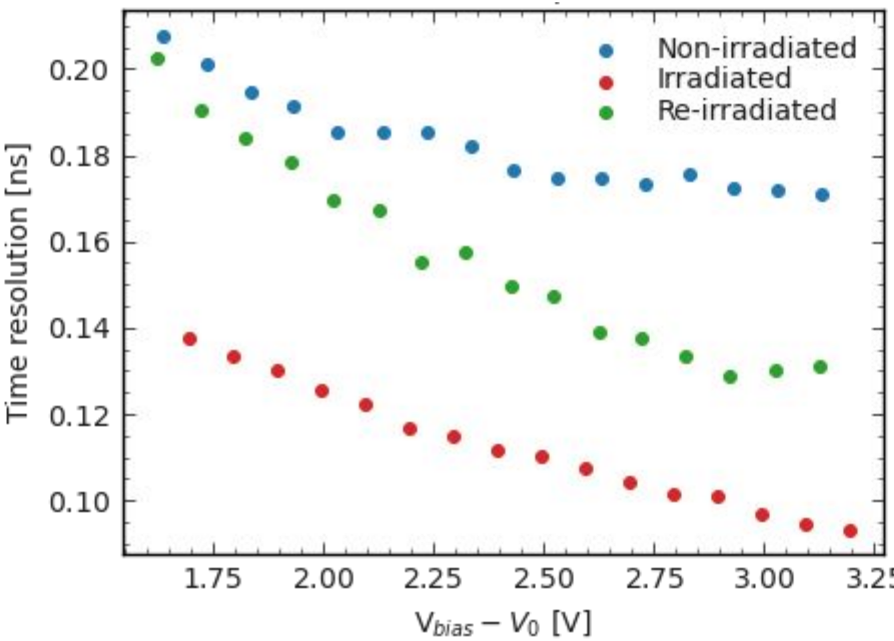
- Non-irradited and re-irradiated time resolution results look consistent to itself
- Irradiated time resolution looks about 40% better in comparison to others datasets

100035 by OnSemi (1 mm × 1 mm × 35 μm) irradiated to level $1 \cdot 10^9$ and re-irradiated to level $1.1 \cdot 10^{10}$ at -35 °C

Single photon peak

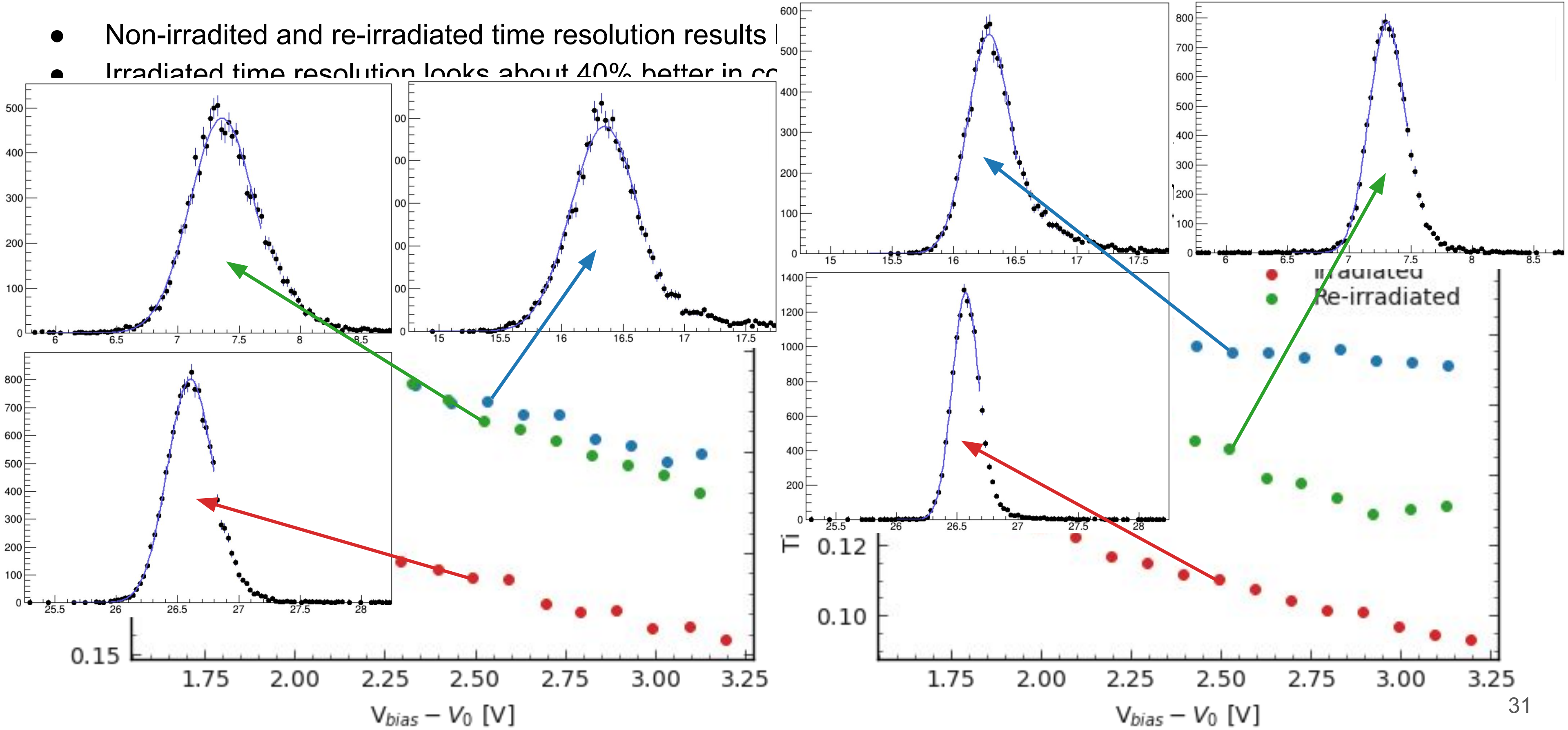


Two photon peak



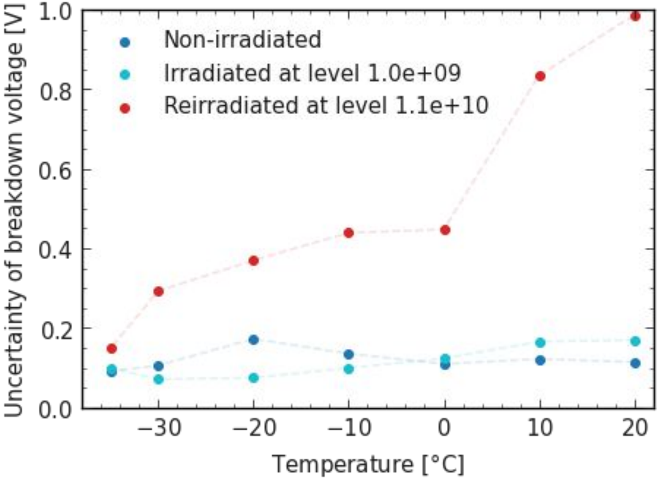
Time resolution for 10035 (OnSemi) module

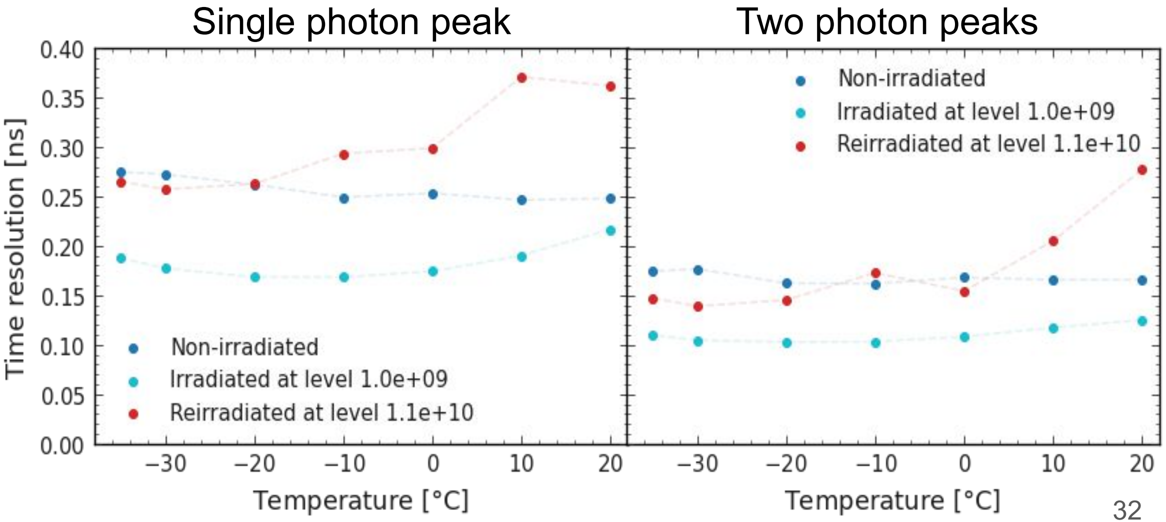
- Non-irradited and re-irradiated time resolution results
- Irradiated time resolution looks about 40% better in co



Results for the 10035 (OnSemi) module

- Overvoltage set to 2.5 V
- Uncertainty of breakdown voltage as function of the temperature demonstrates similar results as for FBK modules, where the threshold to have stable breakdown voltage as function of temperature can be set less $1.0 \cdot 10^{10}$
- Time resolution results for single and two photon peaks show consistent results with FBK and Hamamatsu in comparison between non-irradiated and re-irradiated data.
- The problematic part is non-irradiated results, where 40% better than non-irradiated results. Do we know why?

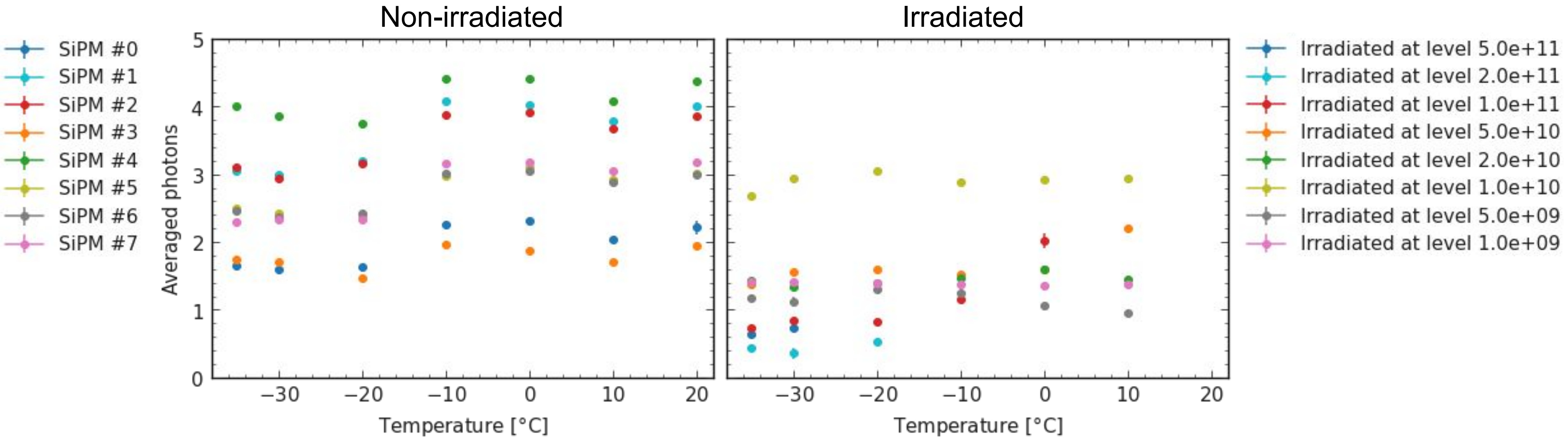




Averaged photons as function of temperature

- Overvoltage set to 2 V

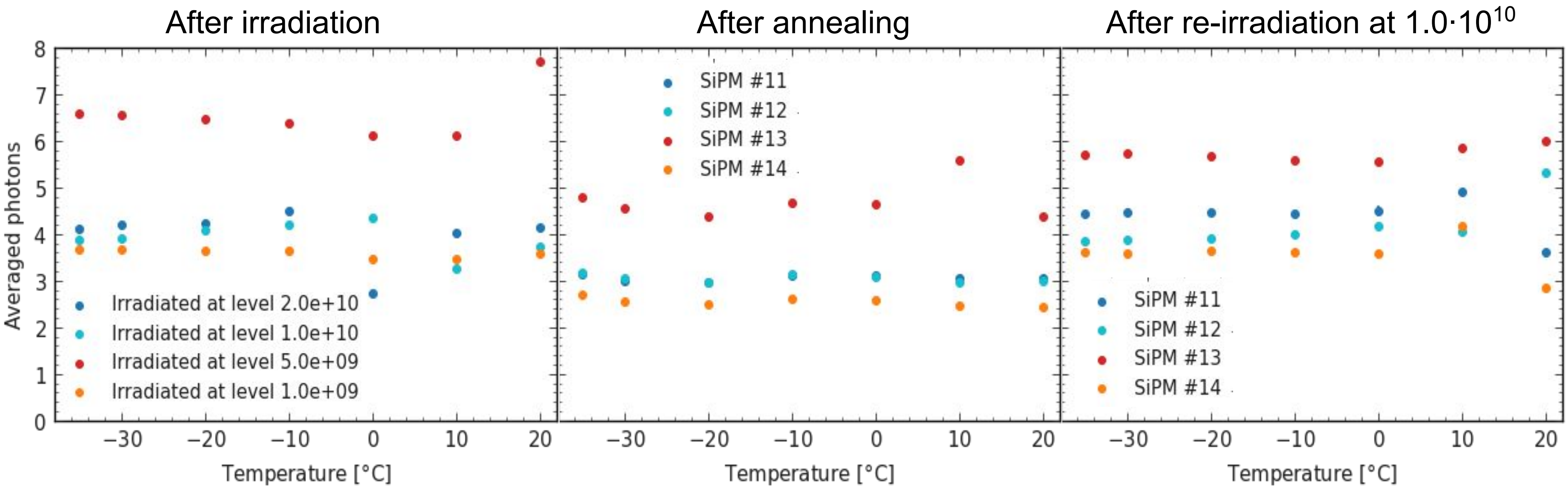
S13360-1350 by Hamamatsu (1.3 mm × 1.3 mm × 50 μm)



Averaged photons as function of temperature

- Overvoltage set to 7.5 V

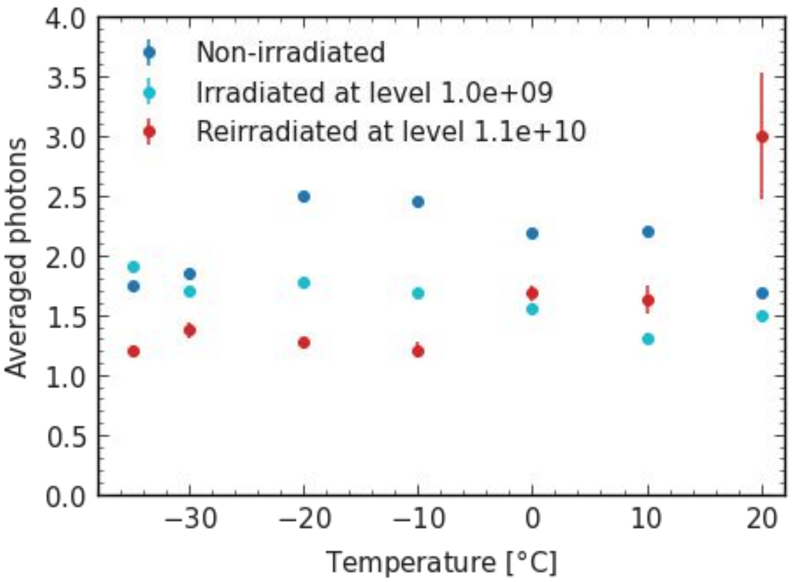
NUV-HD-RH-1015 by FBK (1 mm × 1 mm × 15 μm)



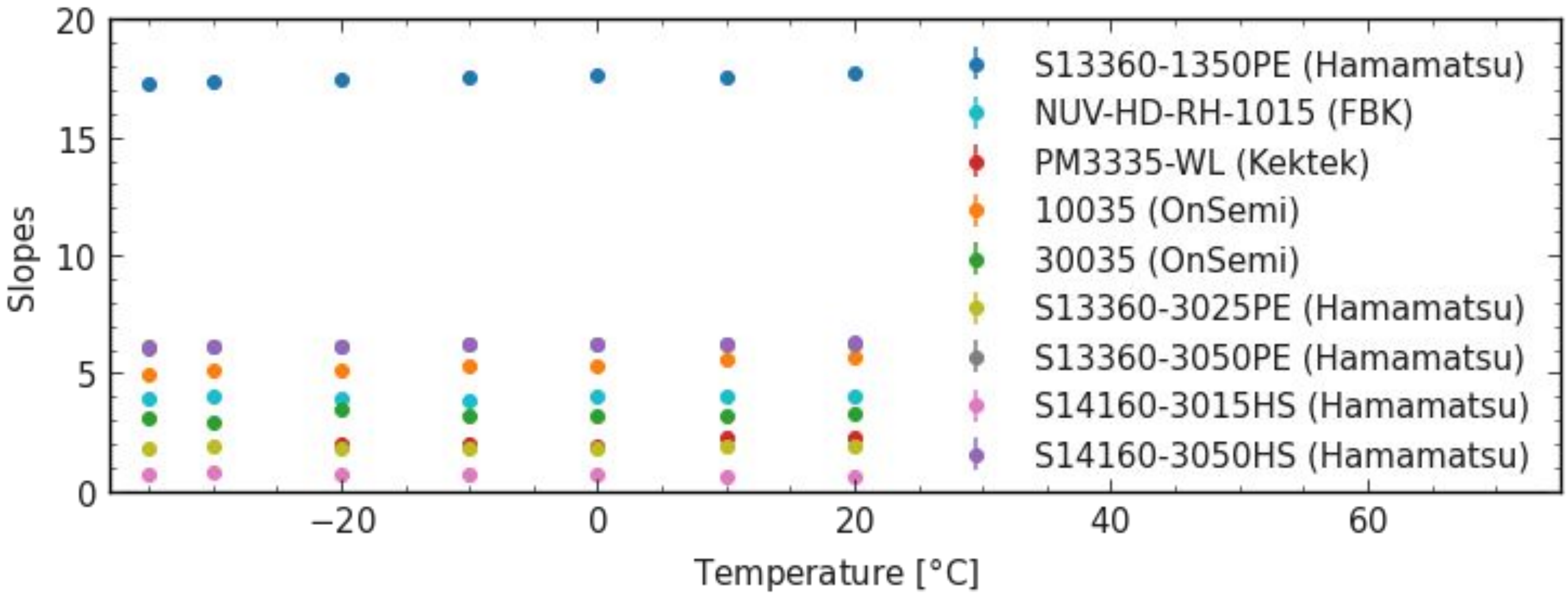
Averaged photons as function of temperature

- Overvoltage set to 2.5 V

10035 by OnSemi (1 mm × 1 mm × 35 µm)

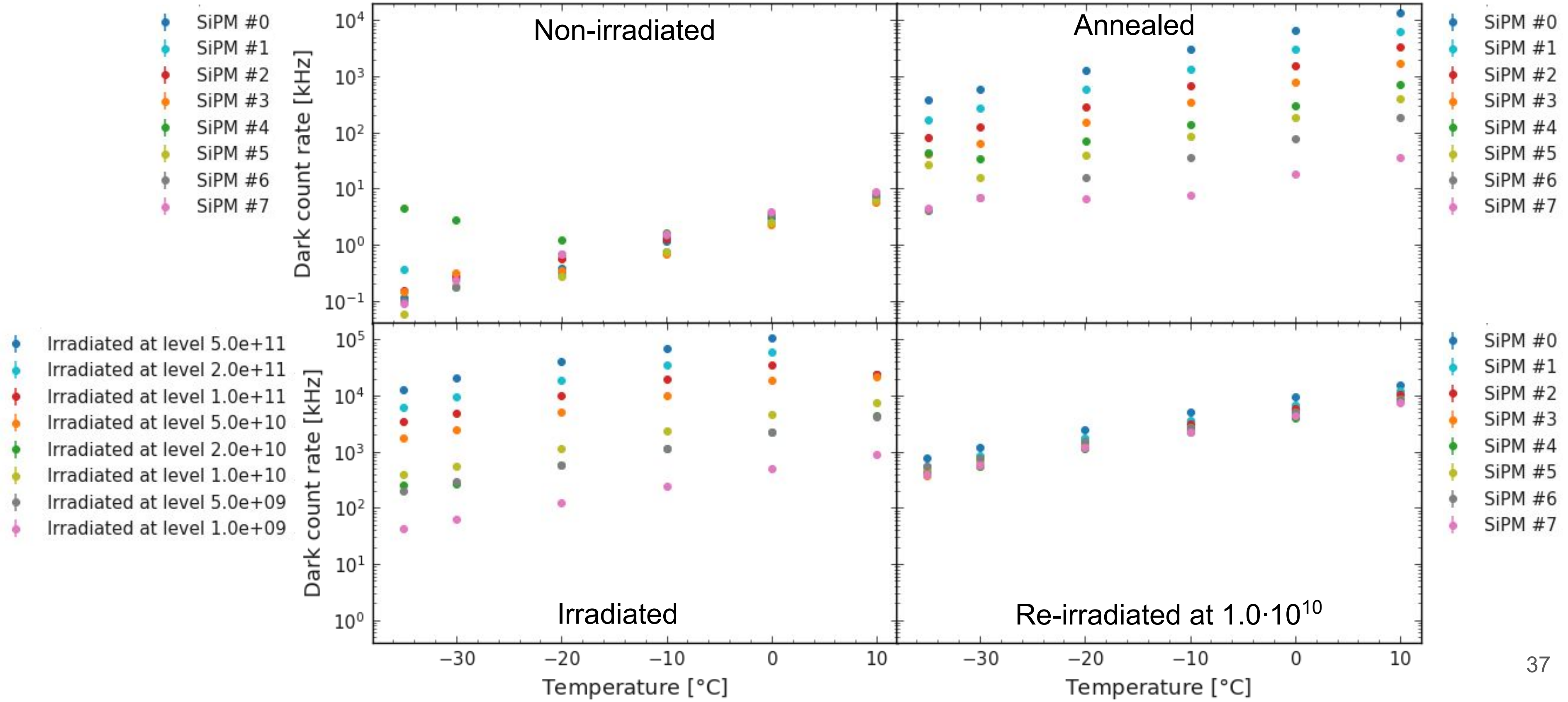


Slope as function of temperature



Dark count rate as function of temperature

- Overvoltage set to 2 V



Dark count rate as function of temperature

- Overvoltage set to 7.5 V