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

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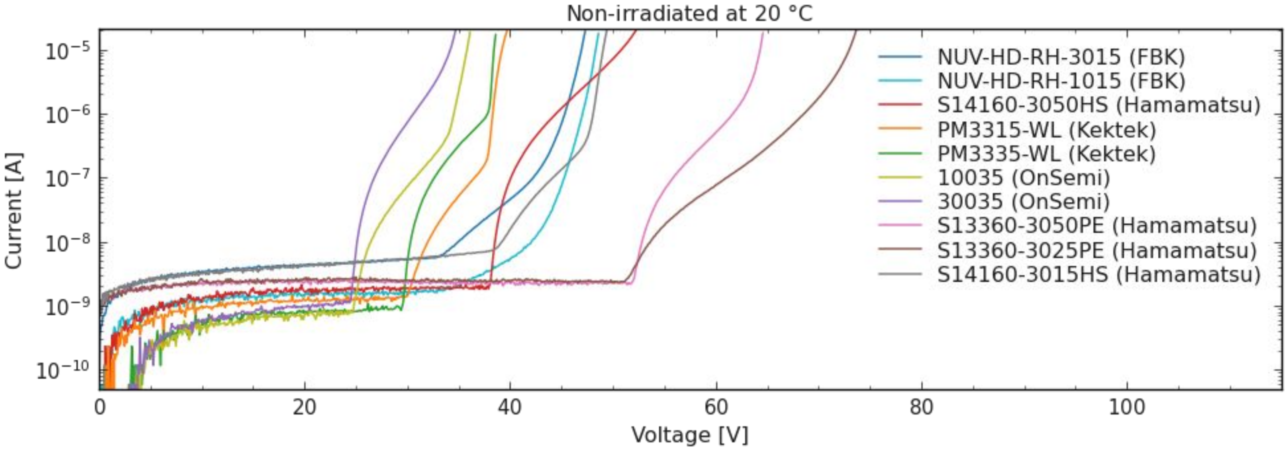
Tests with irradiated modules in Padova

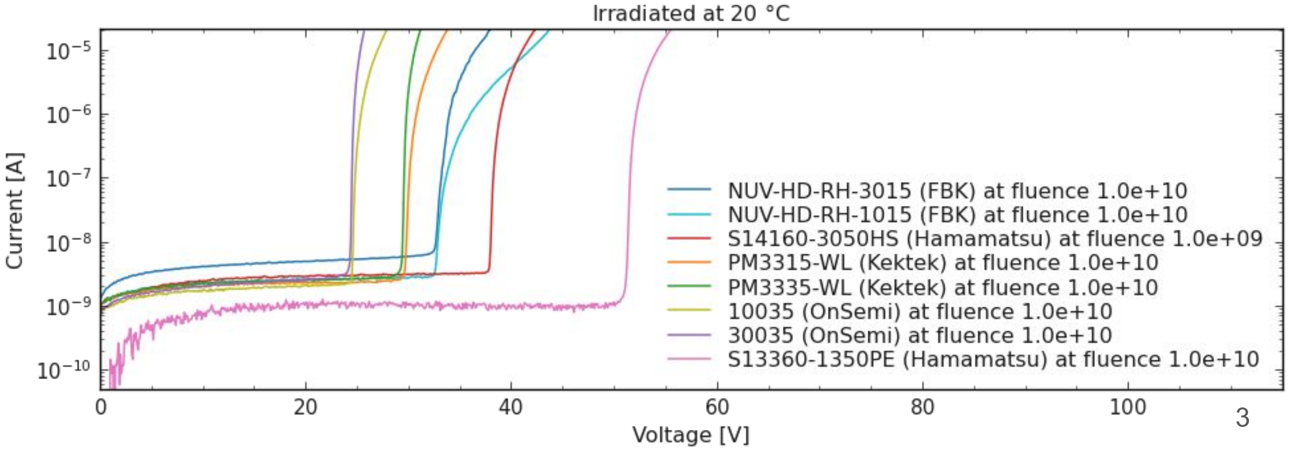
- Eventually MCP-PMTs with extended lifetime can be replaced by SiPMs in next long shutdown.
- We irradiated 32 SiPM modules with different neutron fluxes in LNL INFN, tested by laser, processed and analysed.
- During analysis, we did:
  - Current-voltage characterization,
  - Photon spectra fit using 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 peaks,
  - 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 [Neutron 1 MeV eg/cm^2 fluence]	Re-irradiation
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	$1.0{\cdot}10^{9}$, $1.0{\cdot}10^{10}$	$1.0{\cdot}10^{10}$
Ketek	PM3315-WL	16, 17	3 × 3	15	$1.0{\cdot}10^{10}$, $1.0{\cdot}10^{9}$	$1.0{\cdot}10^{10}$
Ketek	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 characterization

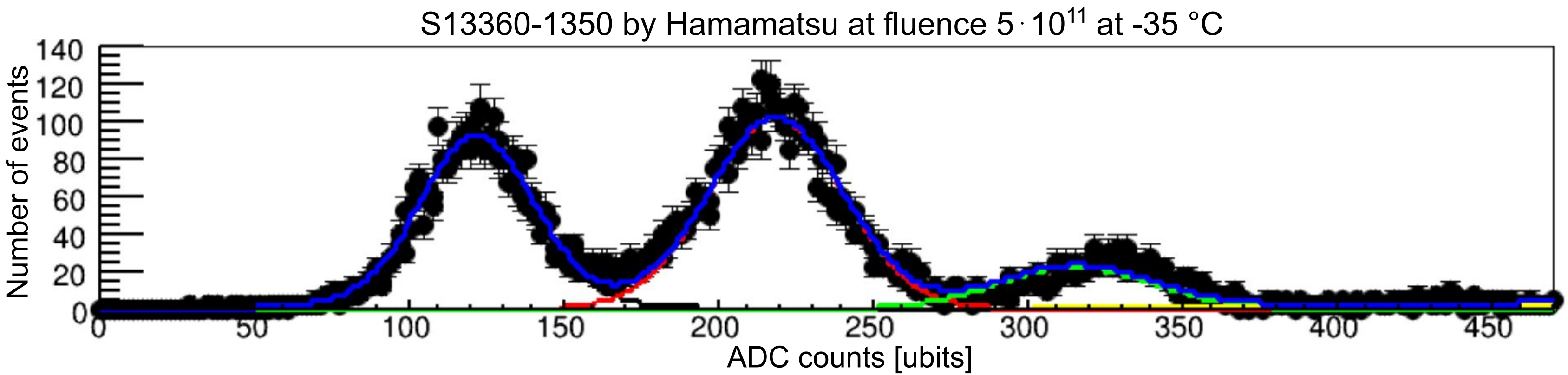
- Current-voltage characterization have been checked for several modules.
- For non-irradiated data current-voltage characterizations slightly change as function of temperature.
- Current-voltage characterizations for irradiated data changed rapidly in comparison with non-irradiated data, but breakdown voltages are consistent with non-irradiated data.





Photon spectra and time resolution fits

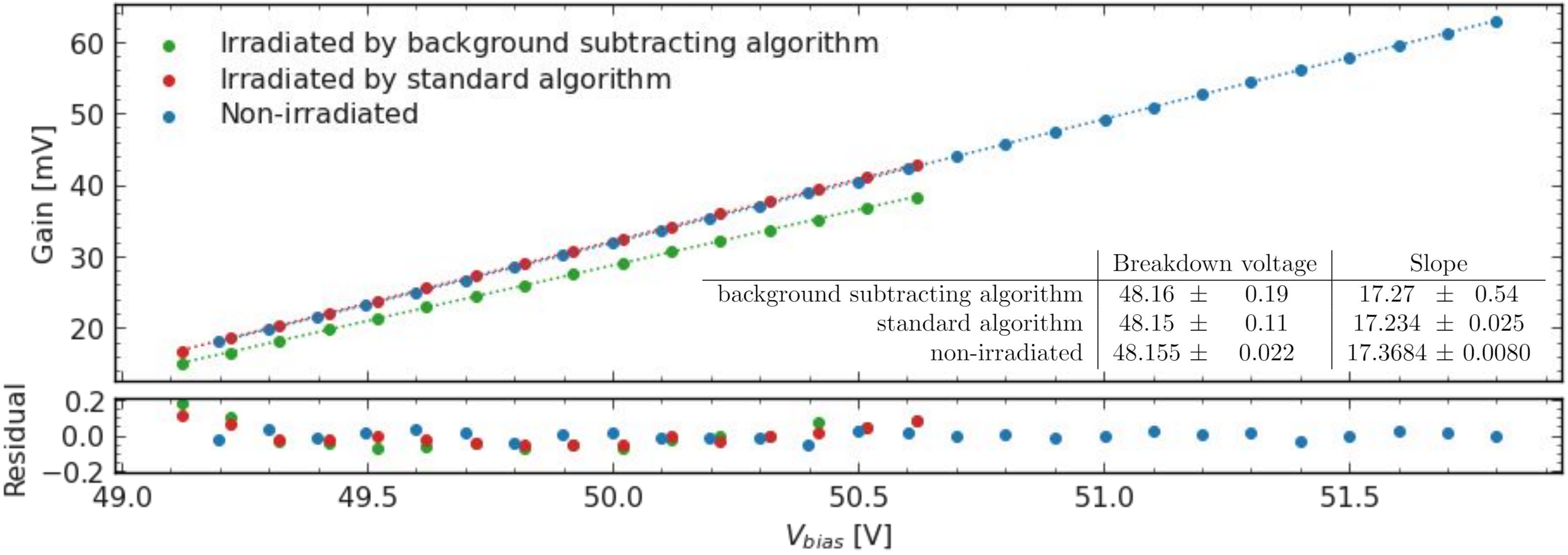
- We are using two different methods for extraction of maximum of photons:
  - Standard algorithm
  - Background subtracting algorithm
- The photon spectra is fitted by poissonian distribution convoluted with gaussian(s).
- Time resolution is fitted twice with gaussian, in the second fit the fitting window is in range (-5 · 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.



Extraction breakdown voltage

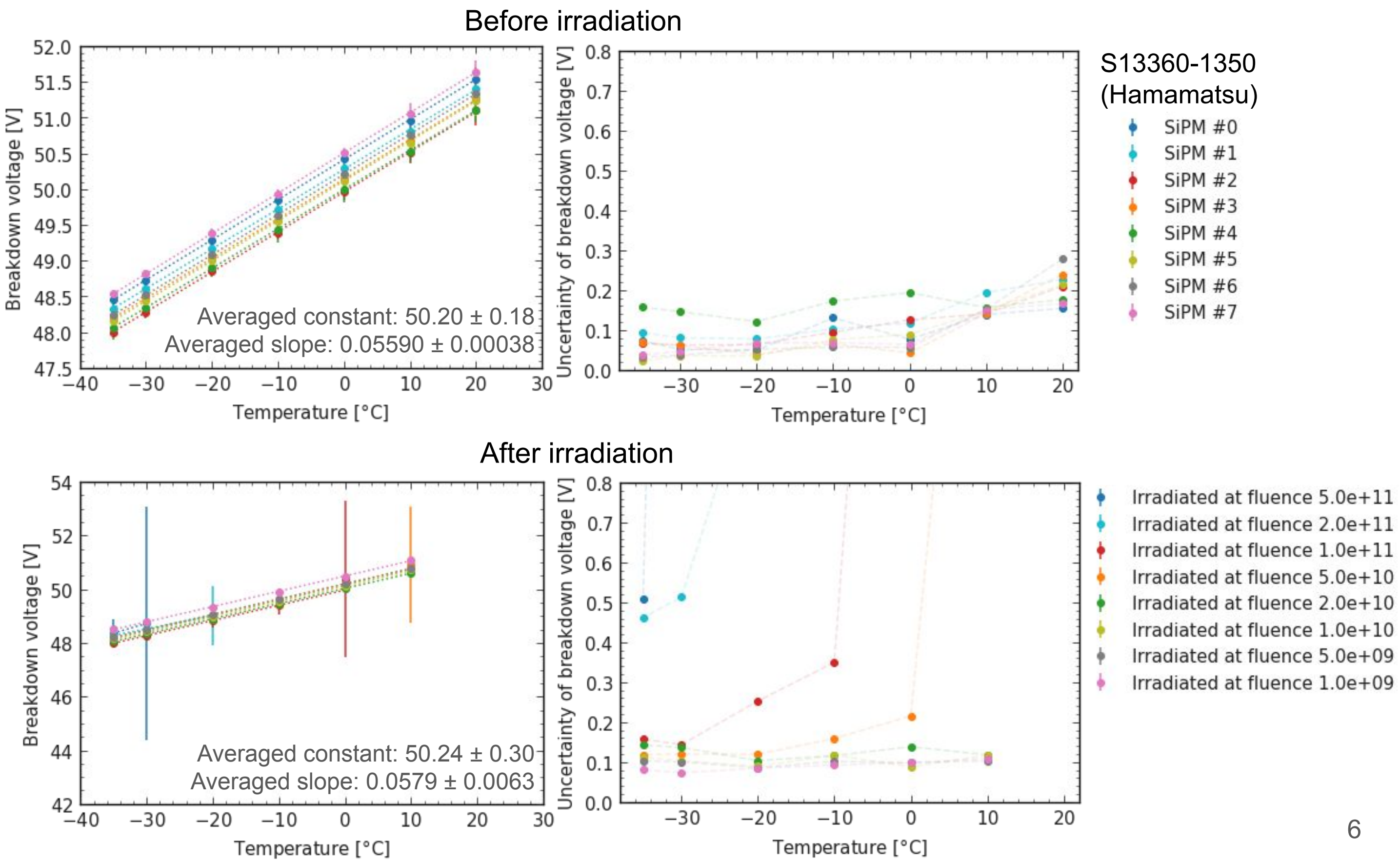
- Breakdown voltage are extracted using linear fit of gains as function of bias voltage.
- Extracted breakdown voltage after irradiation is consistent with results before irradiation.
- Background subtracting algorithm provides less precise result than standard algorithm.

S13360-1350 by Hamamatsu at fluence $1 \cdot 10^{10}$ at -35 °C



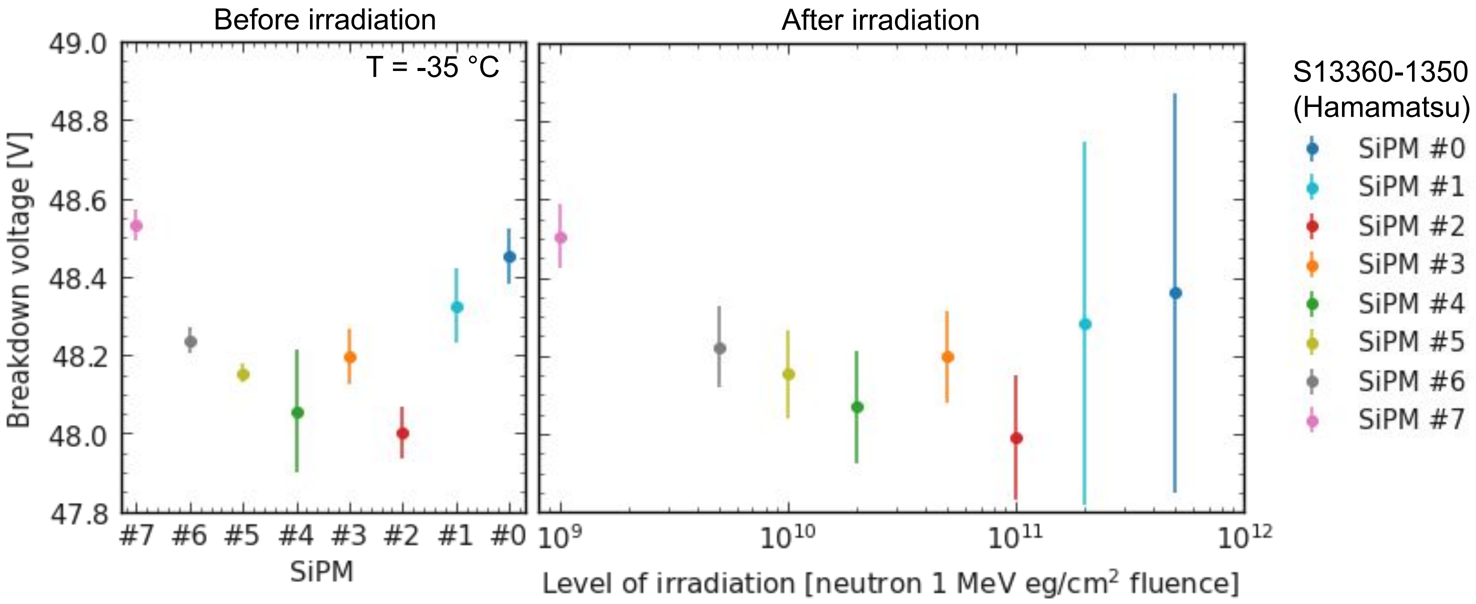
Breakdown voltage as function of temperature

- Breakdown voltages slightly decreasing as function of temperature.
- 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.



Breakdown voltage as function of irradiation

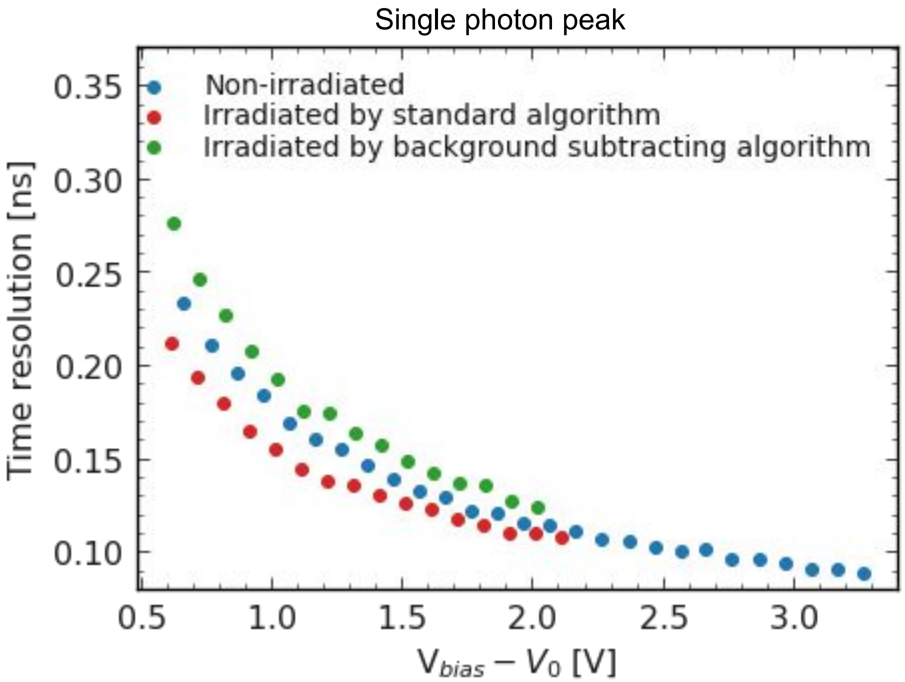
- Breakdown voltage as function of irradiation level does not show any discrepancy.
- Values of breakdown voltages look consistent with values before irradiation.
- Uncertainties of breakdown voltage are higher for high irradiation levels, where it is more difficult extract clear photon spectra than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

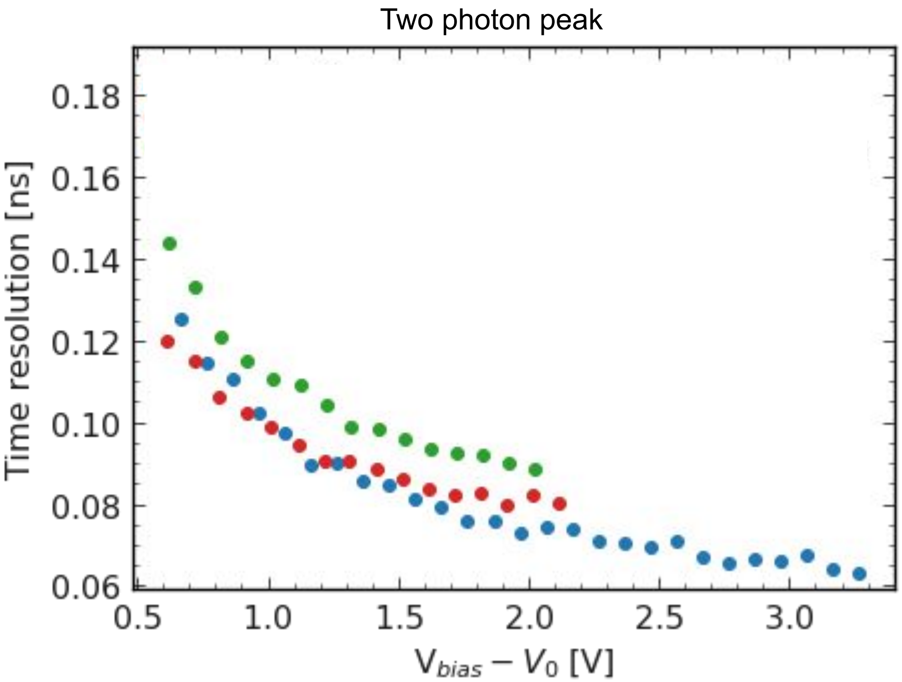


Time resolution

- 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.

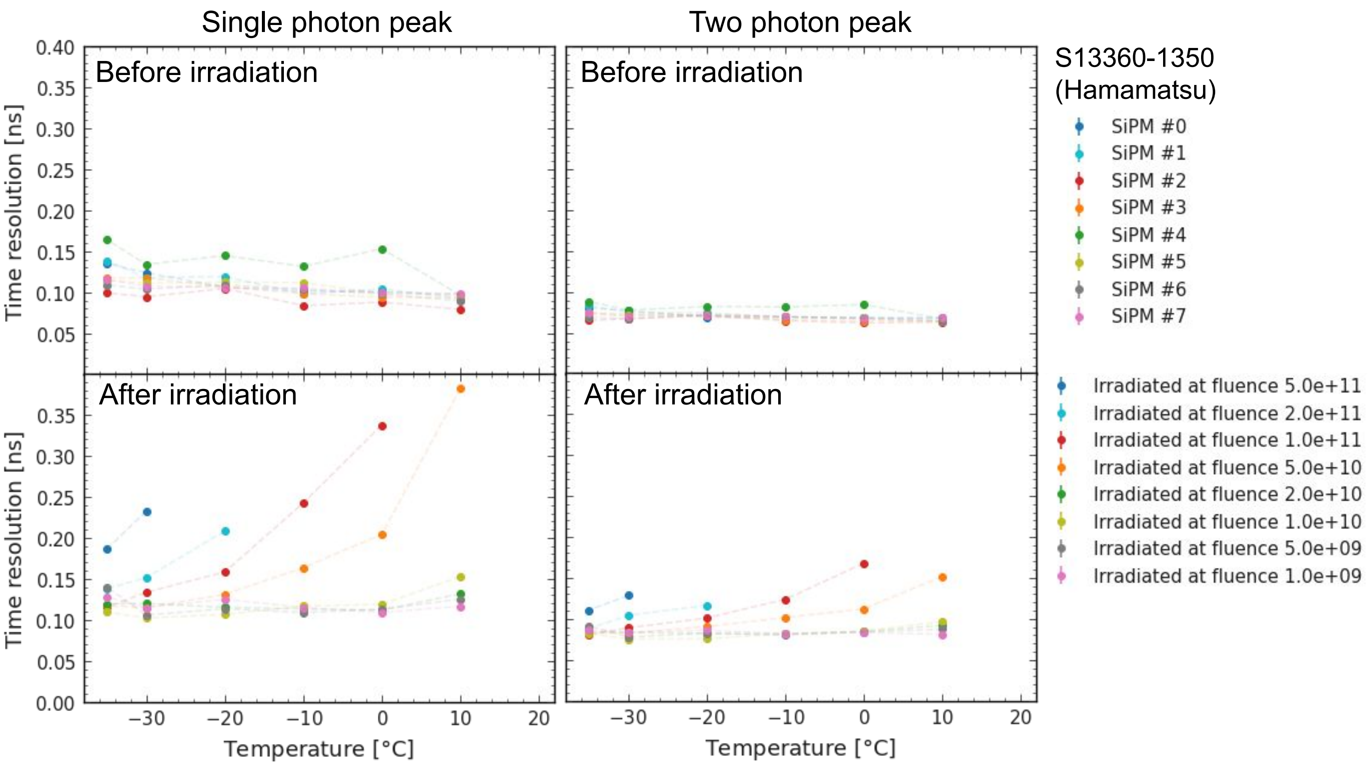
S13360-1350 by Hamamatsu at fluence $1 \cdot 10^{10}$ at -35 °C





Time resolution as function of temperature

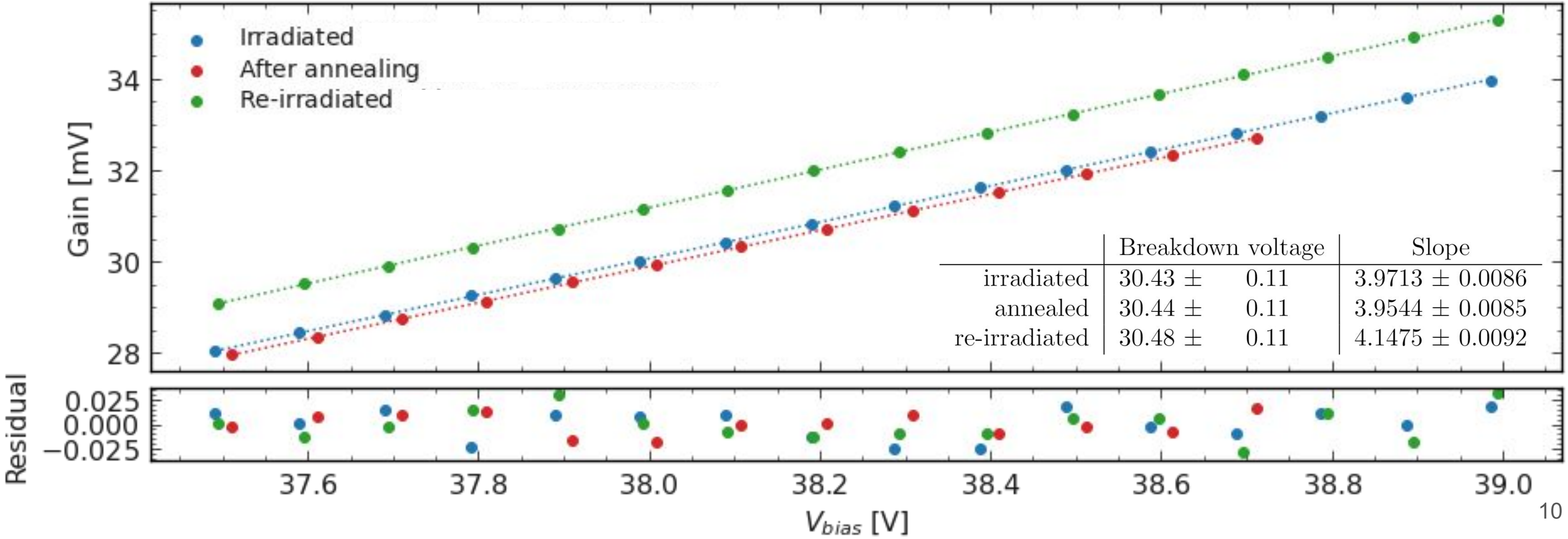
- Overvoltage set to level 2 V.
- For non-irradiated data, the most precise results can be observed between -30 °C and -20 °C.
- For high irradiation levels ($5 \cdot 10^{10}$ and more), time resolution is significantly dependent on temperature.
- Lower temperatures can improve time resolution, but not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

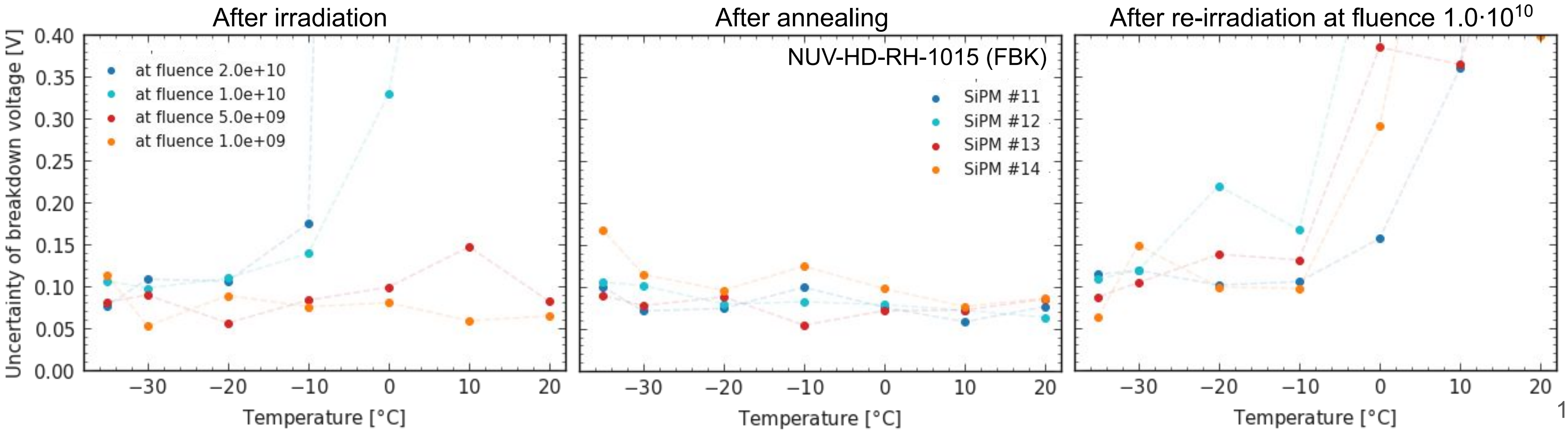
NUV-HD-RH-1015 by FBK at fluence $1 \cdot 10^{10}$ at -35 °C



	Breakdown voltage	Slope
irradiated	30.43 ± 0.11	3.9713 ± 0.0086
annealed	30.44 ± 0.11	3.9544 ± 0.0085
re-irradiated	30.48 ± 0.11	4.1475 ± 0.0092

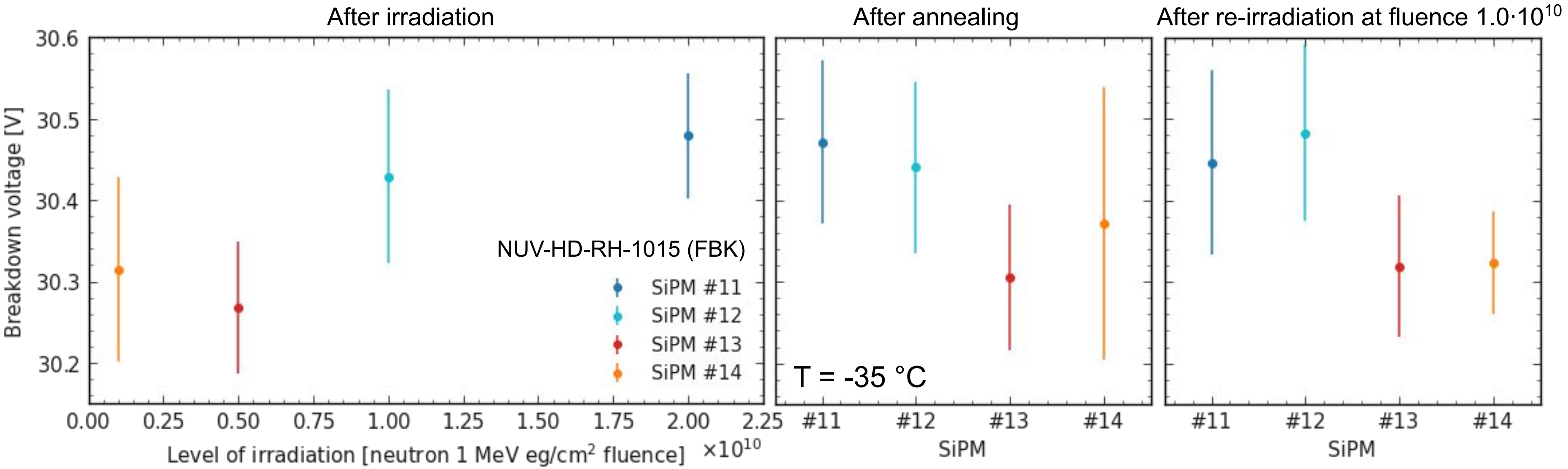
Breakdown voltage as function of temperature

- 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 fluence $2 \cdot 10^{10}$).
- 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.



Breakdown voltage as function of irradiation

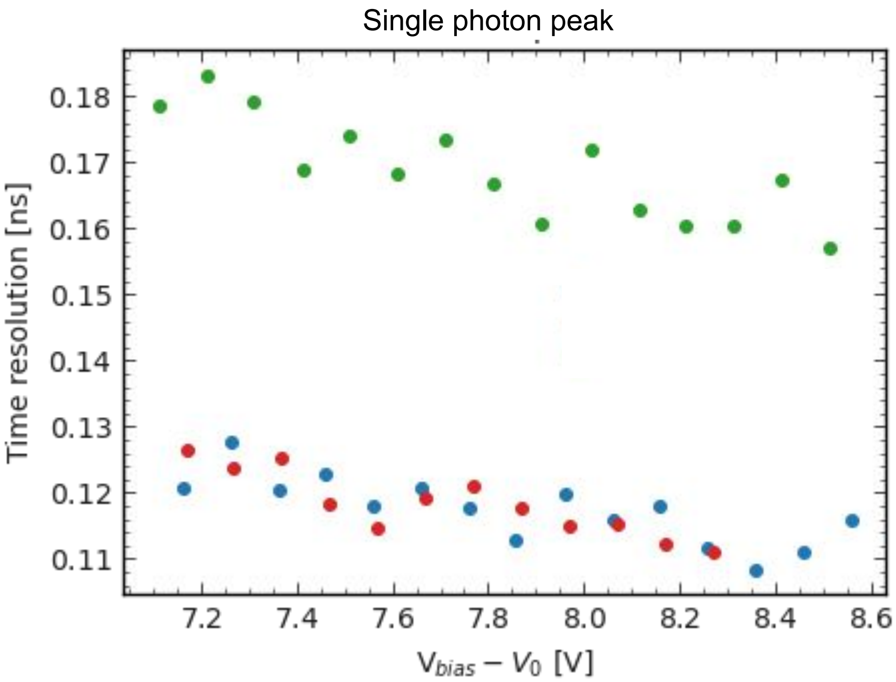
- Breakdown voltage as function of irradiation level shows consistency for irradiated, annealed and re-irradiated data.

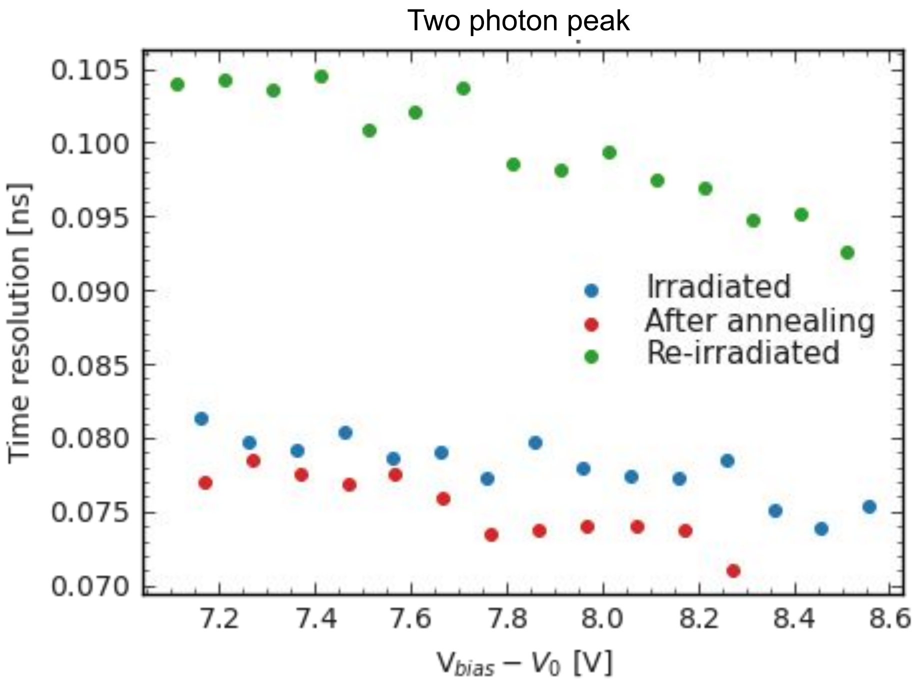


Time resolution for annealing and re-irradiation

- 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.

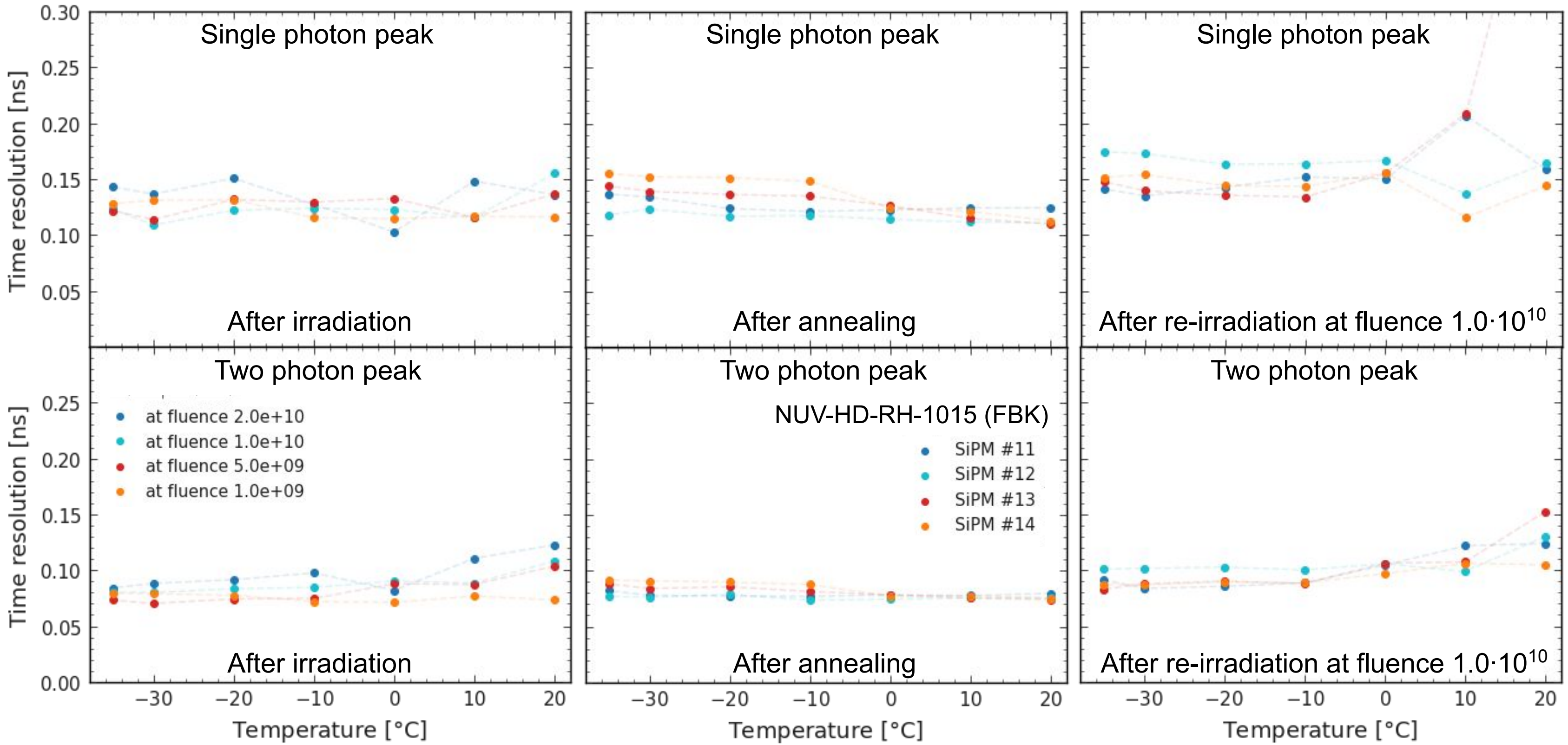
NUV-HD-RH-1015 by FBK at fluence $1 \cdot 10^{10}$ at -35 °C





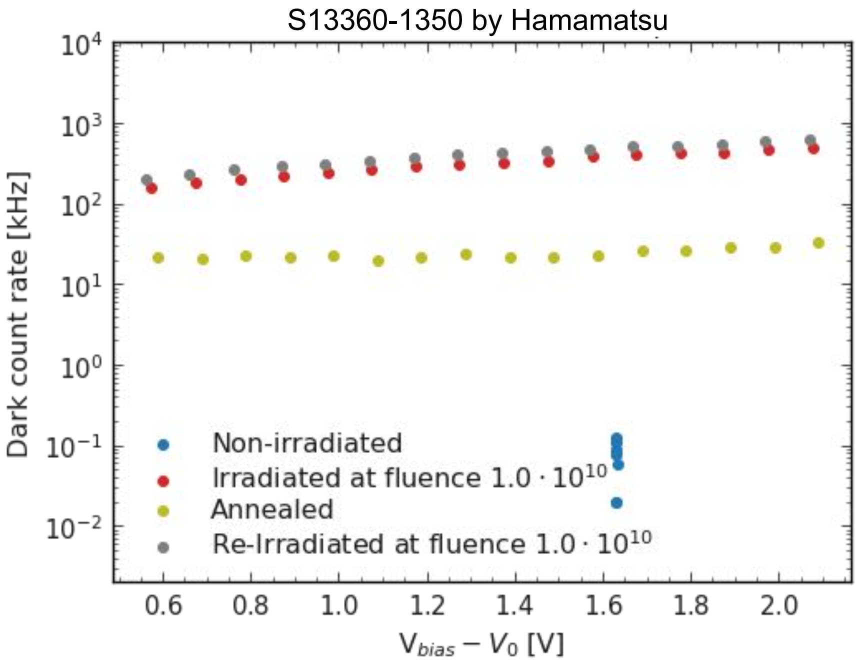
Time resolution as function of temperature

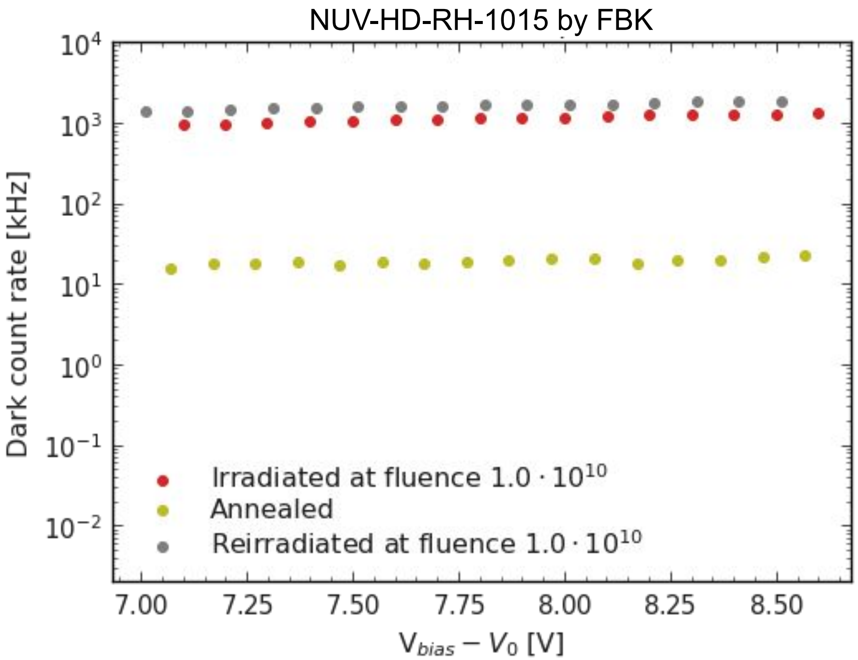
- Overvoltage set to level 7.5 V.
- Higher time resolution for high temperatures have been recovered by annealing.
- Drop between annealed and re-irradiated data is not significant for all studied modules.



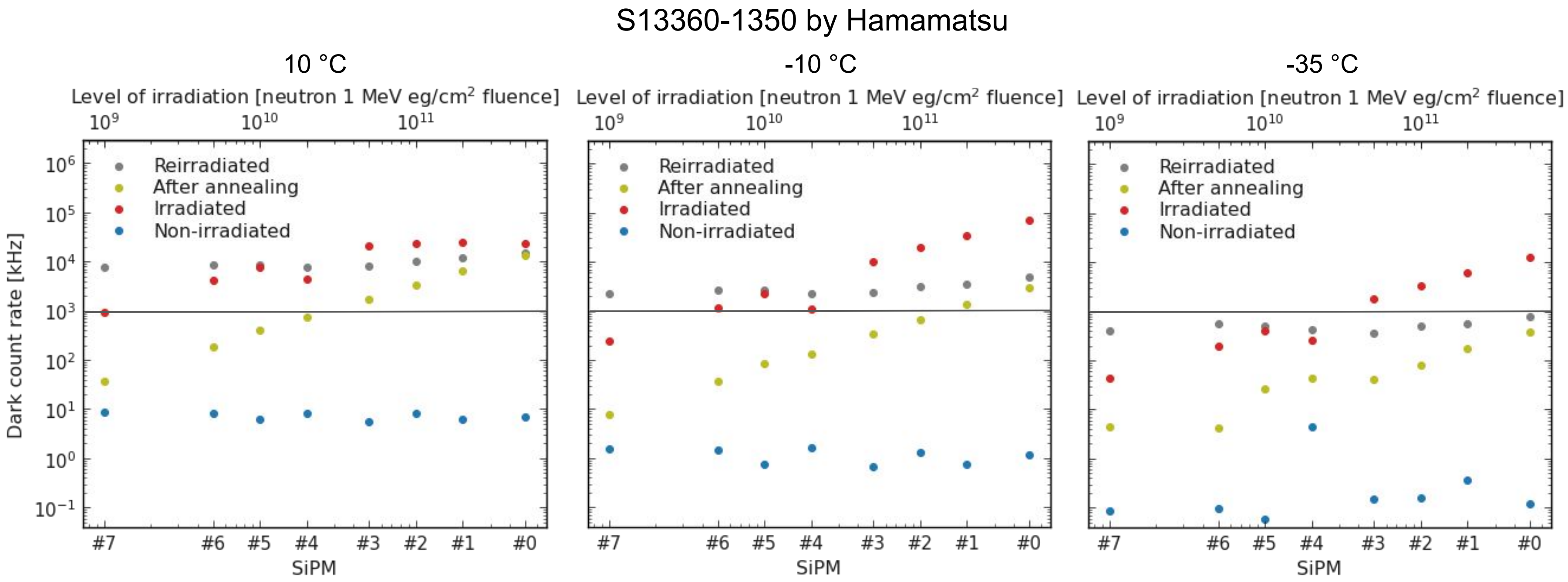
Dark count rates

- 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.



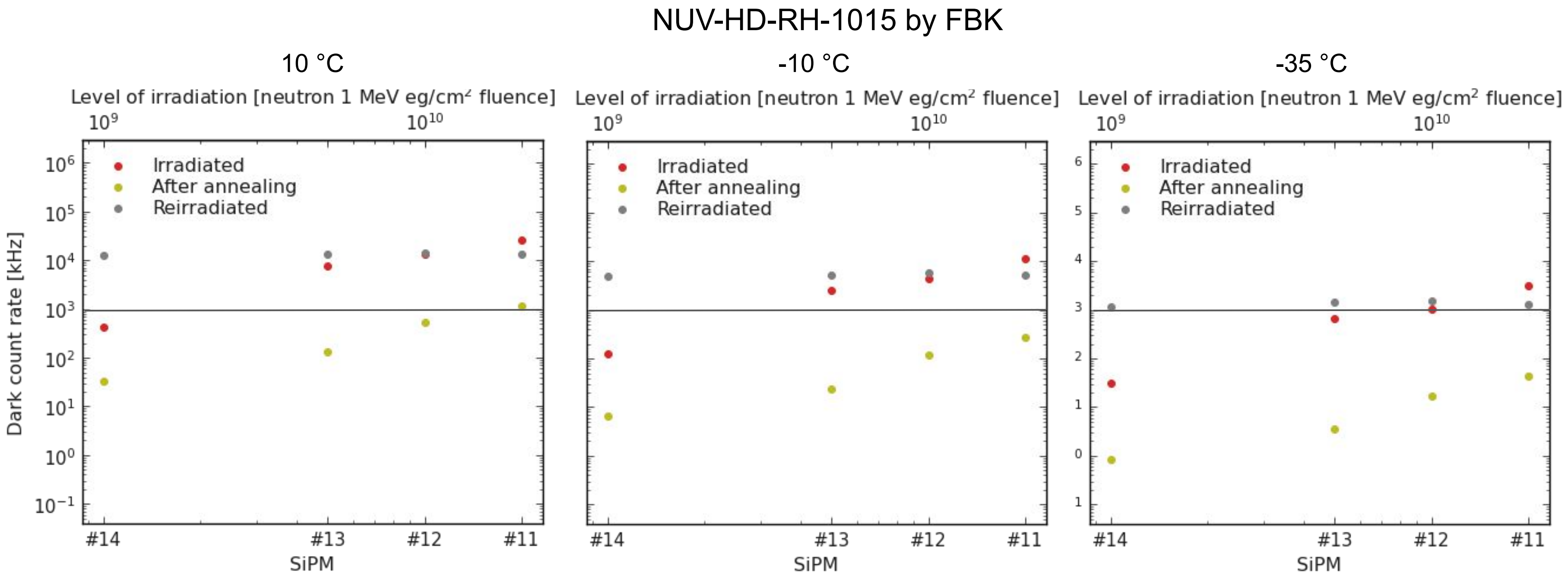


Dark count rates as function of irradiation level



- Overvoltage set to level 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 to $1.0 \cdot 10^{10}$ fluence.
- Re-irradiated results are nicely consistent with irradiated.

Dark count rates as function of irradiation level



- Overvoltage set to level 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 LNL INFN, 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 characterizations do not introduce any bias over temperature, irradiation level and different dataset.
- 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 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 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.
- In the next weeks, we will test, process and analyse next group of modules.

Backup

Tests with irradiated modules in Padova

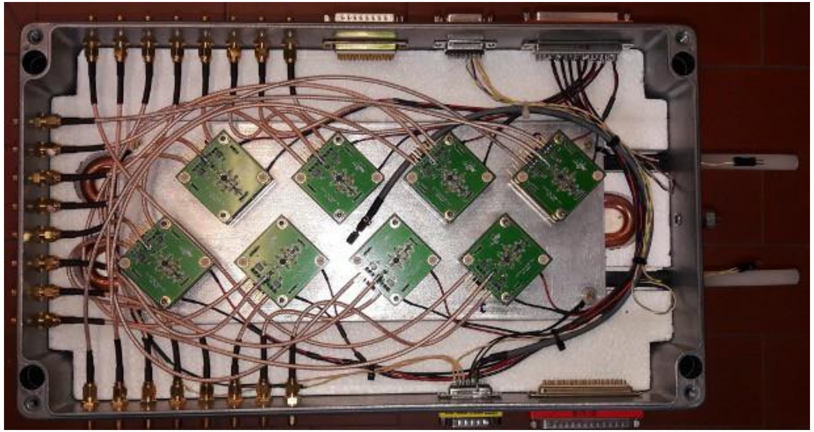
Producer	Code	Index	Non-irradiated	Irradiated	Annealed	Re-irradiated
Hamamatsu	S13360-1350PE[1]	0 - 7	Photon spectra Dark count	Photon spectra Dark count	Dark count	Dark count
FBK	NUV-HD-RH-3015[2]	8 - 10	Dark count	Dark count	Dark count	Dark count
FBK	NUV-HD-RH-1015[3]	11 - 14	Photon spectra Dark count	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.

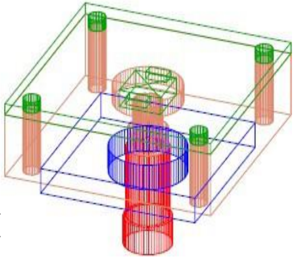
Experimental setup

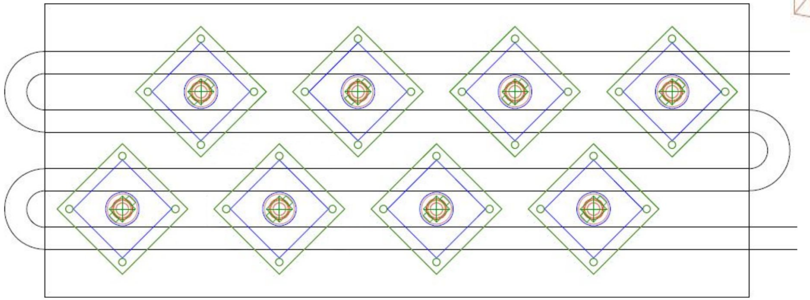
- Measuring characterizations of several available SiPMs for different temperatures and level of irradiations
- Modules have been illuminated with picosecond laser with temperature range from 20 °C to -50 °C

Dark box with SiPM blocks



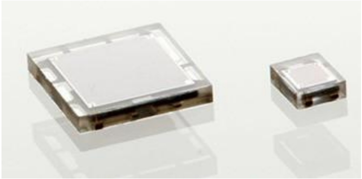
PCB - Amplifier
PCB - SiPM with T sensor
PCB - peltier





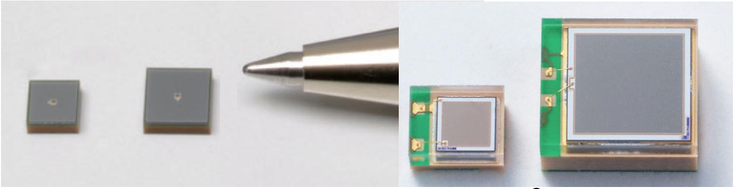
Cooling plate (glycolate water)

OnSemi (35μm)



3×3 - 1×1 mm^2

Hamamatsu (15-25-50 μm)

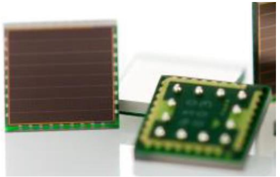


1.3×1.3 - 3×3 mm^2

FBK (15μm)

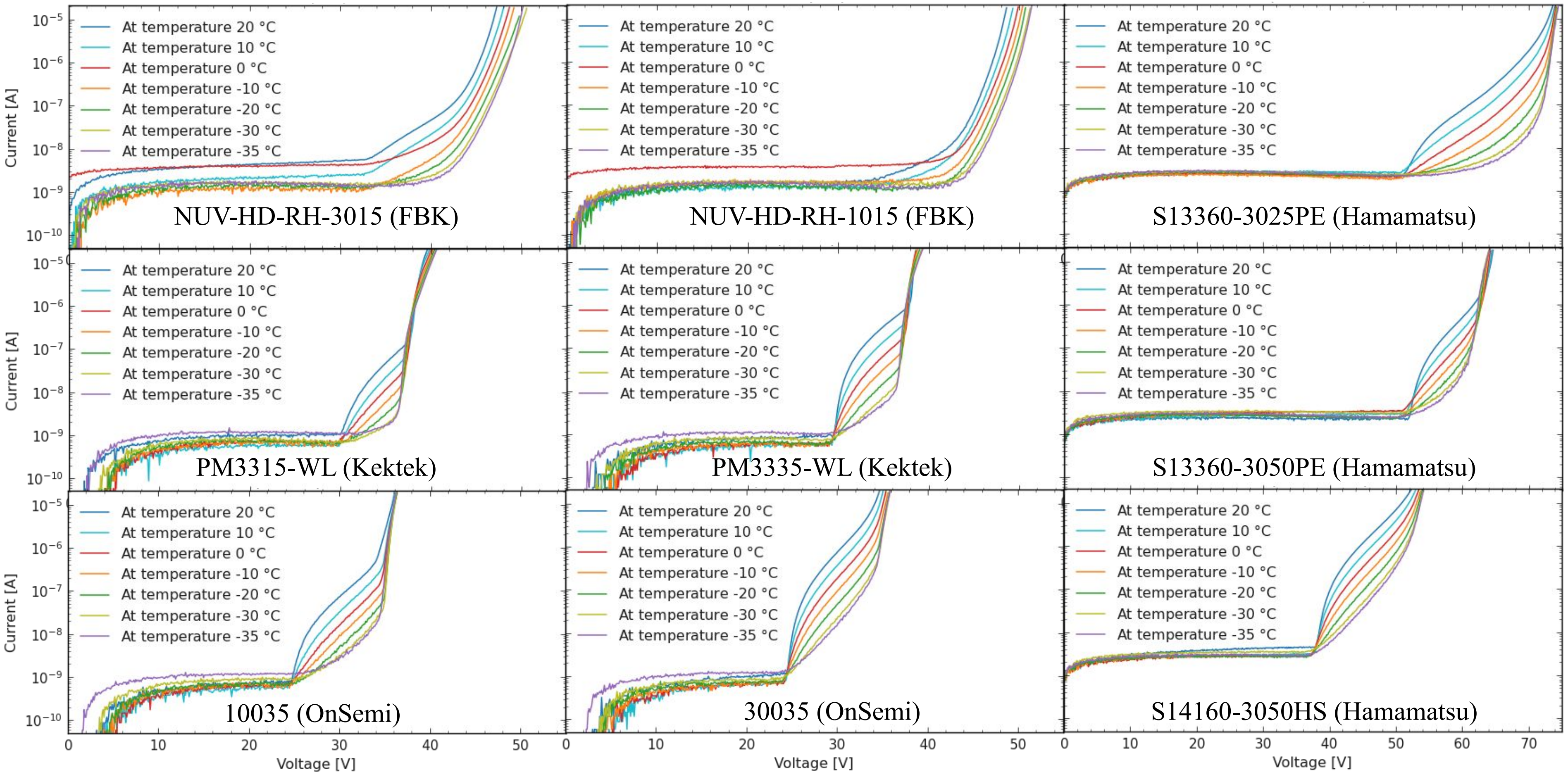
1×1 - 3×3 mm^2

Ketek (15-35 μm)

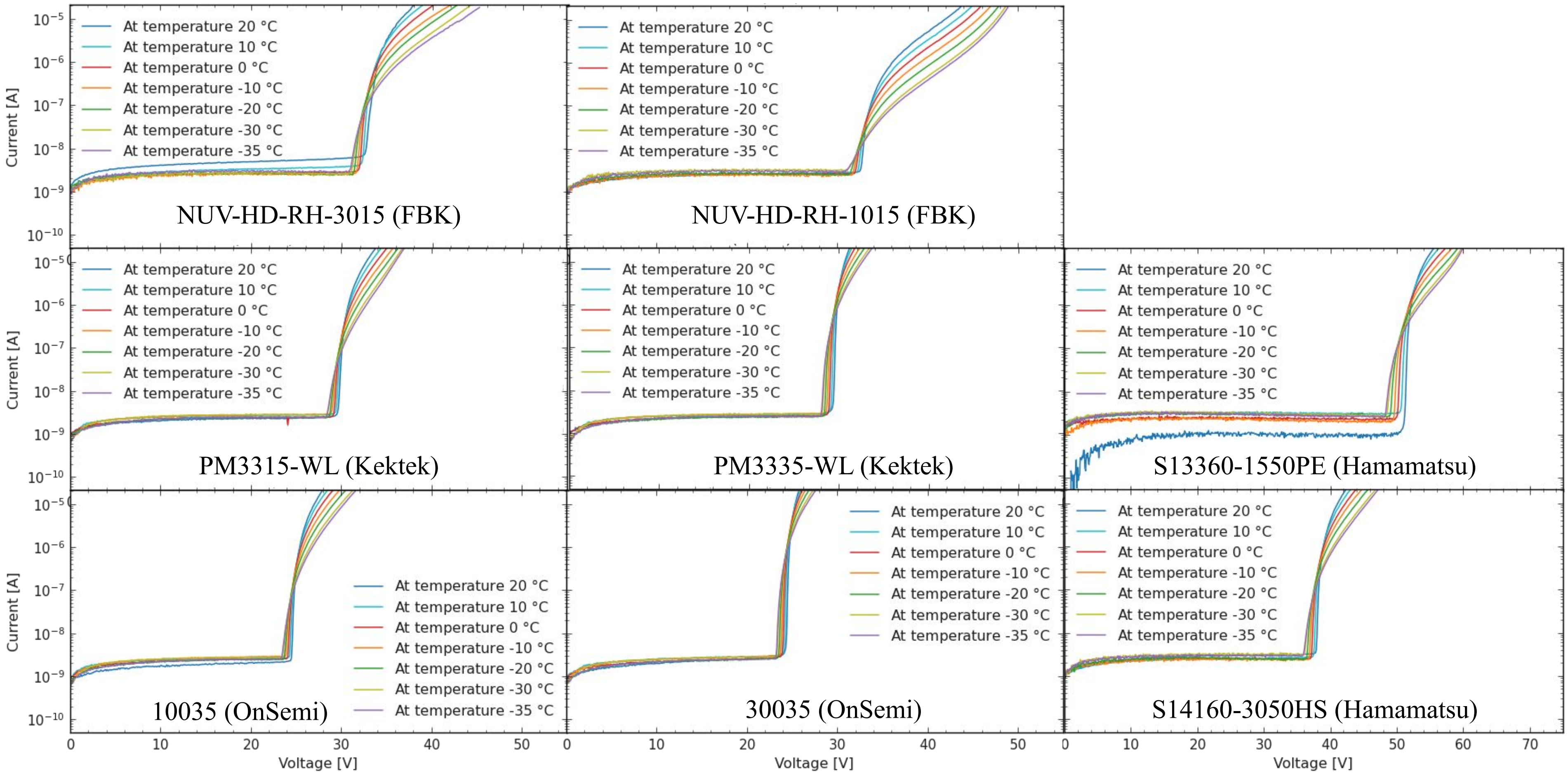


3×3 mm^2

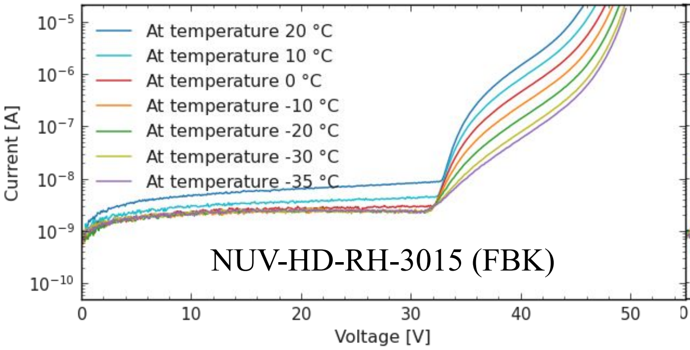
Current-voltage characterizations (non-irradiated)

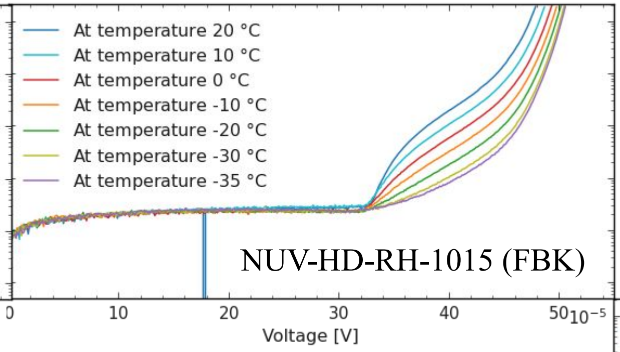


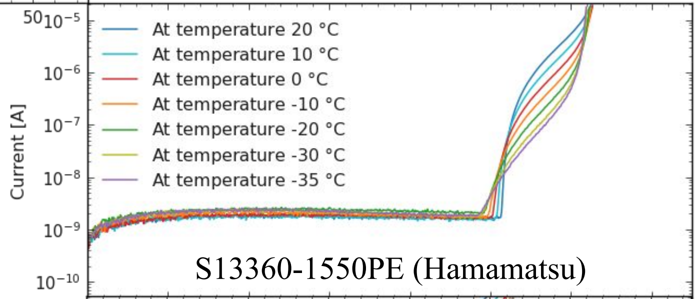
Current-voltage characterizations (irradiated)

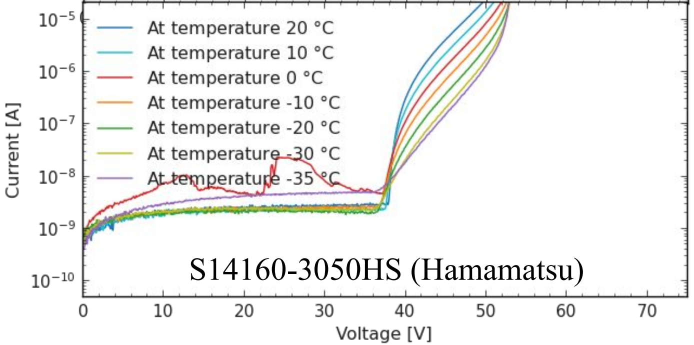


Current-voltage characterizations (annealed)

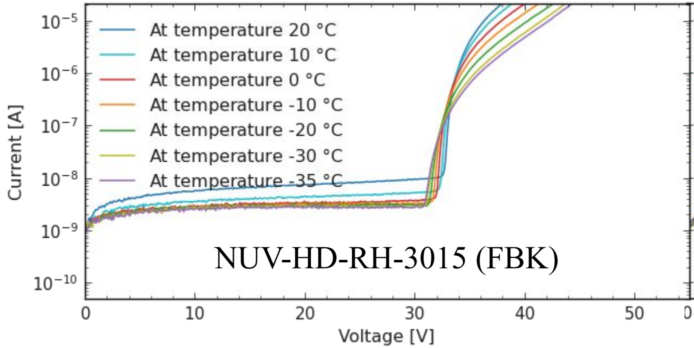


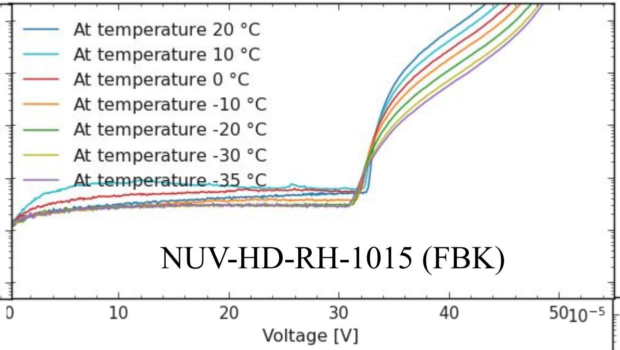


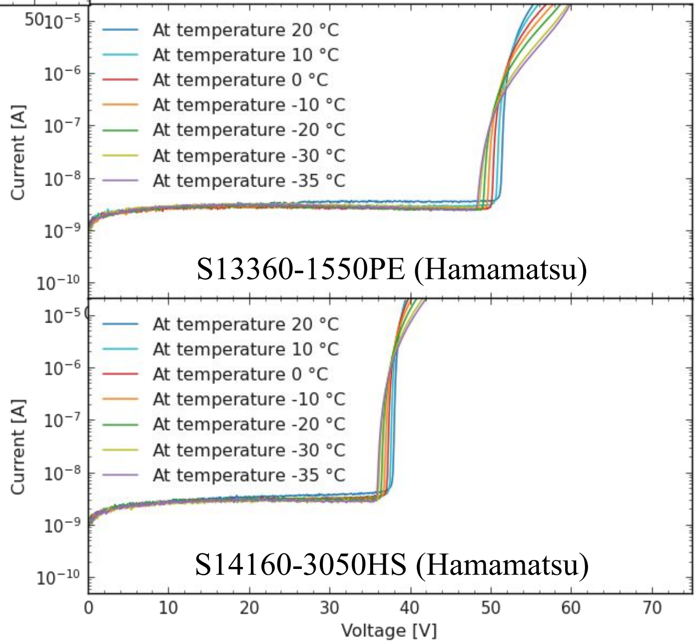




Current-voltage characterizations (re-irradiated)

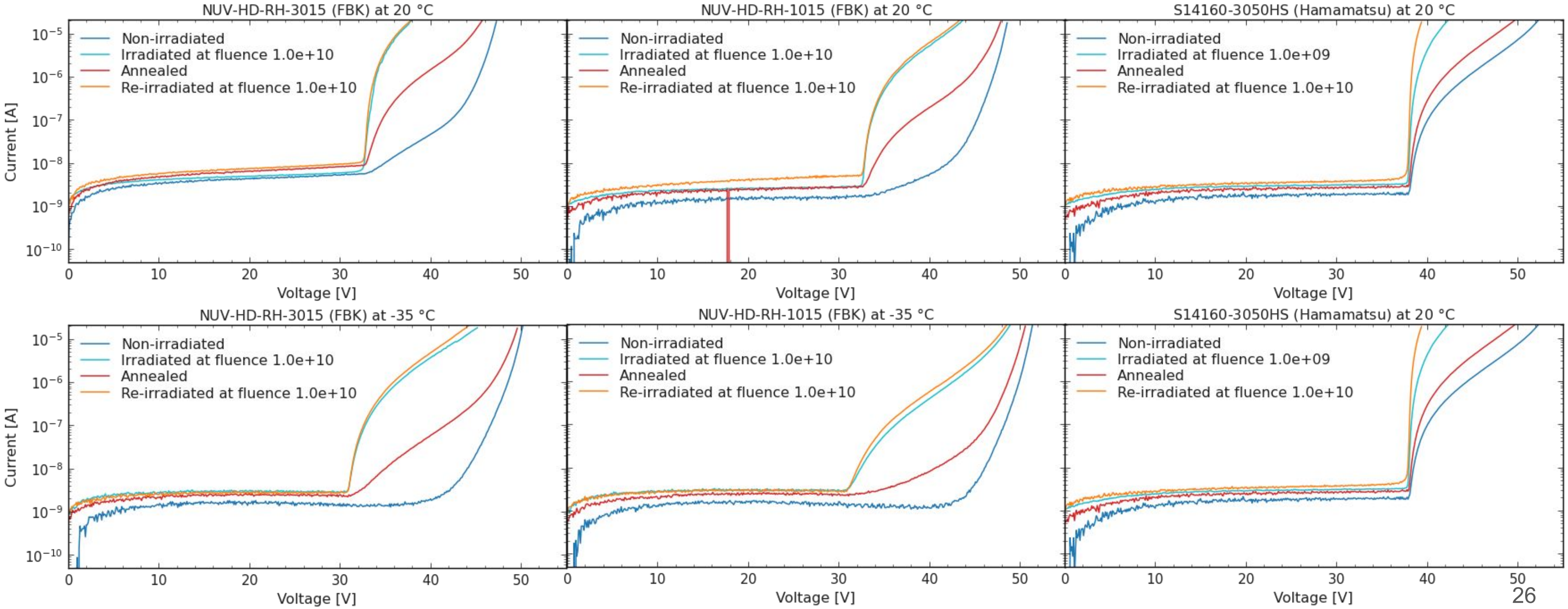






Current-voltage characterizations of FBK modules

- For non-irradiated data, the current-voltage characterizations change as function of temperature.
- For lower temperatures, the current-voltage characterization starts to grow later as for high temperatures.
- After irradiation, annealing and re-irradiation, this behaviour is not observed again.



Photon spectra fits

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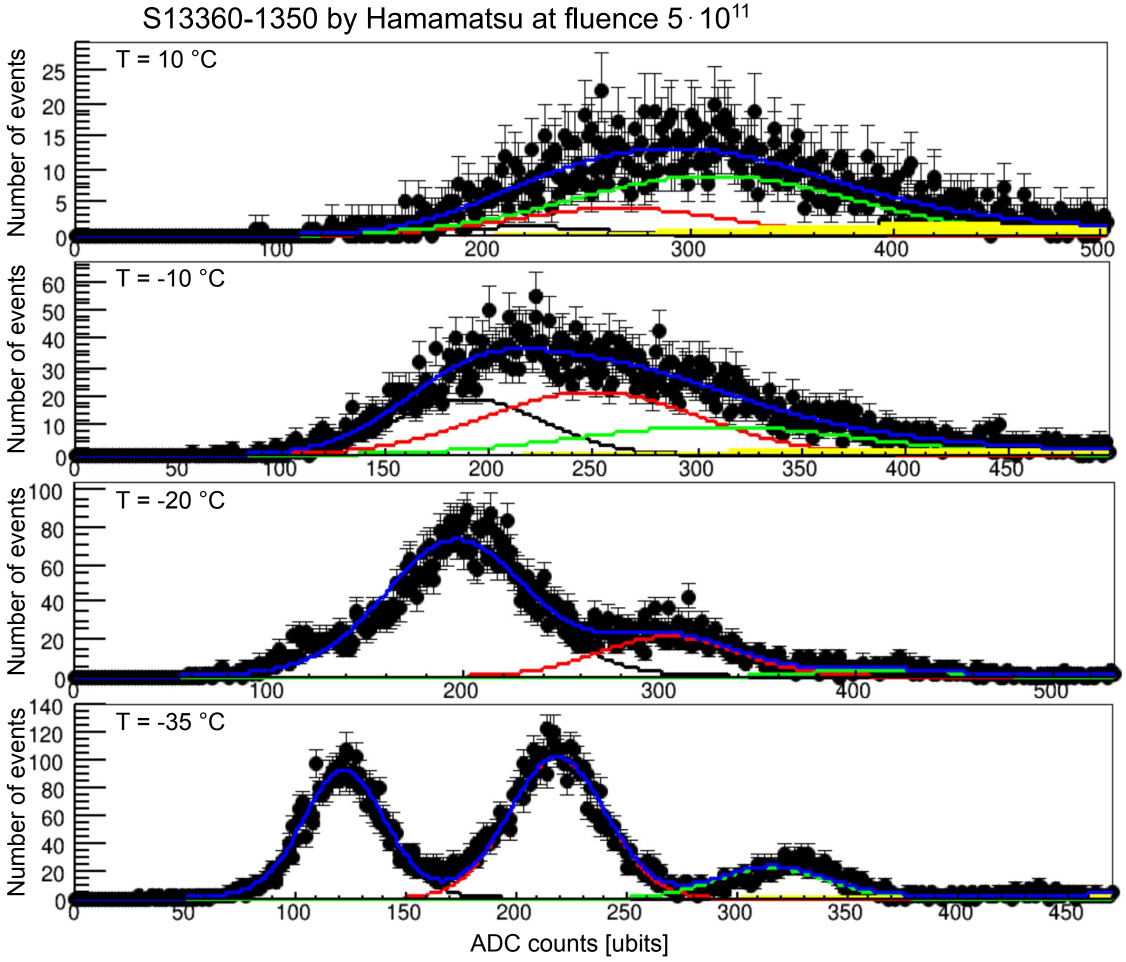
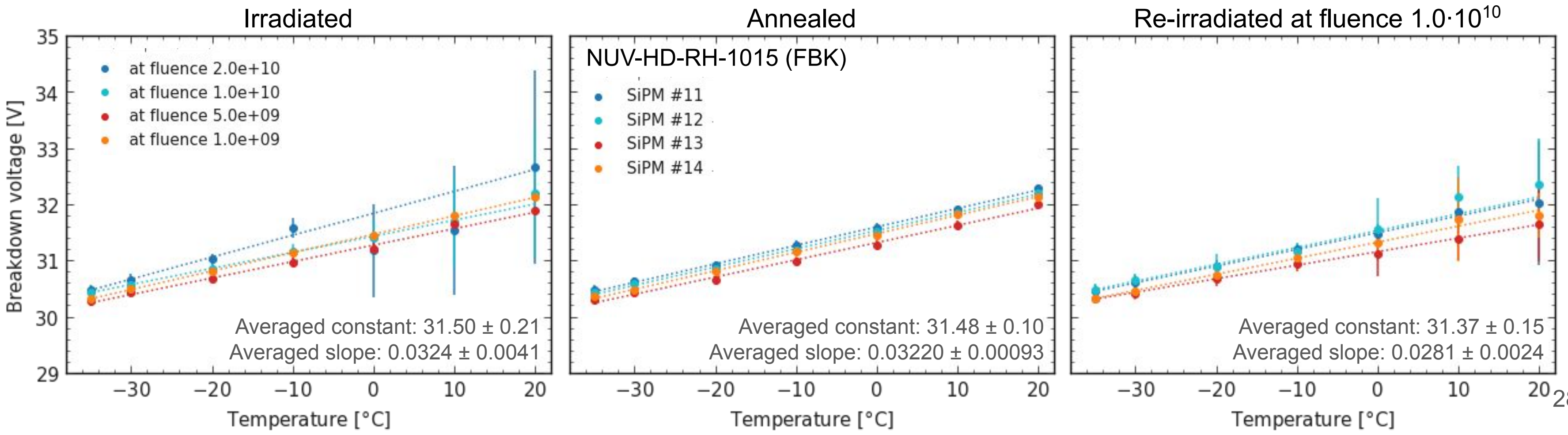
- The photon spectra is fitted by poissonian distribution convoluted with gaussian(s).
- Time resolution is fitted twice with gaussian, in the second fit the fitting window is in range (-5 · sigma, sigma) of previous fit.
- In high temperatures or with large detection area (highly irradiated) modules do not provide sufficient results for photon spectra fit.

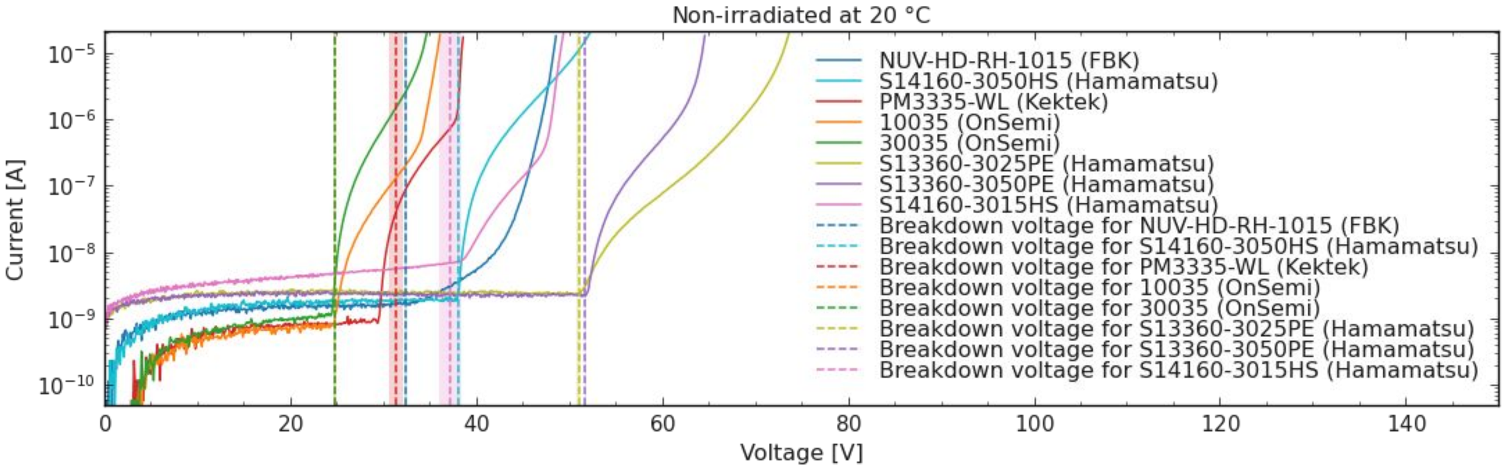


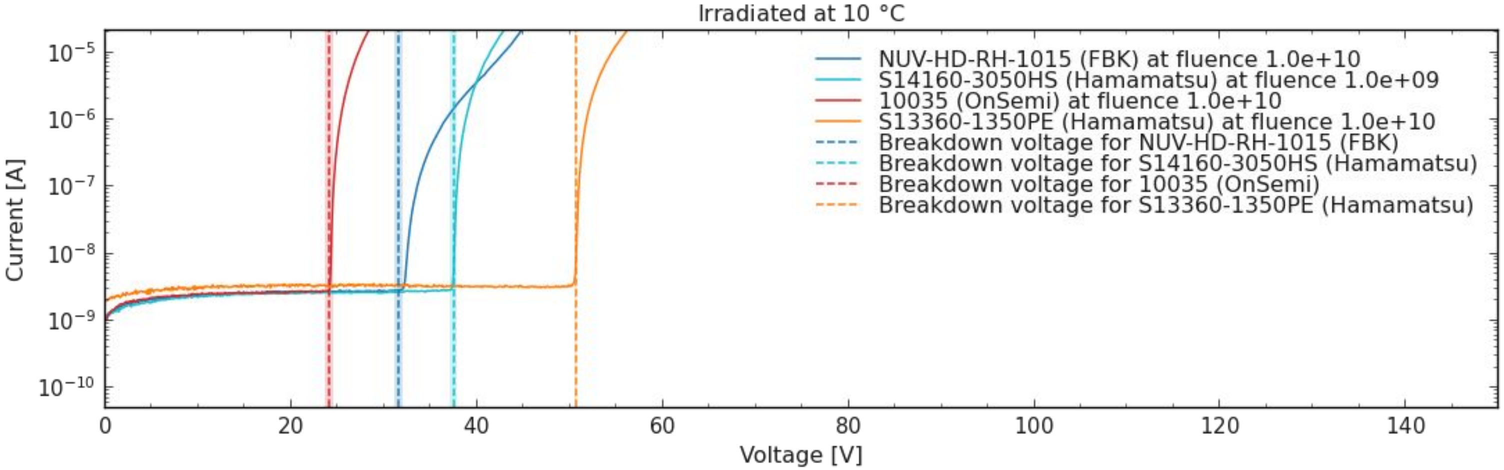
Breakdown voltage as function of temperature

- 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 fluence $2 \cdot 10^{10}$).
- 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.



Breakdown voltages and characterizations

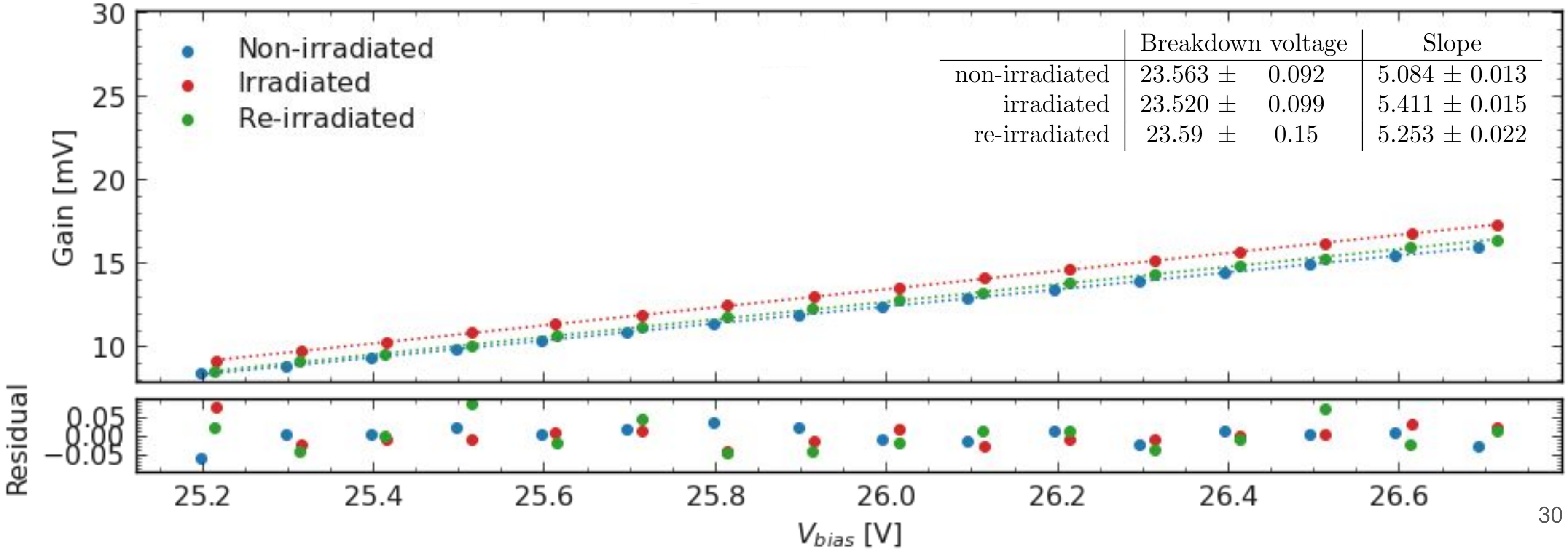




Photon spectra for 10035 (OnSemi) module

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

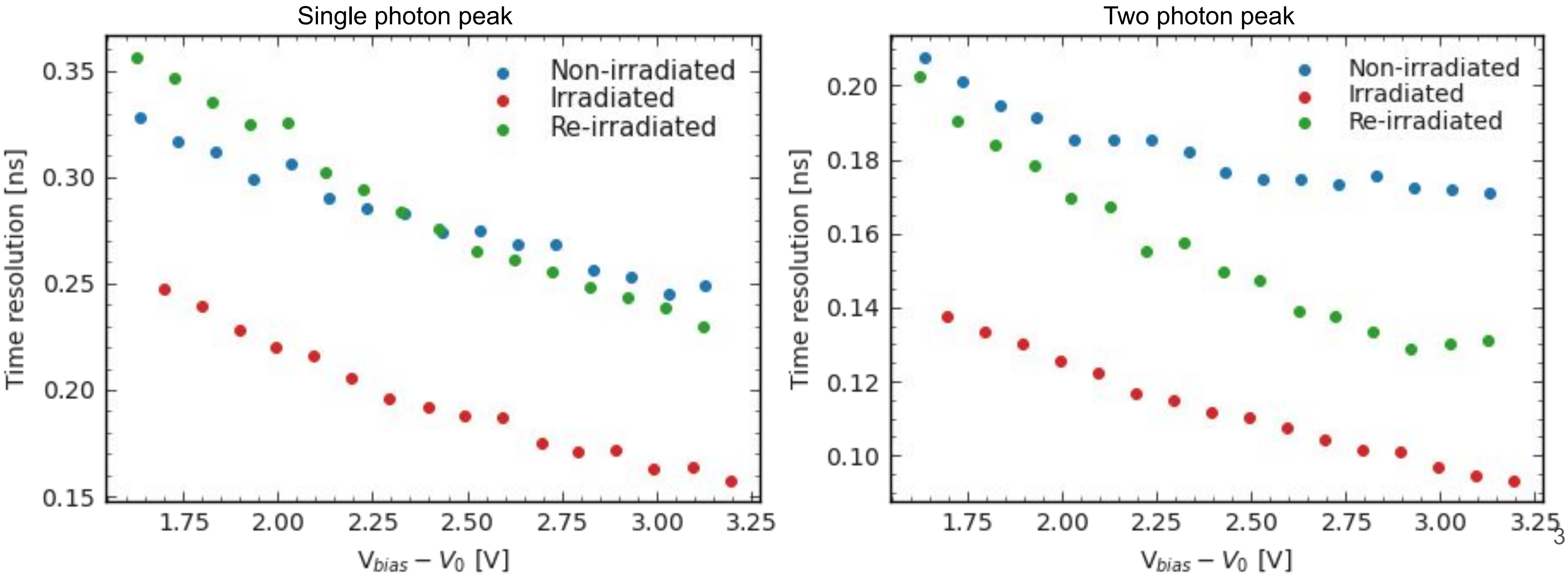
100035 by OnSemi irradiated to fluence $1 \cdot 10^{9}$ and re-irradiated to fluence $1.1 \cdot 10^{10}$ at -35 °C



Time resolution for 10035 (OnSemi) module

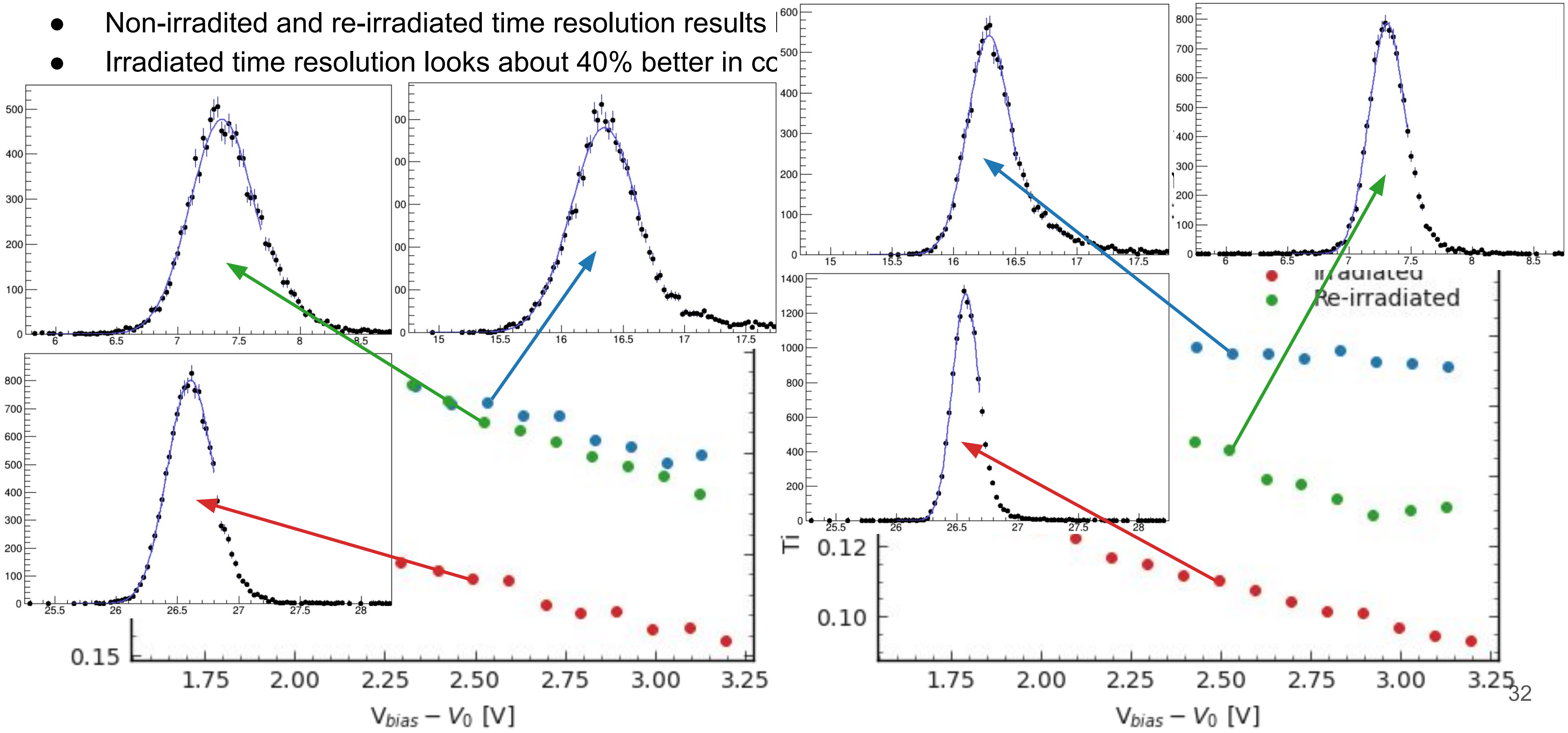
- Non-irradited and re-irradiated time resolution results look consistent to itself.
- Irradiated time resolution looks about 40% better in comparison to others datasets.

100035 by OnSemi irradiated to fluence $1 \cdot 10^9$ and re-irradiated to fluence $1.1 \cdot 10^{10}$ at -35 °C



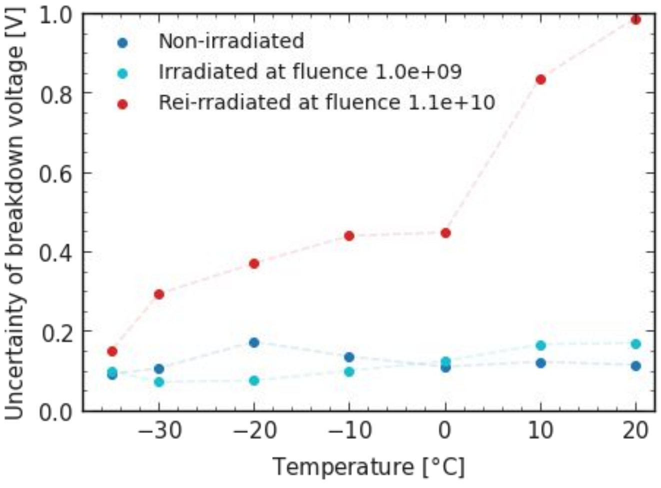
Time resolution for 10035 (OnSemi) module

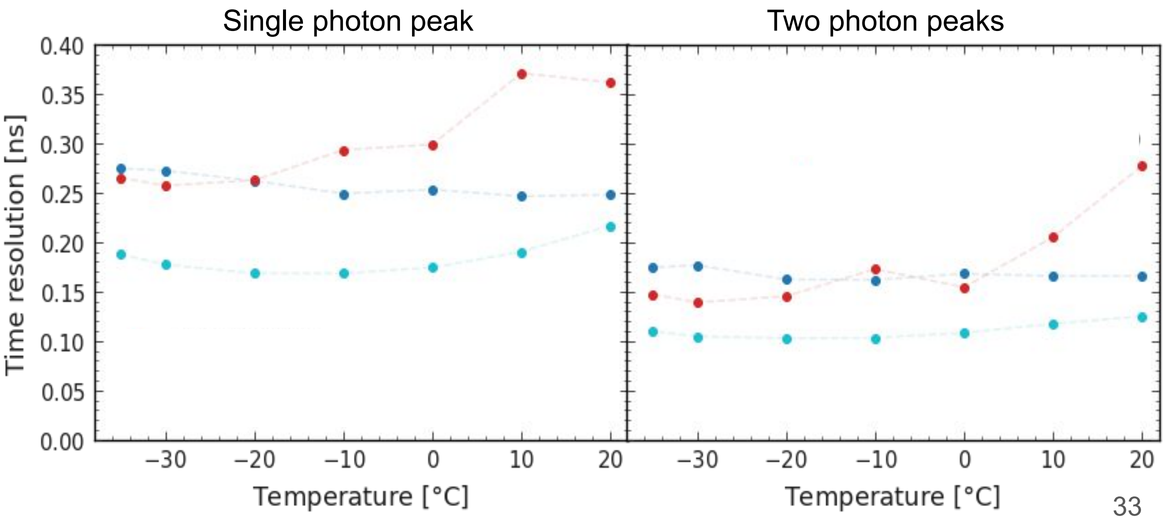
- Non-irradited and re-irradiated time resolution results
- Irradiated time resolution looks about 40% better in cc



Results for the 10035 (OnSemi) module

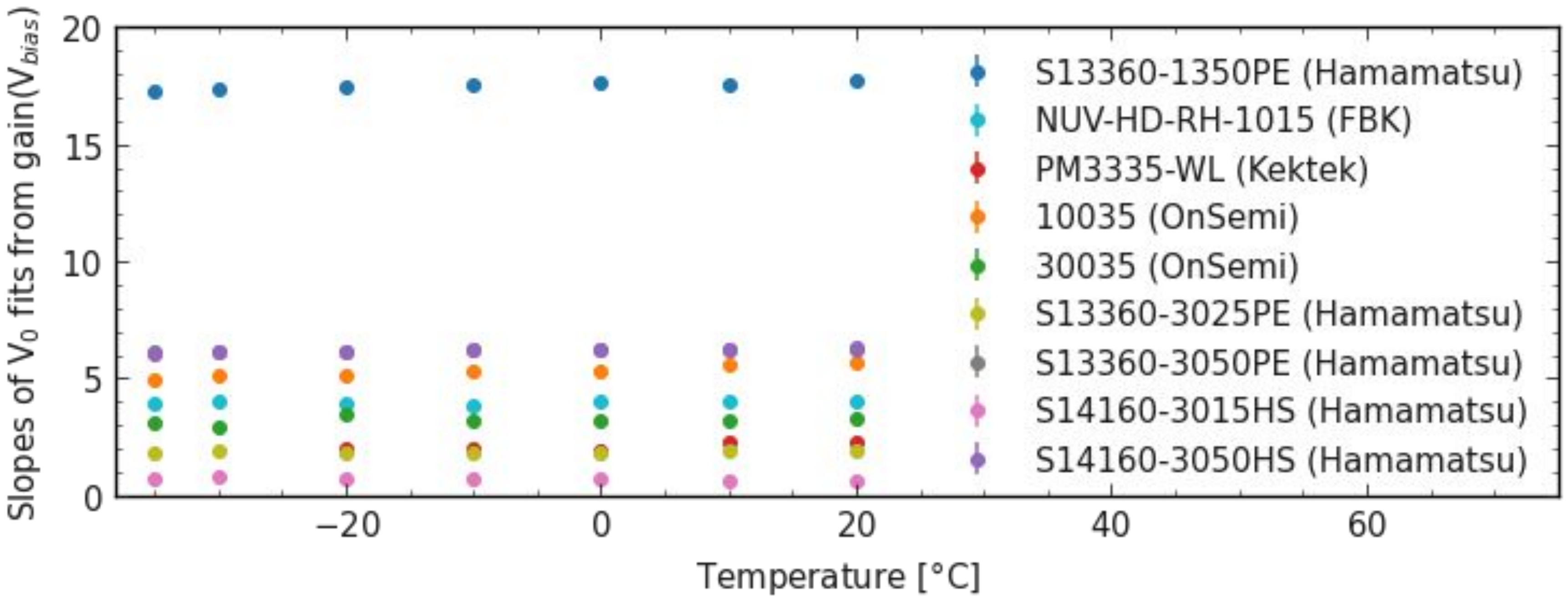
- Overvoltage set to level 2.5 V
- Uncertainty of breakdown voltage as function of the temperature demonstrates similar results as for FBK modules, where the threshold to have stable breakdown voltage as function of temperature can be set less $1.0 \cdot 10^{10}$ fluence.
- Time resolution results for single and two photon peaks show consistent results with FBK and Hamamatsu in comparison between non-irradiated and re-irradiated data.





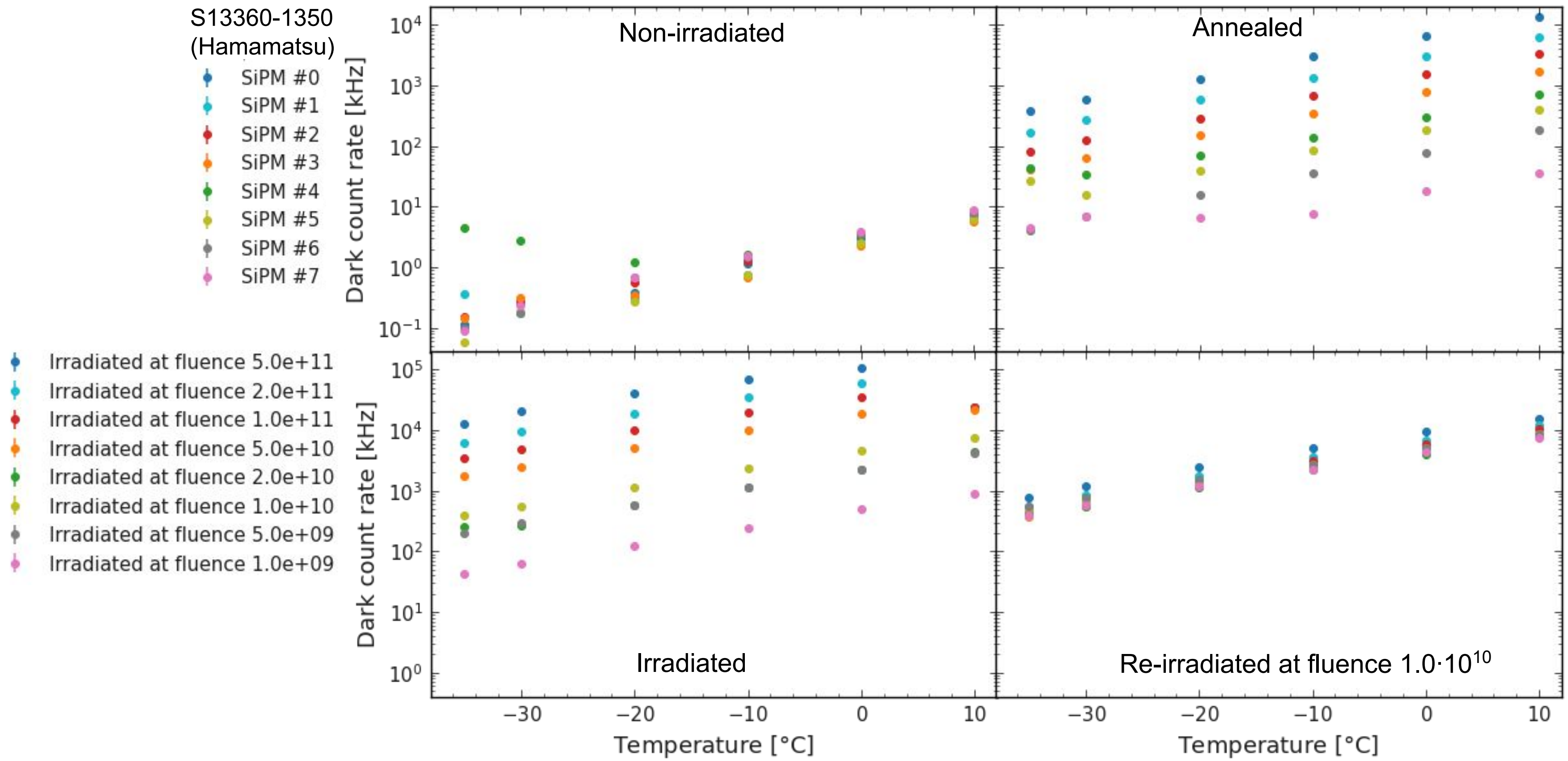
Slopes from extraction breakdown voltages

- Gains as function of bias voltage are fitted using linear function.
- Breakdown voltage are extracted from the fit.
- Slopes from the linear fit can be extracted too.
- Some of numerical values can be found at slides #5 and #10.



Dark count rate as function of temperature

- Overvoltage set to level 2 V



Dark count rate as function of temperature

- Overvoltage set to level 7.5 V