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

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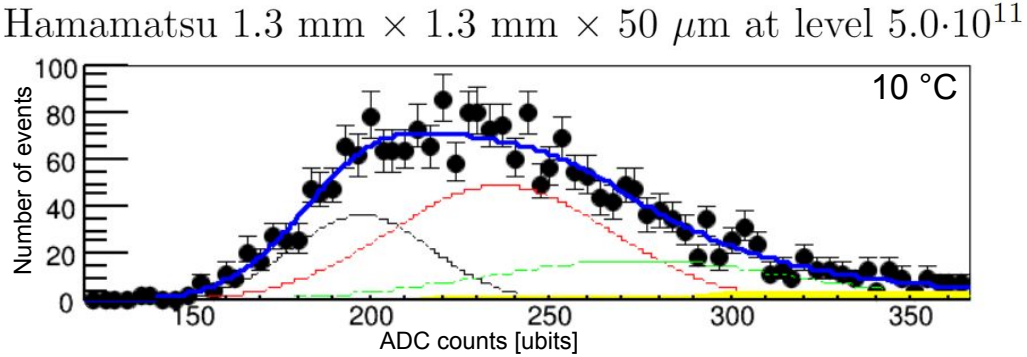
Tests with irradiated modules in Padova

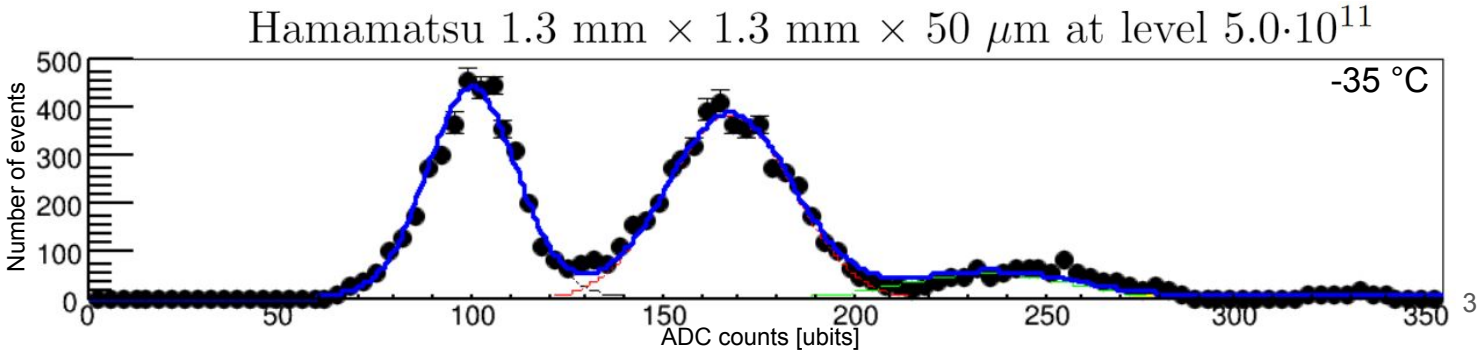
- Eventually MCP-PMTs with extended lifetime can be replaced by SiPMs in next long shutdown.
- We irradiated 24 SiPM modules with different neutron fluxes and tested by laser.
- Sixteen of them are processed to study their response.
- Collected data are read from modules and analyzed:
  - Photon spectra 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 first and second peak of photon spectra
  - Dark count rate measurement
- Compare results using modules after annealing (150 °C for 8 weeks) and re-irradiation

Index	Producer	Dimension [mm×mm]	Pitch [μm]	Neutron 1 MeV eg/cm^2 fluence
0 - 7	Hamamatsu	1.3 × 1.3	50	$5.0{\cdot}10^{11}$ - $1.0{\cdot}10^{9}$
8 - 10	FBK	3 × 3	15	$1.0{\cdot}10^{10}$ - $1.0{\cdot}10^{9}$
11 - 14	FBK	1 × 1	15	$2.0{\cdot}10^{10}$ - $1.0{\cdot}10^{9}$
15	Hamamatsu	3 × 3	50	$1.0{\cdot}10^{9}$

Photon spectra fits

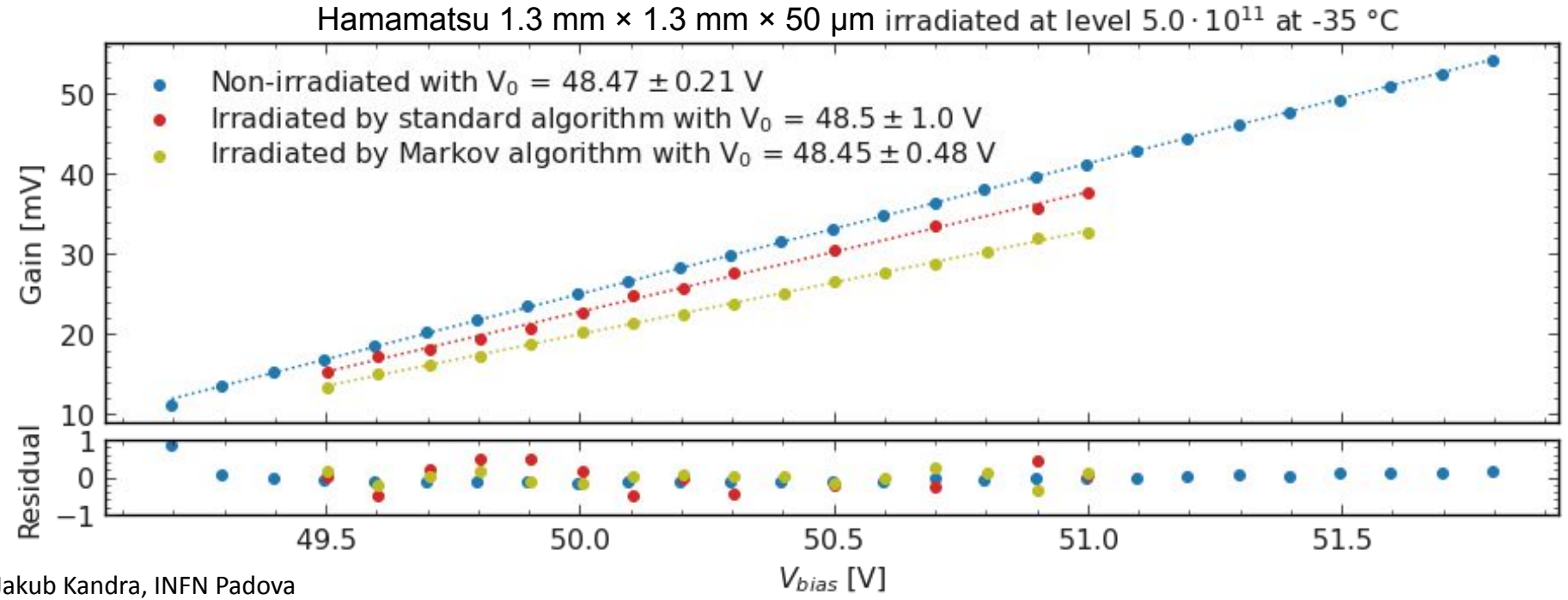
- We are using two different methods for extraction of maximum of photons:
  - Standard algorithm
  - Markov algorithm with background subtraction
- Markov algorithm allows us to provide photon spectra cleaner in harder environments
- Using highly irradiated modules in high temperatures or with large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





Extraction breakdown voltage

- From photon spectra fit gains are extracted and breakdown voltage is extracted from gain as function of bias voltage
- Extracted breakdown voltage after irradiation is consistent with results before irradiation
- Markov algorithm provides precise result as standard algorithm in highly irradiated environment

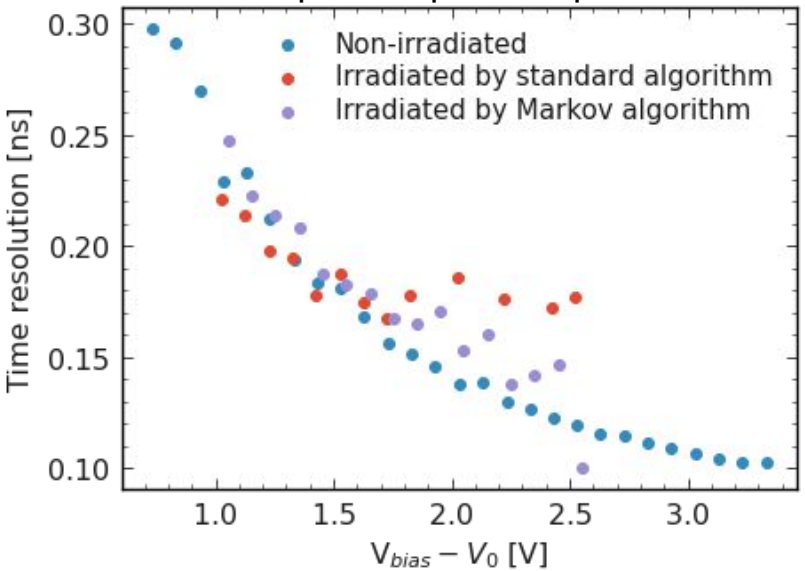


Time resolution

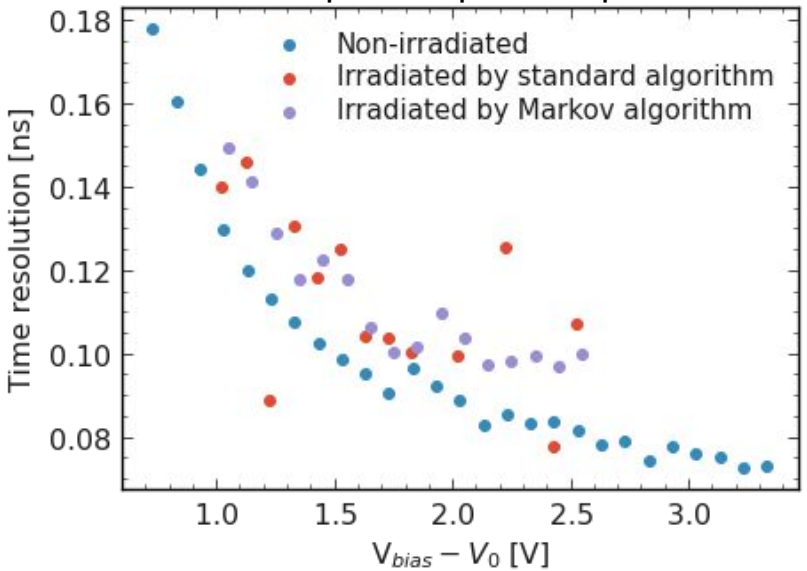
- Then we check time resolution using first and second photons of photon spectra
- Time resolution studies demonstrate time resolution is consistent before and after irradiation

Hamamatsu 1.3 mm × 1.3 mm × 50 μm irradiated at level $5.0 \cdot 10^{11}$ at -35 °C

First peak of photon spectra

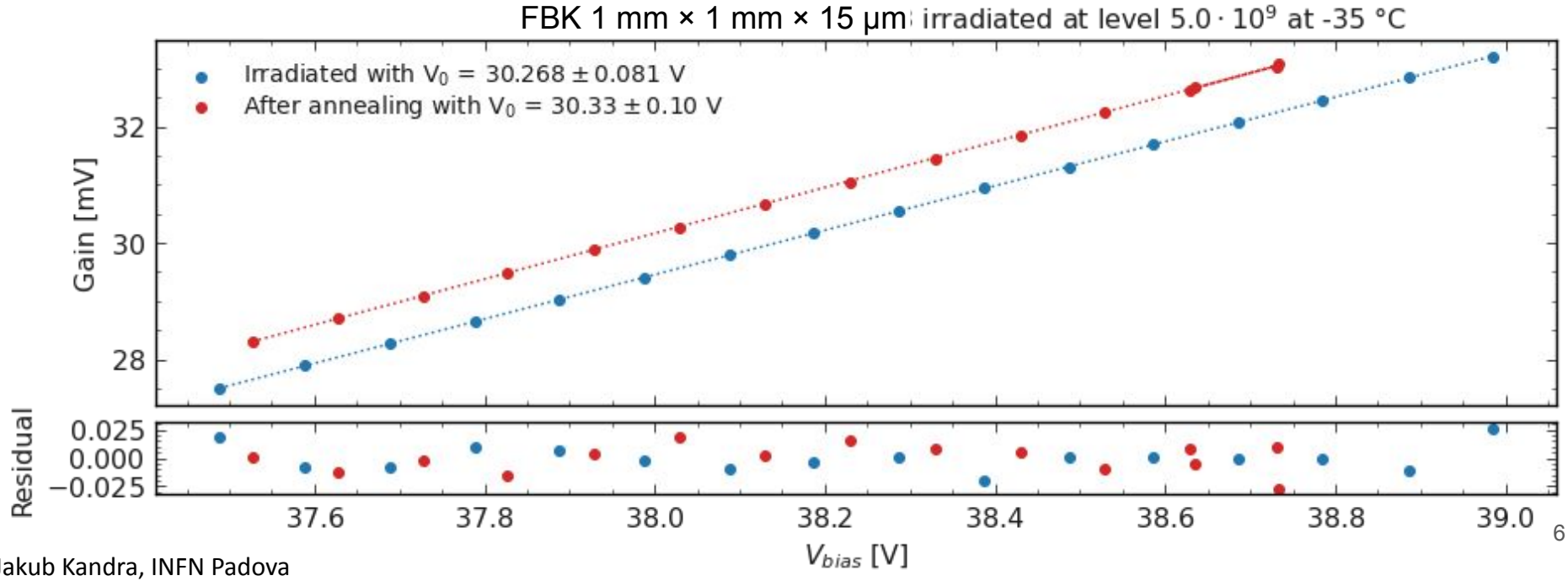


Second peak of photon spectra



Effect of annealing to breakdown voltage

- Additional test has been provided using FBK modules, where photon spectra has been fitted before and after annealing to test if annealing process affect breakdown voltage extraction
- No significant difference has been observed after annealing

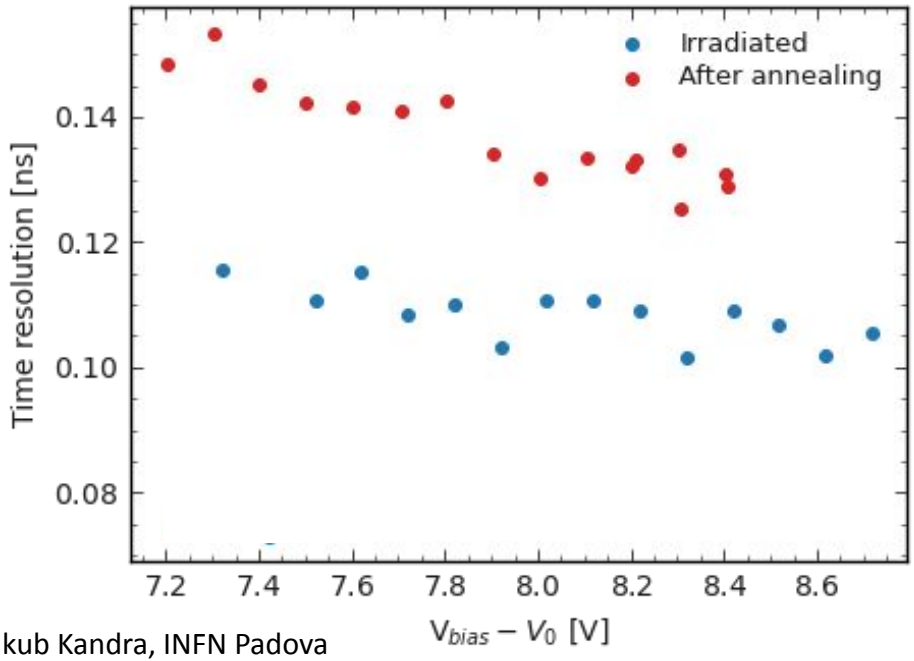


Effect of re-irradiation to time resolution

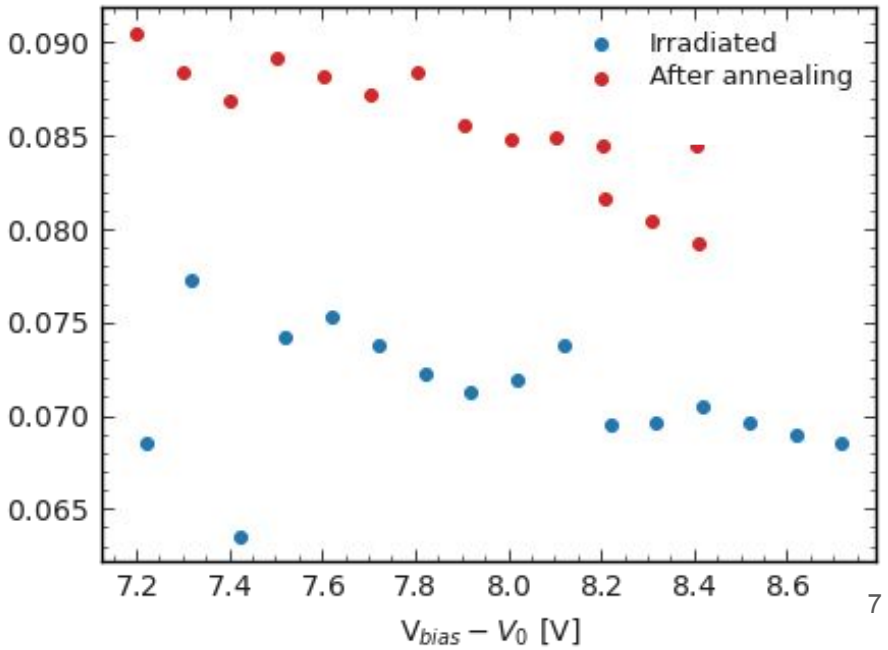
- To check effect of re-irradiation we provide same checks before and after annealing
- Time resolution results keep consistent as before

FBK 1 mm × 1 mm × 15 μm irradiated at level $2.0 \cdot 10^{10}$ at -35 °C

First peak of photon spectra

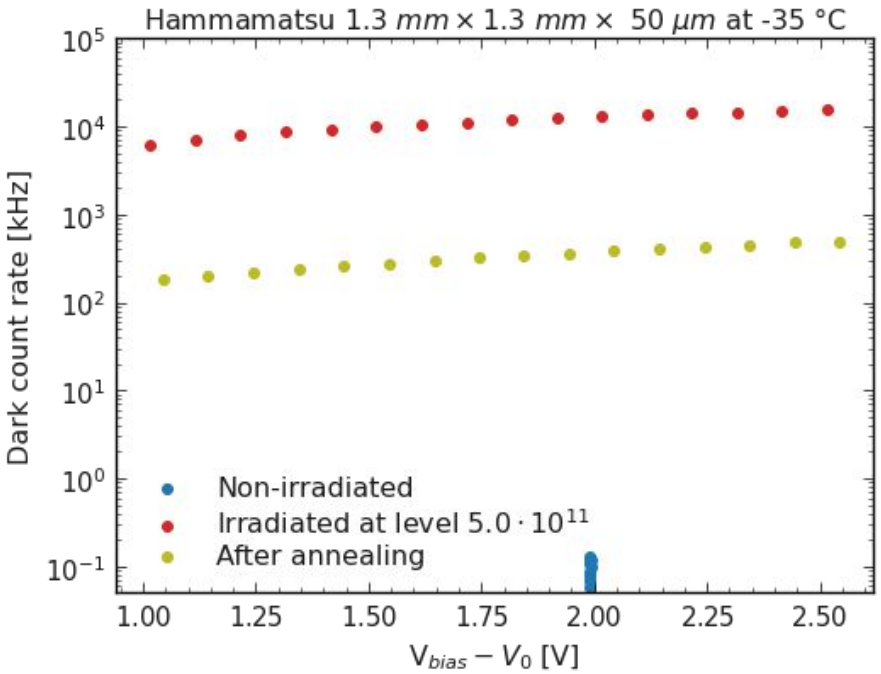


Second peak of photon spectra



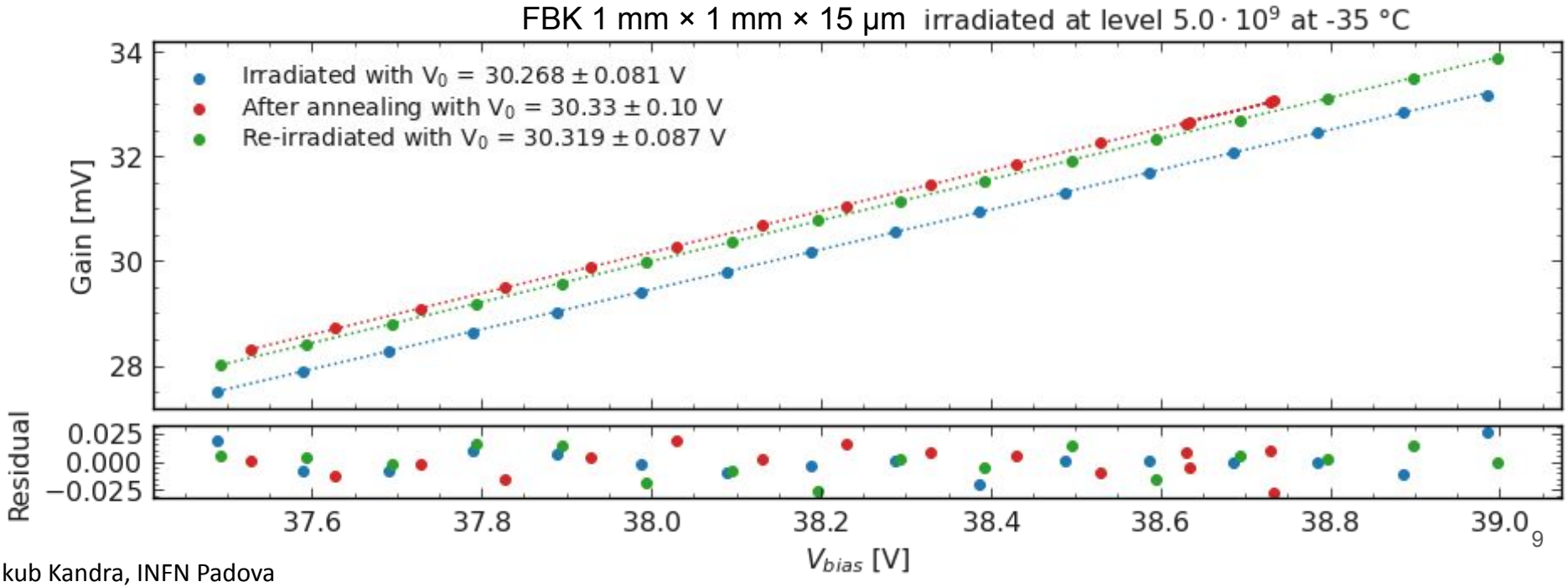
Dark count rates

- We provide dark count rate measurements using non-irradiated, irradiated and annealed data
- Annealing helps to reduce dark count rates in several magnitudes



Effect of re-irradiation to breakdown voltage

- Then modules was irradiated again at level $10.0 \cdot 10^{10}$ to test affect to breakdown voltage extraction
- No significant difference has been observed after annealing

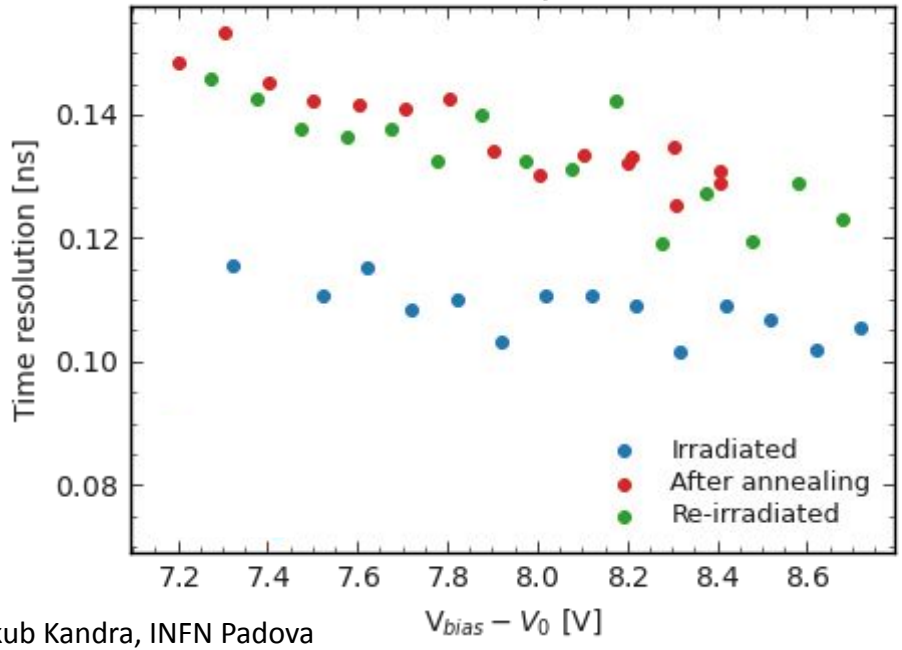


Effect of annealing to time resolution

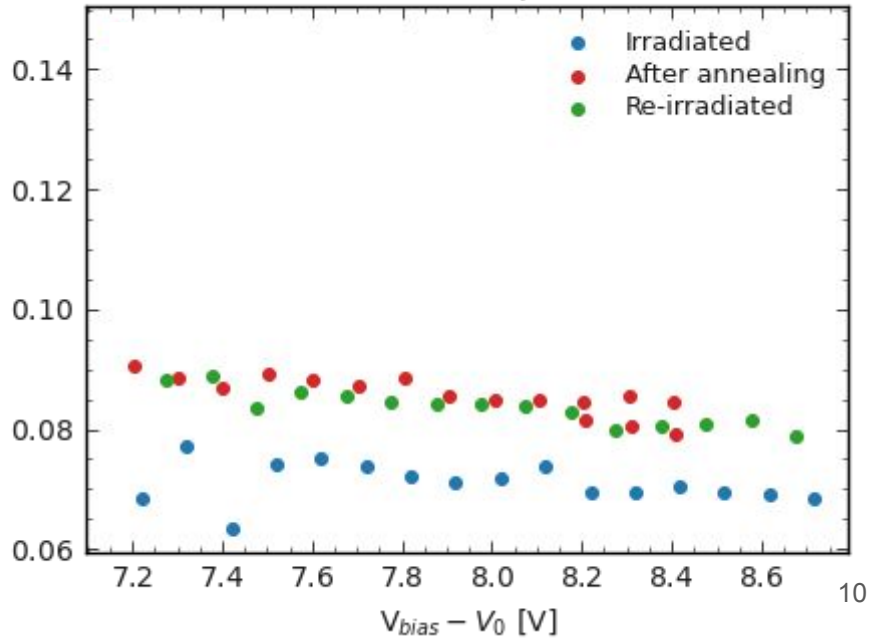
- Then modules was irradiated again at level $10.0 \cdot 10^{10}$ to test affect to time resolution
- Time resolution results keep consistent as before

FBK 1 mm × 1 mm × 15 μm irradiated at level $2.0 \cdot 10^{10}$ at -35 °C

First peak of photon spectra

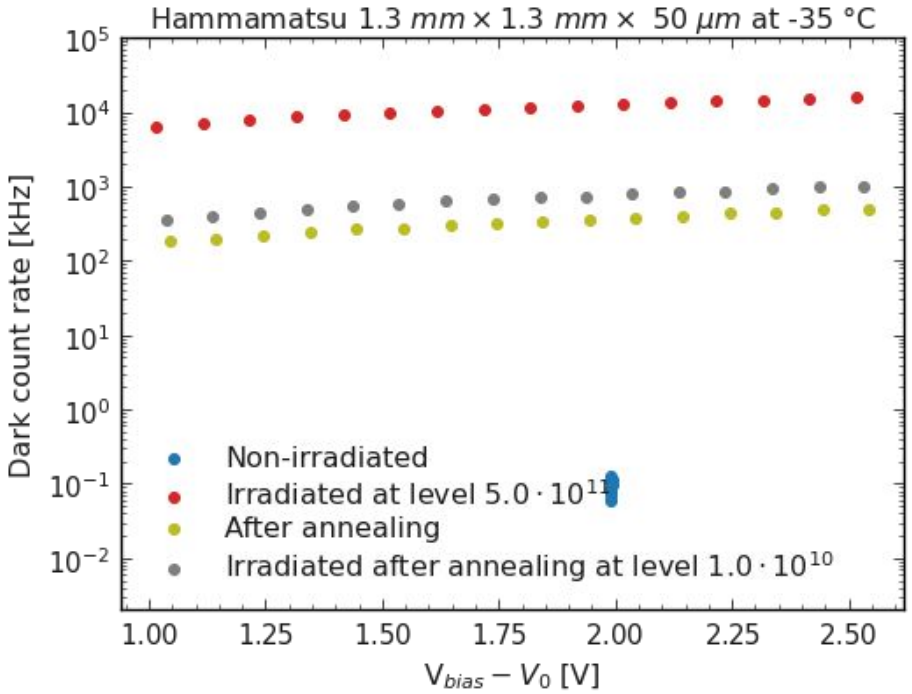


Second peak of photon spectra



Dark count rates

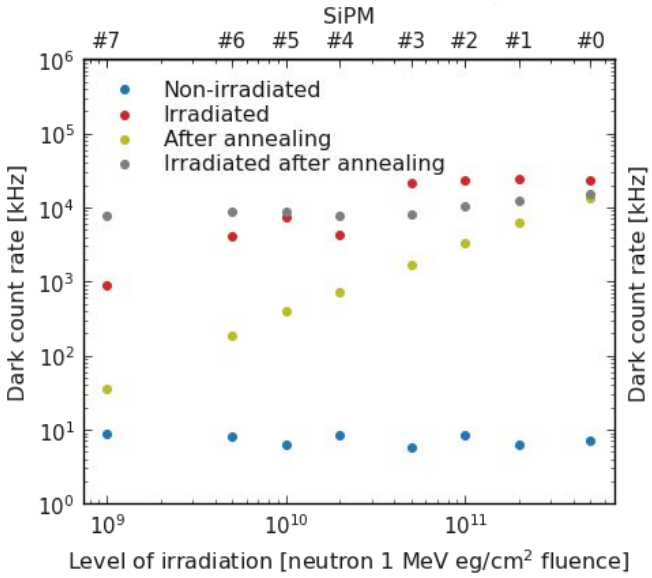
- We provide dark count rate measurements using non-irradiated, irradiated, annealed data and re-irradiated
- Annealing helps to reduce dark count rates in several magnitudes
- Results of re-irradiated are consistent with previous observations



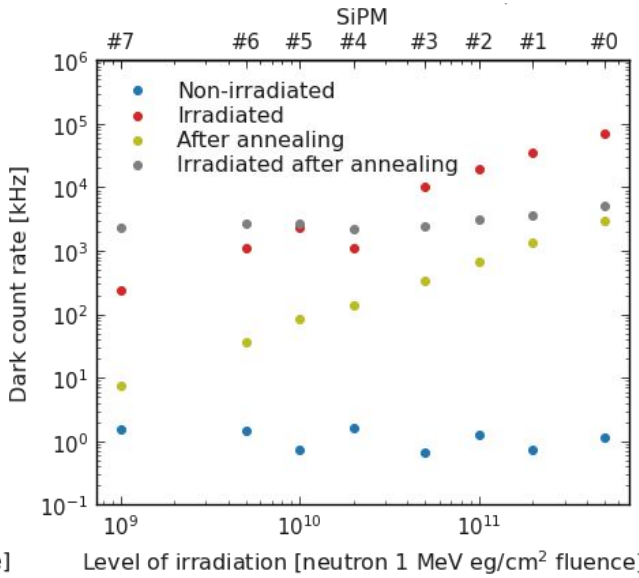
Dark count rates as function of irradiation level

Hamamatsu 1.3 mm × 1.3 mm × 50 μm

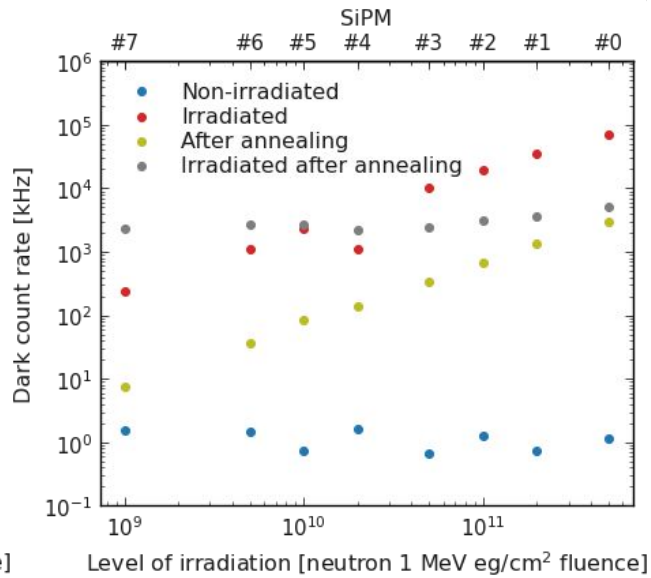
10 °C



-10 °C



-35 °C



- Dark count rates can be recovered by annealing, but not to the level before irradiation.

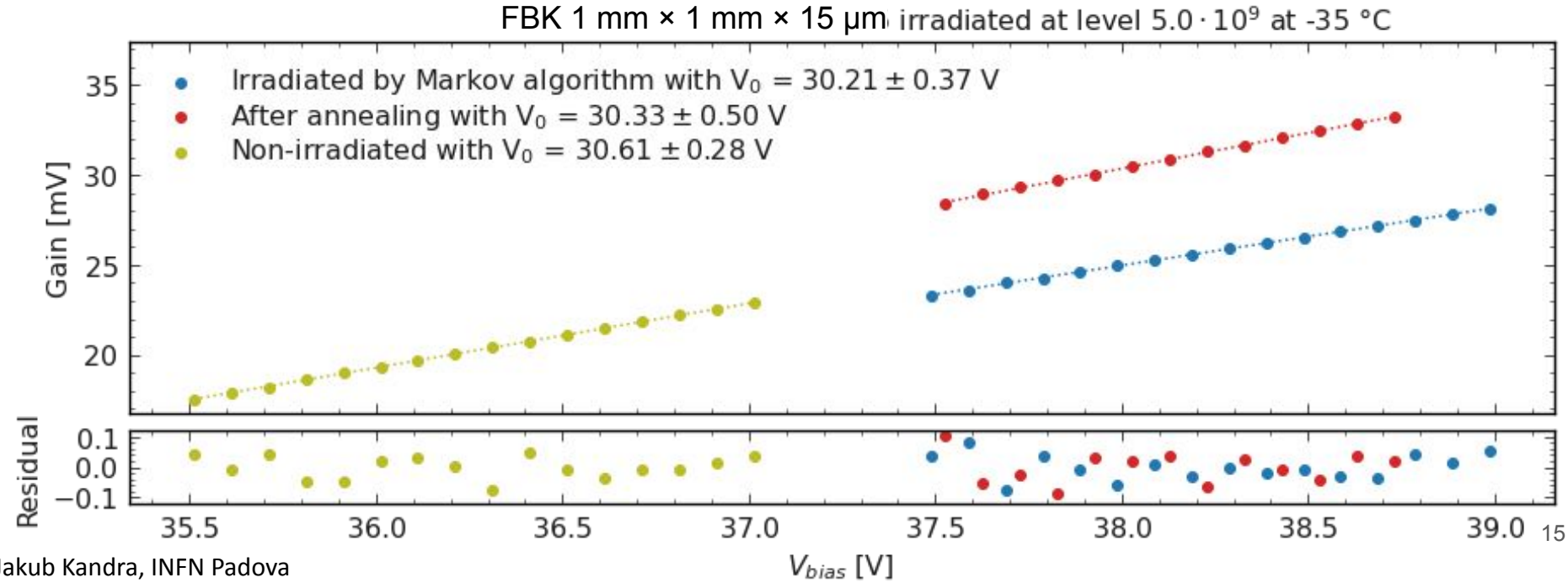
Conclusions and outlook

- We irradiated 24 SiPM modules with different neutron fluxes and tested by laser.
- Sixteen of them are processed to study their response.
- Modules were annealed (at 150 °C for 8 weeks) and processed again
- Then modules were re-irradiated at level $10.0 \cdot 10^{10}$ and processed again
- Collected data are read from modules and analyzed:
  a. Photon spectra fit using two different methods to extract maximum of photons
     - Highly irradiated modules with big sensitive area or at high temperatures worse fitted
  b. Extraction breakdown voltage using fitting of gain as function of bias voltage
     - Results are consistent before, after irradiation, after annealing and after re-irradiation
  c. Time resolution of first and second peak of photon spectra
     - Results are consistent before, after irradiation, after annealing and after re-irradiation
  d. Dark count rate measurement
     - Annealing reduce rates but not to level before irradiation
     - Re-irradiation consistent with previous observations

Backup

Effect of annealing to breakdown voltage

- Additional test has been provided using FBK modules, where photon spectra has been fitted before and after annealing to test if annealing process affect breakdown voltage extraction
- No significant difference has been observed after annealing



Effect of annealing to time resolution

- To check effect to annealing we provide same checks before and after annealing
- Time resolution results keep consistent as before

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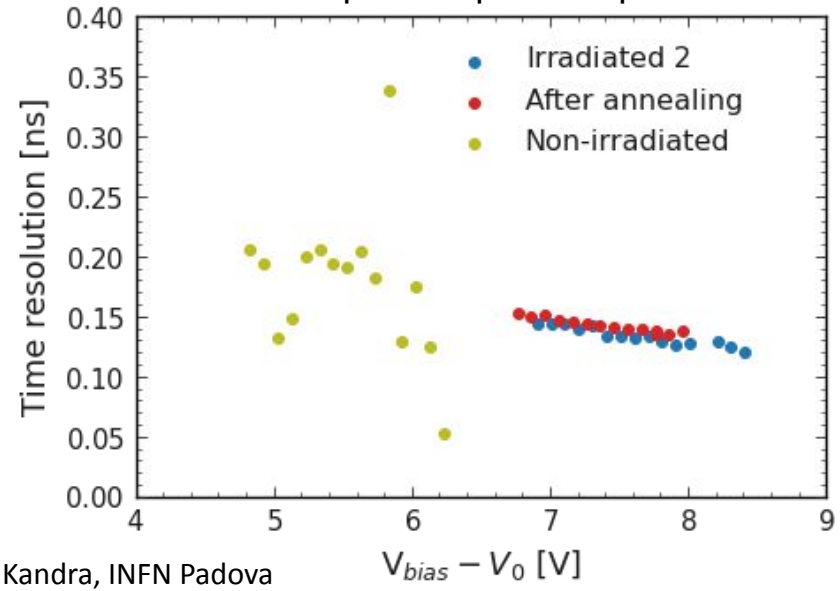
First peak of photon spectra



Second peak of photon spectra