

Application of ultrashort laser pulses for timing characterization of silicon photomultipliers

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Abstract. The application of femtosecond laser irradiation for the investigation of Geiger discharge process in silicon photomultiplier (SiPM) is discussed. It is shown experimentally that sub-picosecond pulses of laser beam focused to micron spot sizes allow studying the dynamics of Geiger discharge process in single cell of silicon photomultiplier. These studies are aimed at identifying the factors limiting the timing resolution of this class of devices.

1. Silicon photomultiplier

Solid state Silicon Photo Multiplier (SiPM) – a fast-paced class of photodetectors intended to register the low intensity pulse of optical radiation. One of the most important SiPM applications is to use it as a part of medical facilities, such as positron emission tomography using the Time-of-Flight Positron Emission Tomography (TOF-PET) [1, 2].

SiPM is a matrix of silicon avalanche photodiodes (cells), combined on a common substrate (see. Figure 1a).

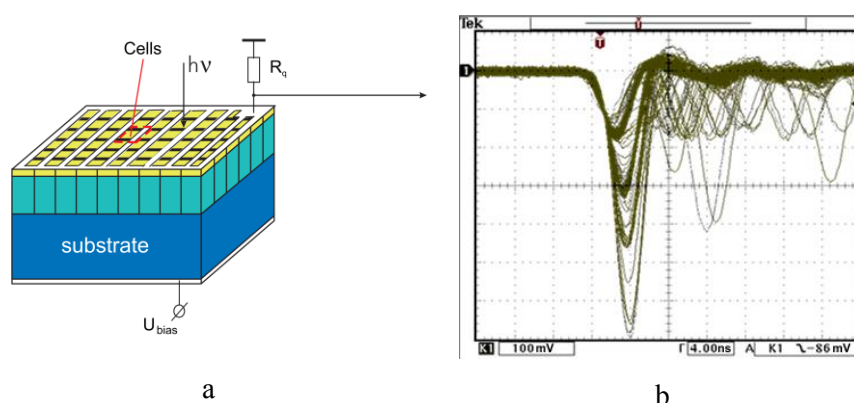


Figure 1. Design (a) and typical SiPM matrix signal oscillogram (b).

Figure 1b shows typical example of SiPM matrix signal oscillogram. General view of its photosensitive surface is presented in Figure 2.

All cells operate in Geiger discharge mode (i.e. biased by voltage, slightly exceeding electrical breakdown threshold), in which photon-generated charge carrier initiates avalanche cell discharge (see. Figure 3).

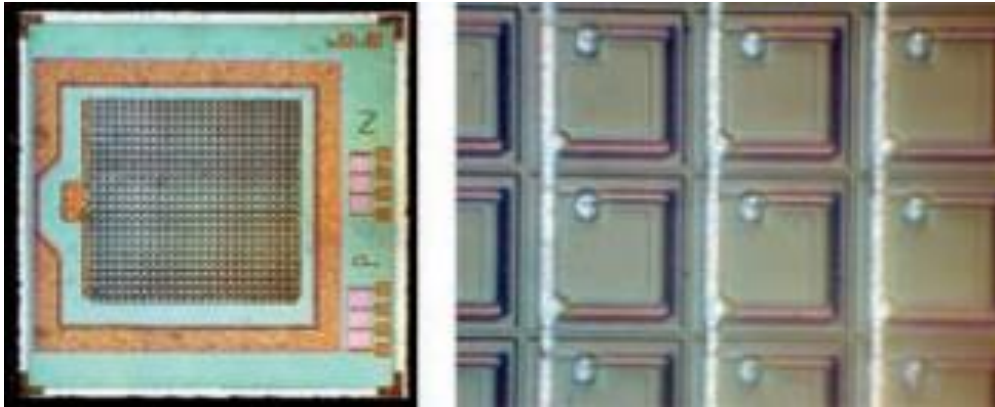


Figure 2. General view and the magnified image of SiPM cells.

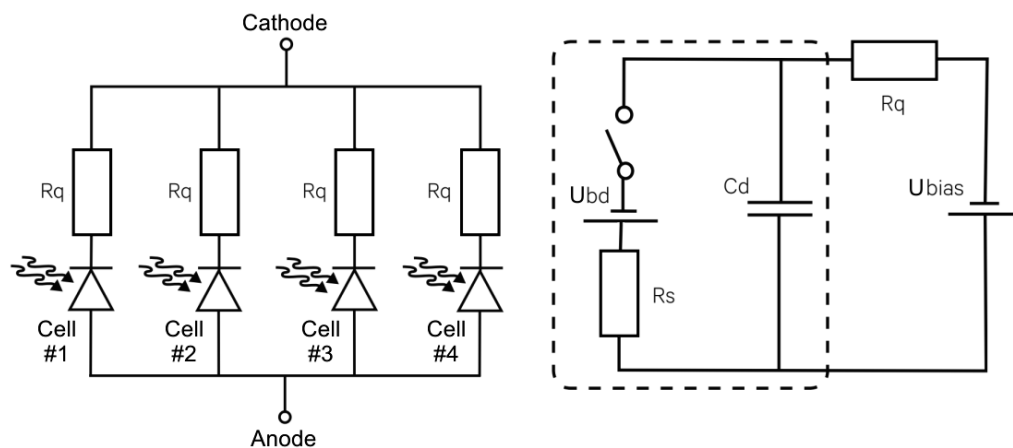


Figure 3. The SiPM equivalent circuit (parallel connection of avalanche photodiodes with quenching resistor R_q). The switch simulates the turn-on of photodiode under single photon excitation.

The most important characteristic of SiPM cell is its extremely high speed of avalanche discharge development. To ensure the best SiPM timing parameters a detailed study of the Geiger discharge process dynamics within a single cell is required. The speed of the avalanche development depends on the applied voltage and the thickness of the depletion region. For example, in [3] it was shown that the time required for the onset of Geiger discharge mode (the discharge signal front duration) may be of the order of 10 ps. To investigate these processes a light source with a light flash duration of 1 ps or less is required for the Geiger discharge initiation.

The research on emission microscopy [4] showed that the area of the avalanche discharge occupies only a very small part of the whole cell area (see Figure 4). So, to guarantee the consistency of the results, the sharp focusing of light radiation to a spot size of about 1 ... 3 μm is needed.

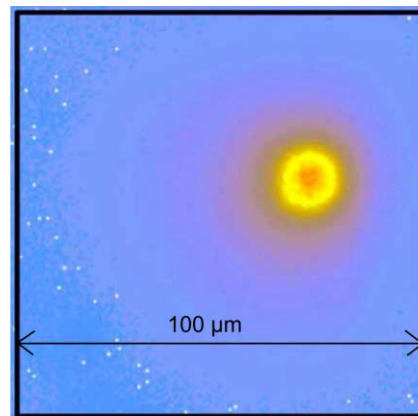


Figure 4. SiPM avalanche emission microscopy image (from [4]).

2. Experiment

In this work we have investigated experimentally the timing characteristics of the single-cell SiPM samples under the ultrashort pulsed optical irradiation. We used the experimental setup, based on femtosecond laser with 870 nm wavelength and 150 fs pulse duration combined with high resolution optical microscope with laser port (figure 5). This setup allowed to focus laser beam to a minimal spot of about 2 μm in diameter or obtain slightly defocused spot up to 200 μm by shifting the device under test away from the focal plane. For precise optical synchronization of the registration process high speed PIN photodiode was used. More detailed description of the setup can be found in [5].

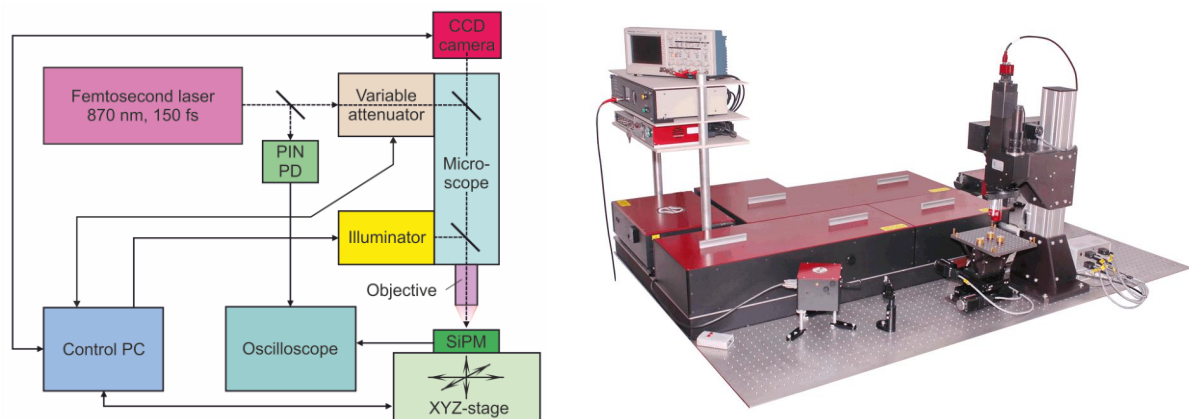


Figure 5. Block diagram and general view of the femtosecond laser experimental setup.

The SiPM electrical response was captured and analyzed statistically using the LeCroy WaveRunner 620Zi oscilloscope with the 2 GHz vertical channel bandwidth and 20 GHz sample rate.

In the experiment we have measured the delay and the jitter of the SiPM single cell discharge relative to the optical pulses registered by PIN photodiode, as a function of laser pulse energy E incident to the cell (see figure 6) and cell voltage for both focused and defocused irradiation with small number of photons.

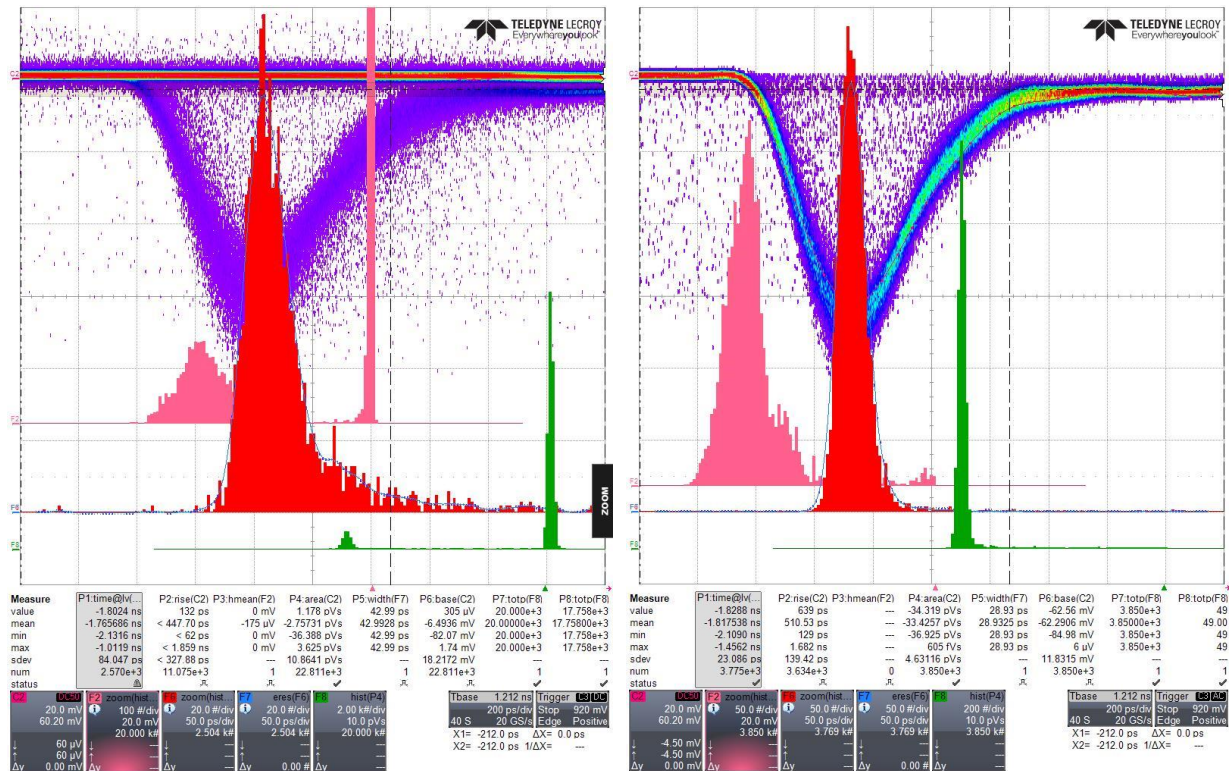


Figure 6. SiPM output electrical pulses at various femtosecond laser pulse energies: 0.1 nJ (left) and 10 nJ (right). Figure also shows the spectra measured by the oscilloscope: red – the registered SiPM electrical pulse time distribution at fixed threshold; green – the total charge (integral of SiPM signal) distribution; pink – the amplitude of SiPM signal distribution.

Figure 7 shows the result of the SiPM output signal oscillograms processing at various energies of laser excitation for 2 μm and 200 μm beam diameters and 35 V and 41 V SiPM bias voltages. Figures 8a and 8b present the dependences of the discharge time fluctuation, i.e. the time resolution (FWHM of the fitting curve), and discharge delay time, respectively, vs. the number of photoelectrons N_{phel} participating in the SiPM cell Geiger discharge initiation. In figure 8a one can see the noticeable decrease of time resolution at low irradiation energies, producing very few photoelectrons. Also, the time resolution for the defocused laser beam of about 10 photons is worse than for focused beam at the same SiPM bias voltage. Figure 8b shows that for the defocused laser beam the SiPM cell discharge happens earlier and takes less time due to the formation of several Geiger avalanches over the irradiated area. The value U_{th} stands for SiPM avalanche breakdown threshold voltage.

We have also investigated the influence of the SiPM bias voltage in the range from 35 – 41 V on the discharge time fluctuation and the delay under femtosecond pulsed laser irradiation. The experimental distributions of output pulse front delay relative to PIN photodiode trigger at various SiPM bias voltages are presented in figure 9 for focused (spot size 2 μm) and defocused (spot size 200 μm) laser beam.

One can see, that with the increase of bias voltage the SiPM cell discharges earlier and the avalanche develops faster. Also, the increase of overvoltage improves SiPM time resolution. Corresponding results of processing data presented in figure 9 are depicted in figure 10.

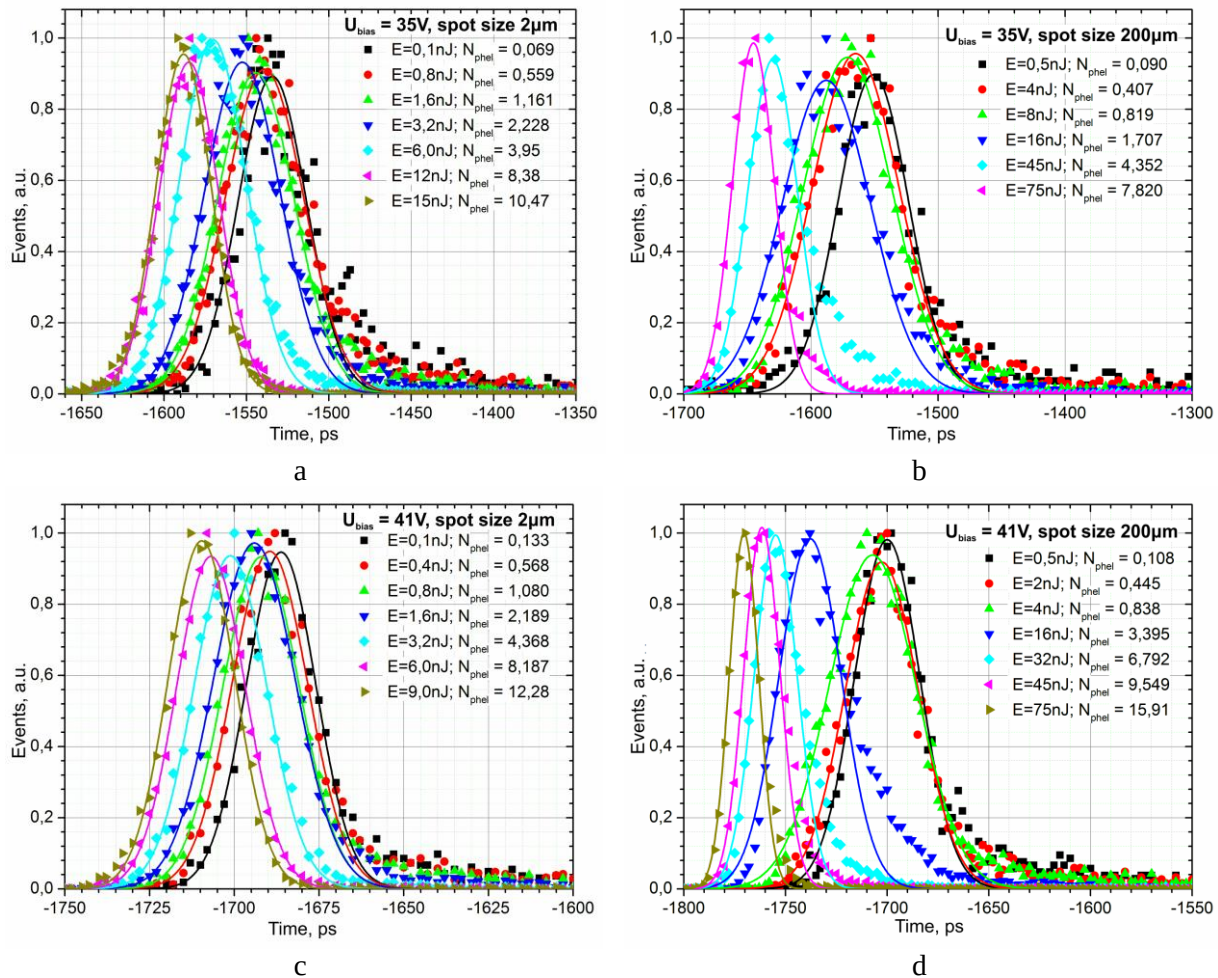


Figure 7. The distributions of output pulse front delay relative to the trigger signal from PIN photodiode for various laser excitation energies: (a) and (c) – beam diameter $2\mu\text{m}$, bias voltage 35 V and 41 V respectively; (b) and (d) – beam diameter $200\mu\text{m}$, bias voltage 35 V and 41 V, respectively. Dots correspond to the experimental data, solid lines – to Gaussian fit.

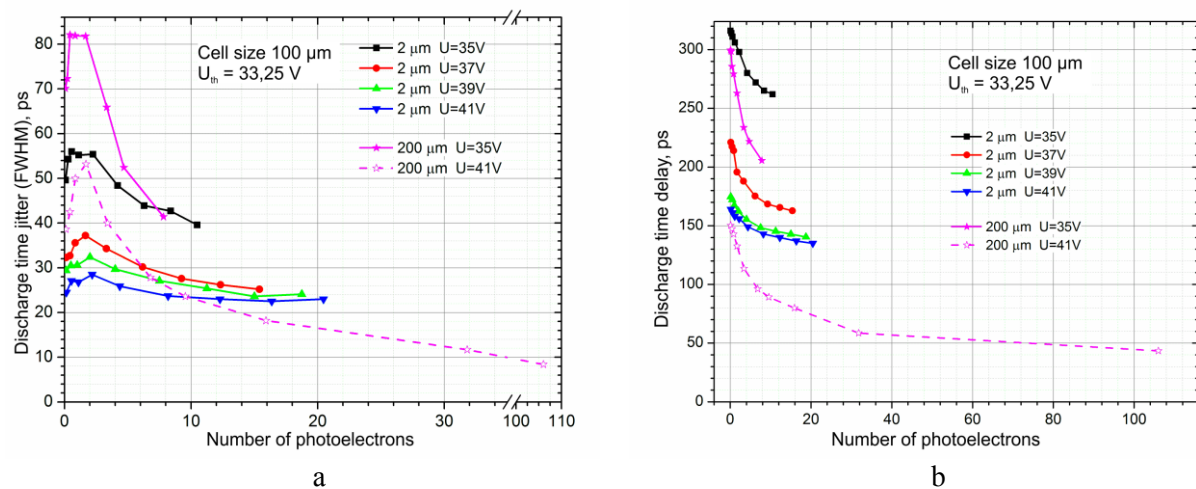


Figure 8. Photoelectrons number dependence of: (a) discharge time fluctuation (time resolution, FWHM of fitting curve); (b) discharge time delay.

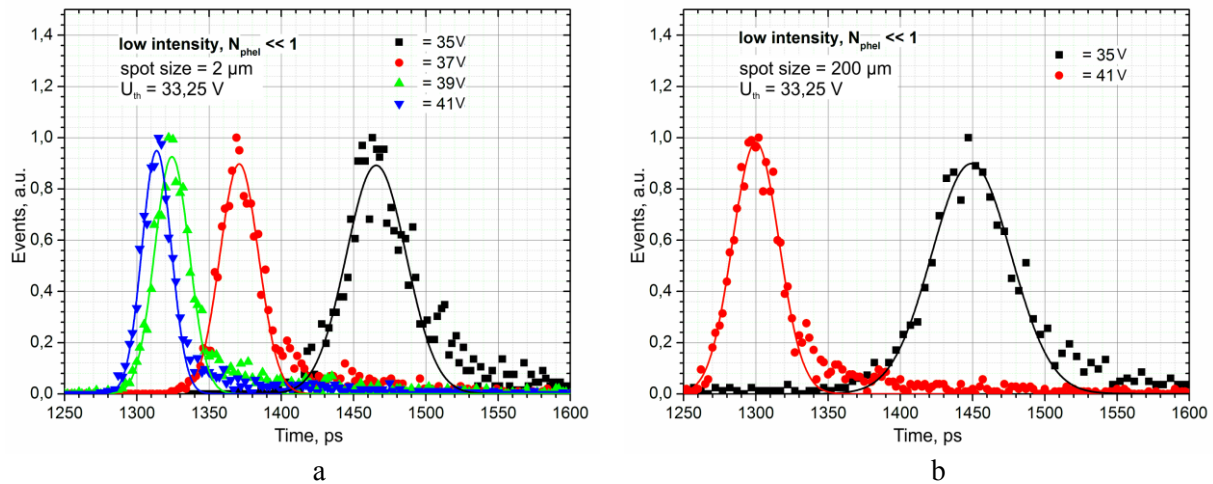


Figure 9. Distribution of output pulse front delay relative to PIN photodiode trigger at various SiPM bias voltages: (a) beam focused to 2 μm ; (b) beam defocused to 200 μm .

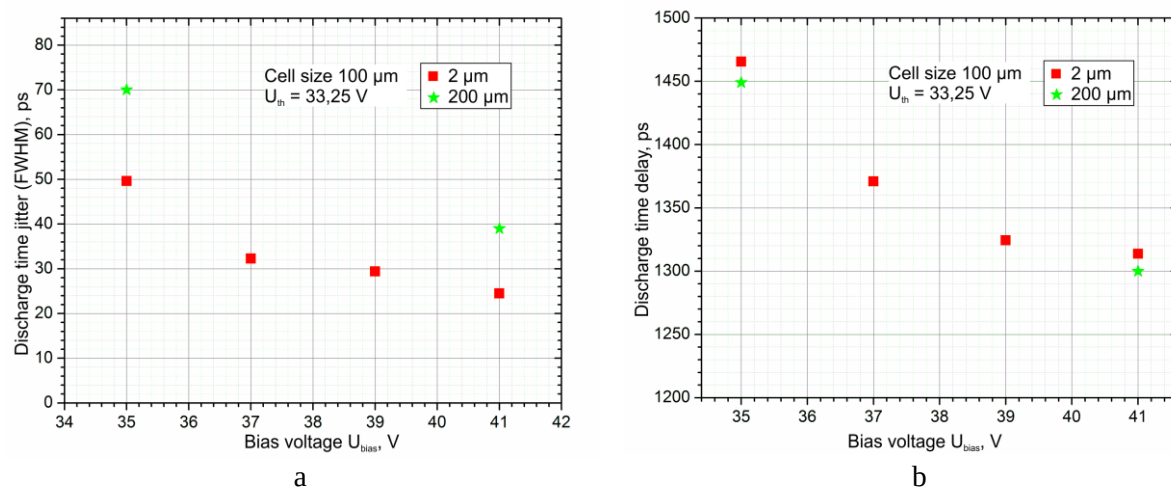


Figure 10. The bias voltage U_{bias} dependence of: (a) discharge time fluctuation; (b) discharge time delay.

3. Conclusion

This work has demonstrated the successful application of femtosecond laser excitation with focused and defocused beam of various intensity for the investigation of timing characteristics of SiPM cells. It was shown, that the usage of the focused laser beam allows to increase the accuracy of SiPM cell time resolution measurements. Such investigations are possible to perform only using the ultrafast light source.

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References

- [1] Conti M 2011 *Nucl. Instr. Meth. Phys. Res., Section A* **648** pp S194-S198
- [2] Yeom J Y, Vinke R and Levin C S 2013 *Physics in Medicine and Biology* **58** (4) pp 1207-1220
- [3] Marano D. et al. 2014 *IEEE Trans. Nucl. Sci.* **61** (1) pp 23-34
- [4] Popova E. et al. 2013 *IEEE NSS/MIC/RTSD* (Seoul)
- [5] Egorov A N, Chumakov A I, Mavritskiy O B, Pechenkin A A, Savchenkov D V, Telets V A, Yanenko A V 2014 *IEEE Radiation Effects Data Workshop (REDW)* pp 247-250