SiPM Sensors

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Commercial SiPM sensors and FBK prototypes



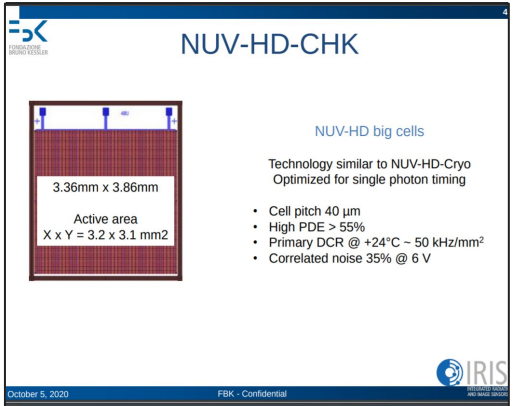


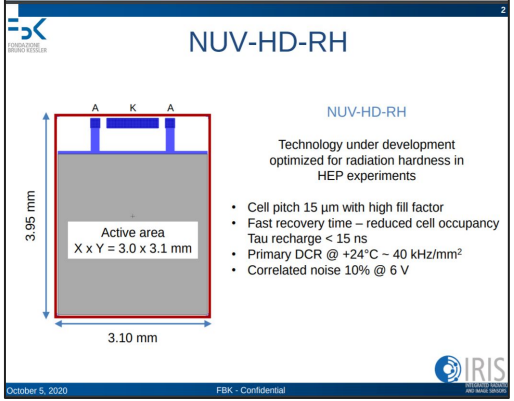
board	sensor	uCell (μm)	V_{bd} (V)	PDE (%)	DCR (kHz/mm^2)	window	notes
HAMA1	S13360 3050VS	50	53	40	55	silicone	legacy model Calvi et. al
	S13360 3025VS	25	53	25	44	silicone	legacy model smaller SPAD
HAMA2	S14160 3050HS	50	38	50		silicone	newer model lower V_{bd}
	S14160 3015PS	15	38	32	78	silicone	smaller SPADs radiation hardness
SENSL	MICROFJ 30035	35	24.5	38	50	glass	different producer and lower V_{bd}
	MICROFJ 30020	20	24.5	30	50	glass	the smaller SPAD version
BCOM	AFBR S4N33C013	30	27	43	111	glass	commercially available FBK-NUVHD

HAMAMATSU PHOTON IS OUR BUSINESS

ON Semiconductor

BROADCOM

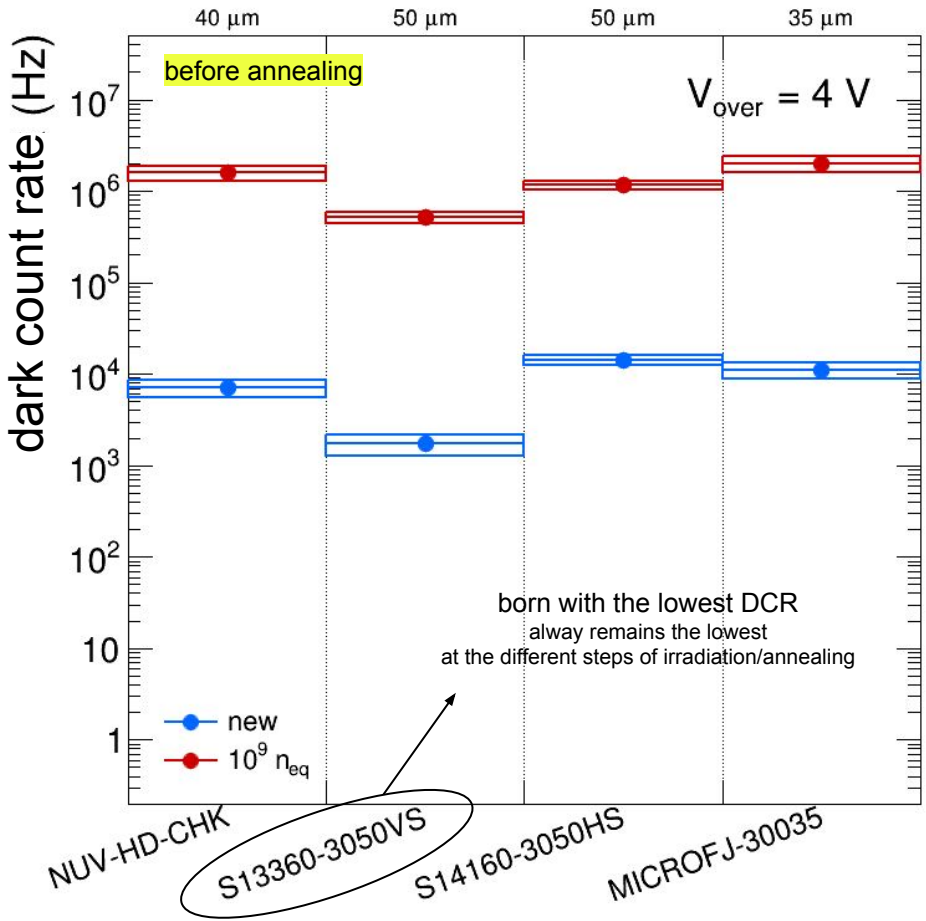


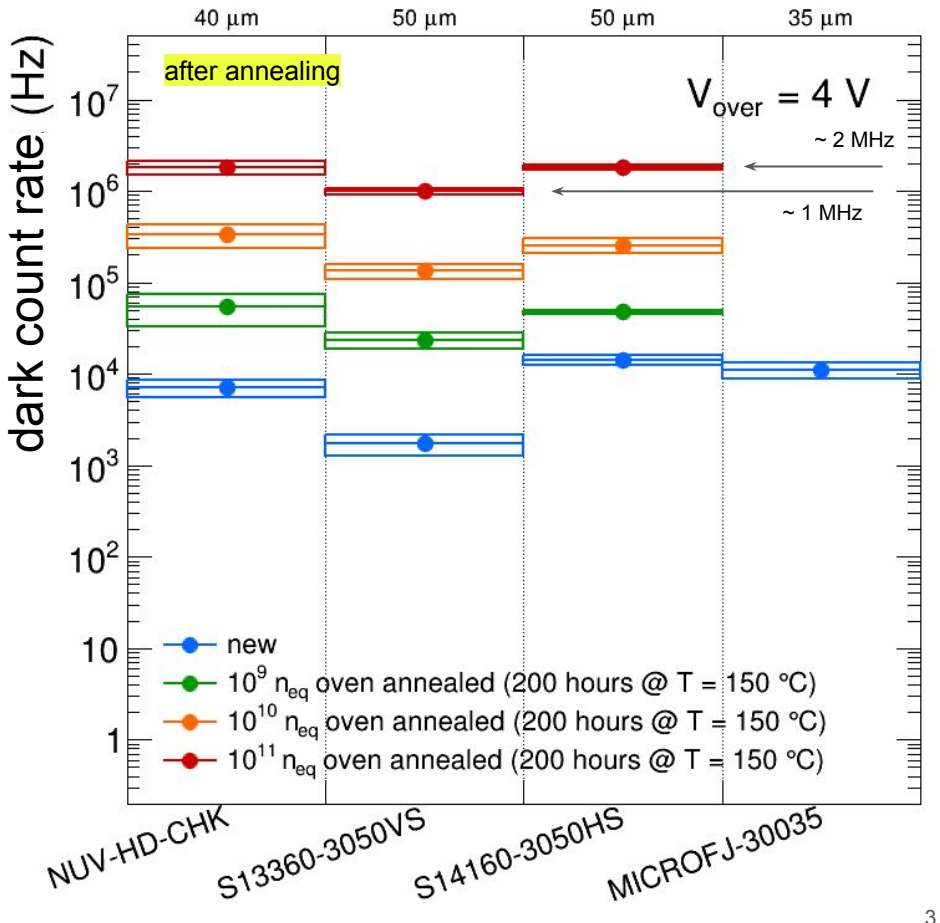


multiple producers: different technologies, SPAD dimensions, V_{bd}, electric field …

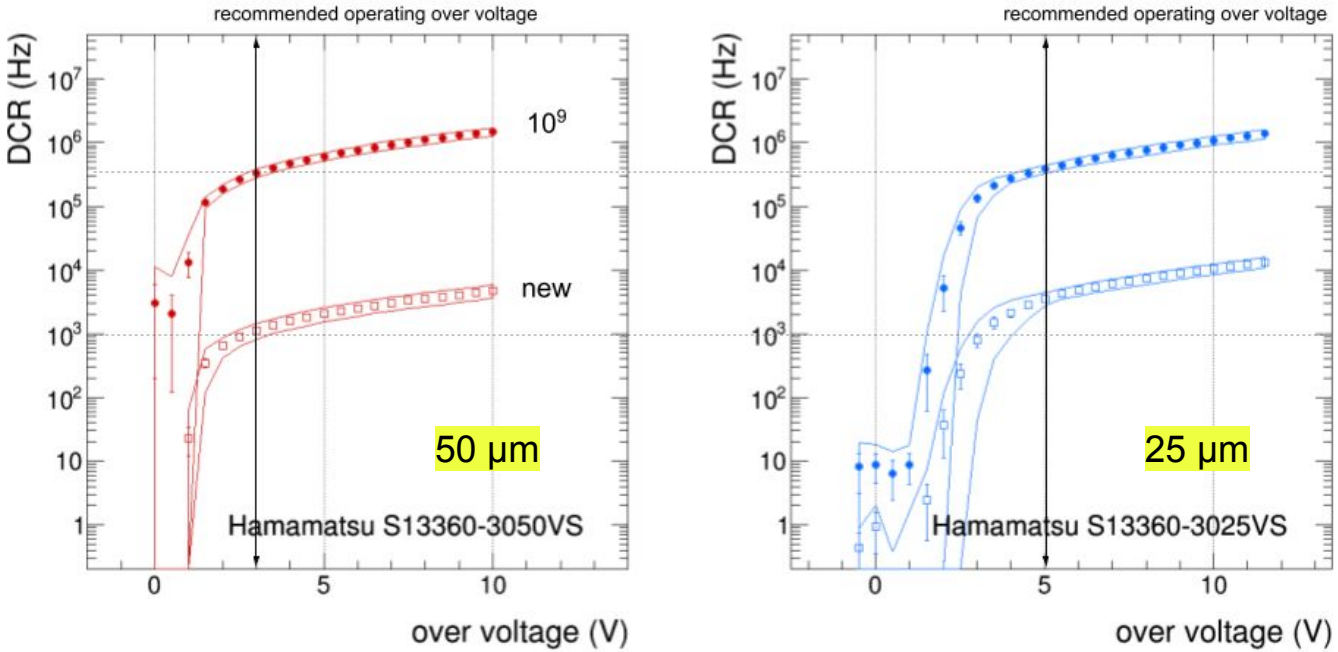
Comparison between different sensors

comparison at same Vover not totally fair
important to consider PDE (and SPTR) → SNR ~ PDE / DCR
unlikely 2x larger DCR is matched by 2x larger PDE





Small vs. large SPAD sensors



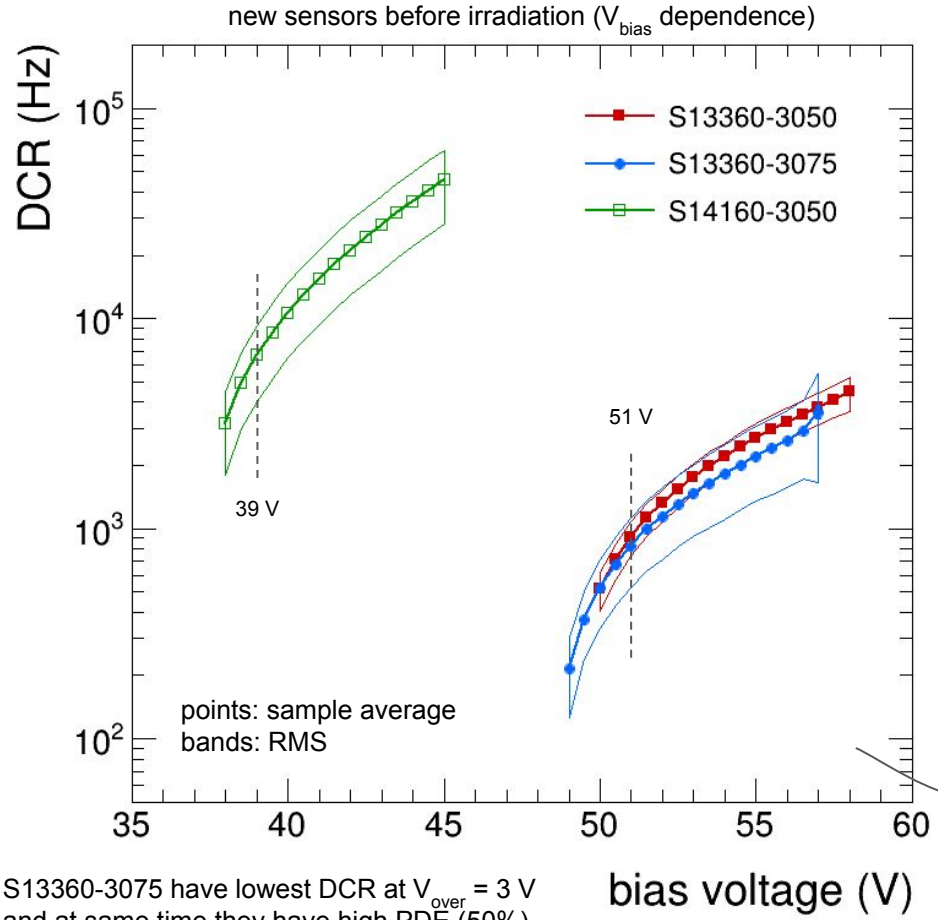
sensors with **small SPADs have lower SNR** also after irradiation

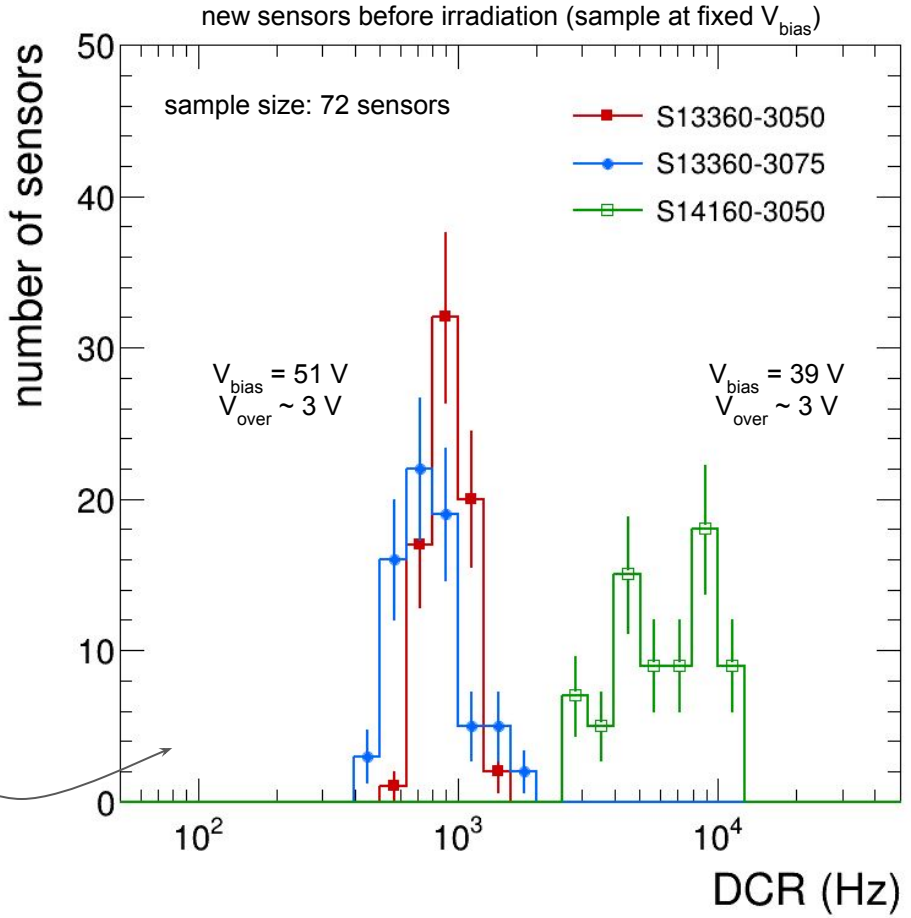
small SPAD sensors are not radiation harder for single-photon applications (RICH)

- **sensors operated at Hamamatsu recommended over-voltage**
  - [datasheet] 50 µm sensors have 40% PDE, 25 µm have 25%
  - [measured] 50 µm sensors have lower DCR than 25 µm when new
  - [measured] both sensors have similar DCR after irradiation

similar results and conclusions obtained with SENSL sensors

Characterisation of new SiPM boards with 75 µm sensors

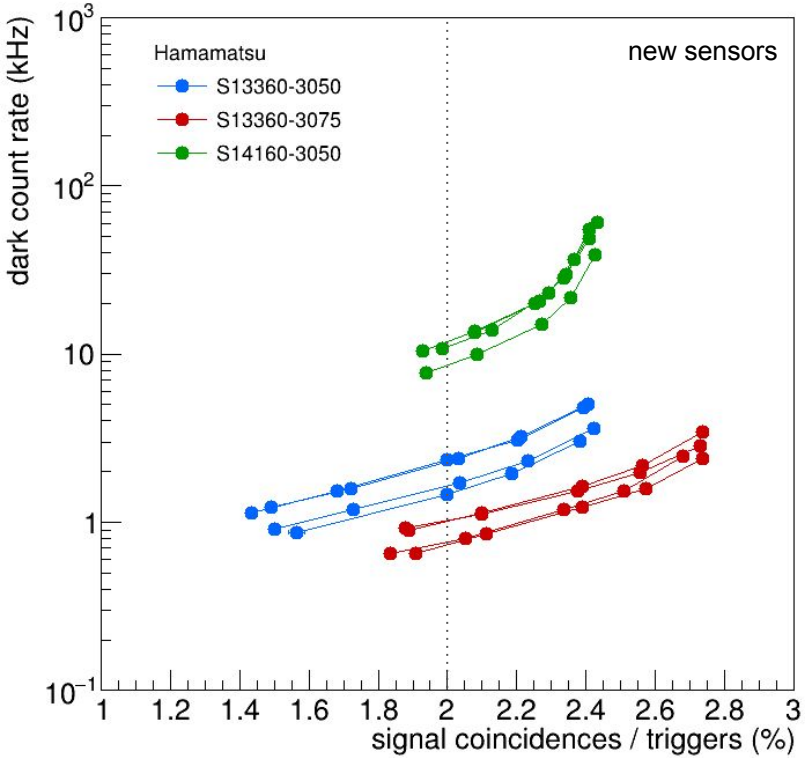




S13360-3075 have lowest DCR at V_{over} = 3 V
and at same time they have high PDE (50%)

DCR vs. PDE comparison between sensors

3 Hamamatsu sensor types, 4 sensors each measured as NEW



proxy for photodetection efficiency

at the same level of detection efficiency

namely, the probability to detect light from laser pulse

different sensors have different DCR level

best: S13360-3075

most promising sensors, large pitch SPADs (75 μm)

second: S13360-3050

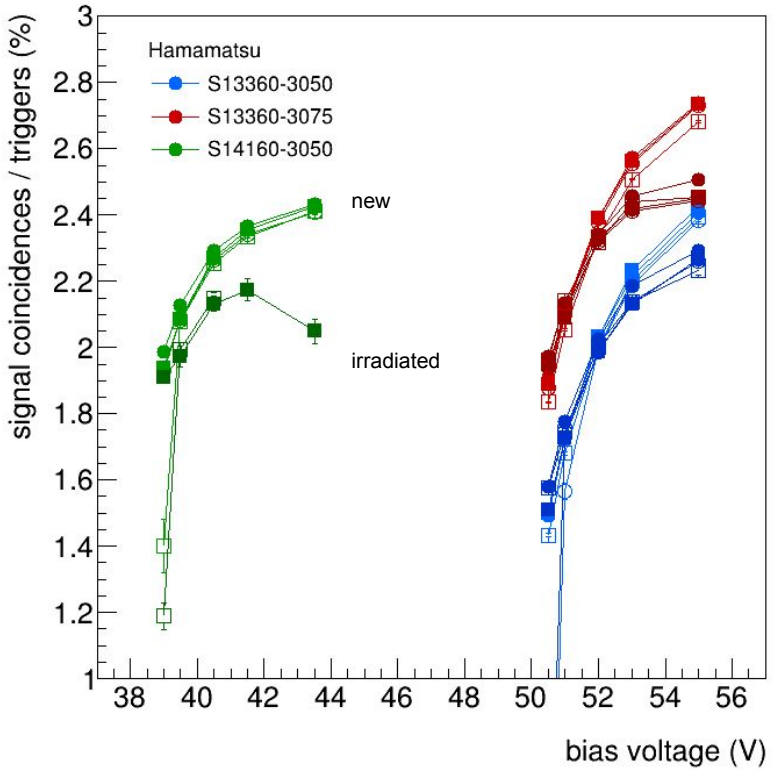
same technology, medium pitch SPADs (50 μm)

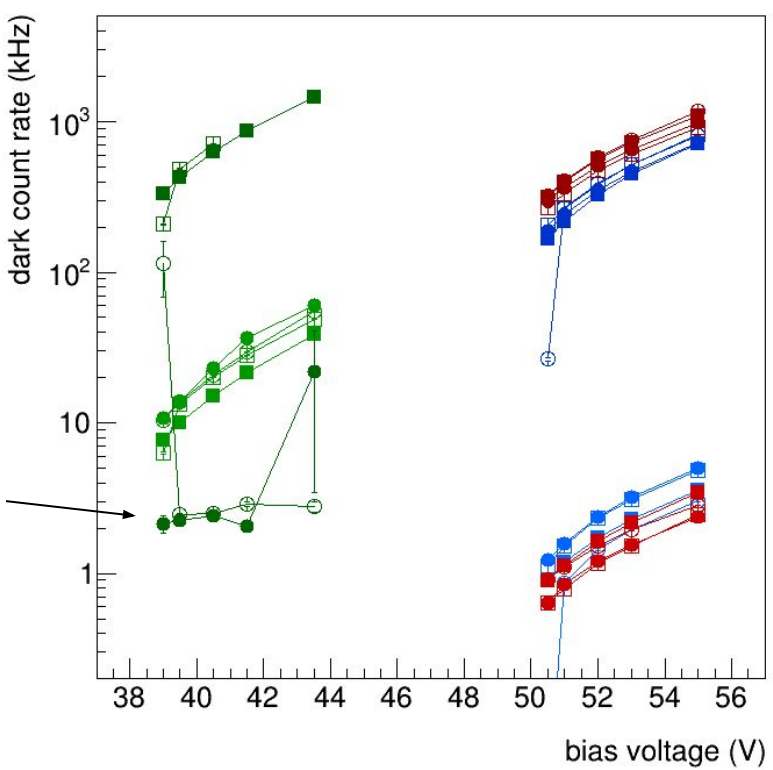
worst: S14160-3050

different technology, medium pitch SPADs (50 μm)

new boards and irradiated boards (10^9 neq)

After irradiation

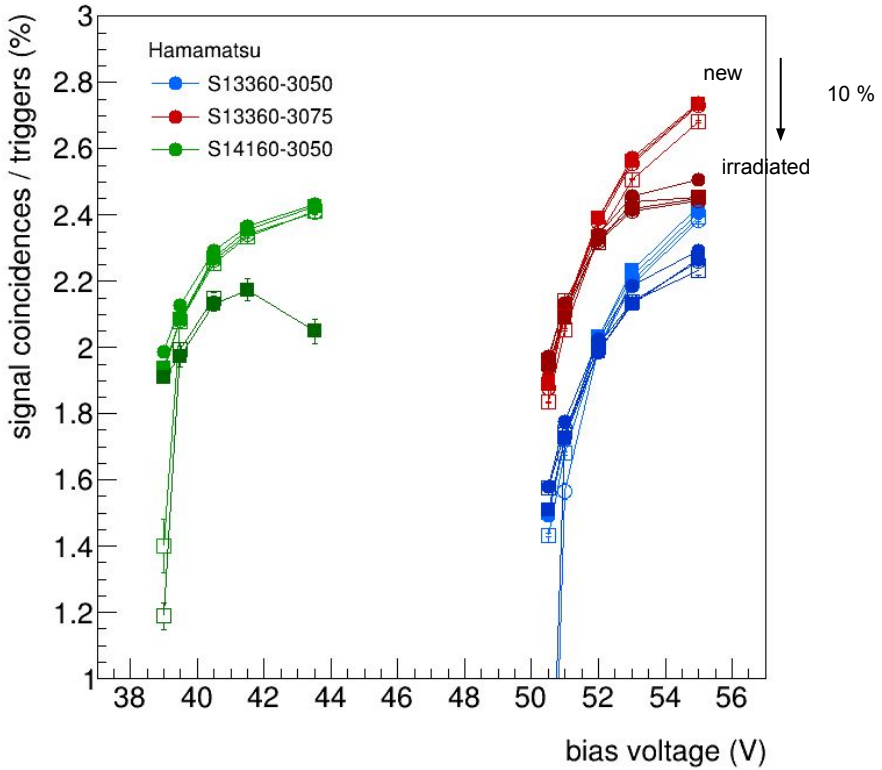


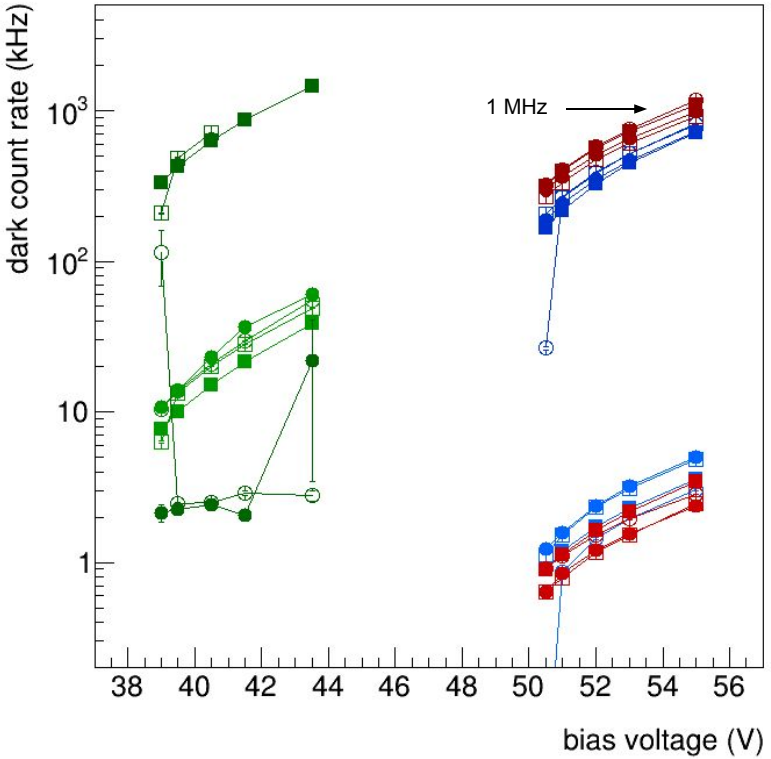


the Hamamatsu S14160-3050 sensors seem to have more troubles to be reconstructed after irradiation

new boards and irradiated boards (10^9 neq)

After irradiation

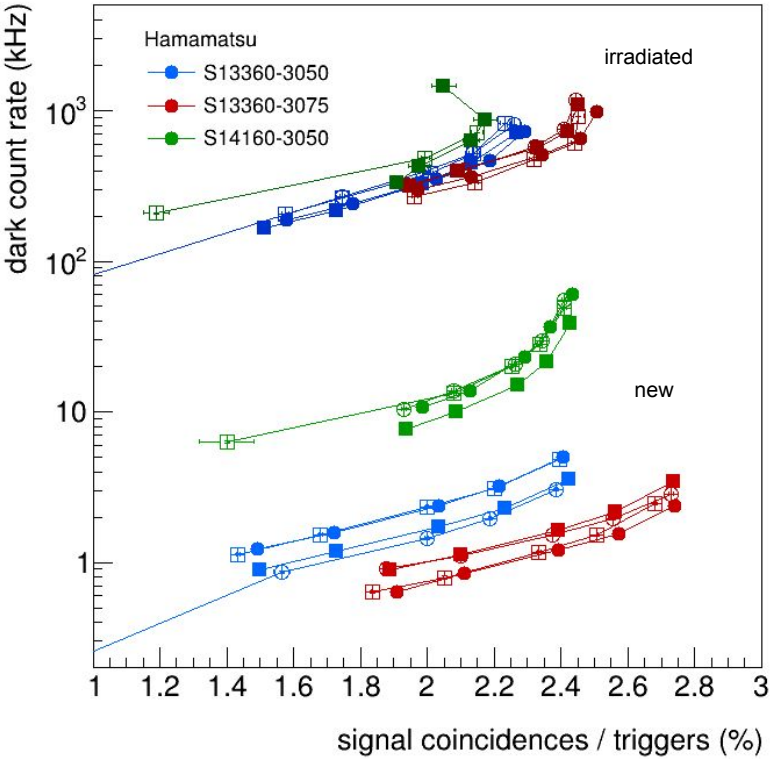


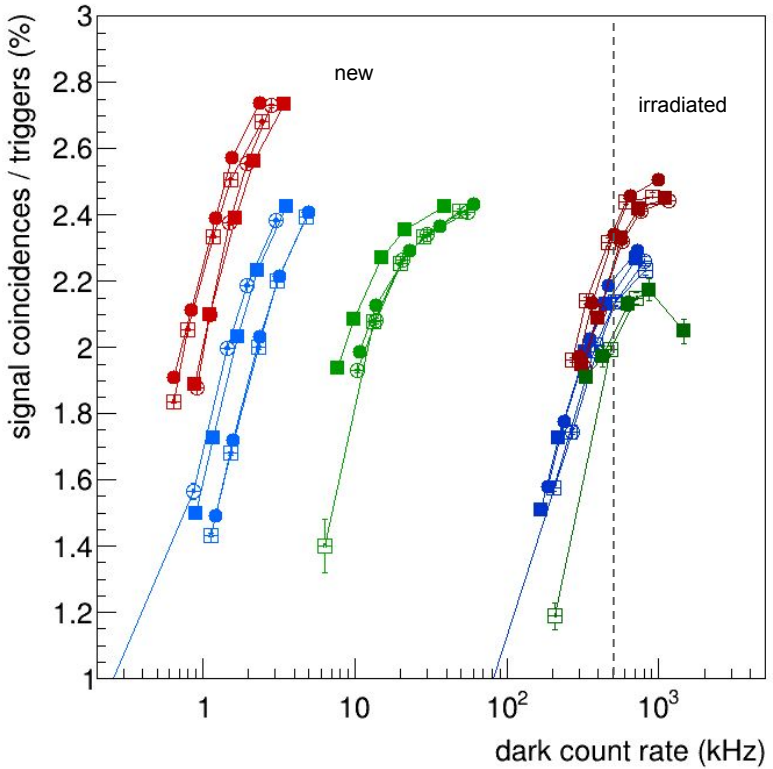


the efficiency loss is likely due to the "after-pulse" suppression algorithm used for analysis
"every signal which is within less than 100 ns wrt. the preceding signal is discarded"
at ~ 1 MHz DCR rate, the probability of having a DCR hit 100 ns before the laser pulse is ~ 10%

new boards and irradiated boards (10^9 neq)

After irradiation

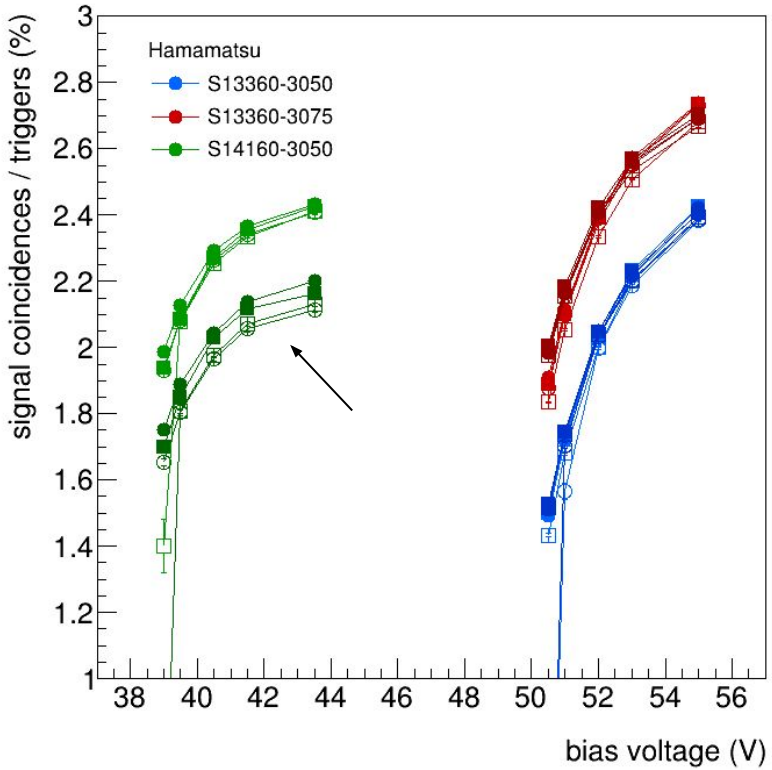


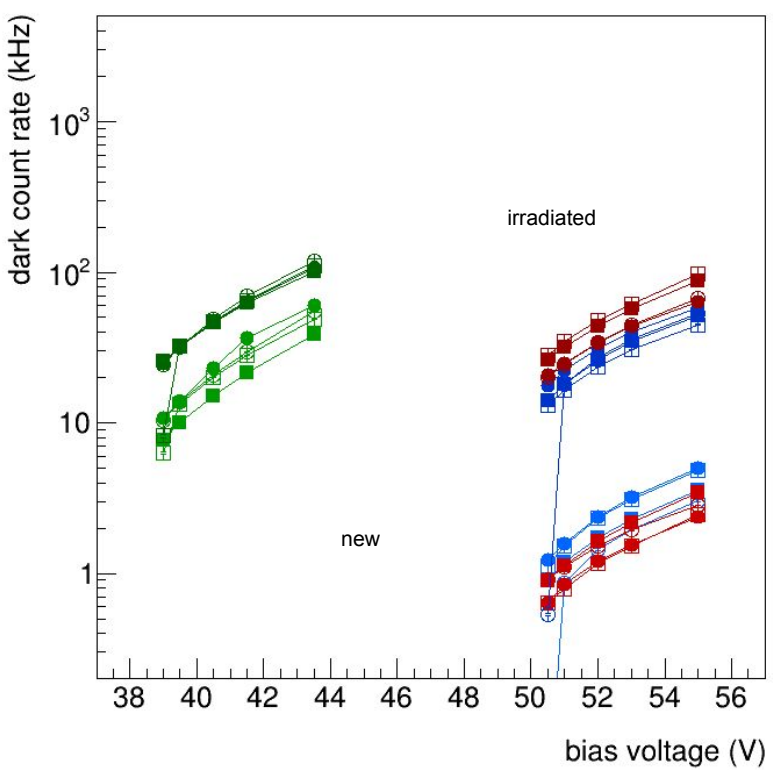


at fixed DCR of 500 kHz after 10^9 neq (without annealing)
the S13360-3075 sensor (75 μm SPADs) is more efficient (20% larger PDE)
caveat: new and irradiated are not the same sensors, so the comparison is not fully quantitative

new boards and annealed boards (10^9 neq)

After irradiation & annealing

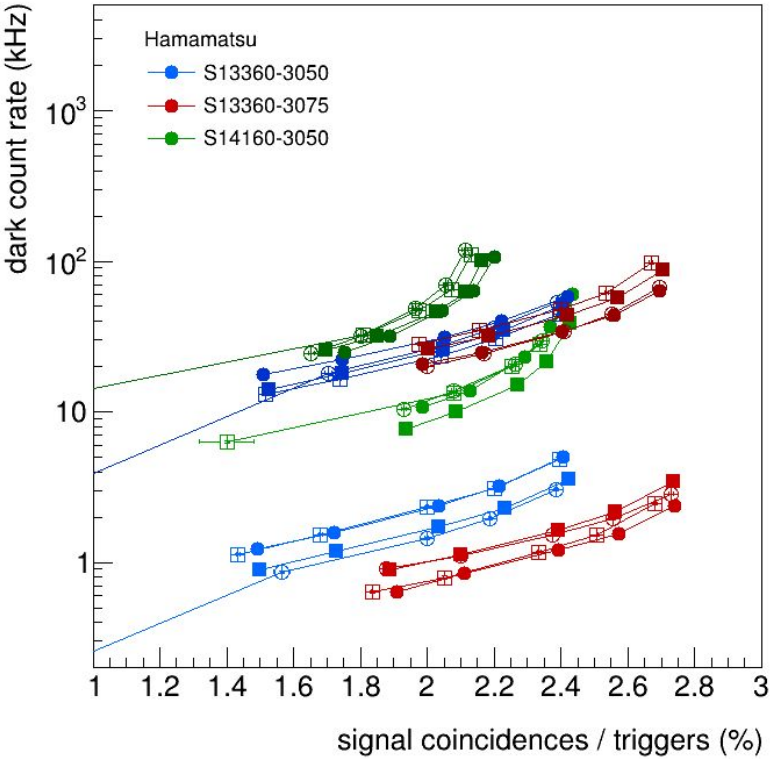


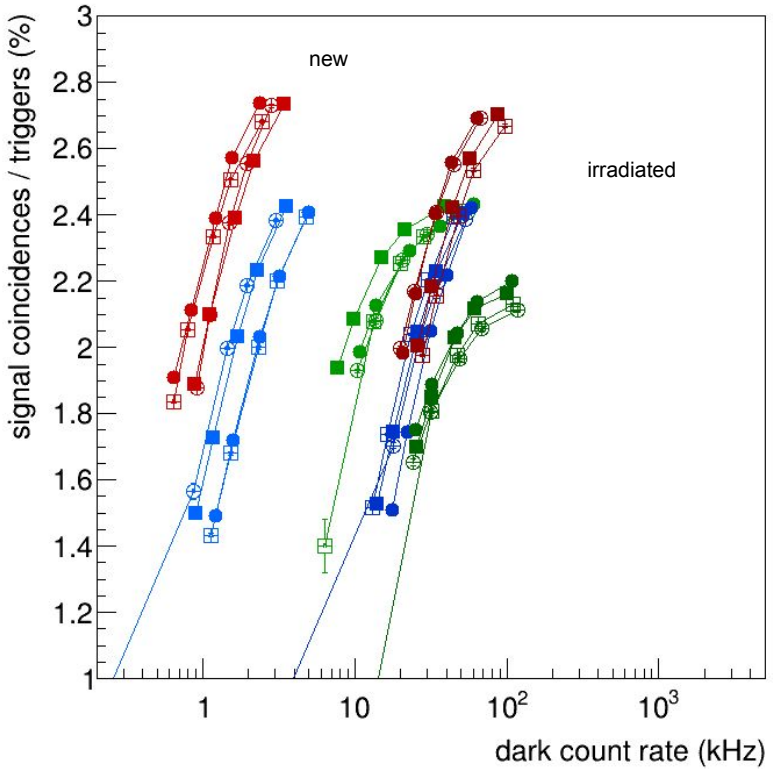


the Hamamatsu S14160-3050 sensors seem to have lower efficiency after irradiation and annealing
in S13360-3050 sensors the efficiency is unaffected, only DCR increases (we know)

new boards and annealed boards (10^9 neq)

After irradiation & annealing





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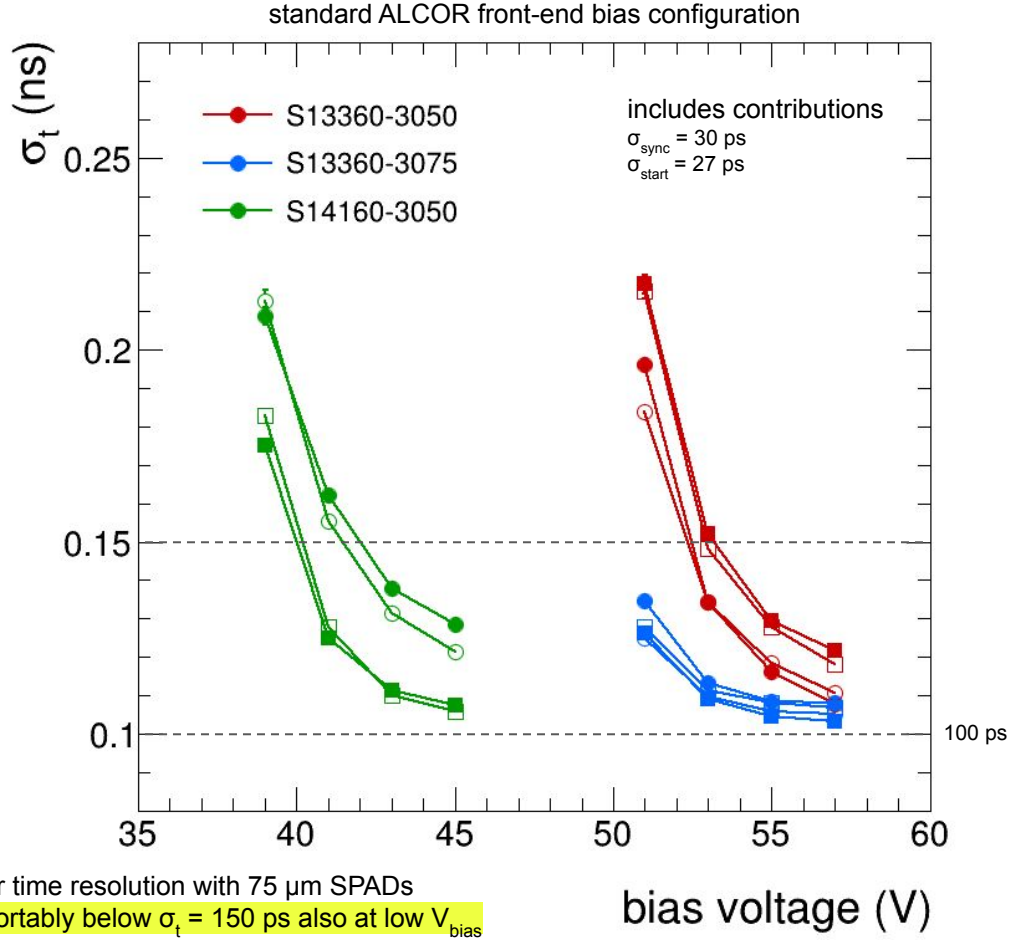
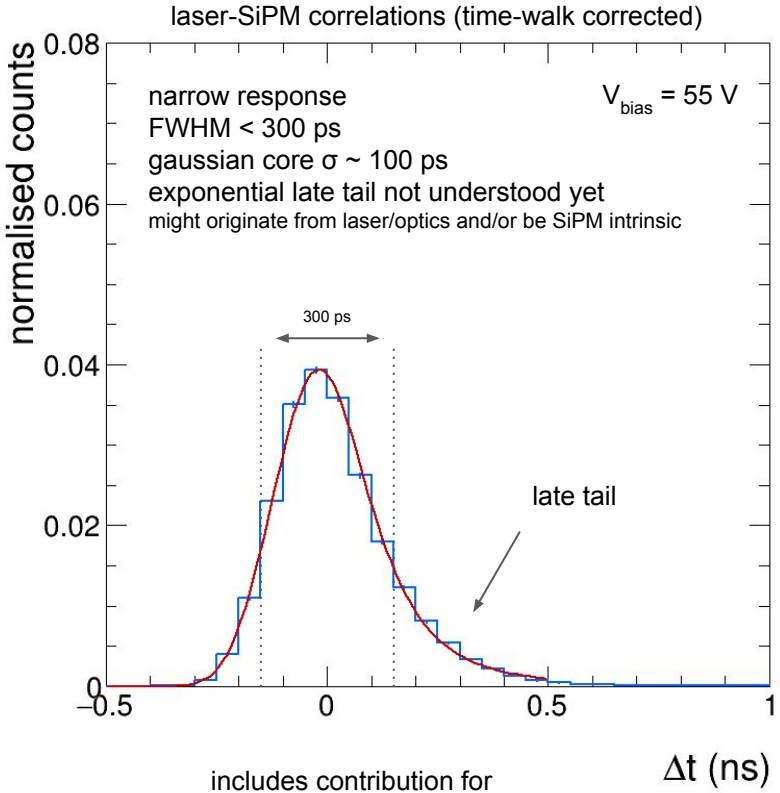
Timing performance measurements with ALCOR



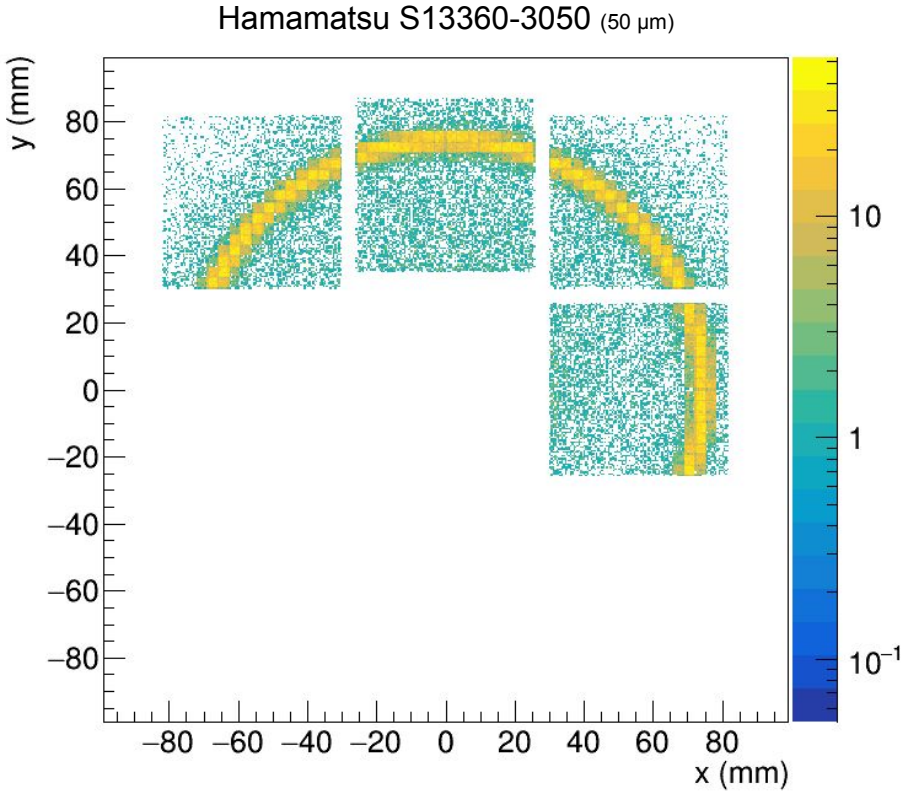


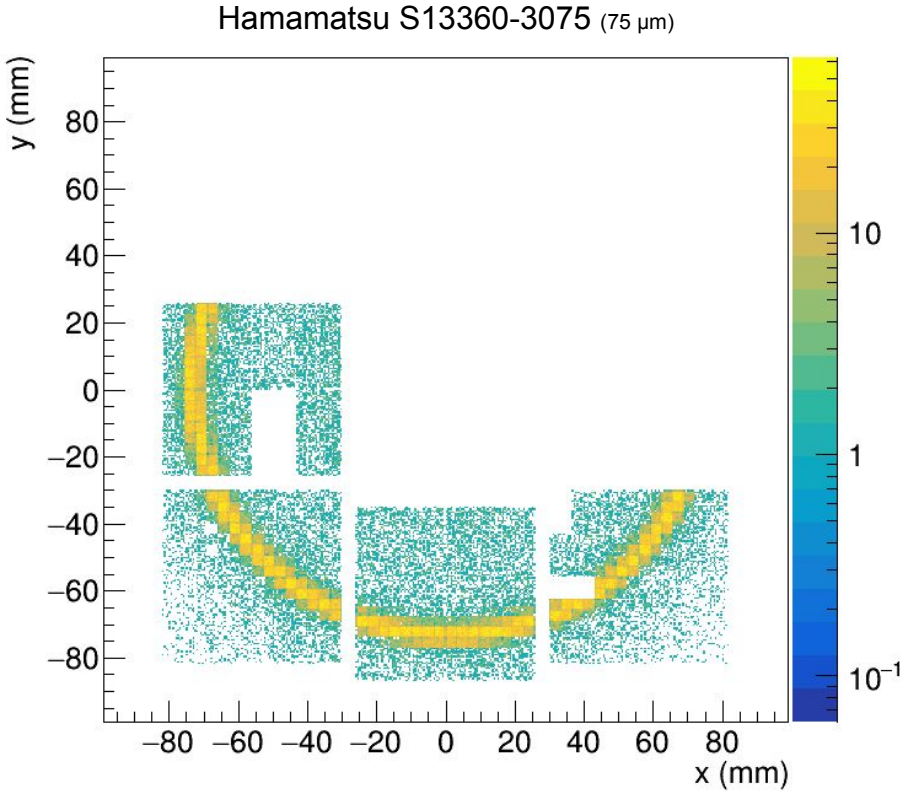
better time resolution with 75 µm SPADs
comfortably below σ_t = 150 ps also at low V_{bias}

includes contribution for
laser-ALCOR synchronization
measured to be σ_{sync} = 30 ps
and reference time resolution
measured to be σ_{start} = 27 ps

Comparison between different SiPM sensors

on the beam line: same Hamamatsu technology, different SPAD sizes



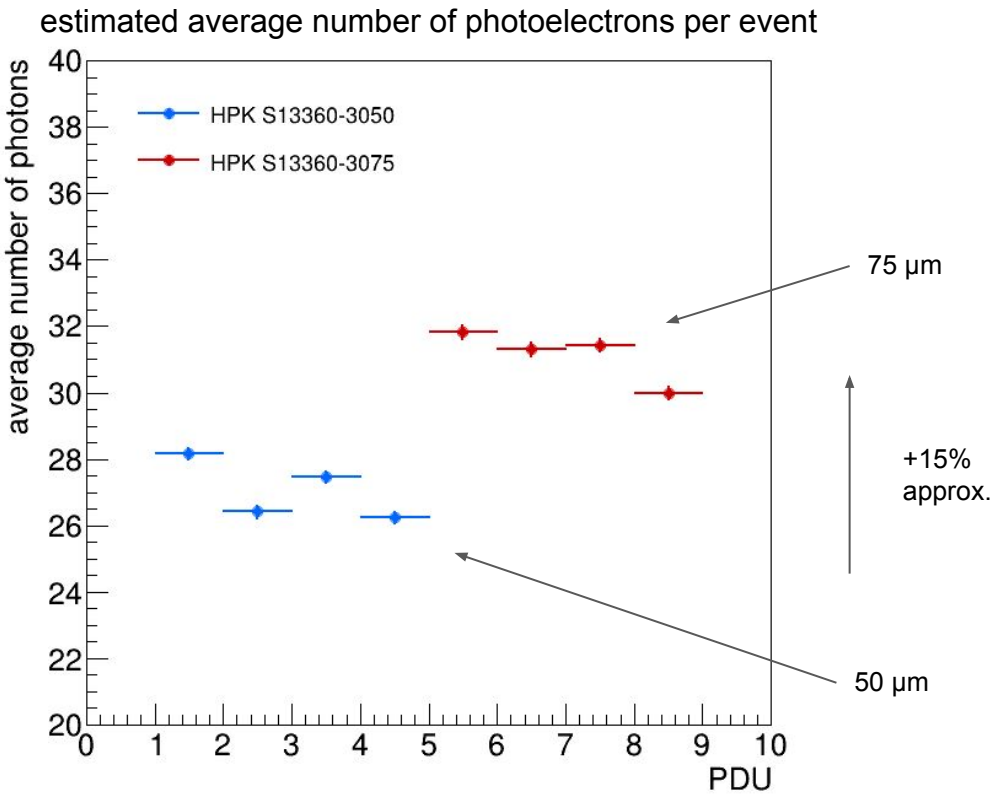


4 PDUs were equipped with one type of sensors

symmetrically, the other four with different sensors

Comparison between different SiPM sensors

on the beam line: same Hamamatsu technology, different SPAD sizes



larger SPADs see more light (at the same overvoltage) than smaller SPADs | observed ~15% more light | expected ~11% from larger fill factor

Summary from the laser measurements

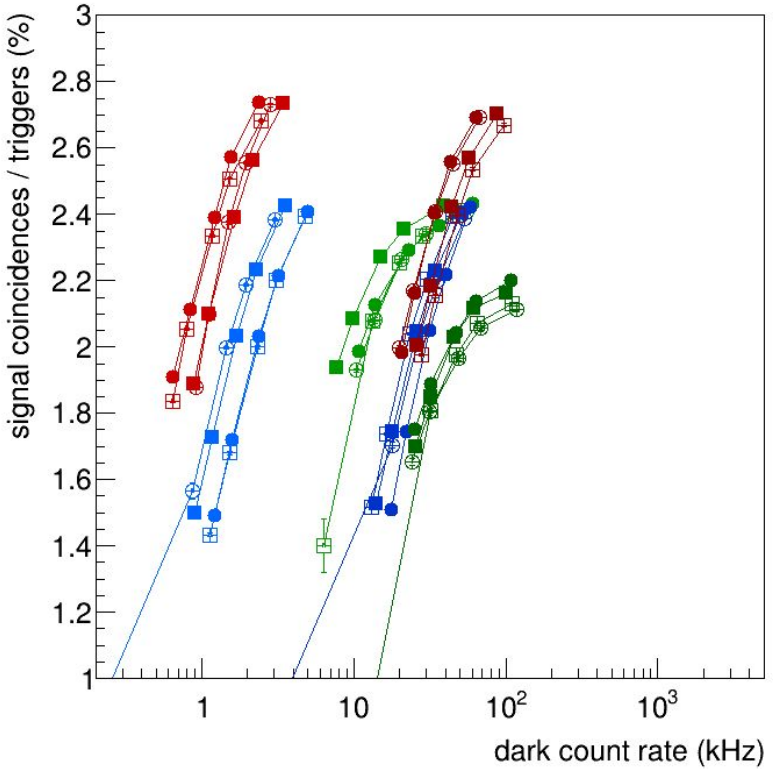
- **Hamamatsu S14160-3050**
  - higher DCR when new
  - troubles after irradiation (perhaps too high DCR for ALCOR)
  - loss in PDE after annealing (this is strange)

→ not a good choice for the dRICH sensors

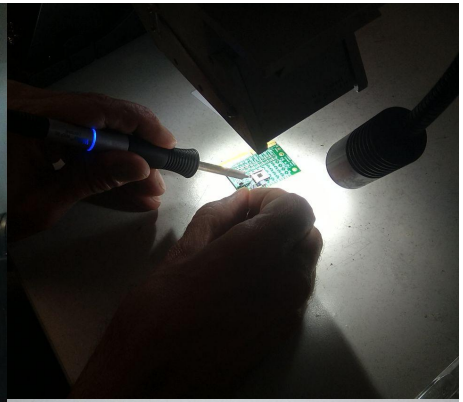
- **Hamamatsu S13360-30xx**
  - 75 μm SPAD sensors are always above the 50 μm in the PDE vs. DCR curve, even though not a large gap after irradiation and annealing
  - 75 μm SPAD sensors have higher gain, hence easier to put discriminator threshold on electronics
  - for the same reason, the signal is "faster" at lower bias voltage and has better single-photon time resolution

even if we have to do a combined 3D (PDE, DCR, SPTR) performance comparison between the sensors, there is <u>good feeling that 75 μm SPADs perform better</u> than 50 μm

new boards and <u>annealed</u> boards (10^9 neq)



New Hamamatsu SiPM prototypes



S13360-3050UVE

newly-developed Hamamatsu SiPM sensors

based on S13360 series

few samples of 50 µm and 75 µm SPAD sensors

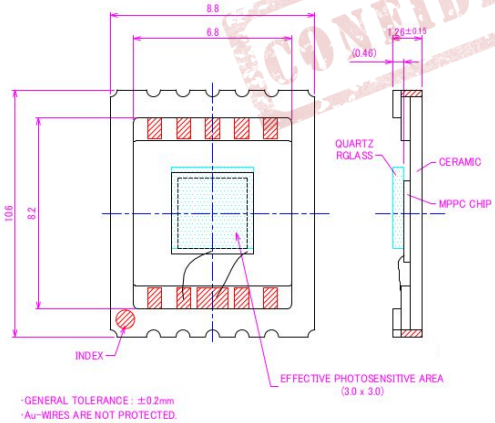
on paper they look VERY promising

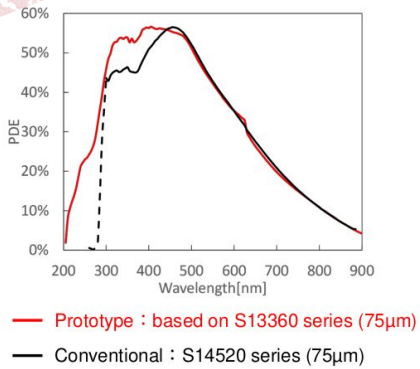
- improved NUV sensitivity
- improved signal shape
- improved recharge time

mounted on EIC SiPM test boards

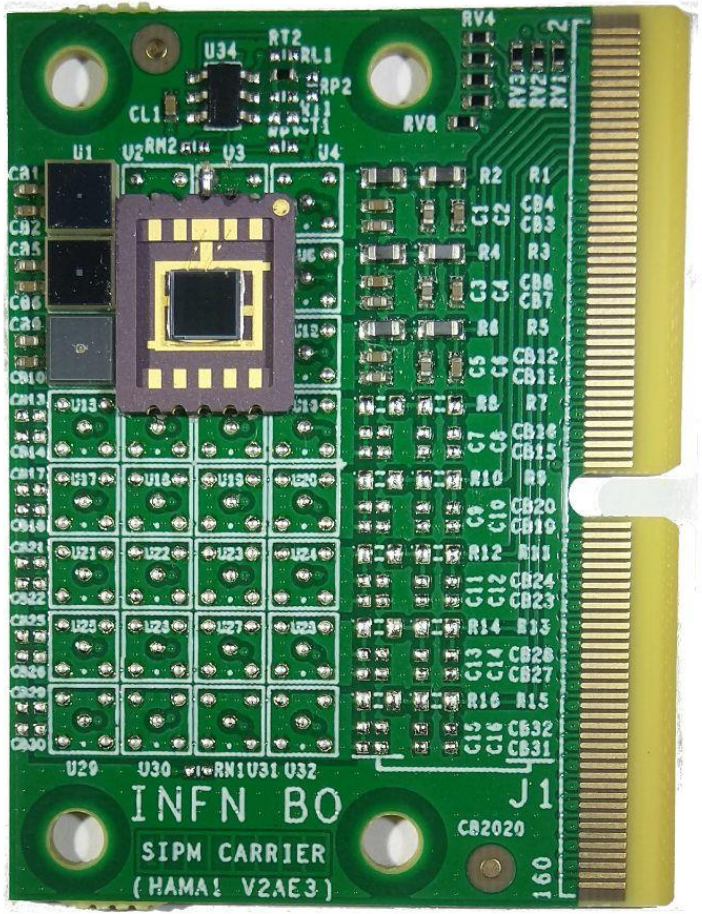
we will characterise and test them in full

irradiation, annealing, laser, …





Picture of the S13360-UVE-SMD mounted on our board



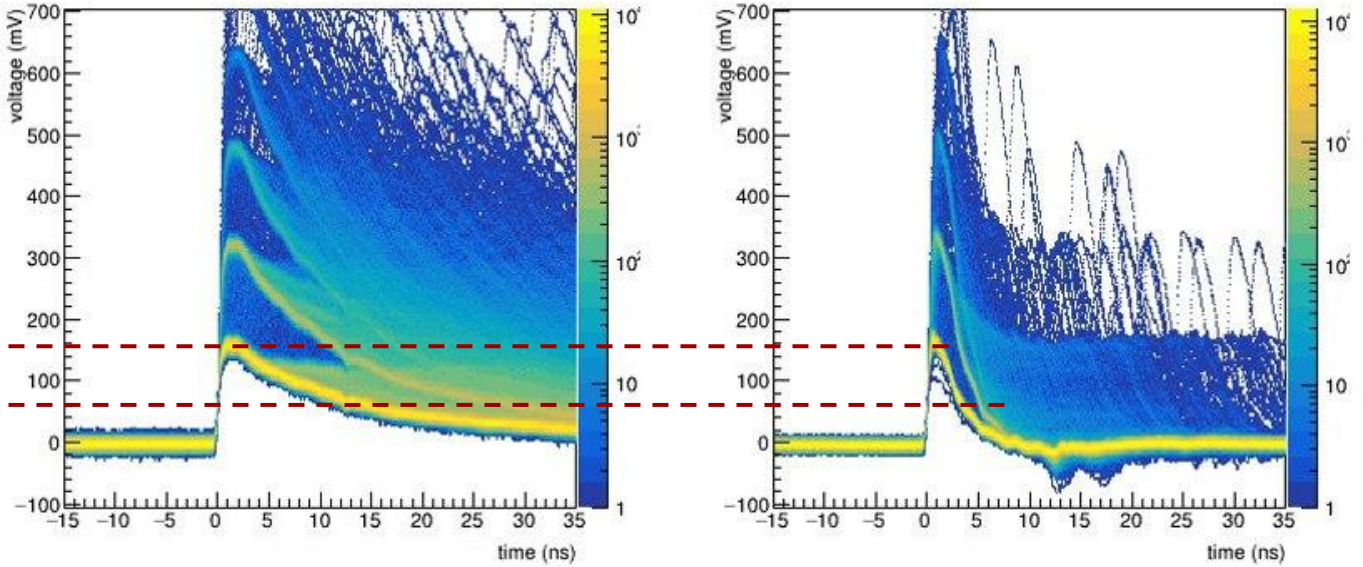
Faster recharge time

S13360-3050

S13360-3050-UVE

same amplitude

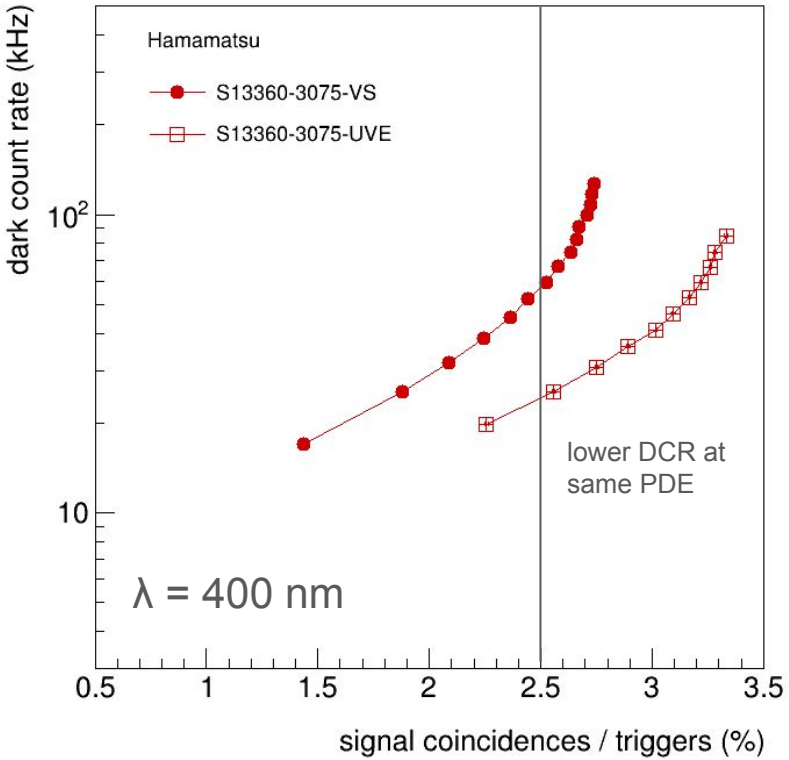
> 5x faster recharge

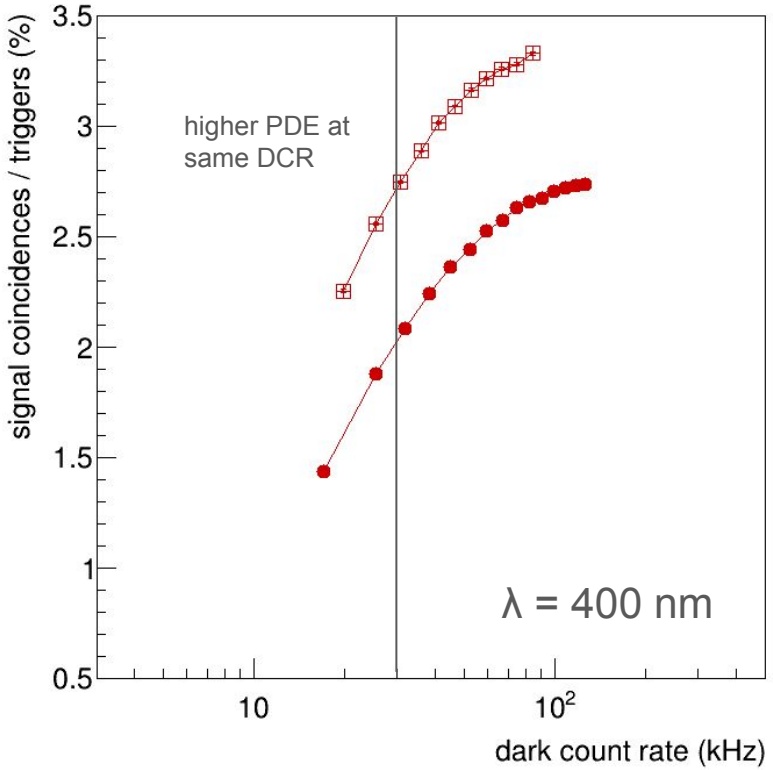


We observe in the UVE sample prototypes a **significantly faster recharge time** with respect to commercial S13360 MPPC devices with same pixel size (ie 50 μm). The recharge time in UVE prototypes is approximately a factor 5 times faster at the same device gain and signal amplitude. Can the fast-recharge improvement be decoupled from the improvement in the NUV PDE sensitivity? **Can the fast-recharge be implemented with custom modifications of the S13360 MPPC TSV technology** with standard silicone resin entrance window?

prototype UVE Hamamatsu sensors (10^9 neq after oven annealing)

After irradiation & annealing



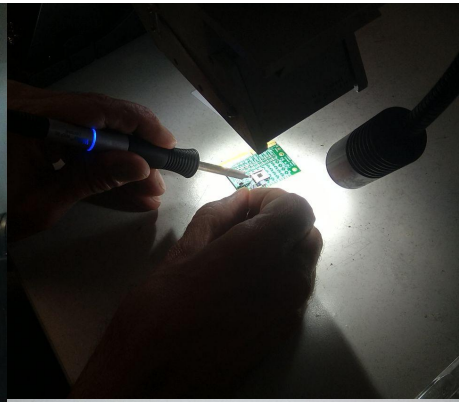


prototype Hamamatsu UVE sensors have significantly higher efficiency than standard sensors
caveat: we only measure PDE at the fixed **laser wavelength of ~400 nm**
prototype sensors have quartz window whereas standard sensors tested by us have silicone
we will study them further, **purchased from Hamamatsu UVE sensors with silicone window**

Discussion with Hamamatsu engineers + shopping

- **had a meeting with Hamamatsu engineers about UV enhanced (UVE) sensors**
  - we wanted to understand if they could provide us with UVE sensor matrices
  - also if they could produce them with the silicone protective resin, rather than a quartz window
    - this because quartz would have added some little complications
    - ask if interested to know more
  - productive meeting, they confirmed they could provide us with what we wanted, namely
    - SiPM matrices 8x8 with UVE sensors
    - SMD mounting
    - silicone resin
- **purchase of single-SiPM sensors Hamamatsu UV enhanced**
  - 30x S13360-3050VS-UVE
  - 30x S13360-3075VS-UVE
  - goal
    - assemble a few small tests boards (6x boards, each with 4 + 4 sensors)
    - perform irradiation and annealing tests on SiPM UVE with silicone window
- **purchase of 8x8 SiPM matrices Hamamatsu UV enhanced**
  - 12x S13361-3075NS-08-UVE
  - 4x S13361-3050NS-08-UVE
  - goal
    - assemble a few PDUs to be used for the upcoming beam test
    - evaluate the expected improved PDE performance with Cherenkov light

New Hamamatsu UVE SiPM sensors for dRICH



S13360-3050UVE

newly-developed Hamamatsu SiPM sensors

UVE based on S13360 series

ordered 50 µm and 75 µm SPAD sensors

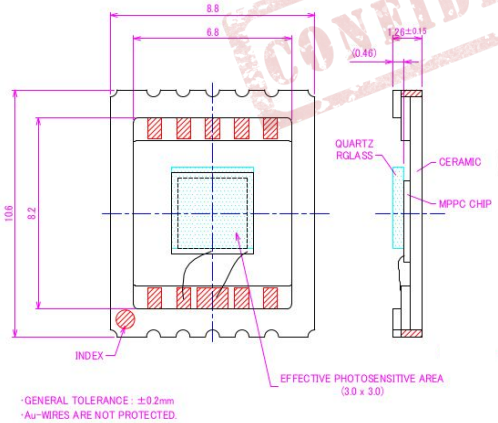
we asked for a special production of single-sensors and 8x8 sensor arrays

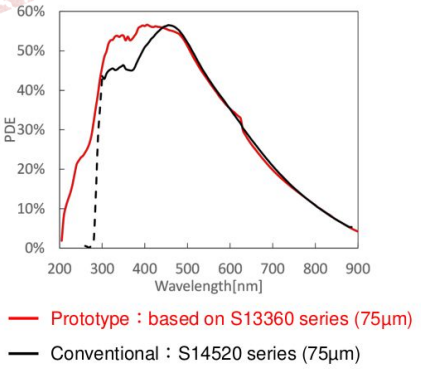
- SMD form factor
- with silicone resin

order placed for 60 sensors (irradiation/annealing tests)

and 20 sensor matrices (beam tests and PDU tests)

expected to arrive beginning of March





Summary

- **SPAD size**
  - small SPADs (25 μm) do not help with DCR and radiation tolerance
  - large SPADs (75 μm) have several advantages at the same over-voltage
    - larger PDE
    - larger gain
    - better SPTR
- **in 2025 we will evaluate the Hamamatsu UVE sensors**
  - those with silicone resin
  - 50 μm and 75 μm SPADs
  - irradiation campaigns and annealing studies
  - assembly of a few prototype PDUs for beam tests