Study of various SiPMs for the e^+e^- collider experiments

Kairui Huang, Wanyi Zhuang, Shiming Zou, Xiyang Wang, Xiaolong Wang

Fudan University, Shanghai

October 26, 2026

Motivation: SiPMs for Future Collider Detectors

- Silicon photomultipliers (SiPMs) are attractive photon sensors for future high-energy physics experiments:
  - high gain and single-photon sensitivity;
  - compact structure and low operating voltage;
  - excellent timing capability.
- They are considered or adopted in multiple detector subsystems:
  - CEPC ECAL, HCAL, Muon Detector, and Cherenkov PID;
  - Belle II upgrade scenarios: iTOP, ARICH, and KLM TOF.
- Detector performance is strongly affected by SiPM gain, dark noise, optical crosstalk, and temperature stability.

Goal: systematically benchmark commercial SiPMs and identify suitable candidates for collider detector applications.

Studied SiPM Devices

- SiPMs from four vendors are compared:
  - NDL: EQR and PSS series;
  - Hamamatsu: S13360 and S14160 series;
  - SensL: MICROFJ series;
  - CECPORT: CECPORT5870111 series.
- Main device parameters:
  - active area: mainly 3×3 mm^2 and 6×6 mm^2;
  - pixel pitch: 20–50 µm;
  - peak sensitivity near 420–450 nm;
  - PDE varies significantly among devices.
- Position-sensitive SiPMs (PSS) are also studied for Cherenkov detector applications.

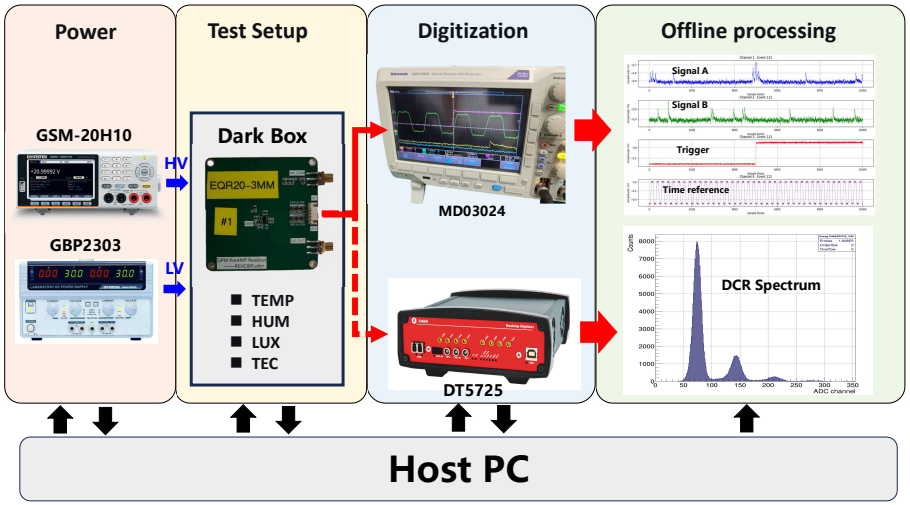
Device Comparison: Main Specifications

The tested devices cover different pixel pitches, active areas, packaging methods, and PDE levels.

Device	Pitch [µm]	Area [mm^2]	V_{br} [V]	PDE peak
NDL EQR20-11-3030	20	3.0×3.0	27.5	46%
NDL EQR20-11-6060	20	6.24×6.24	27.5	46%
NDL PSS-11-6060	20	6.24×6.24	27.5	40%
HPK S13360-6025	25	6.0×6.0	53	25%
HPK S14160-6050	50	6.0×6.0	38	50%
SensL MICROFJ-30035	35	3.07×3.07	24.5	44%
SensL MICROFJ-40035	35	3.93×3.93	24.5	44%
SensL MICROFJ-60035	35	6.07×6.07	24.5	44%
CECPORT CECPORT5870	40	5.88×5.88	38	67%

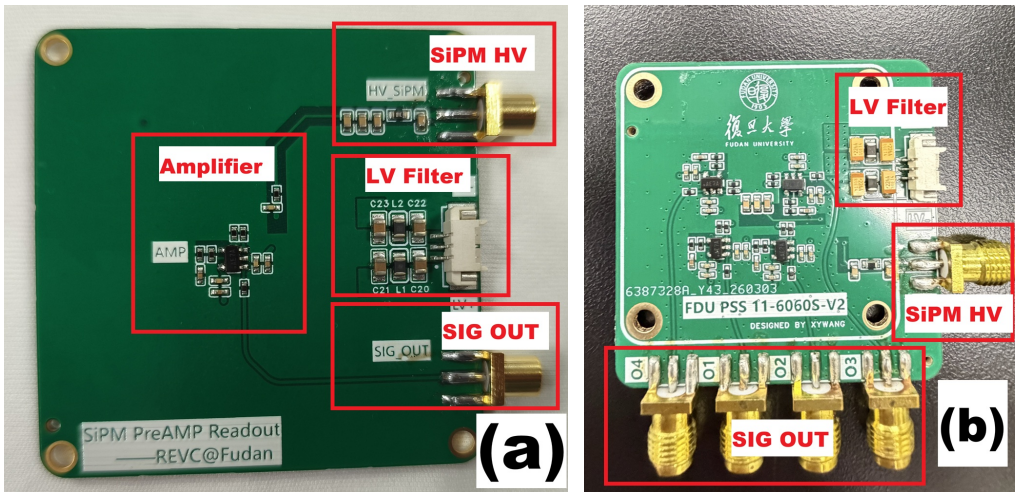
Experimental Setup

- Measurements are performed in a light-tight dark box.
- Bias and power supply:
  - GW Instek GSM-20H10 source-measure unit for SiPM bias;
  - GPS-4303C low-voltage supply for the amplification chain and sensors.
- Two parallel readout paths are used:
  - Tektronix MDO3024 oscilloscope at 2.5 GS/s for waveform and DCR analysis;
  - CAEN DT5725 digitizer for accurate charge and gain measurement.
- Temperature, humidity, and light sensors are monitored; TEC cooling enables temperature-dependent tests.



Preamplifier and PZC Circuit

- A custom preamplifier based on the LMH6629 high-speed operational amplifier is used.
- The design provides:
  - bandwidth exceeding 400 MHz;
  - input-referred noise below 0.6 mV RMS;
  - 50 Ω input impedance for compatibility with most SiPM signals.
- A pole-zero cancellation (PZC) high-pass filter is introduced to reduce dark-count pile-up.
- Single-channel and four-channel versions are used for standard SiPM and PSS readout.



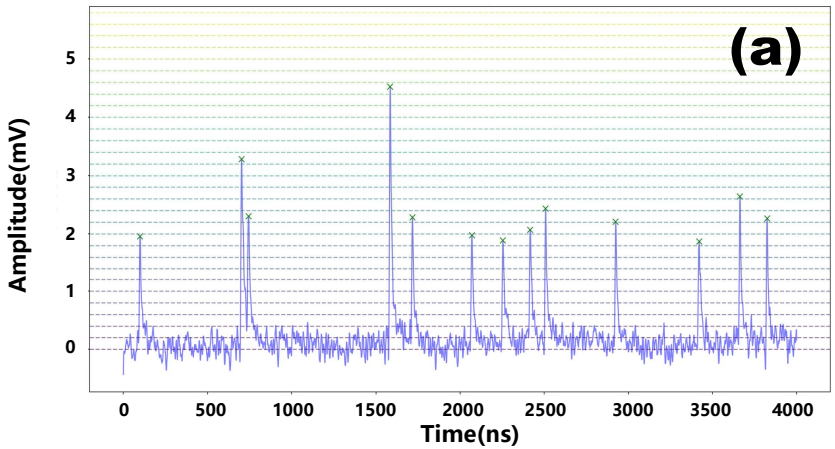
Waveform Processing

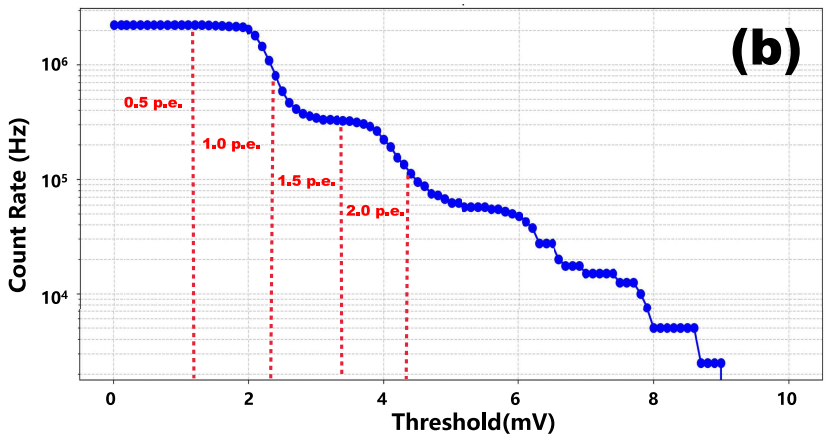
- Waveforms are processed offline with a robust baseline algorithm:
  - each waveform is divided into 50 blocks;
  - the median of quiet blocks is used to estimate the baseline;
  - noise is estimated with the scaled median absolute deviation.
- Pulse detection uses a noise-adaptive threshold.
- Overlapping peaks can be resolved with multi-Gaussian fitting.
- Pulse charge is obtained by integrating the baseline-corrected waveform between two local minima around the peak.

DCR and OCT Measurement Method

- The dark count rate (DCR) is measured by scanning the pulse-height threshold.
- At each threshold, the number of pulses above threshold is normalized by acquisition time and active area.
- The DCR value is taken at the threshold corresponding to 0.5 *p.e.*.
- Optical crosstalk (OCT) is estimated from the DCR values at 0.5 *p.e.* and 1.5 *p.e.*:

$$\mathrm{OCT} = \frac{\mathrm{DCR}_{1.5p.e.}}{\mathrm{DCR}_{0.5p.e.}}.$$





Gain Measurement Method

- Gain is extracted from the integrated charge distribution of the photoelectron spectrum.
- To avoid baseline bias on the pedestal and first peak, the SPE charge is obtained from the interval between the first two peaks.
- The gain is calculated as

$$\mathrm{Gain} = \frac{A_{1p.e.}}{R_{\mathrm{in}}\, A_{\mathrm{pream}}\, e},$$

where

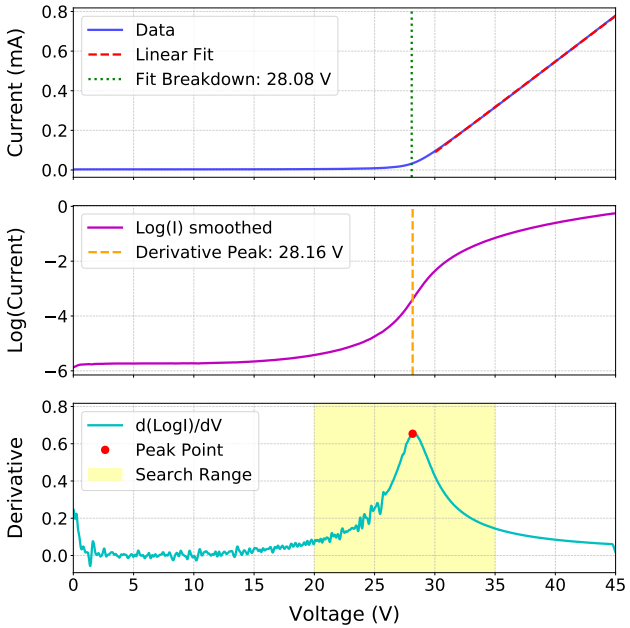
  - $A_{1p.e.}$ is the SPE pulse area in mV · ns;
  - $R_{\mathrm{in}} = 50\ \Omega$;
  - $A_{\mathrm{pream}} = 20$ is the preamplifier gain;
  - e is the elementary charge.

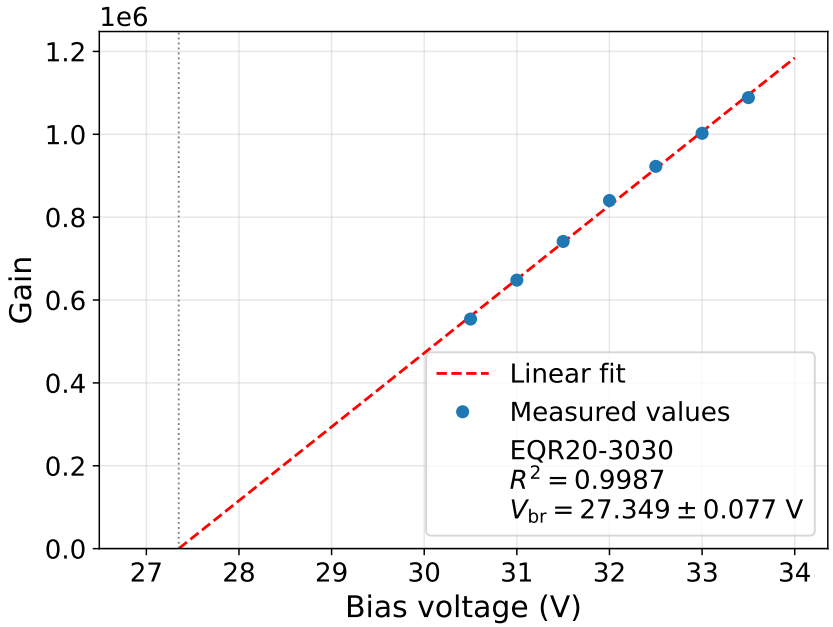
Breakdown Voltage Characterization

- The breakdown voltage V_{br} is a critical parameter because SiPM performance depends on overvoltage:

$$V_{\mathrm{ov}} = V_{\mathrm{bias}} - V_{\mathrm{br}}.$$

- Two methods are used:
  - **Gain-based method:** extrapolate the linear gain–bias relation to zero gain;
  - V_{peak}**-based method:** extract the inflection point from the $\log(I)$–V curve.



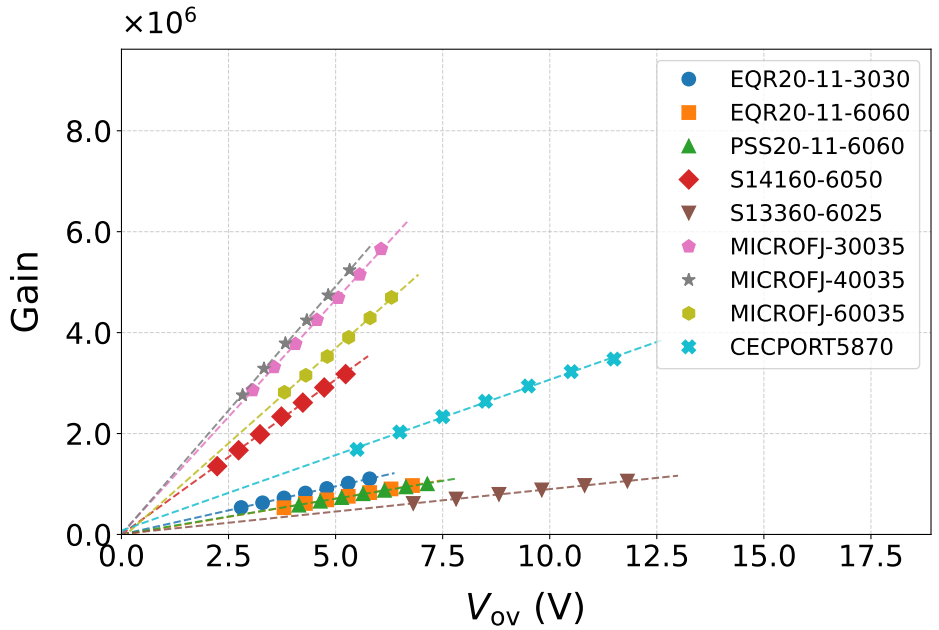


Gain Results

- For all tested SiPMs, gain increases approximately linearly with overvoltage.
- For a Geiger-mode microcell,

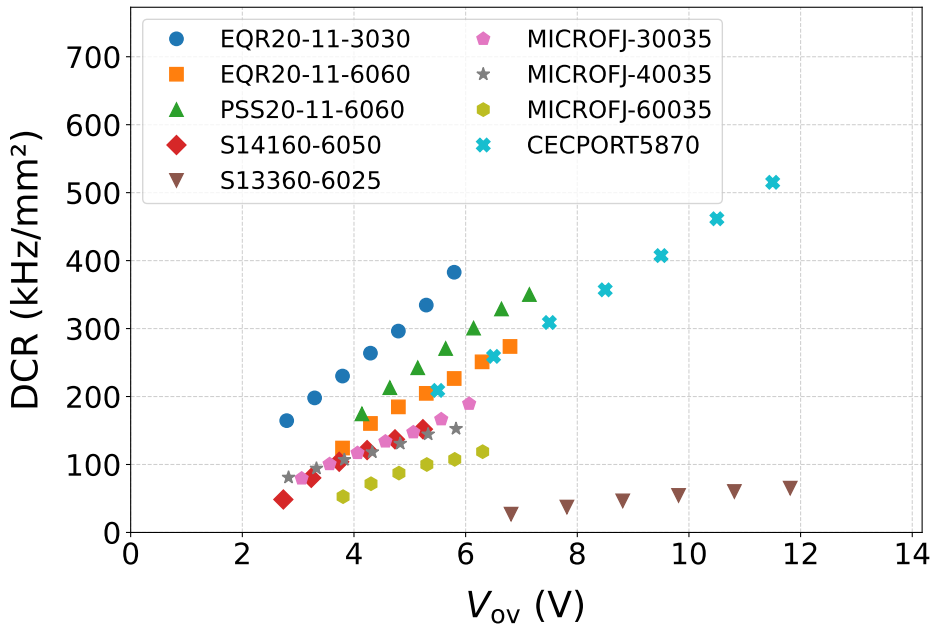
$$M = \frac{C_j(V_{\mathrm{bias}} - V_{\mathrm{br}})}{q_e},$$

  where C_j is the pixel capacitance.
- Therefore, the gain slope reflects the microcell capacitance and device architecture.
- Devices with larger pixel pitch generally show larger gain slopes.
- Within the same product series, devices with the same pitch show similar gain–voltage dependence, almost independent of active area.



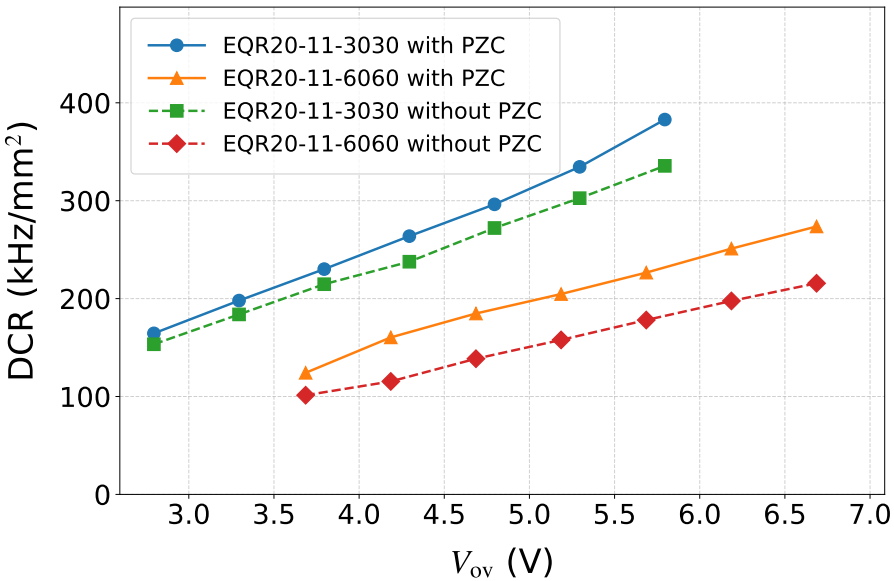
DCR Results

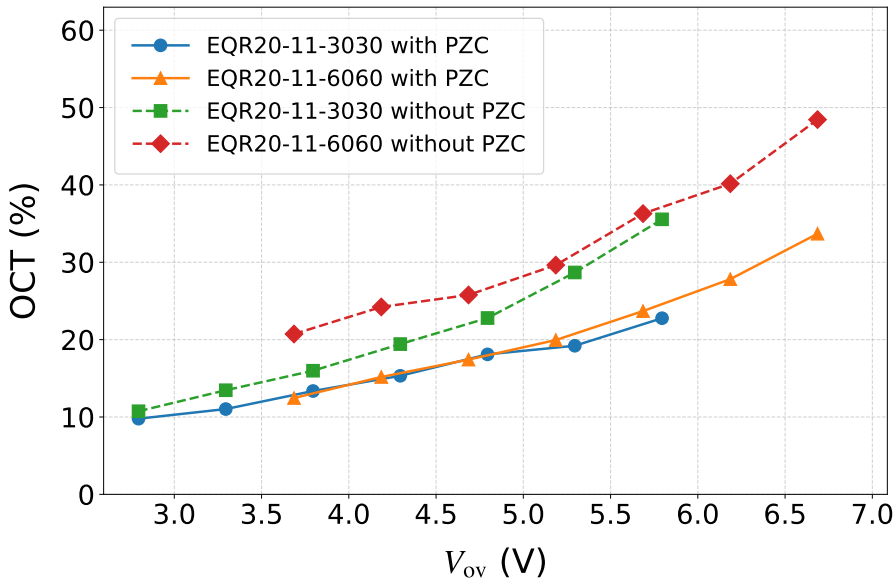
- DCR originates mainly from thermally generated carriers and trap-assisted tunneling.
- DCR increases with overvoltage for all tested SiPMs.
- It depends on several factors:
  - electric-field strength and avalanche probability;
  - pixel pitch and microcell density;
  - wafer defects and impurity concentration;
  - device isolation structure and OCT contribution.
- NDL and CECPORT devices show relatively high DCR, while HPK S13360-6025 shows notably low DCR.



Dark Count Pile-up Effect

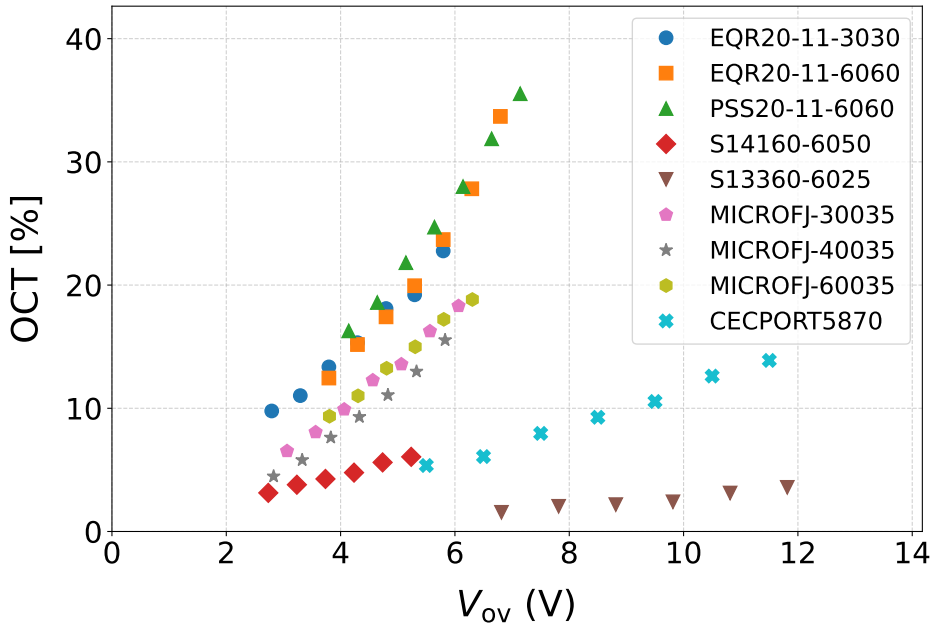
- Large-area SiPMs have larger junction capacitance and broader signal pulses.
- Broader pulses are more likely to overlap in high-DCR conditions.
- Pile-up has two major effects:
  - two dark pulses may be counted as one event, leading to DCR underestimation;
  - overlapping pulses may mimic multi-p.e. signals, leading to OCT overestimation.
- The PZC circuit mitigates these effects by shortening the effective pulse shape.
- However, pile-up cannot be completely eliminated at high bias or high dark rate.





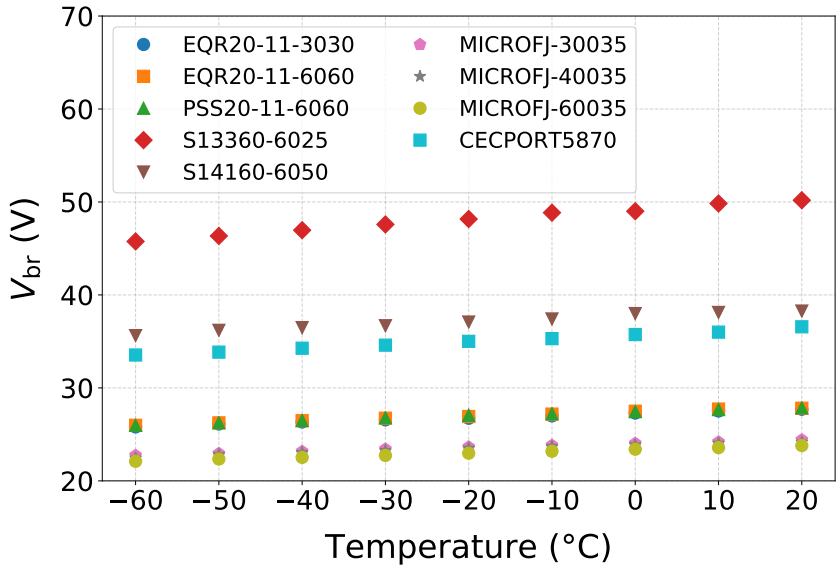
OCT Results

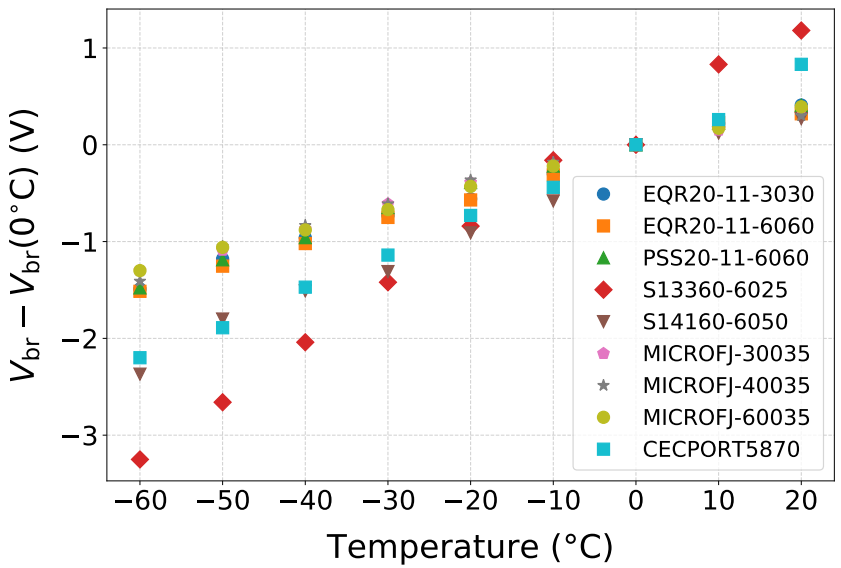
- Optical crosstalk is caused by secondary photons from one avalanche triggering neighboring pixels.
- OCT increases with overvoltage because higher avalanche gain produces more secondary photons.
- OCT is mainly affected by:
  - pixel pitch;
  - inter-pixel isolation structure;
  - device architecture and trench design;
  - pile-up effects in large-area devices.
- Smaller-pitch and weakly isolated devices generally show higher OCT.



Temperature Dependence of Breakdown Voltage

- $V_{\mathrm{br}}(T)$ is measured from $-60^{\circ}\mathrm{C}$ to $20^{\circ}\mathrm{C}$ in $10^{\circ}\mathrm{C}$ steps.
- The breakdown voltage decreases approximately linearly with decreasing temperature.
- Physical interpretation:
  - at lower temperature, lattice vibration is weaker;
  - carriers can gain sufficient energy more easily before scattering;
  - avalanche multiplication starts at a lower voltage.
- The temperature coefficient depends on device type and fabrication process.





Temperature Dependence of DCR

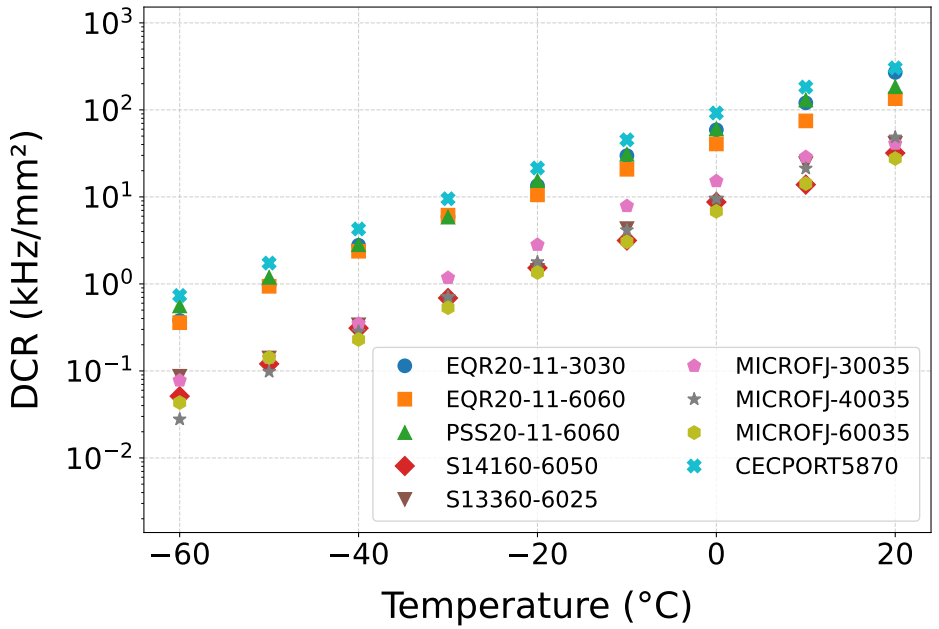
- DCR is measured at temperature-corrected optimal bias:

$$V_{\mathrm{opt}}(T) = V_{\mathrm{br}}(T) + V_{\mathrm{ov}}.$$

- Since DCR is dominated by thermal generation, it decreases rapidly at low temperature:

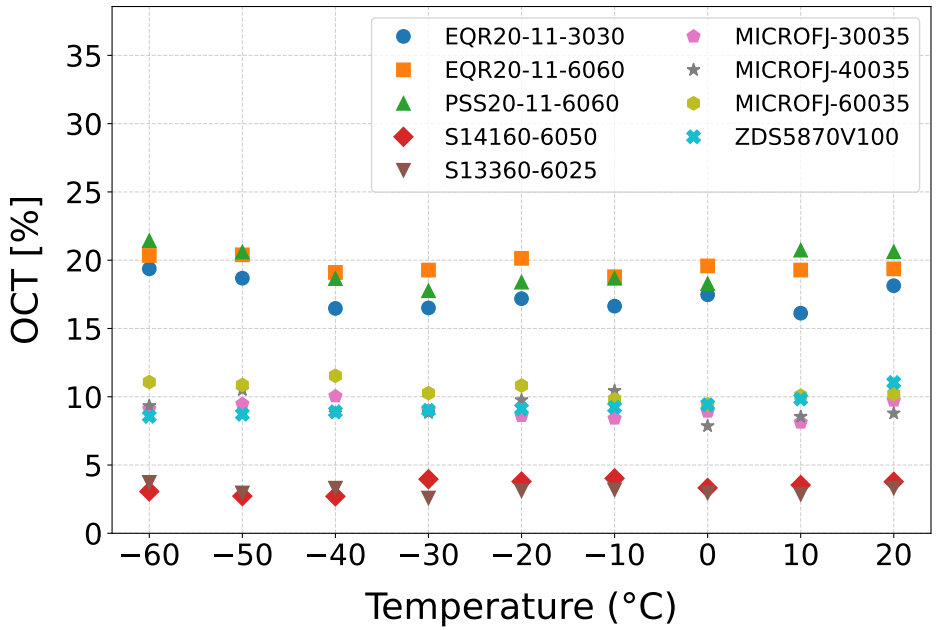
$$N_{0.5p.e.}(T) \approx AT^{3/2} \exp\left(-\frac{E_g}{2kT}\right).$$

- Measurements confirm an approximately exponential decrease of DCR with decreasing temperature.
- At low temperature, the DCR difference between devices becomes significantly smaller.



Temperature Dependence of OCT

- OCT is measured at the temperature-corrected optimal bias $V_{\mathrm{opt}}(T)$ from 20°C to −60°C.
- Optical crosstalk arises from secondary photons generated during an avalanche; it depends mainly on the pixel isolation structure and pitch, and is inherently temperature independent.
- The PZC circuit effectively eliminates dark-count pile-up, removing any indirect temperature influence on OCT via pile-up.
- The measured OCT remains stable over the full temperature range, confirming its temperature independence.
- OCT clearly differentiates SiPMs from different manufacturers: NDL exhibits the highest OCT, followed by SensL and HS, and then HPK, reflecting their distinct isolation schemes.



Performance Comparison and Device-Level Interpretation

- **Gain:**
  - approximately linear with overvoltage;
  - slope mainly reflects pixel capacitance and microcell design.
- **DCR:**
  - increases with overvoltage;
  - sensitive to wafer quality, field profile, pixel density, and pile-up.
- **OCT:**
  - increases with overvoltage;
  - strongly affected by pixel pitch and inter-pixel isolation.
- **Temperature:**
  - V_{br} decreases approximately linearly with temperature;
  - DCR decreases exponentially at lower temperature.

Implications for Detector Applications

- **Precision and low-noise applications:**
  - HPK devices show excellent low-DCR and low-OCT performance.
- **Large-area photon detection:**
  - NDL and CECPORT devices provide high PDE and cost-effective options;
  - pile-up and OCT must be carefully controlled.
- **Timing and TOF systems:**
  - low dark noise and high PDE help improve signal-to-noise ratio and timing resolution.
- **Cherenkov PID:**
  - position-sensitive SiPMs may reduce channel density while preserving spatial information.

Overall: sensor choice should be optimized according to detector geometry, threshold, timing, cooling, and cost requirements.

Summary

- A systematic characterization of commercial SiPMs from NDL, HPK, SensL, and CECPORT was performed.
- Key performance metrics were studied:
  - gain and breakdown voltage;
  - DCR and OCT;
  - temperature-dependent V_{br} and DCR.
- Main observations:
  - gain scales linearly with overvoltage;
  - DCR and OCT are governed by pixel pitch, device structure, and wafer quality;
  - dark count pile-up can bias DCR and OCT measurements for large-area devices;
  - cooling significantly suppresses DCR.
  - OCT shows negligible temperature dependence.
- These results provide guidance for SiPM selection in CEPC and Belle II detector upgrades.

Thanks for your attention!