Electric-Field Dependence of Dark Noise in a Photomultiplier Tube

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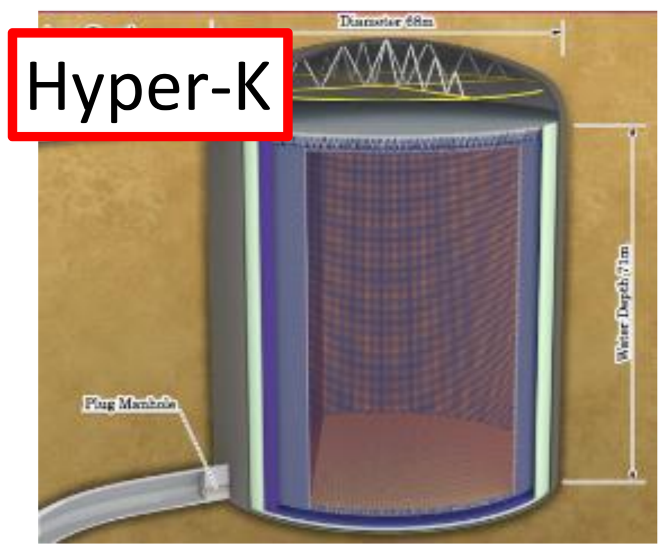
Introduction & motivation

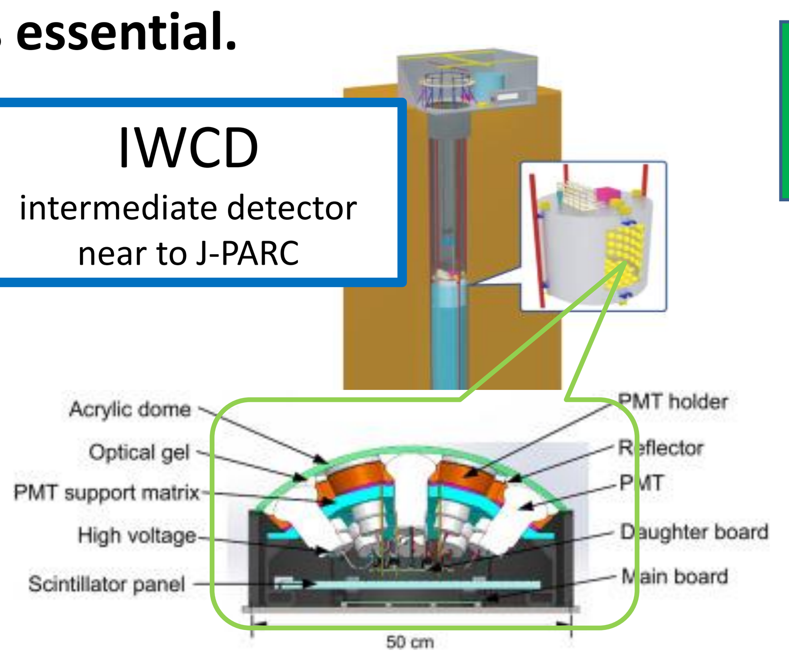
· In neutrino experiments, photomultiplier tubes (PMTs) in water or liquid scintillators are generally used.
· Dark hit is serious background for neutrino measurement such as low energy neutrino detection or neutron-tagging.
· Dark hit is originated from thermal electron on the photocathode.
· On going plans Hyper-Kamiokande and IWCD use PMTs.
⇒**Expectation of the dark rate is essential.**

Hyper-K



20"PMTs used in Hyper-K
+HV mode

IWCD
intermediate detector
near to J-PARC



consists of 19 3"PMTs

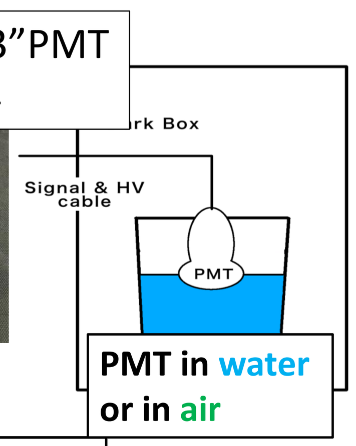
m-PMT in IWCD
either +HV : low dark rate
or −HV : good output waveform

· **For the neutrino physics, it is important to suppress the amount and instability of dark hit rate.**
· **Dark hit rate is affected by the surroundings.**
⇒ **Estimate the impact of environment for dark rate.**

Impact of the detector condition for Dark rate

· To reproduce the effect of surroundings, measure the dark rate of 3"PMT surrounded by water or air.
The bias voltage of this PMT can change +HV or −HV.
·Water and air temperature is about 25℃.
Temperature variation is about 0.2℃ in water, about 0.5 ℃ in air.

Hamamatsu 3"PMT
R14374



mode	+HV		-HV	
condition	in air	in water	in air	in water
dark rate/Hz	291±1	255±1	274±2	21326 ±952

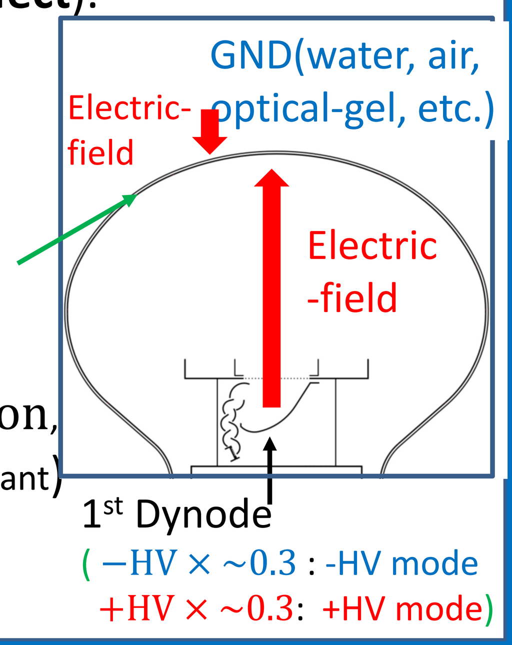
· At −HV mode in water, the dark rate was high and depended significantly on a small temperature change, where the error is dominated by the temperature fluctuation.

· Emission probability of thermal electron depends on the photocathode metal temperature, work function and magnitude of electric-field (**Schottky effect**).
· Electric-field around the photocathode depends on the surrounding environment.

Schottky Effect

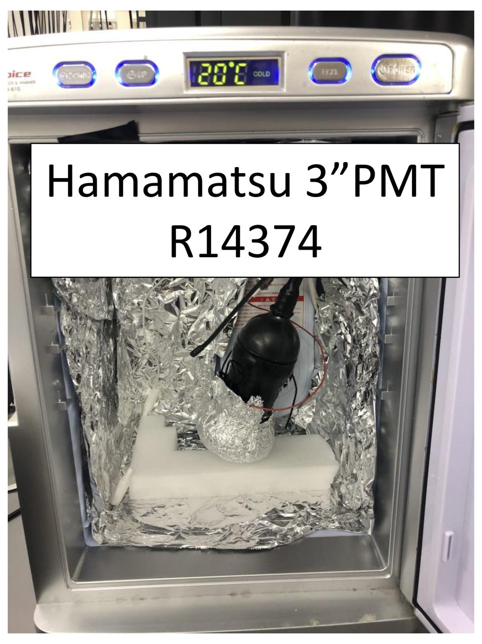
$$J_S = \frac{4\pi m_e (kT)^2}{h^3} \exp\left(\frac{\sqrt{\frac{e^3}{4\pi\varepsilon_0}}\cdot\sqrt{E}-\phi}{kT}\right)$$

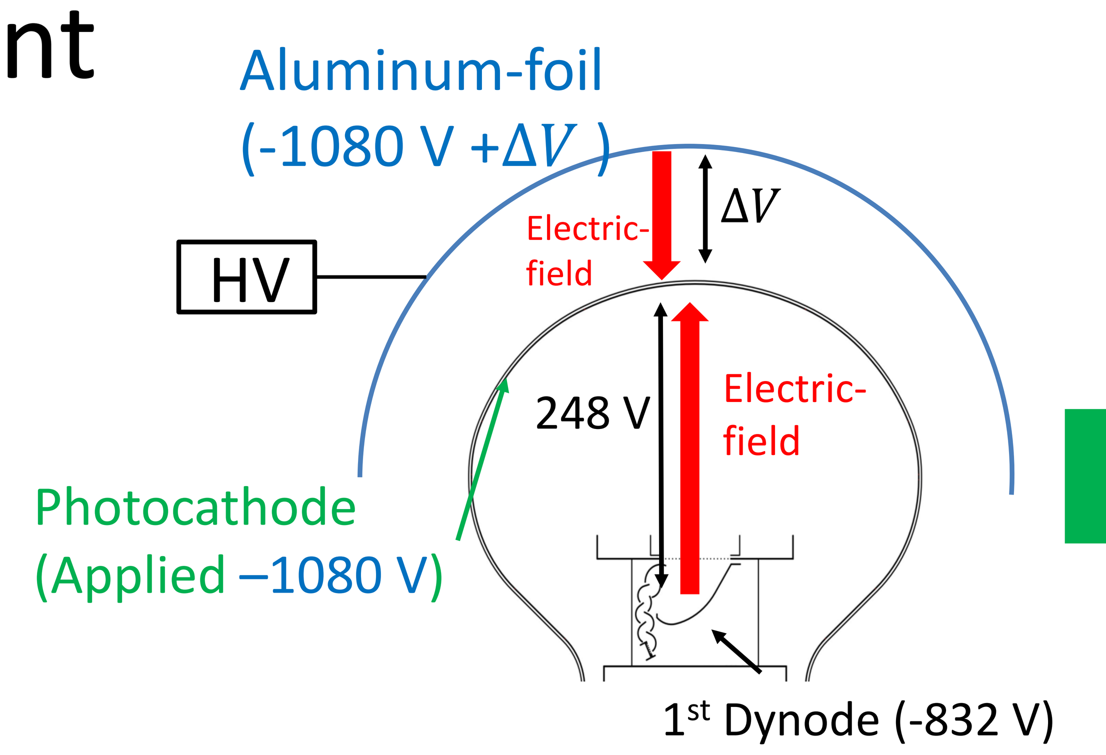
(J_S: thermal electron current density, E: electric − field, ϕ: work function,
m_e: electron mass, k: Boltzmann constant, h: Plank constant, e: electron charge, ε_0: electric constant)



Dark rate could be modeled as a function of temperature and electric-field.

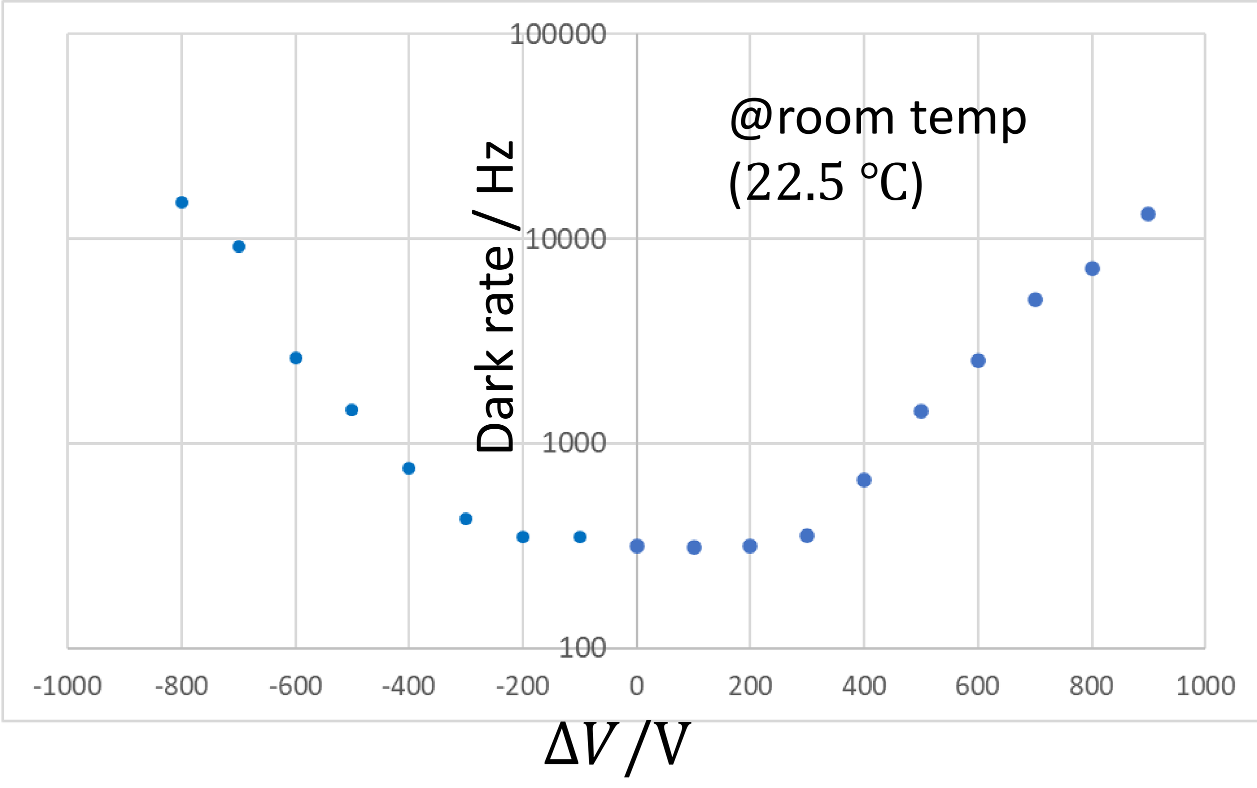
Measurement

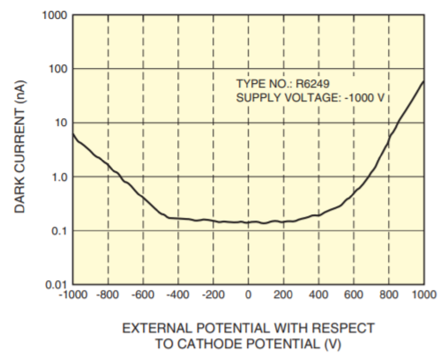




· This time, apply -1080 V to the 3"PMT.
· Photocathode was covered by aluminum-foil with a high voltage applied.
· To control the temperature, PMT was put in warming cabinet.

· Change the voltage ΔV from -800 V to +900 V and measure the dark rate at room-temperature.





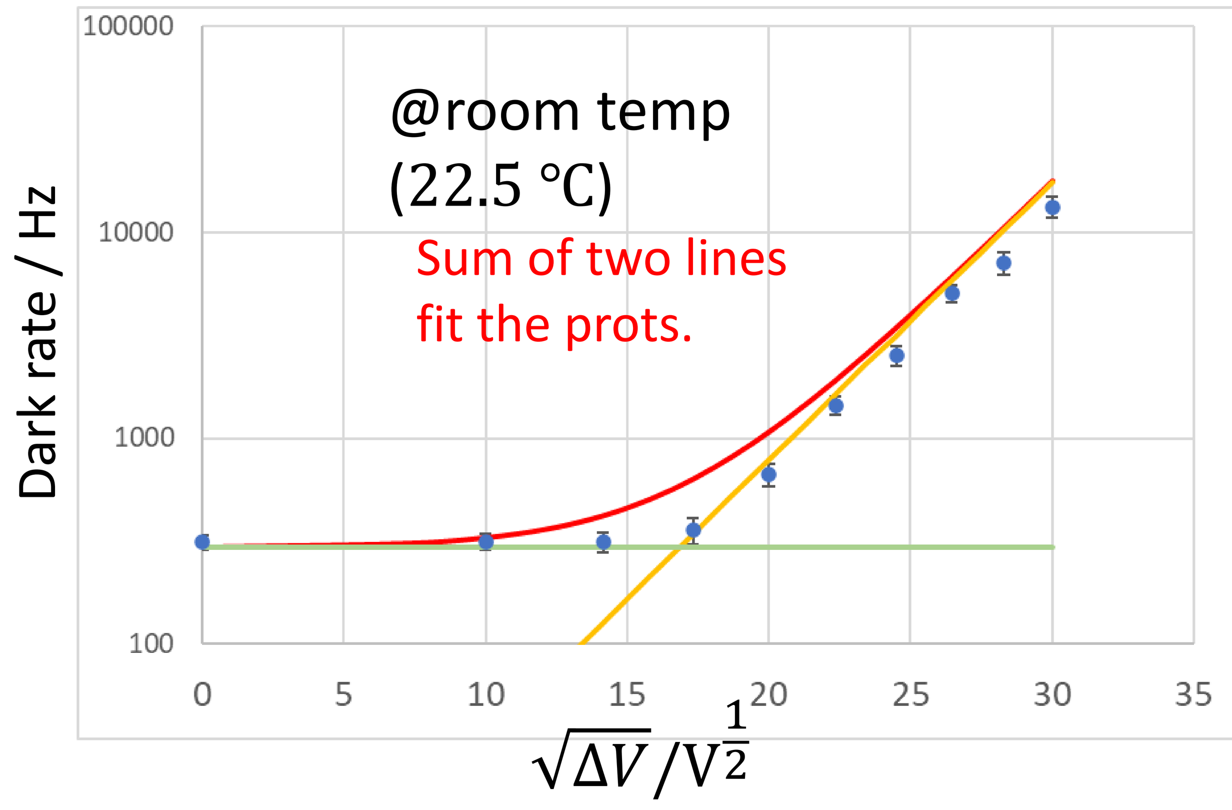
Similar trend to Hamamatsu report

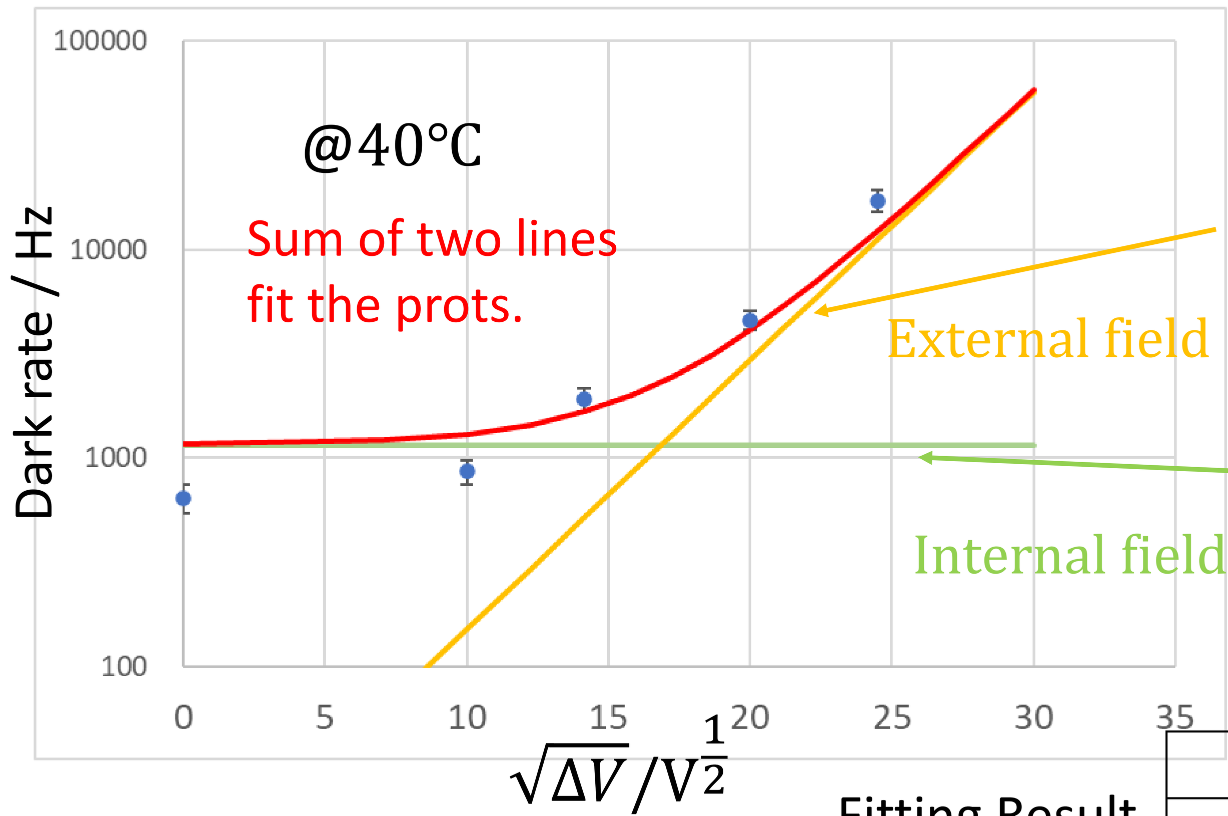
References : PHOTOMULTIPLIER TUBES Basics and Applications FOURTH EDITION , HAMAMATSU (2017) p267

It was confirmed that the dark rate depends on the magnitude of electric-field.

Modeling the dark rate as a function of V and T

·Measure the $\sqrt{\Delta V}$ dependence of dark rate at room-temp and 40℃
· Fitting these two results at the same time.





Fit function

$$\frac{4\pi m_e k^2\cdot S}{eh^3}T^2 \exp\left(\frac{\sqrt{\frac{e^3}{4\pi\varepsilon_0}}\sqrt{\beta_1 \Delta V}-\phi}{kT}\right) + \frac{4\pi m_e k^2\cdot S}{eh^3}T^2 \exp\left(\frac{\sqrt{\frac{e^3}{4\pi\varepsilon_0}}\sqrt{\beta_2\cdot 248\ \mathrm{V}}-\phi}{kT}\right)$$

S: Correspond to the Emitter Area
$\beta_1\cdot\Delta V$: External Electric field
$\beta_2\cdot 248$ V: Internal Electric field

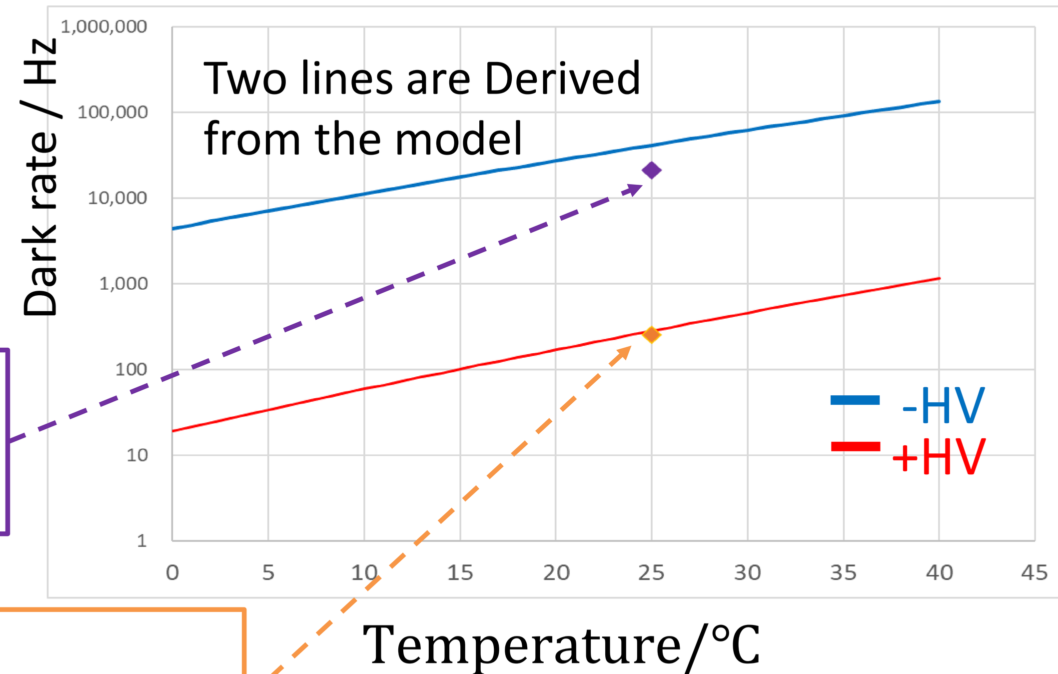
Fitting Result

S/m^2	β_1/m^{-1}	β_2/m^{-1}	ϕ/eV
5.94E-35	4.46E+04	5.10E+04	8.42E-01

Conclusion

·It is confirmed that the dark rate depends on electric-field and temperature.
⇒**The dark rate was modeled as a function of V and T.**
·From this model, for example, if the PMT is put in 25℃ water with 0.2℃ variation, the expected dark rate is 41500 Hz, and the variation is 689 Hz at −HV mode.
At +HV mode, expected dark rate is 282 Hz, the variation is 5.63 Hz.
⇒ **This values are roughly consistent to the measured rate in the water.**

· The model indicates that the dark rate highly depends on the temperature for the PMT with −HV bias in the water and it is sensitive to the grounding around the PMT.



21326 ± 952 Hz
measured at water, 25℃
−HV mode

255 ± 1 Hz
measured at water, 25℃
+HV mode