Photomultiplier Tube (PMT)
Signal Formation & Spurious Pulses

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Contents

1 Introduction

The photomultiplier tube (PMT) remains one of the most sensitive single-photon detectors available, achieving gains of 10^7 with nanosecond timing resolution. Understanding the complete pulse formation process—from photon absorption to the final electrical signal—is essential for interpreting PMT waveforms. Equally important is the characterisation of **spurious pulses** (pre-pulses, late-pulses, and after-pulses) that can mimic or distort the genuine single-photoelectron (SPE) signal.

Where concrete numbers are given, this document quotes specifications of the two 20-inch PMT models used in JUNO (Jiangmen Underground Neutrino Observatory): the **Hamamatsu R12860-50** (dynode PMT, ∼5000 units) and the **NNVT GDB-6201** (MCP PMT, ∼15 000 units) [1]. Key specifications are summarised in Table 1.

Table 1: JUNO 20-inch PMT specifications [1, 2]

Parameter	Hamamatsu R12860-50	NNVT GDB-6201
Type	Dynode	MCP
Diameter	508 mm	508 mm
QE at 400 nm	∼30% (avg.)	∼28.5% (avg.)
Operational gain	1×10^7	1×10^7
HV for 10^7 gain	∼2000 V	∼2500 V
TTS (FWHM)	∼2.7 ns	∼12 ns
Dark count rate (0.25 PE, 22°C)	∼10 kHz	50–100 kHz
SPE peak/valley ratio	∼3–4.8	∼3.5
Pre-pulse ratio	∼0.8%	∼0.5%
After-pulse ratio (0.5–20 μs)	∼10%	∼10%
Collection efficiency (CE)	∼95.6%	∼98%
^{238}U in glass	< 400 ppb	< 75 ppb
^{232}Th in glass	< 400 ppb	< 75 ppb
^{40}K in glass	< 40 ppb	< 30 ppb

2 PMT Signal Formation

The complete transformation of a single photon into a measurable electrical pulse ($\sim 10^7$ electrons at the JUNO operational gain) occurs in approximately 10–50 ns. The process is outlined stage by stage below.

2.1 Photon Absorption & Photoelectron Emission

A photon of energy $h\nu$ strikes the **photocathode**. If $h\nu > W$ (the sum of the band gap and electron affinity of the cathode material), a photoelectron may be liberated via the external photoelectric effect. At the JUNO scintillation wavelength (∼400 nm), the Hamamatsu R12860 achieves ∼30% quantum efficiency (QE).

The Spicer Three-Step Model

(1) **Absorption** — The photon excites an electron from the valence band to a conduction state above the vacuum level.

(2) **Transport** — The excited electron diffuses toward the vacuum surface, losing energy through electron–electron and electron–phonon scattering. Only electrons reaching the surface with energy above the vacuum level can escape.

(3) **Escape** — The electron overcomes the surface potential barrier and is emitted into vacuum.

Table 2: Typical photocathode parameters (R12860 bialkali)

Parameter	Typical value
Quantum Efficiency at 400 nm	∼30% (avg.), max ∼35%
Electron escape depth	10–30 nm
Initial kinetic energy	0–2 eV (broad distribution)
Emission angle	Lambertian ($\propto \cos\theta$)

2.2 Acceleration & Focusing: Cathode → First Dynode

The photoelectron emerges from the cathode with low kinetic energy (0.1–1 eV). The **cathode-to-first-dynode** (K→D1) voltage—a fraction of the total HV, ∼300–500 V for the R12860 at 2000 V total—accelerates it toward D1. Electrostatic focusing electrodes ("venetian blind" or box-and-grid design in the R12860) shape the field to collect photoelectrons from the full 20-inch cathode area onto a small D1 spot.

Why K→D1 dominates Transit Time Spread (TTS): The electric field near the cathode is relatively weak. A 1 eV electron emitted at an unfavourable angle lingers in this low-field region, creating trajectory-dependent delays. Once the electron reaches ∼100 eV, transit time becomes nearly deterministic. This first stage contributes **60–80% of total TTS**. For the R12860, the total TTS (FWHM) is ∼2.7 ns; for the NNVT MCP-PMT, ∼12 ns.

2.3 Secondary Emission at the First Dynode

The ∼100–500 eV primary electron strikes the **first dynode** (BeCu in the R12860). It penetrates 1–10 nm into the material, creating many internal secondary electrons along its track. Those within an escape depth of the surface are emitted into vacuum.

The **secondary emission coefficient** δ is defined as:

$$\delta(E_p) = \frac{\text{number of emitted secondaries}}{\text{incident primary}} \tag{1}$$

where E_p is the primary electron energy. For BeCu at ∼200 eV, $\delta \approx 4$–6.

Statistics at D1

The number of secondaries from a single primary follows approximately a **Polya distribution** (broader than Poisson). The relative fluctuation,

$$\frac{\sigma_{\delta_1}}{\langle \delta_1 \rangle} \approx 0.3\text{–}0.5, \tag{2}$$

is the **dominant contribution to PMT gain variance** because it occurs when the electron number is smallest. Fluctuations in later stages are averaged out. This width together with non-uniform collection efficiency determines the SPE peak-to-valley ratio: ∼3–4.8 for the R12860, ∼3.5 for the NNVT.

2.4 The Dynode Chain (D2 → $\mathbf{D_N}$)

In the R12860 (dynode PMT, 10 stages), electrons undergo successive multiplication at each dynode. In the NNVT GDB-6201, a **microchannel plate** (MCP) replaces the discrete dynode chain. At each stage:

(1) **Acceleration** — Inter-dynode voltage (50–150 V per stage) accelerates secondaries.

(2) **Collection** — Electrostatic focusing guides electrons onto the next dynode.
(3) **Multiplication** — δ new secondaries are produced per incident electron.

The **total gain** for a dynode PMT is:

$$G = \alpha \cdot \delta_1 \cdot \delta_2 \cdots \delta_N \tag{3}$$

where α is the collection efficiency (~95.6% for the R12860, ~98% for the NNVT MCP). With 10 stages and $\delta \approx 5$: $G \approx 5^{10} \approx 9.8 \times 10^6$, which matches the JUNO operating gain of 1×10^7.

The gain variance is dominated by the first few stages:

$$\left(\frac{\sigma_G}{G}\right)^2 \approx \frac{1}{\delta_1} \cdot \frac{\delta}{\delta - 1} \cdot \left(1 + \frac{\sigma_\delta^2}{\langle\delta\rangle^2}\right). \tag{4}$$

2.5 Anode Collection & Signal Readout

After the last dynode, the electron cloud ($\sim 10^7$ electrons at JUNO gain) is collected at the **anode**. The charge $Q = G \cdot e$ deposits on the anode capacitance C_{anode}, producing a voltage pulse.

For the R12860 at $G = 10^7$, $Q = 1.6\,\text{pC}$. Across a $50\,\Omega$ load with $t_{\text{rise}} \approx 2.7\,\text{ns}$ (TTS-limited):

$$I_{\text{peak}} \approx \frac{Q}{t_{\text{rise}}} \approx 0.6\,\text{mA}, \qquad V_{\text{peak}} \approx 30\,\text{mV}. \tag{5}$$

2.6 Pulse Shape

The final voltage pulse results from the convolution of several processes:

- **Rise time** — dominated by TTS of the K→D1 stage (~2.7 ns for R12860, ~12 ns for NNVT).
- **Fall time** — governed by the RC time constant of the anode circuit.
- **FWHM** — convolution of rise/fall times.

A simple phenomenological model:

$$V(t) \approx \frac{Q}{C} \cdot \left(1 - e^{-t/t_{\text{rise}}}\right) \cdot e^{-t/RC}. \tag{6}$$

2.7 Summary Timeline

Table 3: Approximate timeline of signal formation (R12860 at 10^7 gain)

Time	Event	Electrons
$t = 0$	Photon hits photocathode	—
~1 ps	Photoelectron emission	$1e^-$
~8 ns	Cascade reaches D1	$\delta_1 \approx 5$
~9 ns	D2	~25
~10 ns	D3	~125
~11 ns	D4	~625
~12 ns	D5	~3,000
~13 ns	D6	~1.5×10^4
~14 ns	D7	~7.5×10^4
~15 ns	D8	~4×10^5
~16 ns	D9	~2×10^6
~17 ns	D10 (anode)	~10^7
~17−20 ns	Charge pulse rises at anode	—
~20−100 ns	RC decay to baseline	—

Key insight: a single Cherenkov or scintillation photon produces a cloud of 10^7 electrons at the anode within $\sim$17 ns—an amplification of 10^7 in < 20 ns, driven entirely by successive secondary emission.

3 Spurious Pulses: Pre-Pulse, Late-Pulse & After-Pulse

In addition to the main SPE signal, PMTs exhibit three classes of spurious secondary signals distinguished by their timing relative to the main pulse.

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--[Pre-Pulse]--[MAIN PULSE]--[Late-Pulse]--------[After-Pulse]--
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$\sim$ ns before	$t = 0$	$\sim$5–50 ns after	$\sim$0.3–100 μs after

Figure 1: Timeline of the main pulse and the three types of spurious pulses.

3.1 Pre-Pulse

Definition

A small signal that arrives **before** the main pulse, typically by $\sim$1–10 ns.

Mechanism — Direct Dynode Photoemission

(1) A fraction of incident photons pass **through** the semitransparent photocathode without being absorbed (typical transmission $\sim$50%).
(2) These photons strike the **first dynode (D1)** directly.
(3) D1 has non-zero quantum efficiency and emits a photoelectron.
(4) This electron **skips** the cathode-to-D1 gap and begins multiplication at D1.
(5) Consequently, it arrives at the anode earlier than the normal signal by approximately the K→D1 transit time.

Charge Scaling

Because the pre-pulse originates at D1 rather than the photocathode, it misses the first—and largest—stage of secondary multiplication. The total gain of a pre-pulse is therefore reduced by a factor of δ_1 compared to the main SPE pulse:

$$G_{\text{pre}} = \delta_2 \cdot \delta_3 \cdots \delta_N = \frac{G_{\text{SPE}}}{\delta_1}, \qquad \frac{Q_{\text{pre}}}{Q_{\text{SPE}}} = \frac{G_{\text{pre}}}{G_{\text{SPE}}} = \frac{1}{\delta_1}. \tag{7}$$

Since the later dynode chain and anode circuit are identical for both, the pulse *shape* is nearly the same—only the overall scale differs. Both the peak amplitude and the integrated charge are reduced by the same factor. For typical BeCu dynodes with $\delta_1 \approx 4$–6:

$$\frac{Q_{\text{pre}}}{Q_{\text{SPE}}} \approx \frac{1}{4\text{–}6} \approx 15\text{–}25\%. \tag{8}$$

In other words, a pre-pulse carries only about one-fifth to one-quarter of the main SPE charge. This fixed fractional relationship (set by δ_1, not by photon statistics) is a distinctive signature that helps identify pre-pulses in waveform analysis.

Characteristics

Table 4: Pre-pulse characteristics

Property	Description
Timing	∼1–10 ns *before* the main pulse
Amplitude	Much smaller than SPE (D1 QE ≪ photocathode QE; the electron misses the full K→D1 acceleration and the full D1 secondary yield)
Rate (R12860)	∼0.8% of pulses (JUNO acceptance: ≤1%)
Rate (NNVT)	∼0.5% of pulses (JUNO acceptance: ≤1%)
Distinction	Always leads the main pulse; fixed fractional amplitude

A variant mechanism: some photoelectrons emitted from the cathode with unusually high initial kinetic energy and favourable trajectories can transit K→D1 faster than average, contributing an early shoulder to the main pulse.

3.2 Late-Pulse & Rediffused Electrons

Definition

A pulse arriving **after** the main pulse with a modest delay, typically ∼5–50 ns, and amplitude comparable to the SPE.

Mechanism — Elastic/Inelastic Backscattering from D1

(1) A primary photoelectron strikes the **first dynode (D1)**.
(2) With probability ∼5–15%, instead of producing true secondaries, the primary undergoes:
  - **Elastic scattering** — it bounces off D1 losing little energy, or
  - **Inelastic scattering** — it loses energy and is re-emitted as a lower-energy electron.

(3) The scattered electron—termed a **rediffused electron**—travels back into the cathode–D1 gap.
(4) The electric field returns it to D1 after a **round-trip flight time** (∼5–50 ns).
(5) It then produces the normal secondary cascade → a delayed pulse.

What is a Rediffused Electron?

A **rediffused electron** is a primary electron that, upon striking a dynode, **fails to produce proper secondary emission** and is instead backscattered or re-emitted from the dynode surface with reduced energy. The term "rediffused" reflects the physical picture: the electron diffuses *into* the dynode material, undergoes a random walk through multiple scatterings, and diffuses *back out*—as opposed to transferring its energy to other electrons.

When a primary electron (∼100–500 eV) hits a dynode, there are two competing outcomes:

- **True secondary emission (desired):** The primary penetrates ∼1–10 nm into the material, creates ∼20–50 internal secondaries along its track, and ∼5 escape into vacuum with low energy (∼1–5 eV).
- **Rediffusion:** The primary is *not absorbed* but bounces back out—either elastically (preserving most energy) or inelastically (after losing energy inside the material).

Note: The term "rediffused" applies to discrete-dynode PMTs like the R12860. For NNVT MCP-PMTs, the analogous process involves electron backscattering from microchannel wall surfaces, with different geometry and field configuration.

Physical Mechanisms of Rediffusion

Elastic backscattering — The primary electron scatters off a single surface atom (Rutherford-like scattering at high angle). Energy loss is minimal ($m_e \ll m_{\text{nucleus}}$). Probability: ∼1–3% for typical dynodes at 100–300 eV.

Inelastic rediffusion — The primary enters the dynode material, loses energy through electron–electron scattering, undergoes a series of small- and large-angle scatterings (a random walk), and by chance returns to the surface. If its residual energy exceeds the surface potential barrier, it is re-emitted into vacuum.

Energy Spectrum

The energy distribution of rediffused electrons is broad and distinct from true secondaries:

- **True secondaries**: sharp peak at ∼1–5 eV.
- **Inelastic rediffused**: broad continuum from ∼10 eV up to $\sim 0.8\,E_p$.
- **Elastic rediffused**: narrow peak at ~ 0.9–$0.98\,E_p$.

The total rediffused fraction (elastic + inelastic) is typically **10–30%** for BeCu dynodes at 200–300 eV.

Material Dependence

Table 5: Rediffusion coefficient η for common dynode materials at 300 eV

Material	η	Notes
BeCu (beryllium copper)	0.15–0.25	R12860 dynode material
SbCs (antimony-cesium)	0.10–0.15	Lower rediffusion; higher δ
AgMg (silver magnesium)	0.20–0.30	Older tubes
GaP (gallium phosphide, NEA)	0.05–0.10	Very low rediffusion

Negative Electron Affinity (NEA) materials like GaP significantly reduce rediffusion because electrons thermalised in the conduction band can still escape—the surface barrier is effectively zero. The BeCu dynodes in the R12860 have $\eta \approx 0.15$–0.25, meaning late-pulses are an intrinsic feature at the few-percent level.

Consequences of Rediffusion

(1) **Late-pulses** — The rediffused electron returns to D1 after a round-trip flight time, producing the delayed ∼SPE signal described above.

(2) **Reduced effective** δ — The effective secondary emission coefficient is $\delta_{\text{eff}} = (1 - \eta) \cdot \delta$. The fraction η produces zero true secondaries (just one rediffused electron), broadening the SPE gain distribution.

(3) **Gain non-linearity at high currents** — At very high instantaneous currents, rediffused electrons can overlap spatially and temporally with the main cascade.

(4) **After-pulsing via late-dynode rediffusion** — Rediffusion at later dynodes, where backscattered electrons travel to *earlier* dynodes and are re-multiplied, can contribute to the broader after-pulse structure.

Characteristics

Table 6: Late-pulse characteristics

Property	Description
Timing	∼5–50 ns *after* the main pulse
Amplitude	Comparable to SPE (undergoes full multiplication)
Rate	∼3–10% of pulses (dynode PMTs)
Dependence	Increases with higher K→D1 voltage
	(higher primary energy → higher backscatter probability)

In JUNO, late-pulses are not separately quoted in the standard acceptance criteria but are implicitly included in waveform characterisation and SPE calibration studies. The ∼2.7 ns TTS of the R12860 makes late-pulses at 5–50 ns cleanly resolvable from the main pulse.

3.3 After-Pulse

Definition

A pulse arriving **much later** than the main pulse—microseconds after—often with amplitude larger than the SPE.

Mechanism A: Ion Feedback (dominant)

(1) During the electron multiplication cascade, the dense electron cloud (especially in later stages, $\sim 10^7$–10^8 electrons) collides with **residual gas molecules** (H_2, He, CH_4, CO, N_2, etc.) in the vacuum tube.
(2) These collisions **ionise** the gas molecules, producing positive ions.
(3) Positive ions **drift backward** against the accelerating electric field toward the photocathode or first dynodes.
(4) When a positive ion strikes the photocathode, it liberates **multiple electrons** (ion-induced secondary emission: an ion can knock out 5–20 electrons).
(5) These electrons are multiplied normally → a large, delayed output pulse.

The delay is large because ions are heavy. The ion drift time scales as:

$$t_{\text{delay}} \propto \frac{d}{\sqrt{V}} \sqrt{\frac{m_{\text{ion}}}{2e}} \tag{9}$$

where d is the drift distance, V the voltage, and m_{ion} the ion mass. Typical ion drift times: **0.5–100 μs**, depending on ion species, PMT geometry, and applied voltage.

Mechanism B: Optical Feedback (secondary)

(1) Electrons striking dynodes produce **scintillation light** in the dynode material or residual gas.
(2) This light can propagate back to the photocathode, producing additional photoelectrons.
(3) The resulting delay equals the photon time-of-flight (negligible) plus normal electron transit time → typically **30–100 ns** after the main pulse.

Characteristics

Table 7: After-pulse characteristics

Property	Description
Timing (ions)	∼0.3–100 μs after main pulse
Timing (optical)	∼30–100 ns after main pulse
Amplitude	Can be **larger** than SPE (multiple e^- per ion strike)
Rate (R12860)	∼10% of pulses (0.5–20 μs window)
Rate (NNVT)	∼10% of pulses (0.5–20 μs window)
JUNO spec.	≤15% for both PMT types
Dependence	Proportional to residual gas pressure; worsens with tube aging

Both PMT types in JUNO show after-pulse ratios of ∼10% for the 0.5–20 μs window, within the ≤15% acceptance limit. The NNVT MCP-PMT benefits from lower residual gas ionisation probability due to the shorter electron path length in the microchannel plate structure.

3.4 Summary Comparison of Spurious Pulses

Table 8: Comparison of pre-pulse, late-pulse, and after-pulse

Property	Pre-Pulse	Late-Pulse	After-Pulse
Origin	Photons hitting D1	e^- backscatter at D1	Ion/optical feedback
Delay	−few ns	+5–50 ns	+0.3–100 μs
Amplitude	Small	∼SPE	1–20× SPE
Rate (R12860)	∼0.8%	∼3–10%	∼10%
Rate (NNVT)	∼0.5%	∼few%*	∼10%

*MCP-PMTs generally have lower late-pulse rates due to shorter electron flight paths and different multiplication geometry.

Table 9: Differential diagnosis of delayed signals in a PMT

Phenomenon	Origin	Delay	Amplitude
Rediffused e^- (late-pulse)	e^- backscattered from D1	5–50 ns	∼SPE
True secondary	Internal e^- from primary at dynode	0 (main pulse)	∼SPE
Ion after-pulse	Positive ion → cathode	0.3–100 μs	1–20× SPE
Optical after-pulse	Scintillation photon → cathode	30–100 ns	∼SPE
Pre-pulse	Photon bypasses cathode → D1	−few ns	$<$ SPE

4 Key PMT Output Pulse Parameters

For reference, Table 10 summarises the characteristic features of the PMT output pulse, with JUNO-specific values where applicable.

Table 10: Summary of PMT output pulse characteristics

Feature	Typical value (dynode)	JUNO R12860	Physical origin
Rise time	1–10 ns	∼2.7 ns	TTS in K→D1; initial e^- velocity spread
Fall time	2–20 ns	RC-limited	RC time constant of anode circuit
Transit Time Spread (TTS)	1–10 ns (FWHM)	∼2.7 ns	Path-length and velocity variations (dominated by K→D1)
Gain	10^5–10^8	1×10^7	$G \approx \delta^N$
SPE peak/valley	2–5 (good tubes)	∼3–4.8	Poisson statistics at D1; CE non-uniformity
Dark count (0.25 PE)	10–10^4 cps	∼10 kHz	Thermionic emission ($\propto e^{-W/kT}$); radioactivity (^{40}K in glass <40 ppb)
Collection eff.	90–98%	∼95.6%	Focusing electrode design
Pre-pulse ratio	< 1%	∼0.8%	Photons passing through cathode
After-pulse ratio	1–15%	∼10%	Ion feedback (0.5–20 μs window)

Key Physical Points

- **Cathode to D1** contributes the largest TTS share because the electric field is weakest there. The R12860's excellent 2.7 ns TTS results from optimised focusing electrode geometry.
- **Dynode chain statistics** follow a Polya branching process, with gain variance dominated by the first few stages.
- **Space charge saturation** occurs at very high pulse currents ($I_{\text{peak}} > 10$–100 mA), where the electron cloud's own space charge distorts inter-dynode fields.
- **Voltage divider sag** occurs at high average currents, when the bleeder current cannot replenish charge at the last dynodes fast enough, causing gain droop.
- **Low-background glass** for the NNVT GDB-6201 (^{238}U, ^{232}Th <75 ppb, ^{40}K <30 ppb) significantly reduces the radioactive contribution to dark noise compared to the R12860 (<400 ppb U/Th).

5 Conclusion

The PMT converts a single photon into a macroscopic electrical pulse through a cascade of secondary emission across multiple dynode stages, achieving gains of 10^7 in ∼10–50 ns. The two 20-inch PMT models employed by JUNO—the Hamamatsu R12860-50 (dynode) and the NNVT GDB-6201 (MCP)—each present distinct performance profiles, with the R12860 offering superior timing (∼2.7 ns TTS) and the NNVT offering higher collection efficiency (∼98%) and lower radioactive background.

Three classes of spurious signals affect PMT waveform interpretation:

- **Pre-pulses** (photons bypassing the cathode and striking D1, arriving ∼ns early; ∼0.5–0.8% at JUNO);
- **Late-pulses** (rediffused/backscattered electrons from D1, arriving 5–50 ns late; ∼3–10%);
- **After-pulses** (ion feedback and optical feedback, arriving μs late; ∼10% in the 0.5–20 μs window for both JUNO PMT types).

Among these, **rediffused electrons**—primary electrons that backscatter from a dynode instead of producing true secondaries—are the direct physical cause of late-pulses and contribute to gain broadening through the reduced effective $\delta_{\text{eff}} = (1-\eta)\delta$. Understanding these phenomena at the level of individual PMT waveforms is critical for energy reconstruction, vertex resolution, and background rejection in large-scale liquid-scintillator experiments.

References

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