Visualizing Nuclear Spectrums with Photomultiplier Tubes

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Motivation: The pfRICH Detector

- Brookhaven Laboratory Electron-Proton/Ion collider contains proximity-focusing Ring Imaging Cherenkov (pfRICH) detector for determining post-collision particle mass
- High Rate Picosecond Photodetectors (HRPPDs) convert and amplify Cherenkov photons
- HRPPDs must be tested in a high neutron flux environment

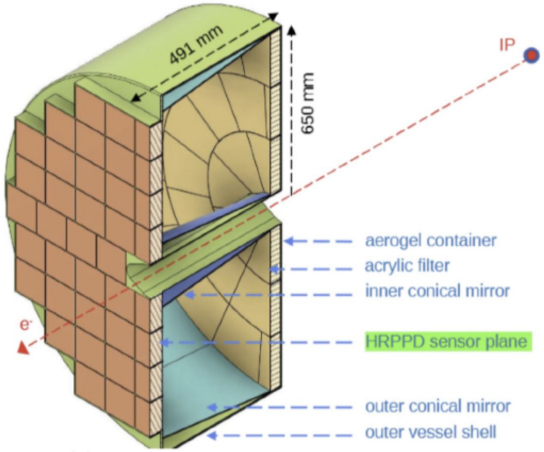


Fig 1. Autocad rendering of pfRICH detector [pfRICH autocad: ePIC Collaboration (2023), pfRICH Conceptual Design Report (Draft 1.1), BNL.

Motivation: Neutron Flux

- EIC conditions will be simulated with Americium-Beryllium neutron source:

$$^{241}Am \rightarrow \ ^{237}Np + \alpha$$
$$^{9}Be + \alpha \rightarrow \ ^{12}C + n$$

- Shifting neutron spectrum with polyethylene layers simulate conditions
- Recreating spectrums with available β, μ, and γ sources validates ability to create neutron spectrum
- Method: Scintillators and PMT’s

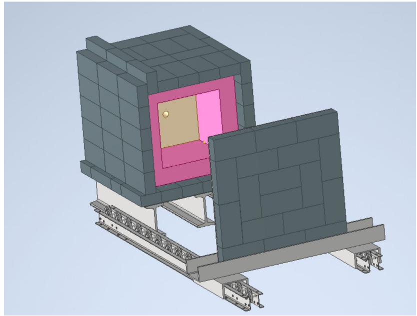


Fig 2. Autocad rendering of neutron shielding for pfRICH HRRPD testing

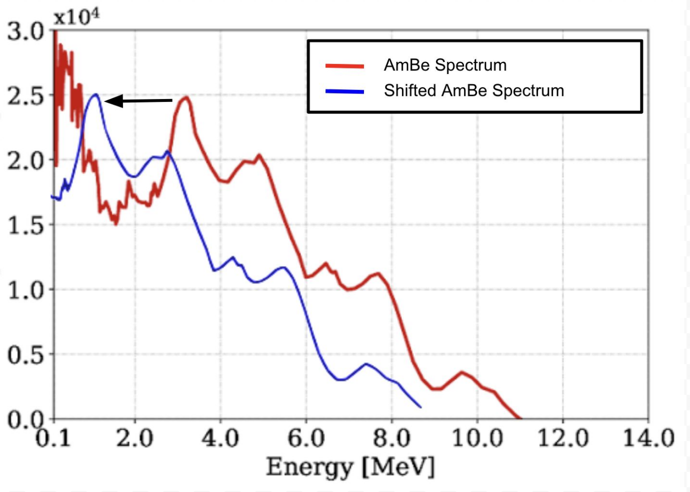


Fig 3. AmBe Spectrum [AmBe spectrum: Cecchetto et al. (2021), IEEE Trans. Nucl. Sci. 68(5): 873–883.] (Modified)

Photon Multiplier Tubes and Scintillators (EJ-200)

- No radiation damage unlike SiPMs
- PMT: Photoelectric effect converts photons to electrons
- PMT: secondary cascade multiplies electrons
- Matching scintillator emission to PMT sensitivity and source energy
- Linear relationship between deposited energy and PMT signal for β decay:

$$V_{signal} = E_{source} \cdot \varepsilon_{scin} \cdot \varepsilon_{coll} \cdot \varepsilon_{quantum} \cdot gain \cdot q_e/\tau \cdot Z$$

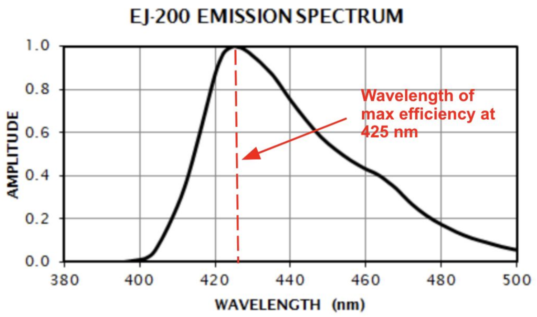


Fig 4. EJ200 Emission Spectrum [EJ200 spectrum: Eljen Technology (2023), EJ-200/204/208/212 datasheet.]

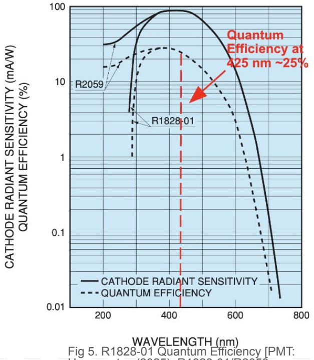


Fig 5. R1828-01 Quantum Efficiency [PMT: Hamamatsu (2025), R1828-01/R2059 datasheet, no. TPMH1259E06.]

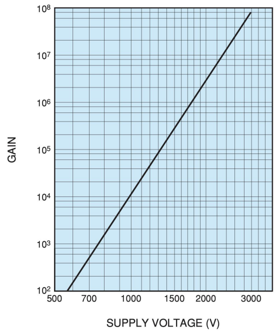
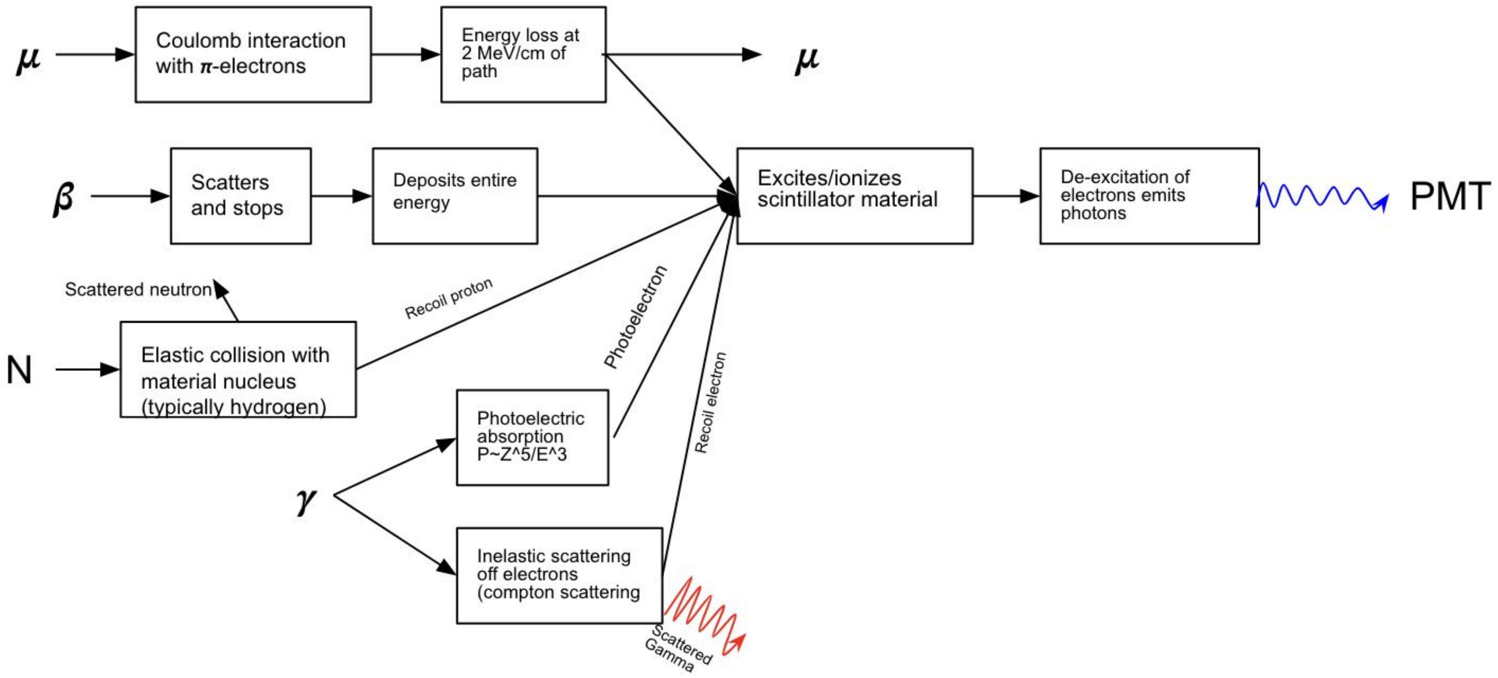


Fig 6. R1828-01 Gain as a function of voltage [PMT: Hamamatsu (2025), R1828-01/R2059 datasheet, no. TPMH1259E06.]

Scintillation



Setup for β and μ detection

- Goal: Maximize energy resolution (full energy absorption, high light yield)
- Hamamatsu R1828-01 PMT: low background, high gain, precise linearity
- EJ-200 Scintillator, wave guide, PMT coupled with optical matching grease EJ-550
- Mylar and electrical tape wrapping to minimize light loss; results in unknown light collection efficiency (ε_coll)

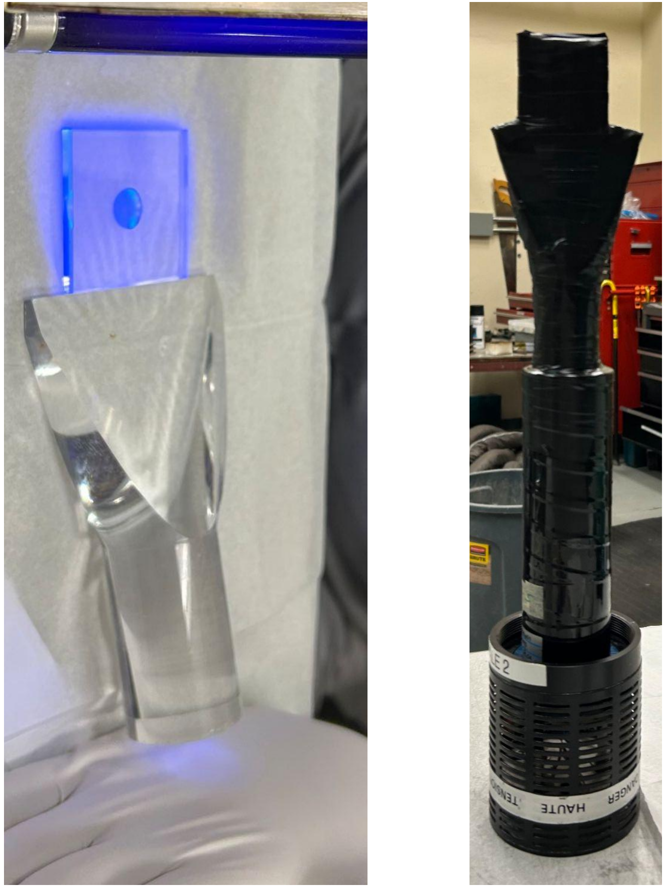


Fig 7. Scintillator, Wave guide, and PMT coupling process

Setup for β and μ detection

- Recycled electronics from XP2020 PMT; mismatched voltage dividers

	K	G	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	A
Ideal	1.2	2.8	1.2	1.8	1	1	1	1	1	1	1.5	1.5	3	2.5	
Current	1.5	7.1	2	1.5	1	1	1	1	1	1	1.5	1.5	3.3	2.8	

Table 1. Ideal voltage ratio for Hamamatsu R1828-01 compared to available electronics

Specific Parameters for Current Setup	
EJ200: Scintillation Efficiency (ε)	10,000 photons/1 MeV e^-
EJ200: Pulse Width FWHM (τ)	2.5 ns
EJ200: Density	1.023 g/cm^3
EJ200: Z_eff	~5.4
Impedence (Z)	50 Ω
Operating Voltage	1200 V

Table 2. Specific parameters for β and μ data collection

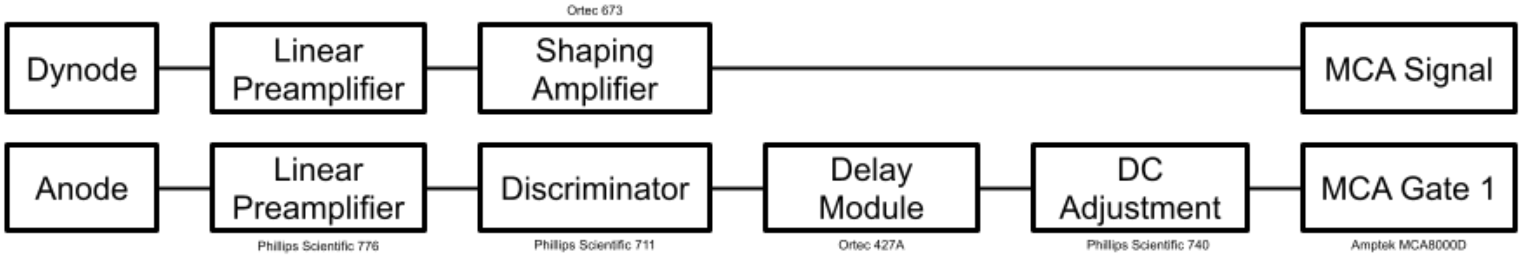


Fig 8. Box diagram of NIM modules used in signal processing

Cosmic Muon Detection

- Expected Landau-Gauss distribution around 0.8 MeV (4 mm path length)
- Coincidence measurements with SiPM Cosmic Watch verify measurement accuracy
- Results independent of scintillator
- 1 incident per sq. cm/min → 25/min for EJ200 scintillator setup; experimental rate of 29.5 counts/min

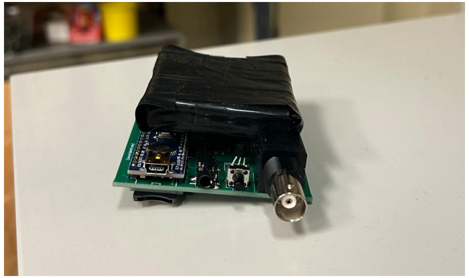


Fig 10. Cosmic Watch SiPM detector

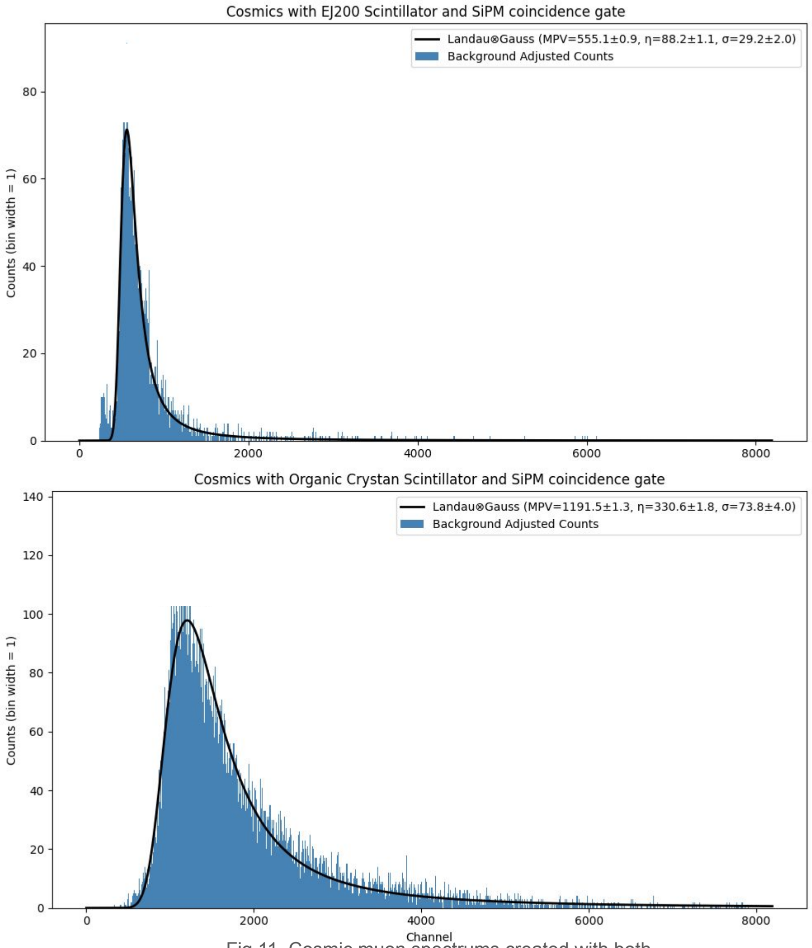


Fig 11. Cosmic muon spectrums created with both EJ200 and Organic Crystal Scintillators

Sr90 β Detection

- Spectrum produced by uncollimated 1 mCi source, scalar background subtracted
- Relative peak locations predicted by pulse linearity

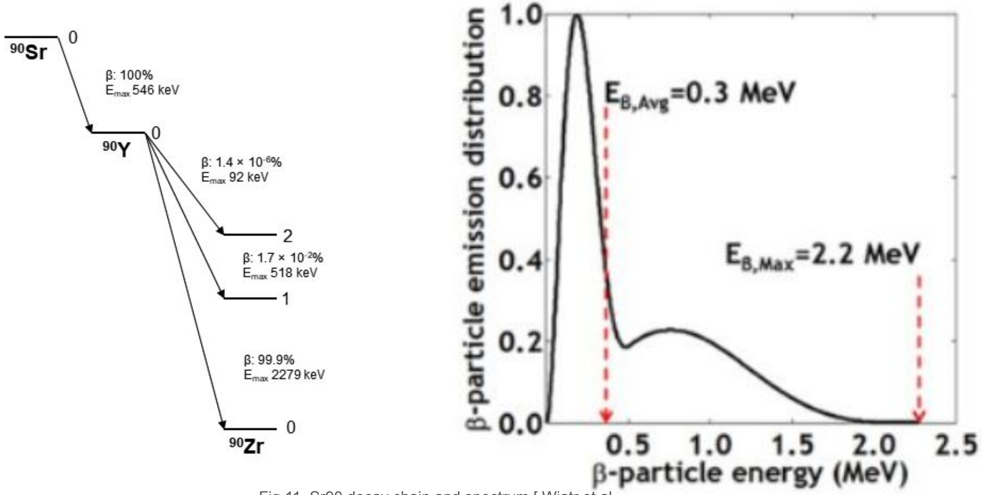


Fig 11. Sr90 decay chain and spectrum [Wiatr et al. (2022), Nukleonika 67(2): 67–72.]

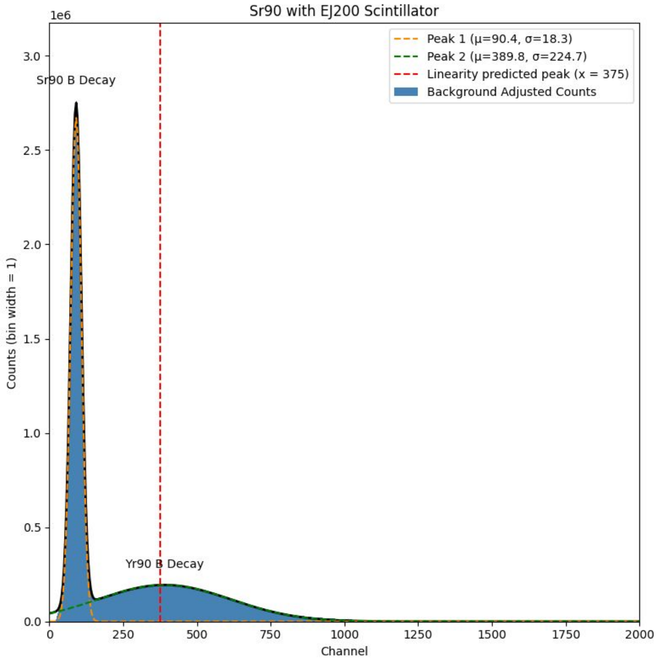


Fig 12. Background subtracted Sr90 spectrum produced with EJ200 scintillator

Gamma Sources

- Current scintillators are mostly dominated by Compton Scattering; no clear photopeak
- Dense, fast, high light yield crystals needed to produce a spectrum with proper resolution

Detector Material Properties				
Material	Density g/cc	Z-Effective	Light Yield photons/MeV	Peak Wavelength nM
NaI(Tl)	3.67	32	38,000	415
SrI(Eu)	4.59	48.2	80,000	435
LaBr(Ce)	5.08	40.5	70,000	380
CeBr	5.18	40.8	68,000	371
CLYC	3.31	25.3	20,000	370
CZT	5.78	42.4	-	-
Ge	5.36	32	-	-

Table 3. Properties of various common gamma detector scintillating materials [Bronson (2020), EPJ Web Conf. 225: 09004.]

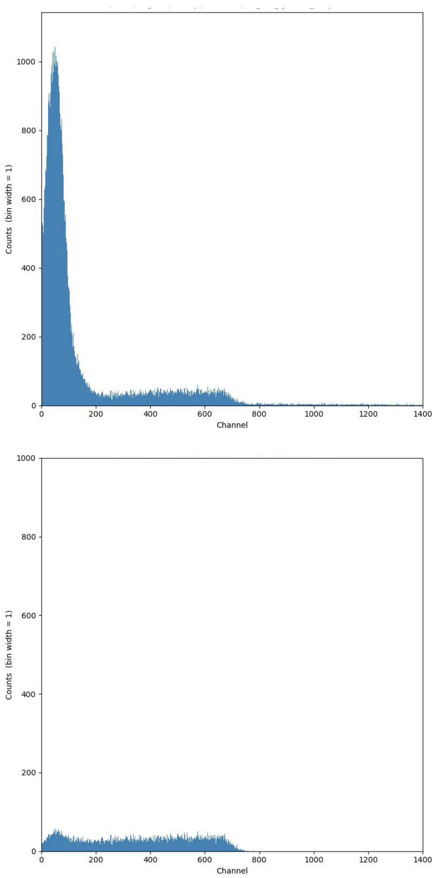


Fig. 13. Example of compton edge in spectrum with background adjustment

Looking Forward: Neutron Testing

- Scintillators contain Lithium-6 or Boron-10, large nuclear cross section
- CLYC (Cs2LiYCl6:Ce): dual-mode gamma-neutron scintillator, 370 nm emission peak

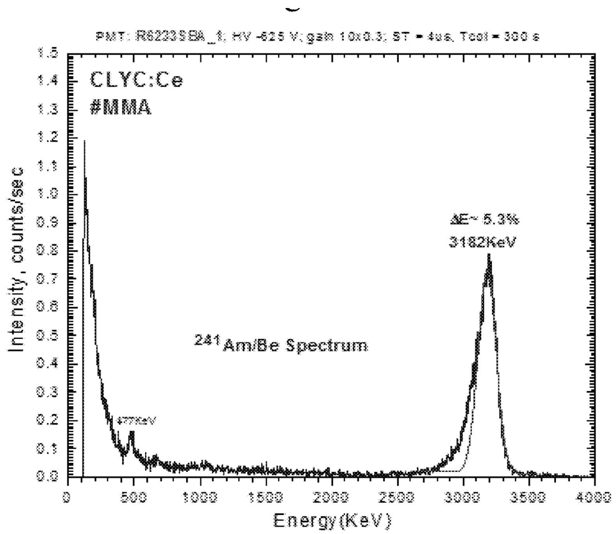


Fig. 14. AmBe spectrum produced with CLYC scintillator and PMT [Shah et al. (2022), U.S. Patent No. 11,384,285.]

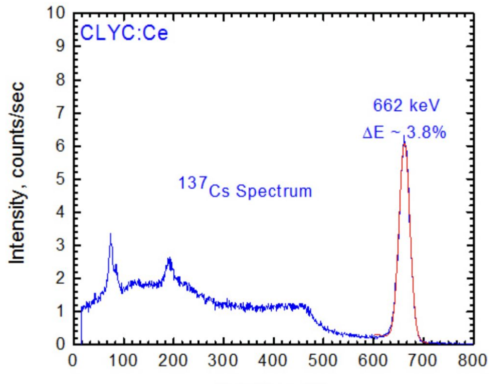


Fig. 15. Cs137 (gamma) spectrum produced with CLYC scintillator and PMT [RMD, Inc. (n.d.), CLYC gamma-neutron scintillator datasheet.]

Acknowledgements

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Citations

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