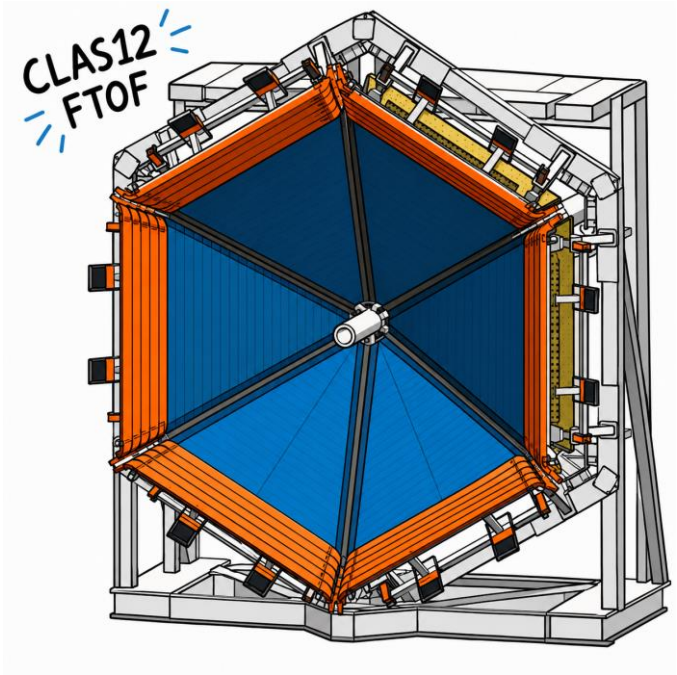
FTOF OPERATIONS AND PERFORMANCE

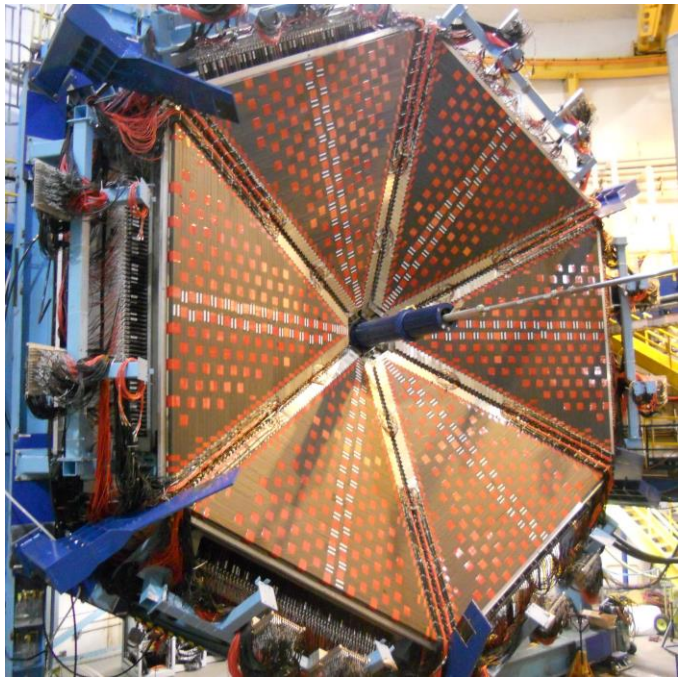
CONSIDERING FTOF OPERATIONS FOR RG-H



Outline:

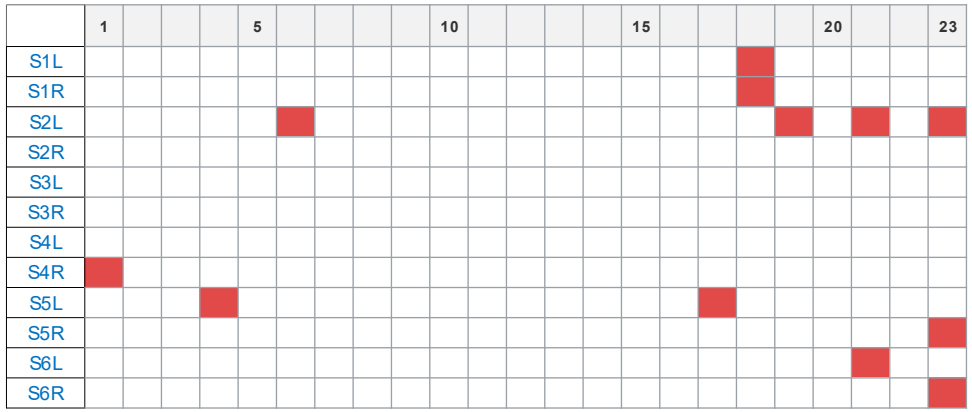
- Hardware, timing, & PID
- PMT aging
- Rates & operating limits
- Lower-gain operation
- RG-H conditions & simulations
- High-lumi tests & path forward

Daniel S. Carman
Jefferson Laboratory

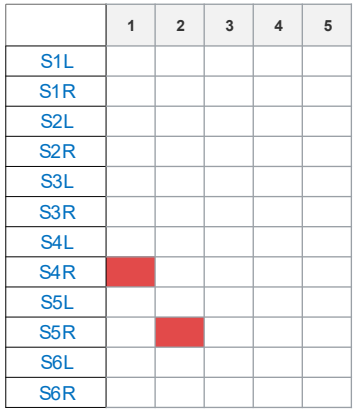


FTOF Hardware Status

Panel-1a



Panel-2



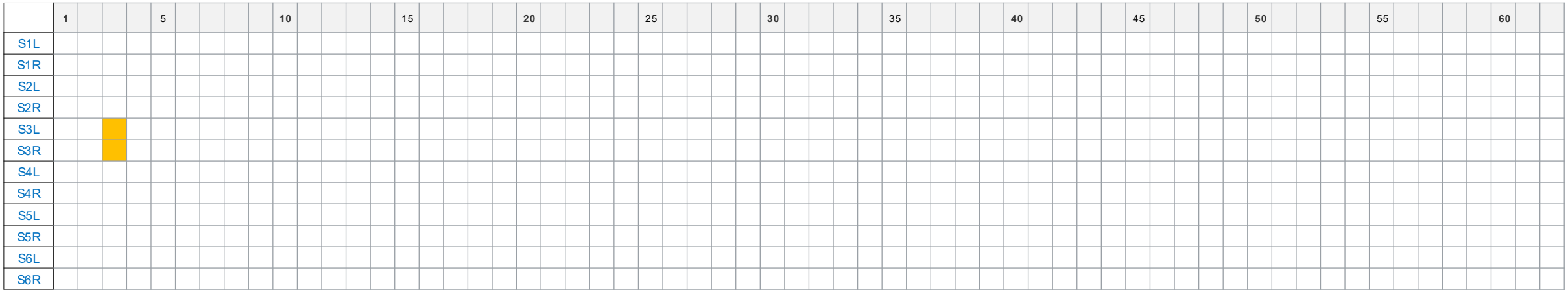
2025

PMT problem

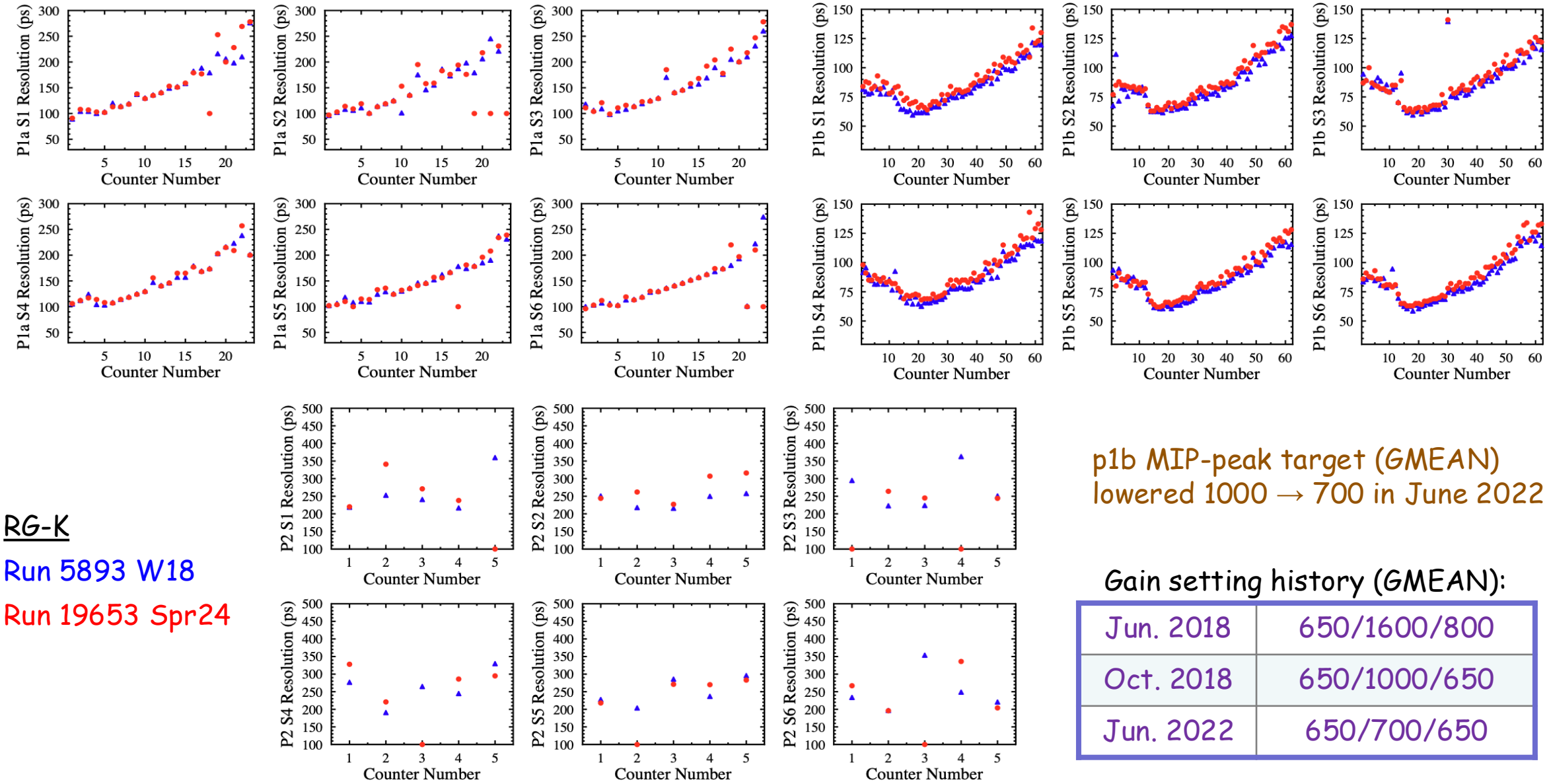
Grounding problem

Functioning

Panel-1b



FTOF Timing Resolution



RG-K

Run 5893 W18

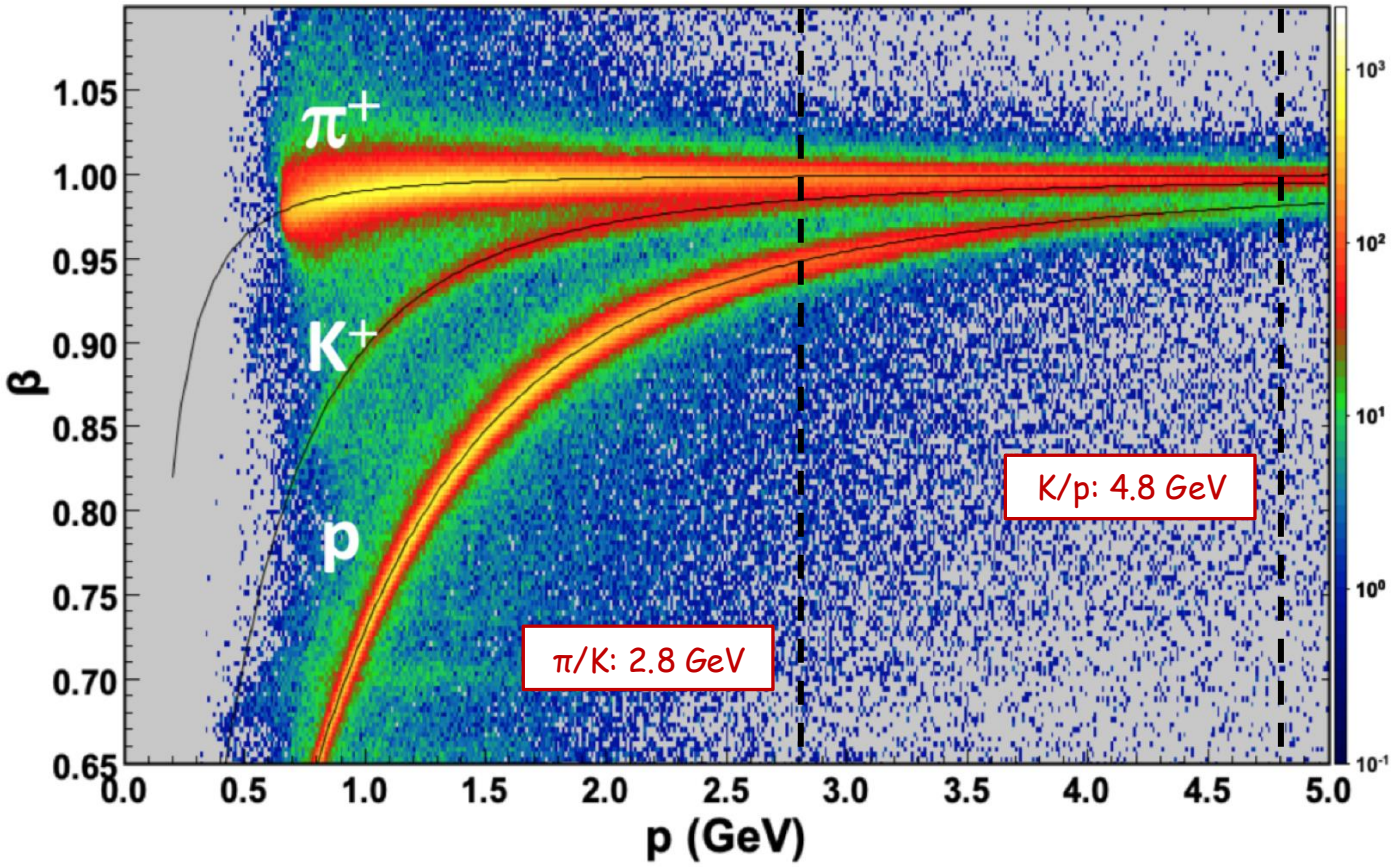
Run 19653 Spr24

p1b MIP-peak target (GMEAN) lowered 1000 → 700 in June 2022

Gain setting history (GMEAN):

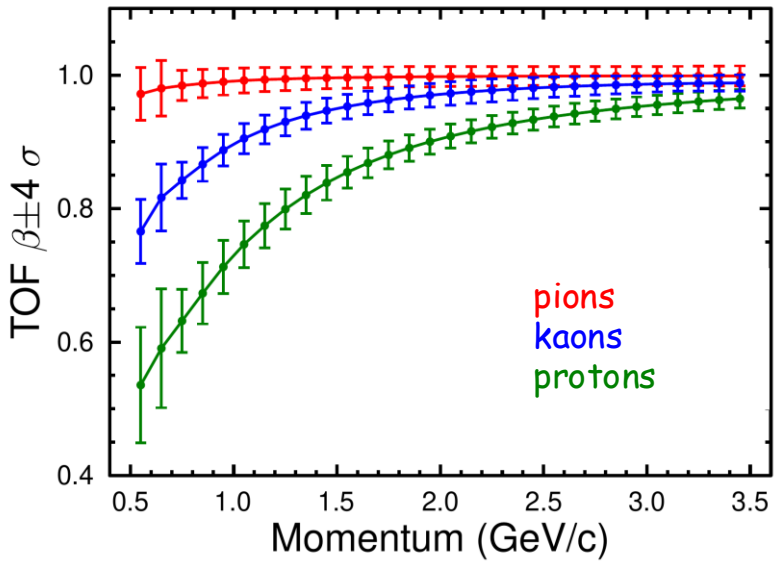
Jun. 2018	650/1600/800
Oct. 2018	650/1000/650
Jun. 2022	650/700/650

FTOF Particle Identification



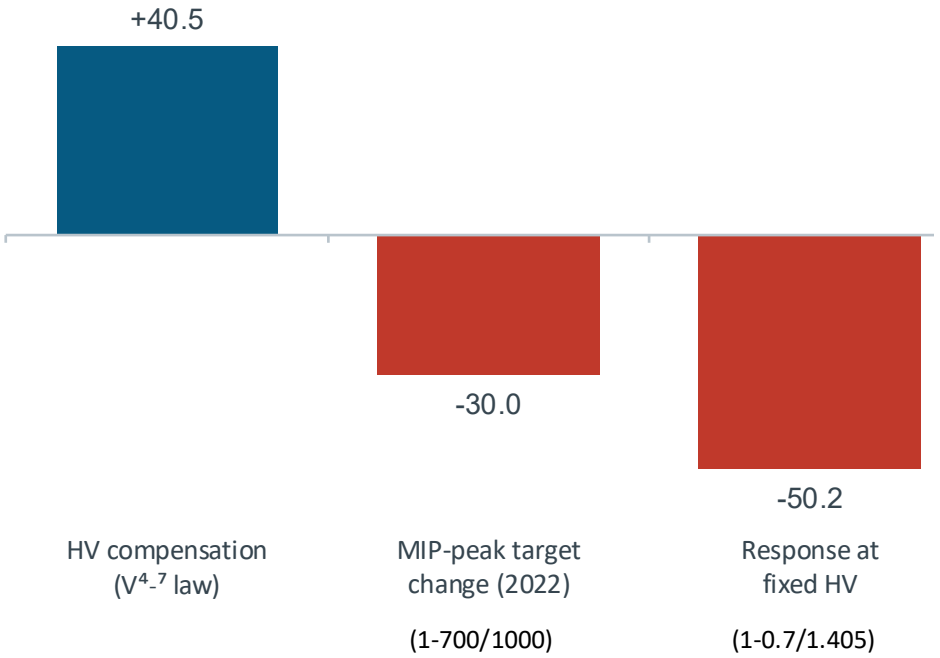
Nominal FTOF 4σ separation:

- π/K to 2.8 GeV
- K/p to 4.8 GeV
- π/p to 5.4 GeV



FTOF PMT Aging: 2018 → 2025

FTOF panel-1b R9779 PMTs
Fall 2018 vs. Summer 2025



"~12 years":
years until the HV reaches the R9779 1.75 kV max
$(1750/1337)^{4.7} \approx 3.5$ gain headroom at ~10%/yr loss

AVG. OPERATING HV

1244 → 1337 V

+7.5%

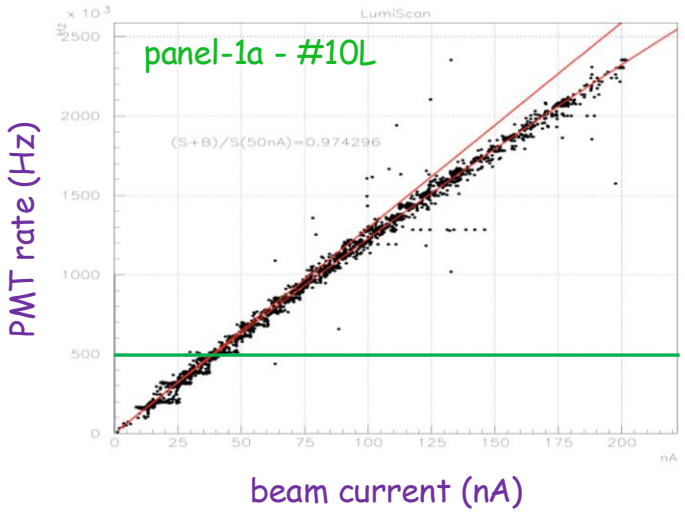
ADC MIP-PEAK TARGET

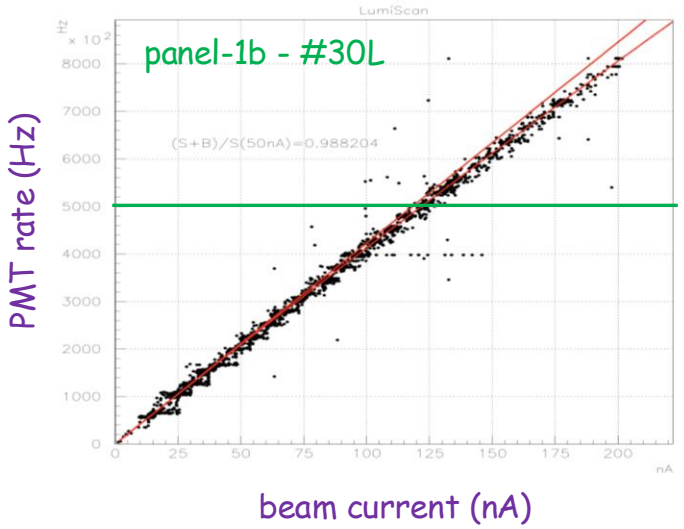
ch 1000 → 700

lowered June 2022

- Average gain loss is ~10%/year ⇒ ~12 years of remaining life (assuming equal integrated charge/year)
- Increasing the luminosity by factor R, increases average yearly gain loss by R*10% and decreases the lifetime by 12/R

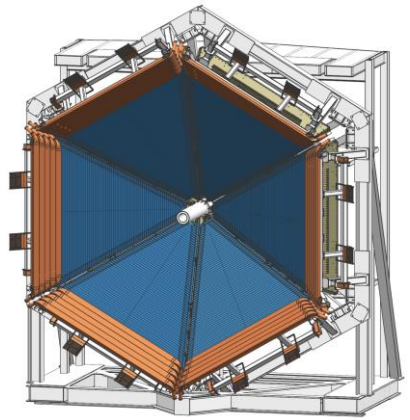
FTOF Operations





NTT scan on LD_2 – 2/2020

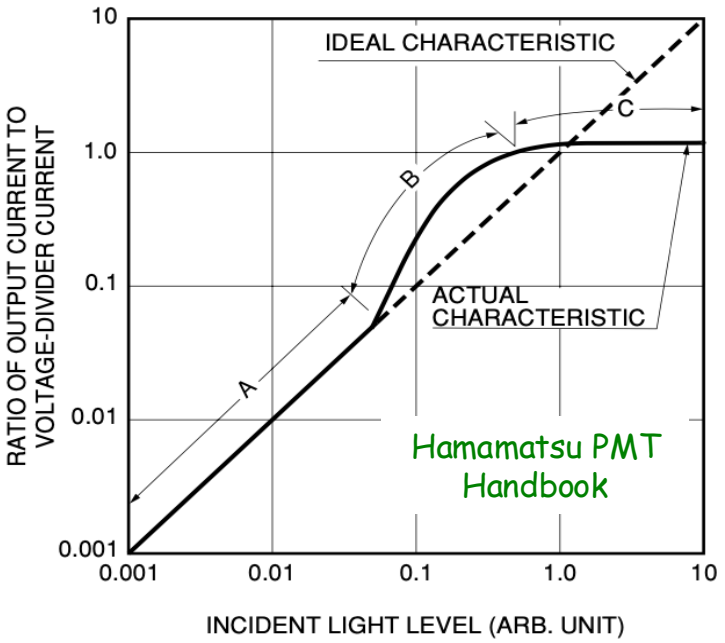
- PMT types:
  - p1a – EMI 9954A / Philips XP2262 – 2", 12-stage, active base
  - p1b – Hamamatsu R9779 – 2", 8-stage
  - p2 – EMI/Photonis 4312KB – 3", 12-stage, active base
- Typical operating rates (inbending torus):
  - RG-A: 100–200 kHz/PMT @ 50 nA LH_2; RG-B: 200–350 kHz/PMT @ 50 nA LD_2
  - RG-C and since (RG-D, -K, -E, -L): up to ~500 kHz on the hottest bars
- PMT stability:
  - Measured: rate response linear to ~500 kHz; slowly developing non-linearity beyond for p1b
  - Observed: small timing shifts between low- and high-luminosity calibrations; possible gain shifts vs. beam current
  - Estimated: ~10% FADC pile-up at 10^{35} $cm^{-2}s^{-1}$
- p1a/p2 active dividers: operating near the edge of their active range is a danger zone for stability and calibration



p1b
1-2 MeV threshold

p1a: 15 cm, p1b: 6 cm, p2: 22 cm

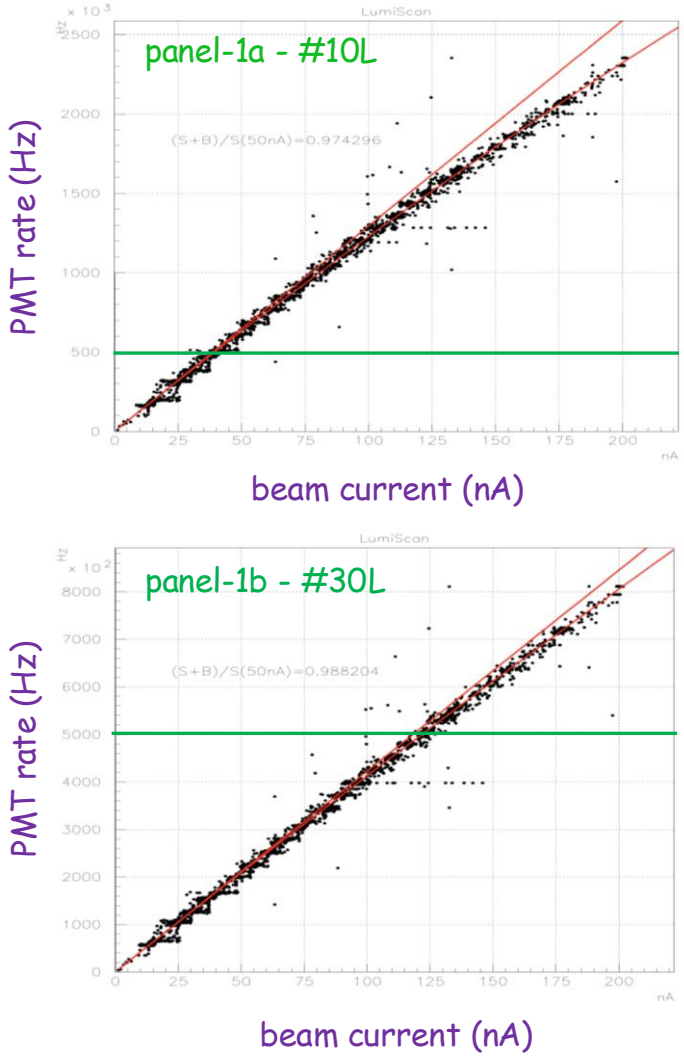
FTOF Operations: PMT Linearity



A: linear – stable gain, calibratable

B: transition – active-divider danger zone (p1a, p2)

C: saturation

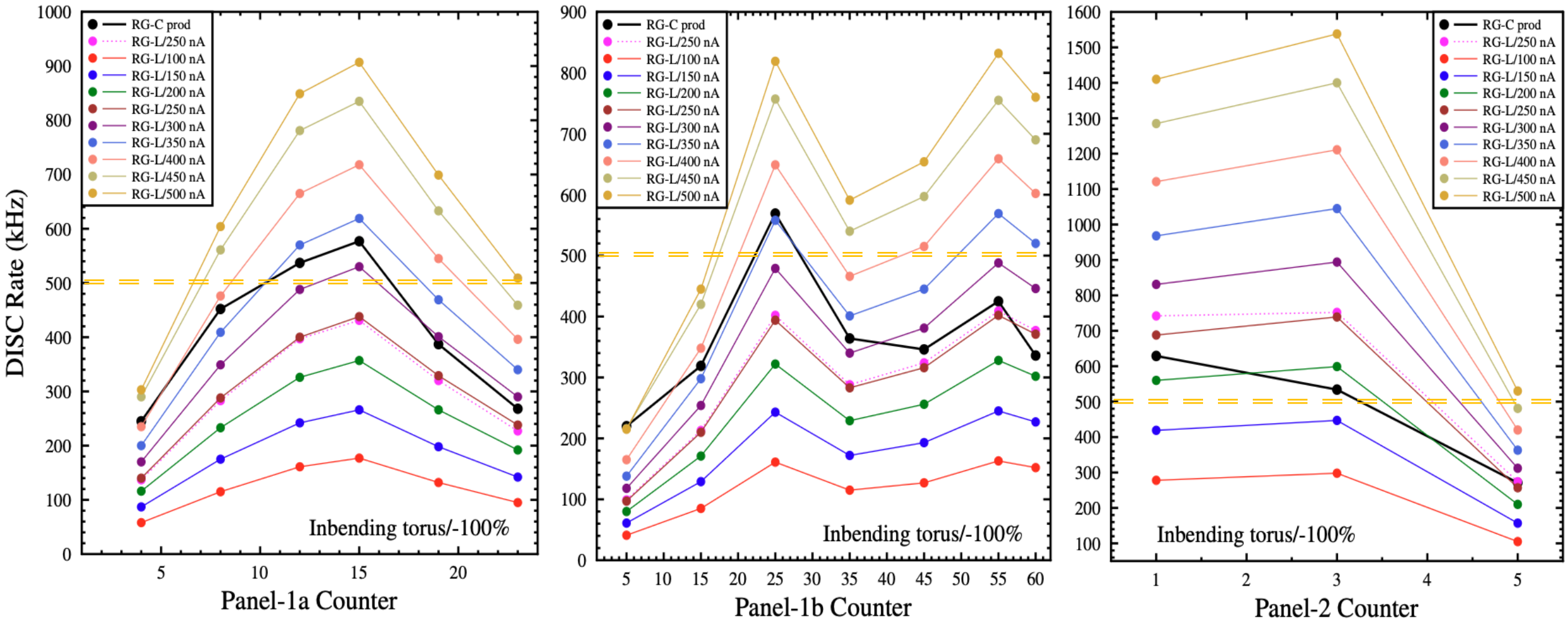


NTT scan on LD_2 – 2/2020

Why a ~500 kHz limit?

- Output tracks light only while the anode current is small compared to the divider current (region A)
- "Incident light" ∝ rate × charge per hit: beam current is a proxy only at fixed gain and energy deposit
- Beyond the knee, gain depends on rate → gain matching and time-walk constants drift with beam current
- Lower gain moves operation back down the curve (see Operation at Lower Gains)

FTOF Rate Limitations



- - - ~500 kHz/bar: conservative guideline set from RG-C experience; nominal since for RG-D, RG-K, RG-E, RG-L

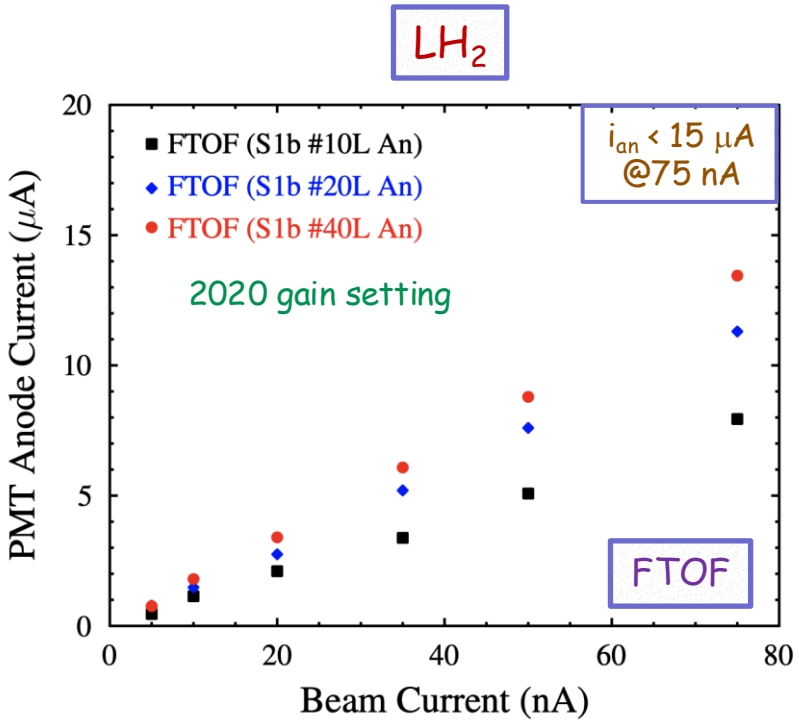
p1b likely tolerates ~2× luminosity (possibly at reduced HV) – to be quantified in the planned high-luminosity test

FTOF Operating Considerations

- PMT Ratings:

TOF	PMT Type	i_{anode}^{max}	HV^{max}	Gain
FTOF p1a	9954A	100 μA	2.5 kV	$6x10^6$
FTOF p1a	XP2262	200 μA	2.5 kV	$6x10^6$
FTOF p1b	R9779	100 μA	1.75 kV	$1x10^6$
FTOF p2	4312KB	150 μA	2.5 kV	$3x10^7$

p1b anode-current ranges:
- ≤ ~20 μA: established safe level
- ~20–40 μA: untested – gain shifts, faster aging
- ≳ 40–50 μA: danger zone



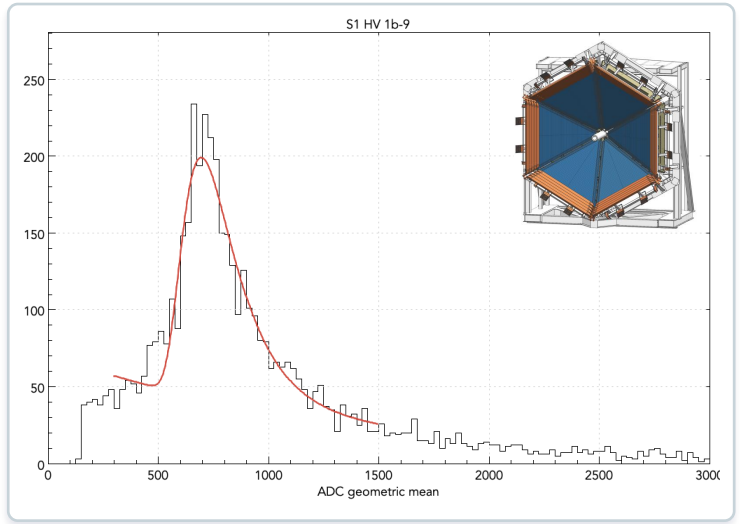
- RG-H MC limits (preliminary GEMC, S4 off):
  - Baseline MC (ELMO cone): S1 ~55–65 μA; S2-S6 ~25–40 μA
  - + Pb torus shield (prelim.): S1 ~35–49 μA; S2–S6 ~10–19 μA (≈ RG-A)
  - PMT lifetime: typically 300–1000 C (Hamamatsu PMT Handbook)
  - Charge per beam-day: 20 μA ≈ 1.7 C, 40 μA ≈ 3.5 C, 65 μA ≈ 5.6 C
  - Options: shielding optimization, reduced HV in hot sectors, turning off S1

Operation at Lower Gains

$$\sigma_t^2 = \sigma_{stat}^2 + \sigma_{elec}^2 + \sigma_{TTS}^2$$

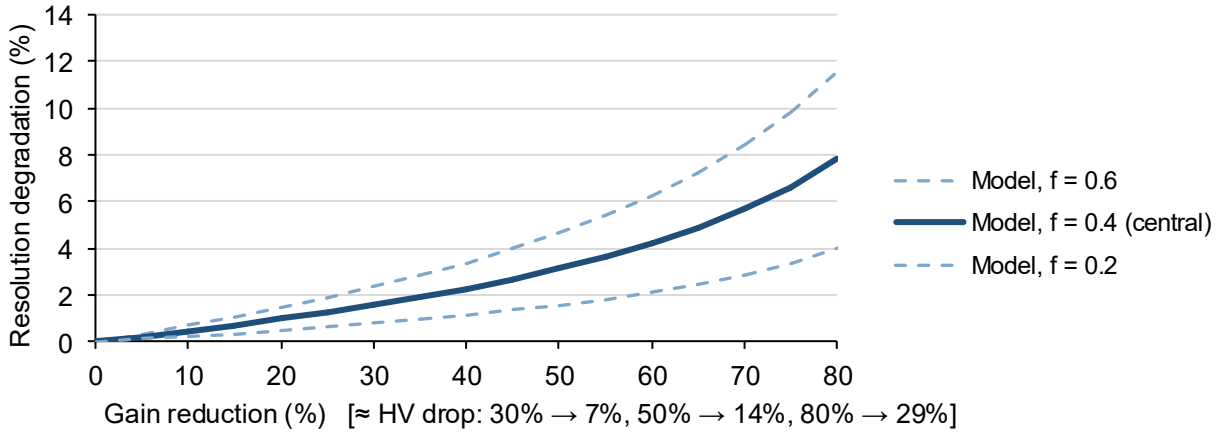
$$\propto 1/\sqrt{N_{pe}} \qquad \propto 1/\text{gain} \qquad \propto 1/\sqrt{V}$$

- σ_{stat} — photoelectron-statistics term; set by light yield/QE, essentially independent of gain
- σ_{elec} — electronic-noise; protectable by lowering the discriminator threshold in step with gain
- σ_{TTS} — transition-time-spread term; intrinsic to the PMT, unavoidable regardless of electronics



FTOF (panel-1b, paddle 9) — representative MIP-peak GMEAN

Resolution Degradation vs. Gain Reduction



Assumes discriminator threshold retuned in step with HV

The price for PID:

- π/K reach $\propto 1/\sqrt{\sigma_t}$
- e.g. 20% worse σ_t: π/K 2.8 → ~2.5 GeV

RG-H Run Conditions

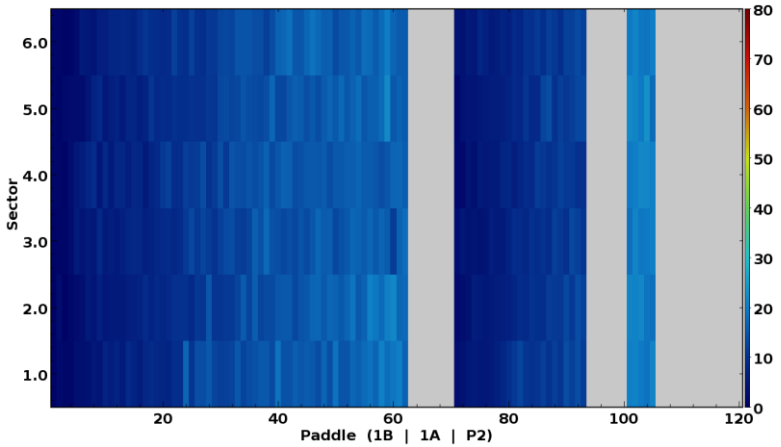
	RG-A	RG-H
Beam	10.6 GeV, ~40-50 nA	10.6 GeV, ~1 nA
Target	5 cm LH_2	3 cm NH_3, 5 T transverse dipole
Luminosity	~5×10^{34} $cm^{-2}s^{-1}$	5×10^{33} $cm^{-2}s^{-1}$
Torus	Full field - negatives inbending and outbending	Full field - negatives inbending; both polarities likely
Shielding	Standard CLAS12	Baseline: ELMO cone; under optimization: + Pb torus shield
Run length	139 PAC days (~200 calendar days)	125 PAC days (~250 calendar days)
Special		S4 off (synchrotron radiation); e^+ background in S1

~10× lower luminosity than RG-A, yet average FTOF anode currents ~2× higher
S1: above tolerance with the baseline shielding; near the tolerance limit with the preliminary torus shield

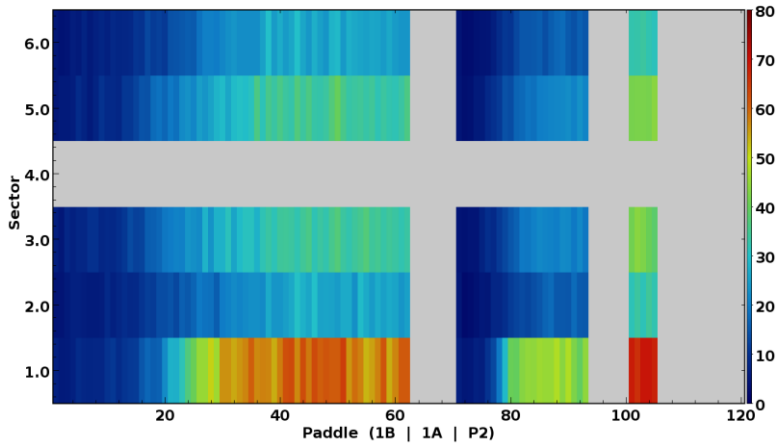
RG-H FTOF Projections

PMT Anode Currents (μA)

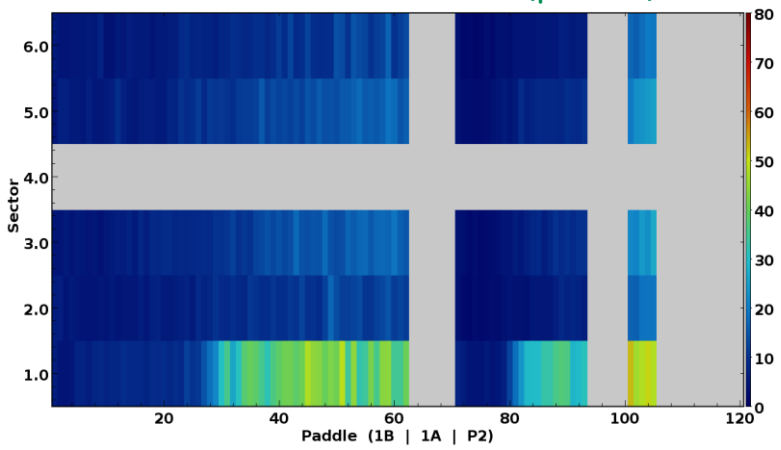
RG-A (75 nA)

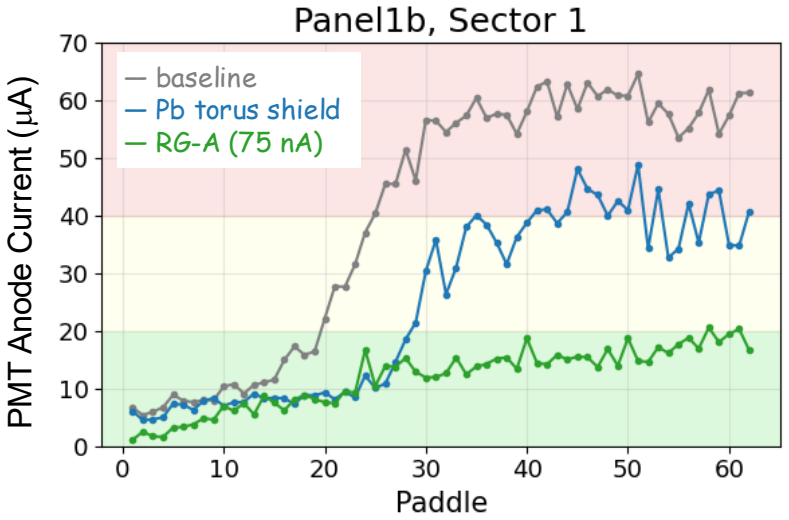


RG-H baseline (ELMO cone)



RG-H + Pb torus shield (prelim.)





Anode current vs. tolerance

- Baseline: S1 p1b above tolerance; other sectors ~1.5–2× RG-A
- Pb torus shield (prelim.): S2–S6 at RG-A levels; S1 near the 40 μA limit – moving in the right direction

Bands: ≤20 μA safe, 20–40 μA caution, >40 μA high

S1: next steps

- Further shielding optimization
- Reduced HV
- Turn S1 off

How important is S1 to RG-H physics?

Krishna Neupane simulations

Planned FTOF High Luminosity Tests

- Items to study in beam test:
  - Luminosity scan on LH_2 or LD_2 up to ~3× nominal – FTOF scaler rates vs. beam current
    - Ammeter readout of selected channels (incl. hottest p1b bars): anode current vs. beam current – checks rate as a proxy for anode charge
    - Rate stability of p1a/p2 PMTs vs. current
  - 2-hr/100 M trigger runs at $\mathcal{L}_{nom}$ × 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 with full timing and energy calibration
    - Timing/gain stability vs. luminosity
  - FADC performance (pile-up) at higher luminosity
  - System performance vs. beam current at reduced HV – understanding impact on resolution
- Items to study via simulation (RG-H GEMC):
  - Validate against measured RG-A conditions: anode currents and rates at the same thresholds
  - Run simulations for above luminosity scan settings (deliver predictions *before* beam test) – helps to ensure simulation is truly connected to reality

Input welcome: what should be added for RG-H conditions?

Summary and Path Forward

FTOF (2026):

- Timing stable since 2018; 4σ PID: π/K 2.8, K/p 4.8, π/p 5.4 GeV
- ~500 kHz/bar and ~20 μA: conservative guidelines; p1b likely tolerates ~2× luminosity, possibly at reduced HV

RG-H conditions (preliminary GEMC):

- Baseline (ELMO cone): average anode currents ~2× RG-A; S1 above tolerance; S4 off
- Preliminary Pb torus shield: S2–S6 at RG-A levels, S1 near the 40 μA tolerance
- p1a/p2 not needed for RG-H: reduced HV or off

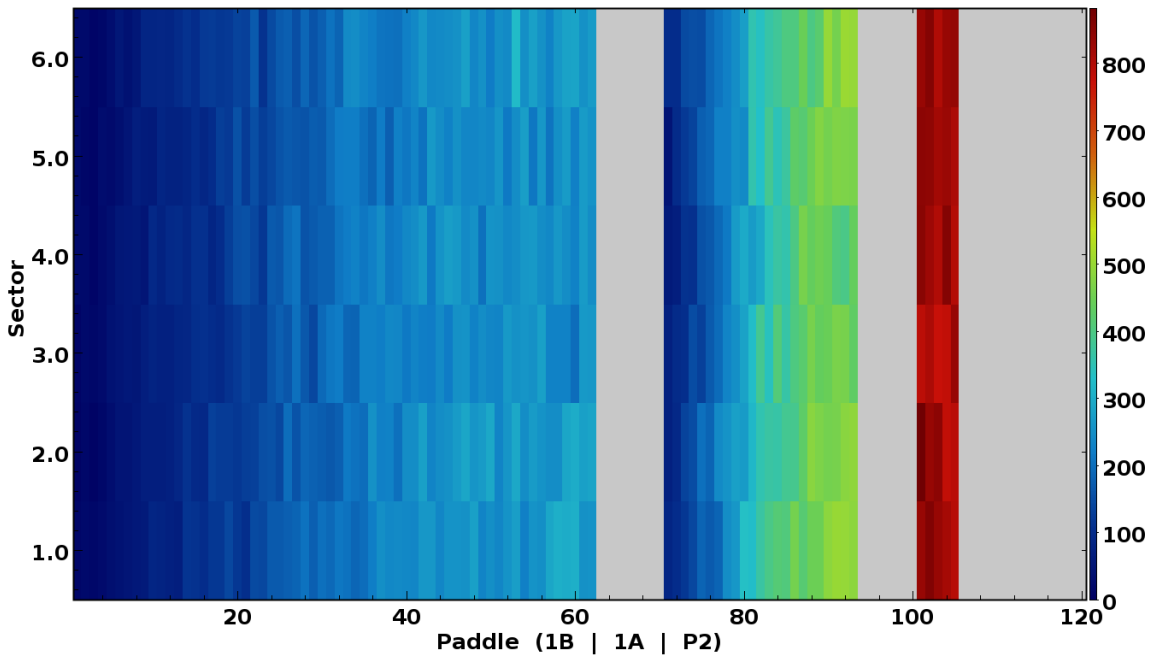
Path forward:

1. Complete the planned high-luminosity test: rates, anode currents, calibration stability, pile-up, and reduced-HV performance
2. Complete the RG-H simulations and validate them against data: matched thresholds, realistic gains, anode currents – connected to high-luminosity test results
3. Higher luminosity has a price: p1b PMTs age ~10%/yr and the R9779 is no longer produced. Replacement is ~$2M (~800 PMTs – R13809 ??), ~8 weeks per array plus overhead, with arrays removed from the Forward Carriage – possibly needed before RG-H

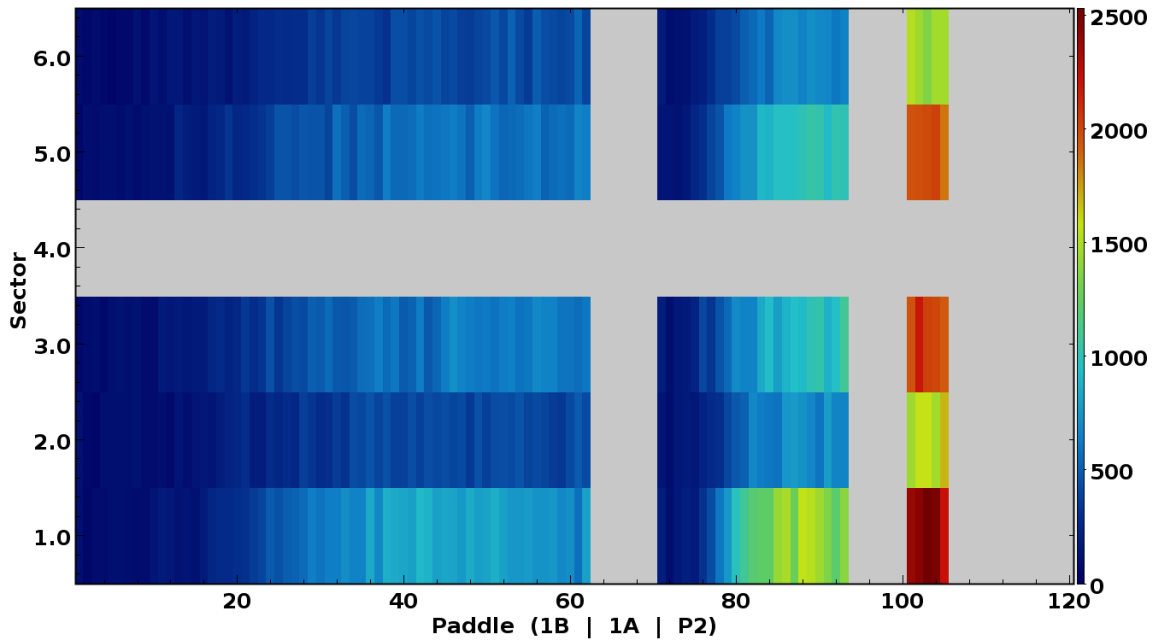
Backup Slides

Backup: Simulated FTOF Rates

RG-A at 45 nA: rate (kHz), max ≈ 880



RG-H baseline (ELMO cone), S4 off: rate (kHz), max ≈ 2500



GEMC 5.10 (K. Neupane). 1 MeV threshold. Rates depend on threshold: compare only at matched (data-equivalent ~1–2 MeV) thresholds. Note the different color scales.

Operation at Lower Gains

$$\sigma_t^2 = \sigma_{stat}^2 + \sigma_{elec}^2 + \sigma_{TTS}^2$$

$$\propto 1/\sqrt{N_{pe}} \qquad \propto 1/\text{gain} \qquad \propto 1/\sqrt{V}$$

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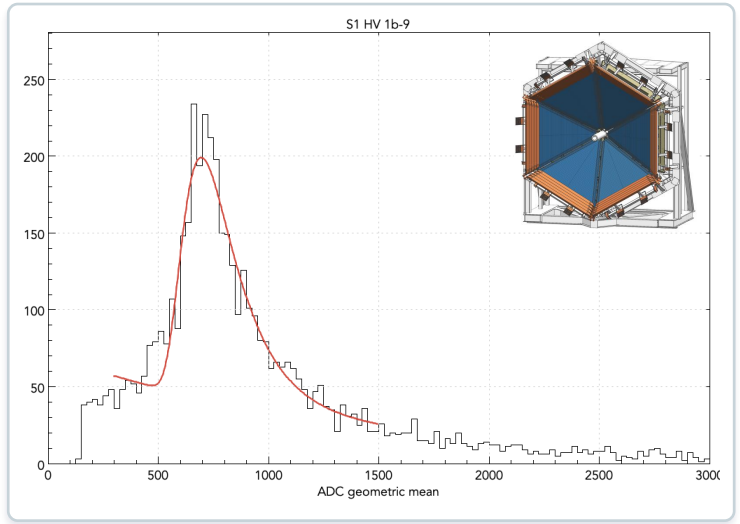

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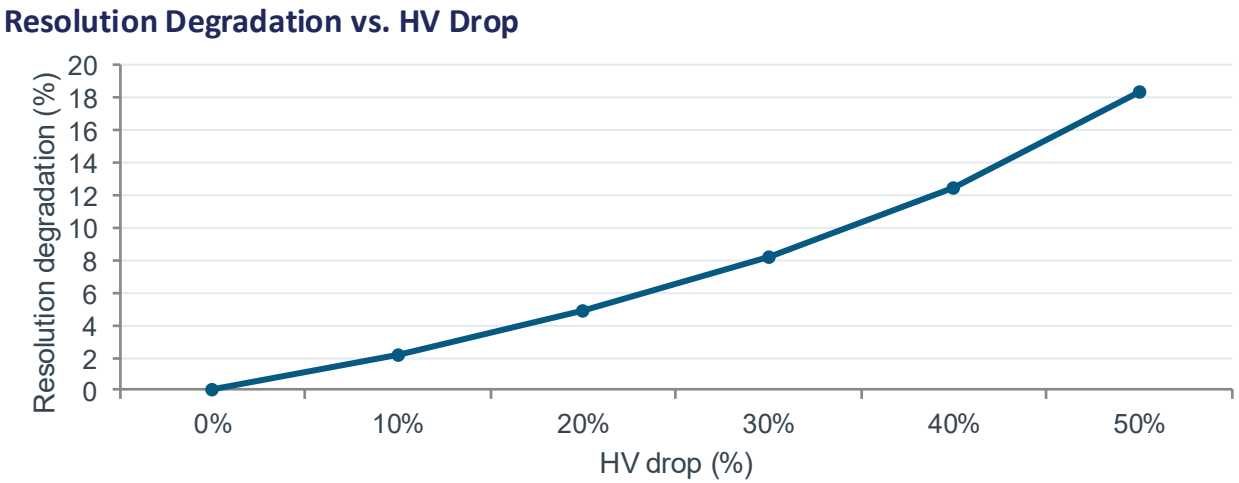

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