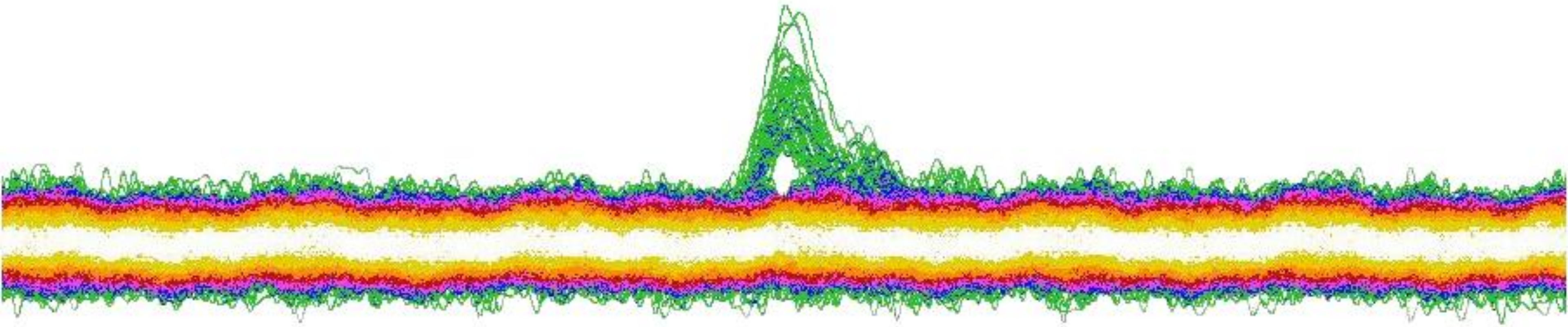
High-efficiency gigahertz-gated InGaAs/InP single-photon detection system based on RF interferometry



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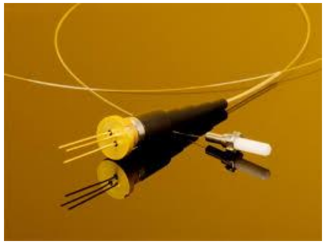
NDIP14, Tours, July 4th 2014

DARPA

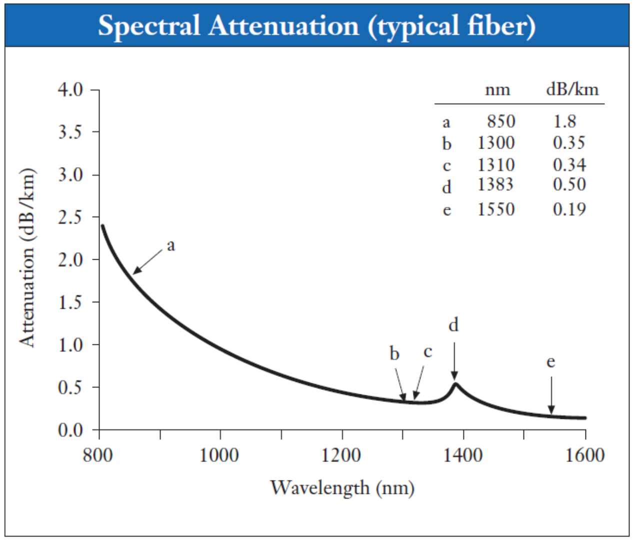
jqi Joint Quantum Institute

NIST National Institute of Standards and Technology Technology Administration, U.S. Department of Commerce

InGaAs/InP SPADs



- Single pixel, 25 µm, heterostructure APD
- Sensitive from 950 nm to 1650 nm (1.31 eV to 0.75 eV)
- Dark count rate ≈ 10^4 s^{-1} (not much to do here)
- Afterpulsing: notorious. Long lived traps.
  - Gated mode (usually), 1 µs to 10 µs holdoffs
  - Inefficient in low-probability single-photon processes where pump rates > 10^9 s^{-1}
  - Quantum key distribution, heralded single-photons, entanglement distribution, single-photon nonlinear optics
- Alternatives are superconducting, or photon upconversion to Si band



High-speed periodic gating schemes operate at gate rates > 10^9 s^{-1}

- Periodicity facilitates detection of smaller avalanches

Our approach to high-speed gating uses RF interferometry

- Approaches the fundamental limit to avalanche discrimination
- Achieves the highest reported detection efficiency.

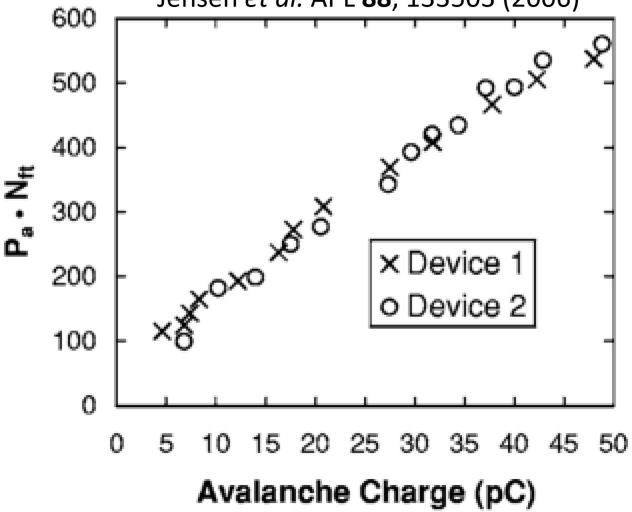
Afterpulsing & Total charge

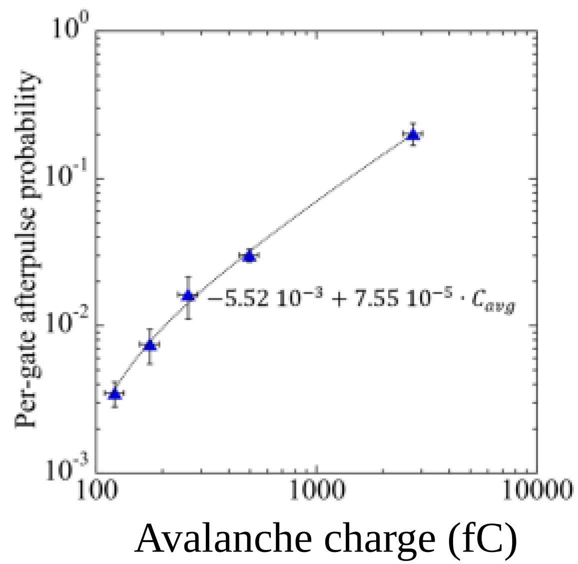
$$R(t) = R_{DC} + R_s + \underbrace{P_a \frac{N_{ft}}{\tau_{trap}} e^{-\frac{(t+t_{h.o.})}{\tau_{trap}}}}_{\text{Afterpulsing}}$$

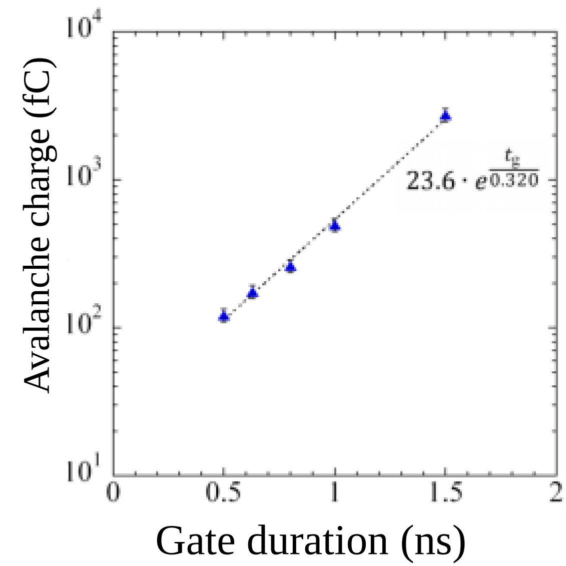
$P_a \equiv$ avalanche prob.
$N_{ft} \equiv$ # filled traps
$\tau_{trap} \equiv$ trap lifetime*
$t_{h.o.} \equiv$ hold-off time

To have a short hold-off, we need low afterpulse probability.

Jensen *et al.* APL **88**, 133503 (2006)





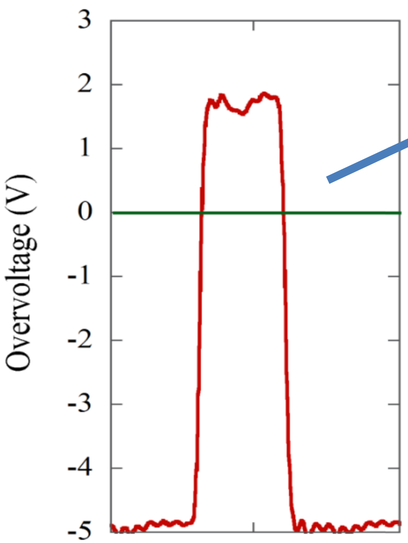


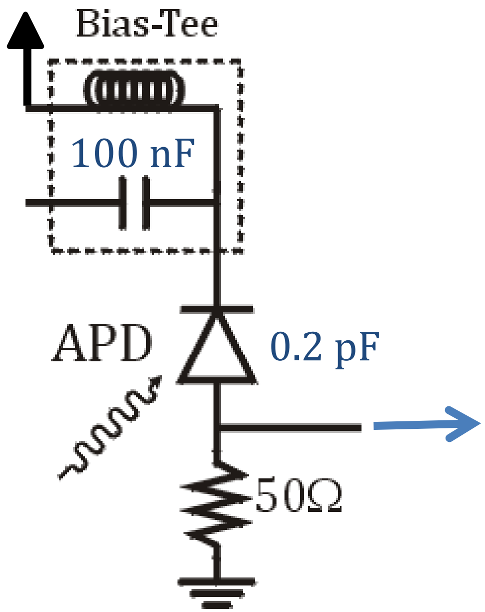
Linear with avalanche charge… over a couple of orders.

Afterpulse probability grows exponentially with gate duration (good!)
→ use short gates & be sensitive to tiny avalanche signals

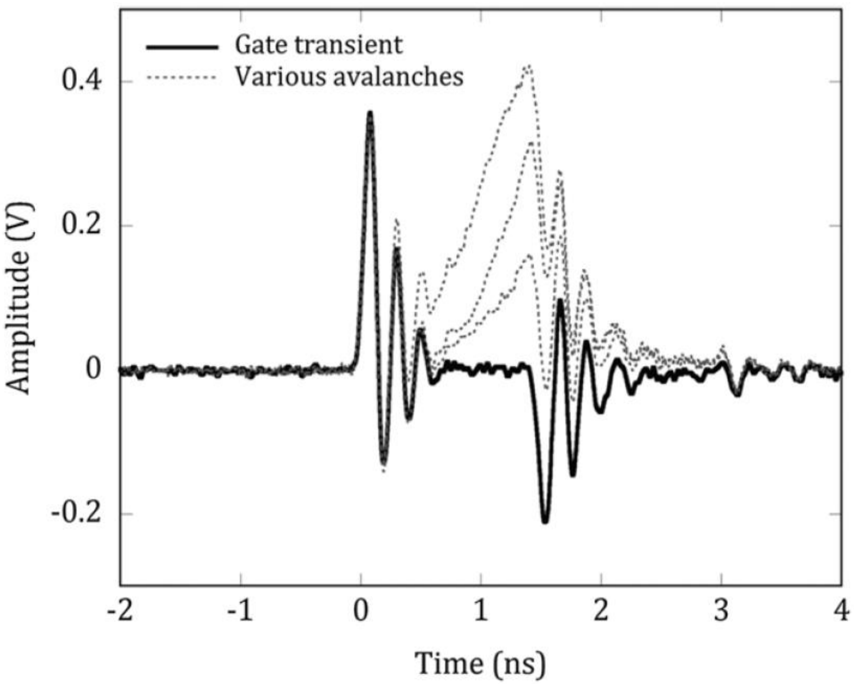
Gate transient

Gate pulse





Output from SPAD

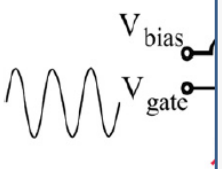


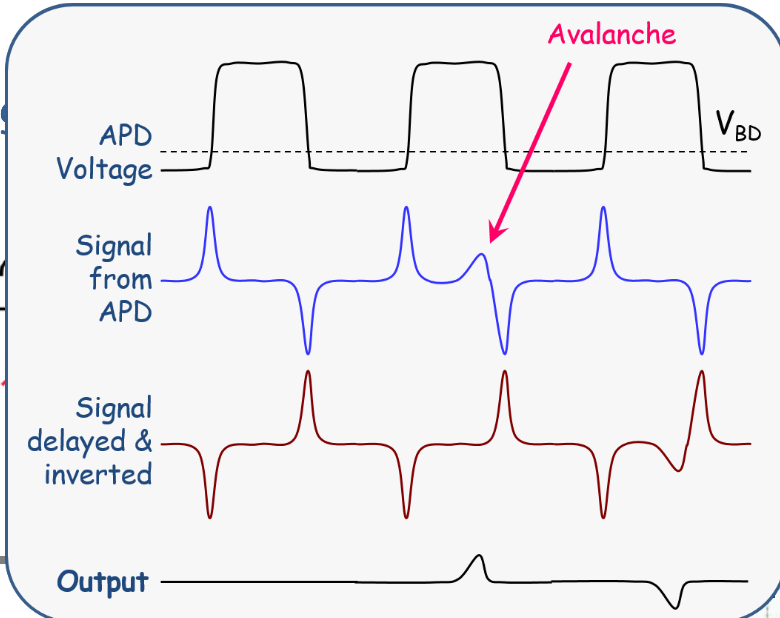
Must suppress the transient gate signal

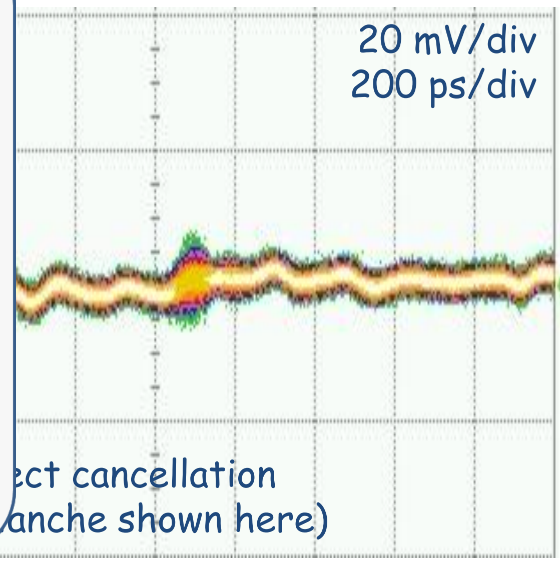
- determines minimum required charge to detect a photon
- more challenging as gate duration decreases

Prior art

Periodic g



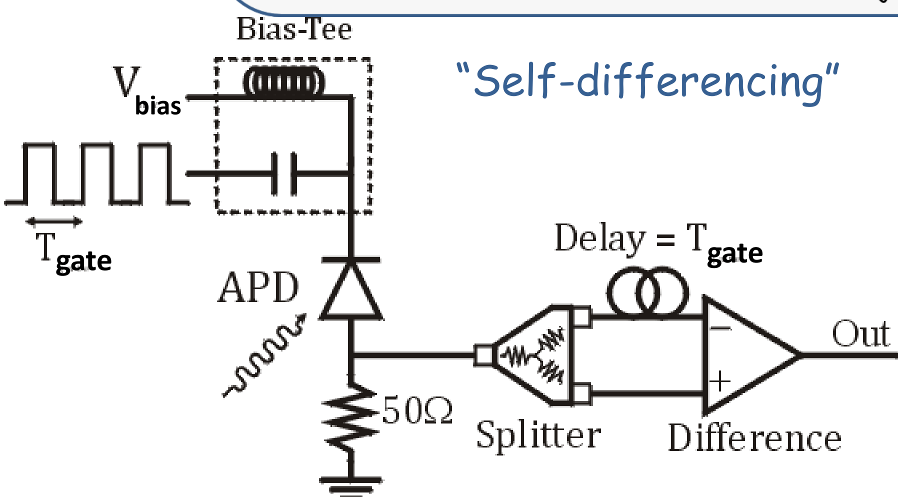




duration
ort avalanche

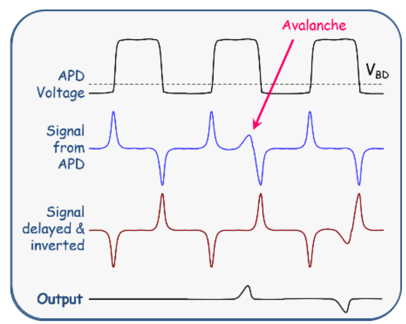
.4, 10043 (2006)],
20531 (2011)],
.2, 6 (2012)], ...

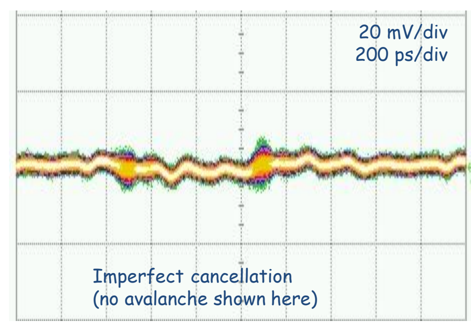
ect cancellation
anche shown here)



"Self-differencing"

≈ 5% to 20% d.e.
≈ 10 ns to 50 ns holdoff
≈ 10^{-3} per-gate afterpulse probability

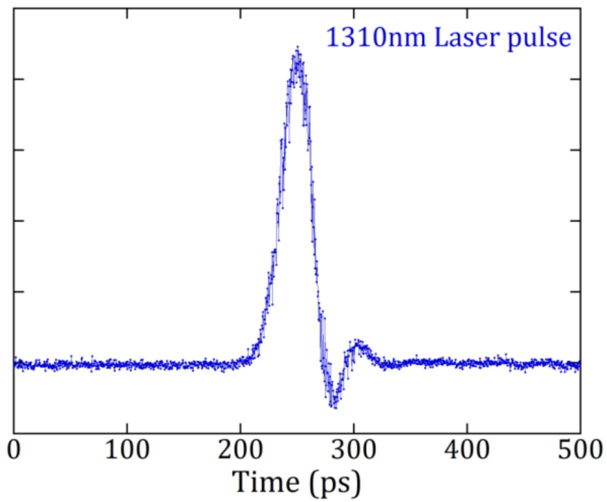


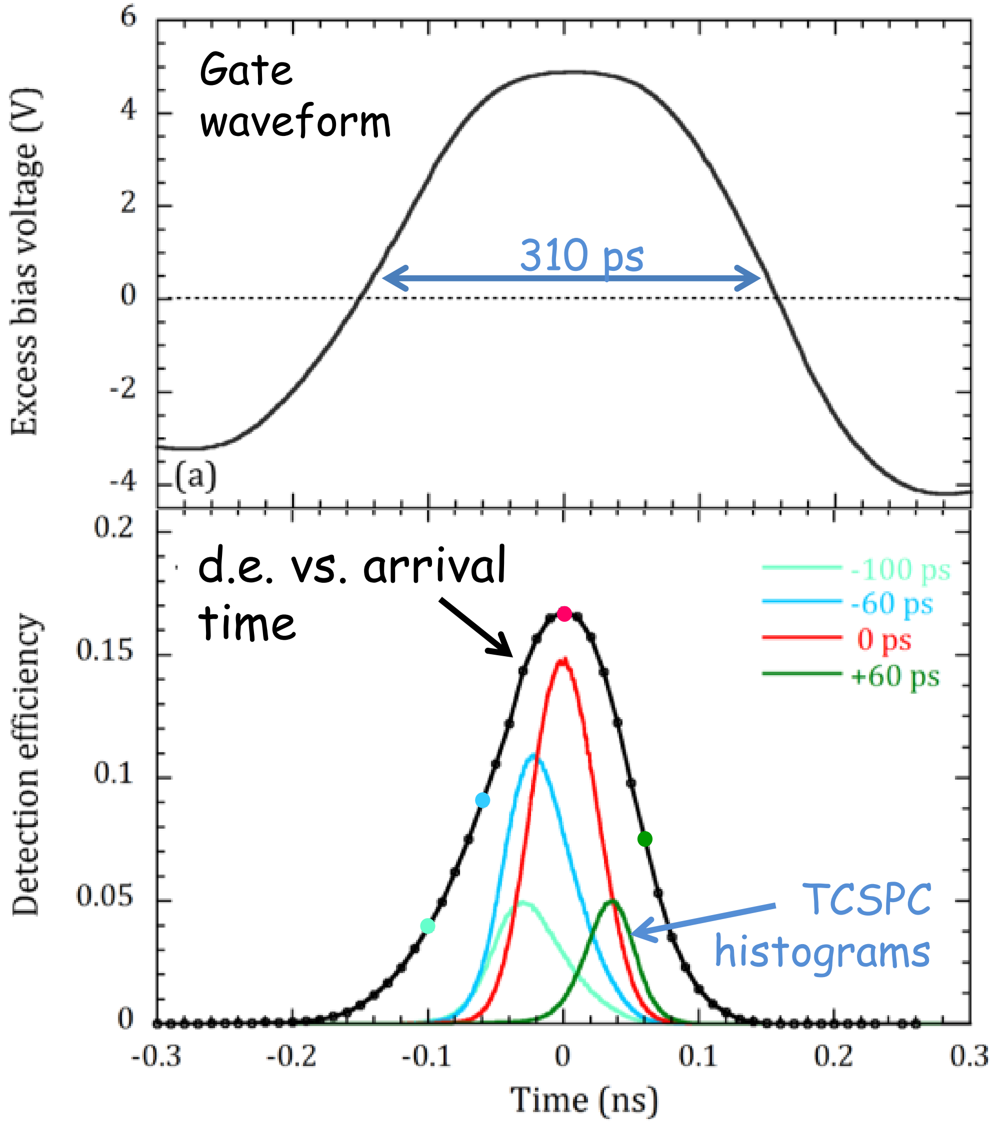


- \+ Arbitrary gate duration
- \- Difficult to optimize cancellation
- \- Splitters attenuate avalanche

[Yuan *et al.*, *Appl. Phys. Lett.* **91**, 4 (2007)],
[Zhang *et al.*, *Appl. Phys. Lett.* **95**, 9 (2009)],
[Tosi *et al.*, *Single-photon Workshop* (2013)], ...

Briefly: regarding timing resolution

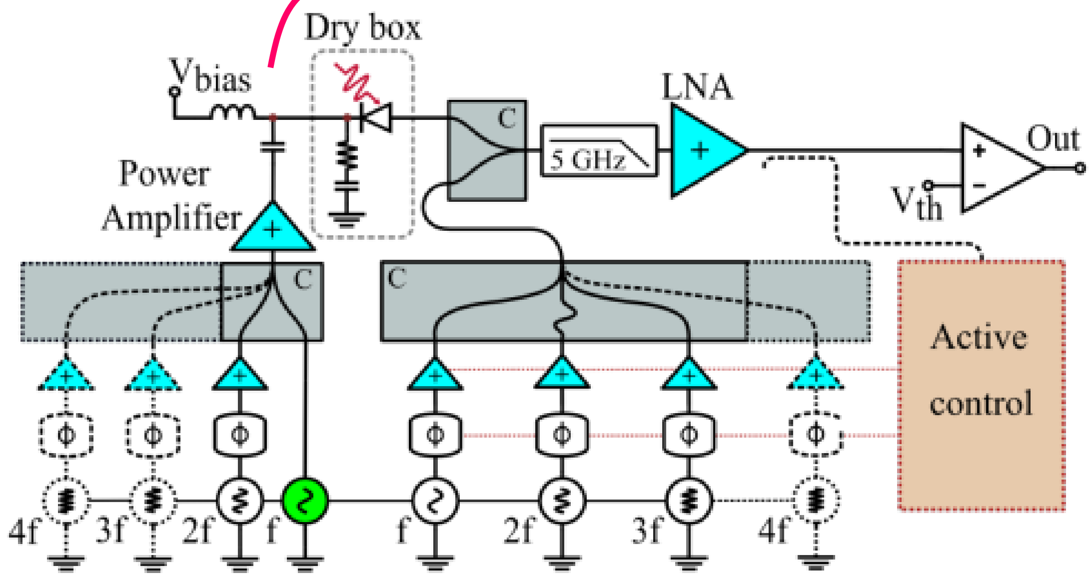




d.e. profile determines timing resolution, not output histogram

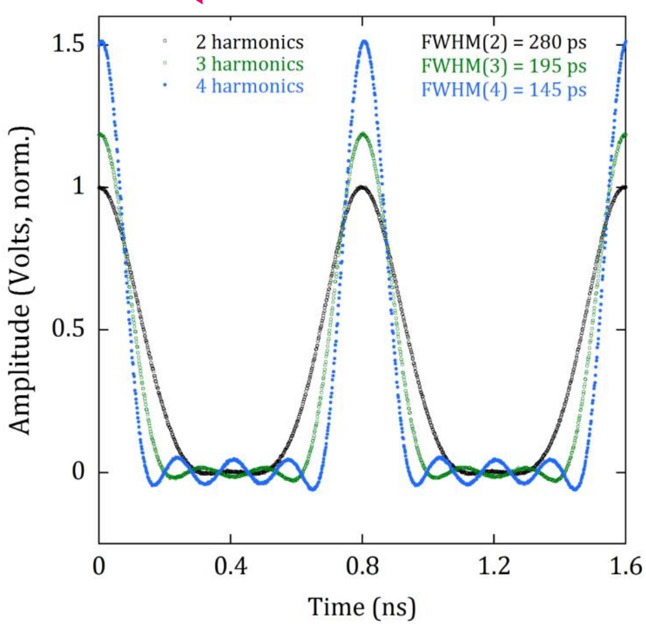
Harmonic subtraction (interferometry)

SPAD attenuates, shifts, mixes harmonics



Assemble gate waveform

Amplitude and phase control for each harmonic → **destructive interference**

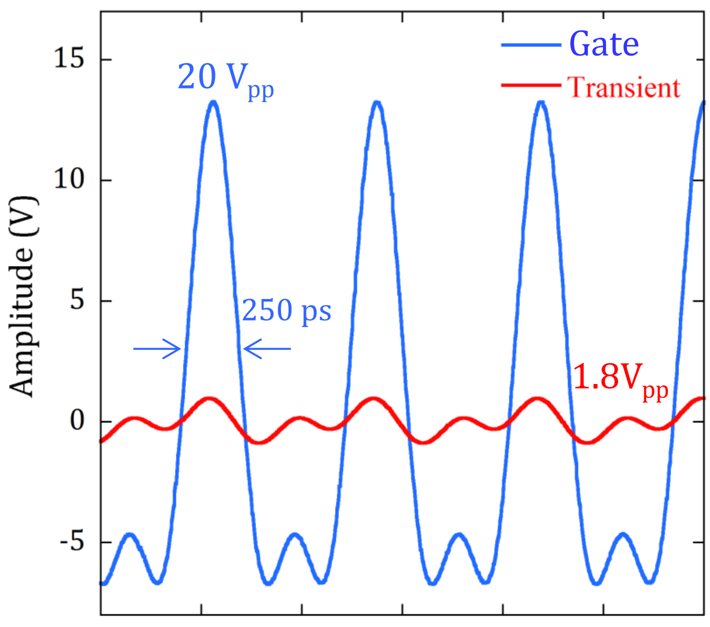


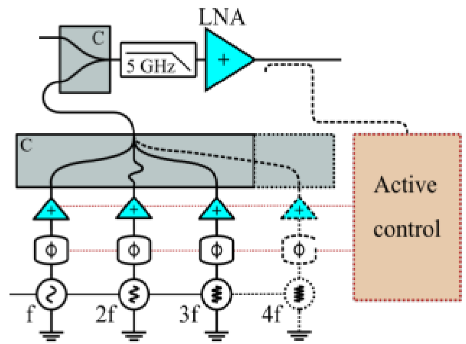
- Maintains extremely high quality gate rejection even with fast large gates (1.25 GHz, > 20 V pkpk)
- Avalanche signal loss is low
- Low noise
- Can vary number of harmonics used

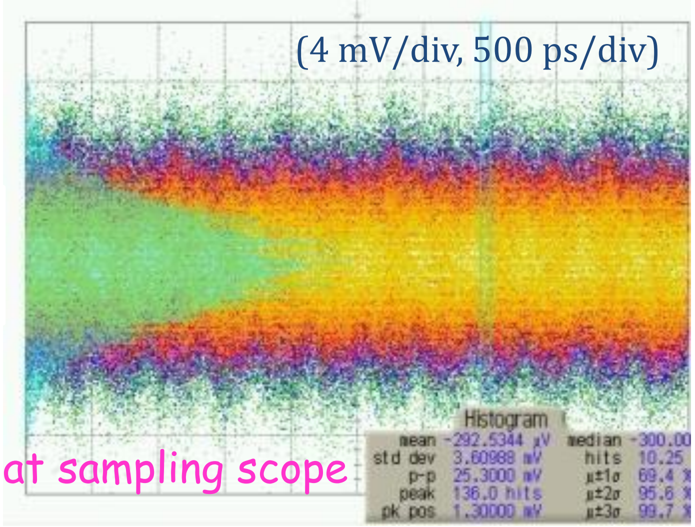
[Restelli *et* al., APL **102**, 141104 (2013)]

Sensitivity of interferometric readout

Gate signal applied and transient







at sampling scope

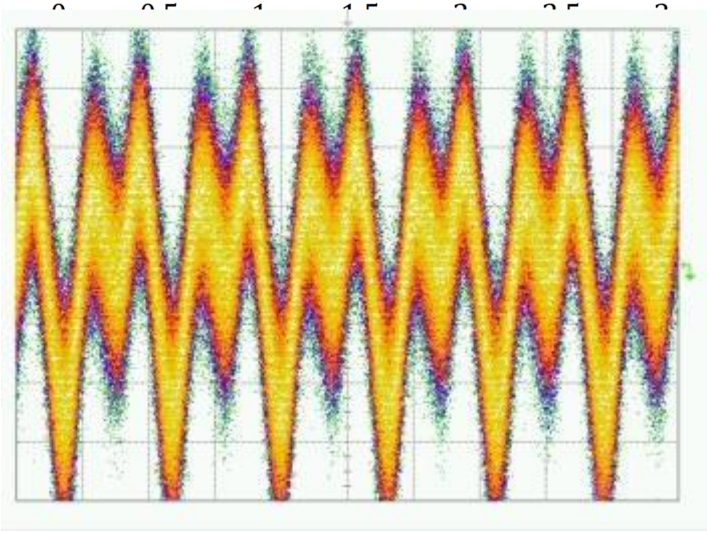
Measured cancellation: 3.6 mV rms

Measured scope floor: 1.8 mV rms

LNA gain: 16 dB (6.3x)

Min. 5σ threshold at anode ≈ 2.5 mV
< 10x Johnson-noise limit
crude estimate for 280 ps ≈ 7 fC

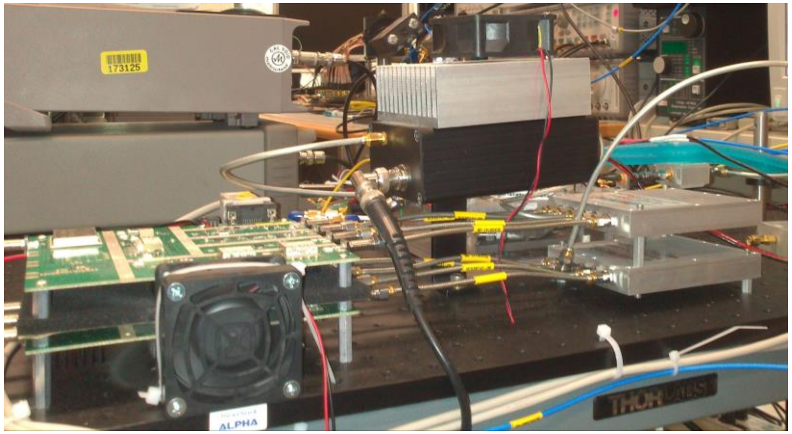
5σ Johnson noise (50Ω, 5 GHz, 300 K) = 0.3mV
5σ ≈ 10^{-7} prob. of false detection

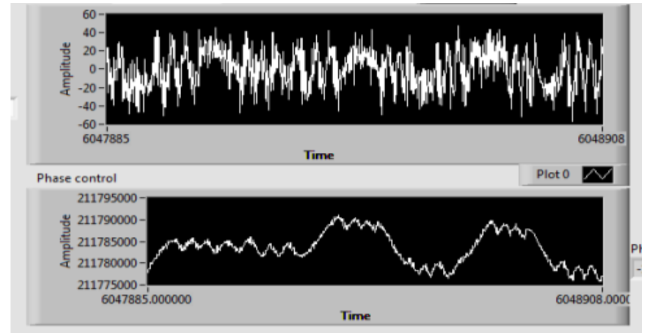


Gate sig. ~ 10 V/ns
Threshold ~ 2 mV
→ 200 fs = 42 μm coax
→ Active control required

Active control in operation

A version of the system

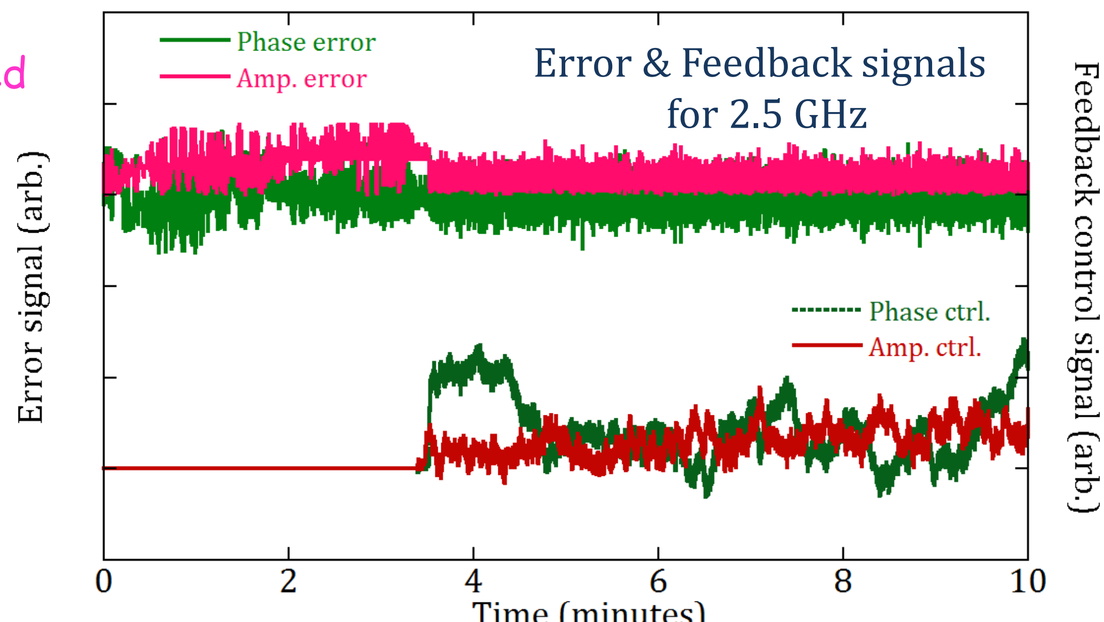




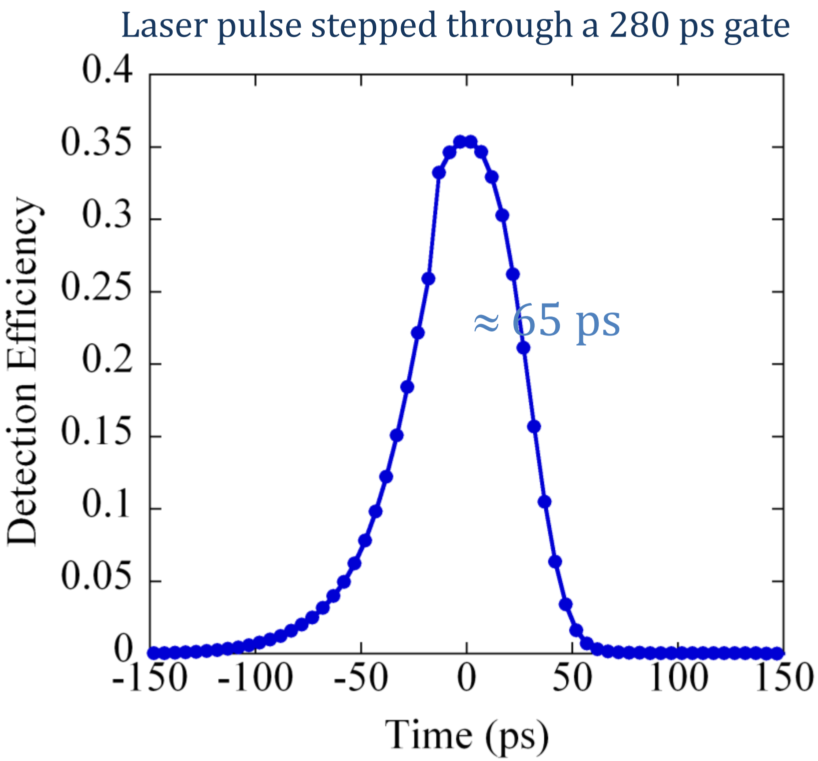
Compensating for my hand waving over the board

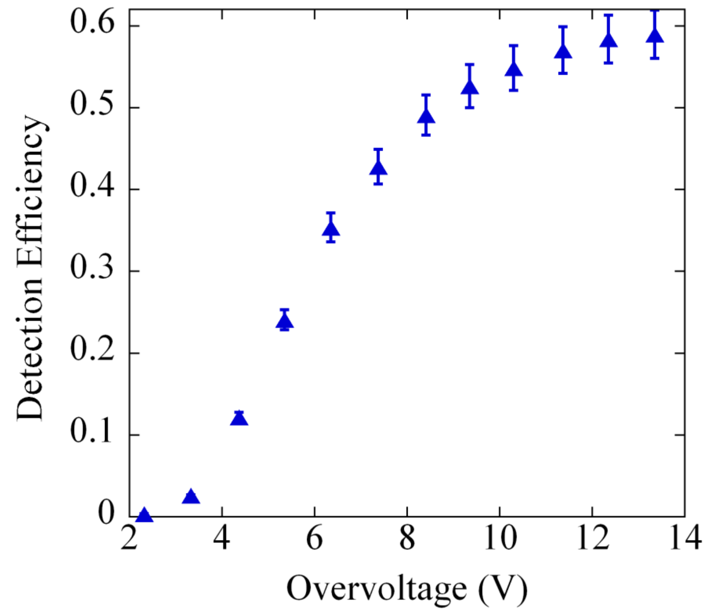
All 4 harmonics actively controlled

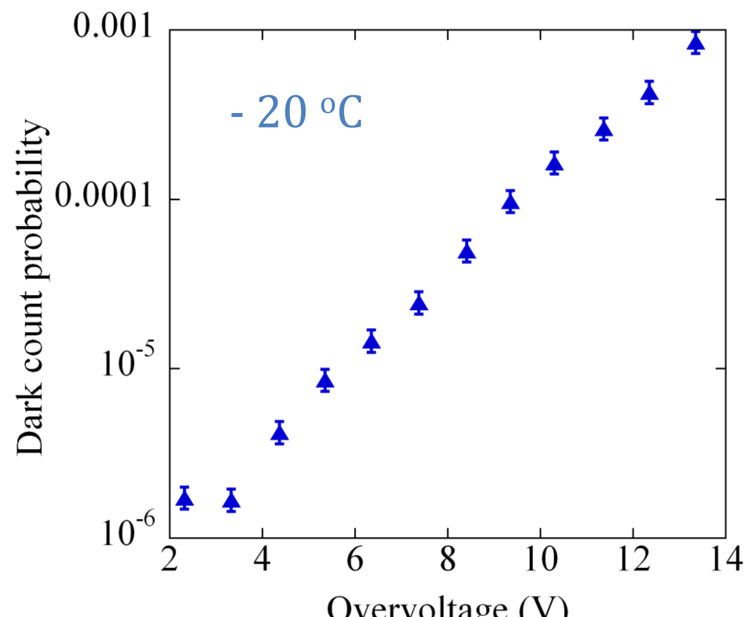
Loop not yet optimized.



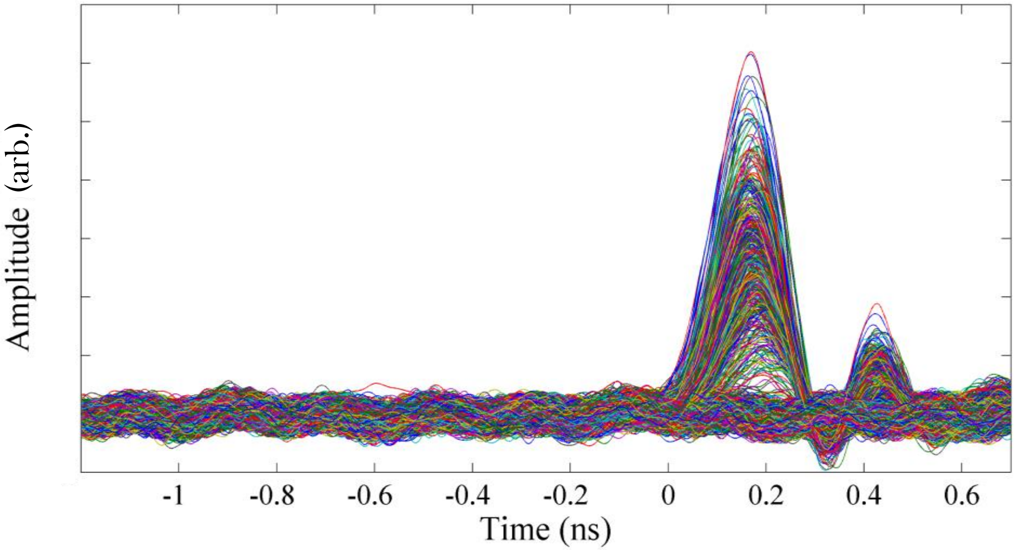
Detection efficiency & Dark counts

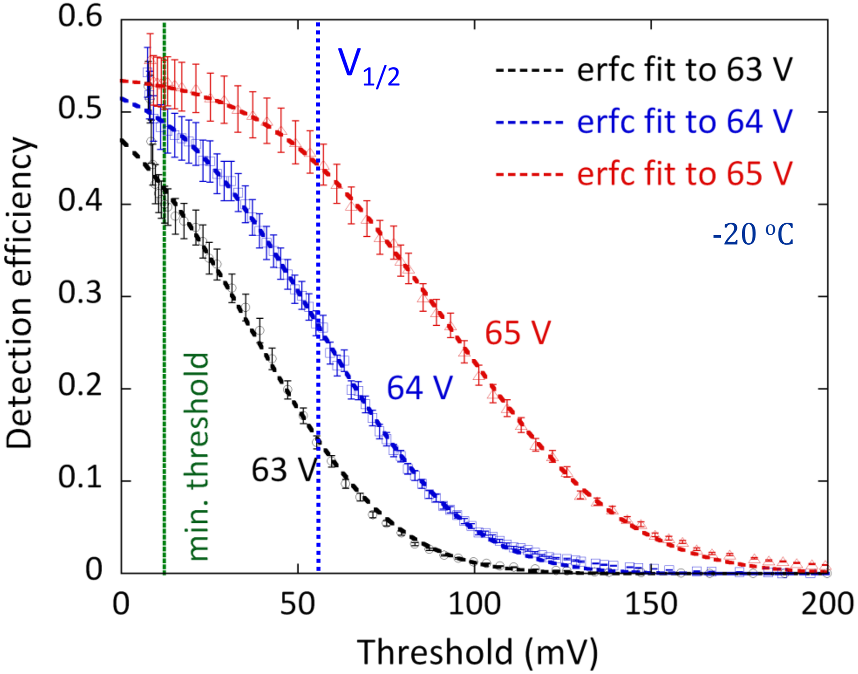






Efficiency & Minimum detectable charge





Corroboration of minimum detectable charge:

Measure average avalanche charge (counter/picoammeter)

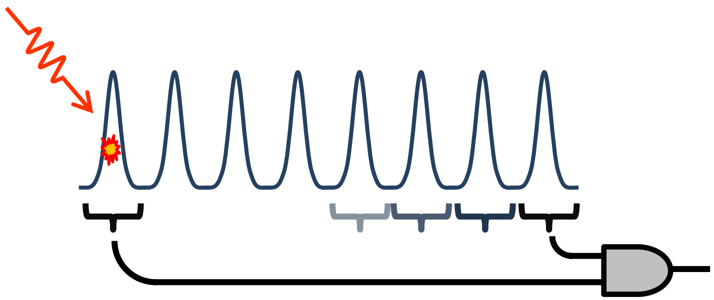
Assume (1) amplitude and charge proportional

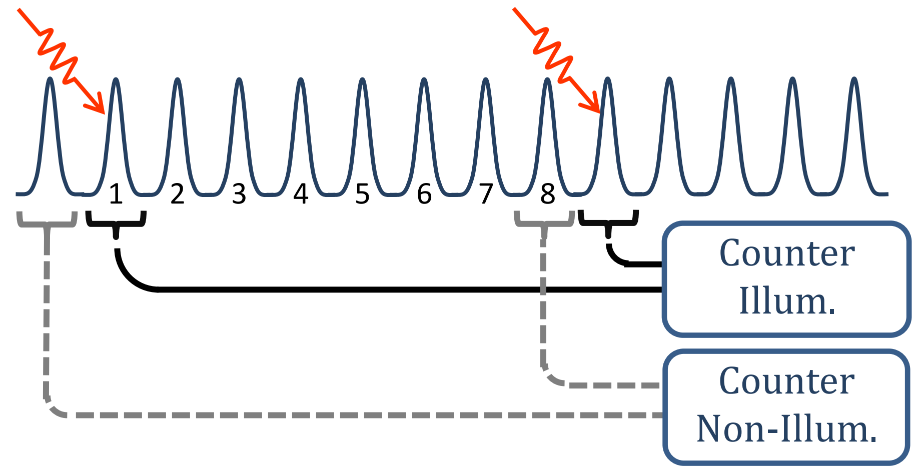
(2) average amplitude = mean amplitude

Threshold $V_{1/2}$ where counts drop by ½ equals amplitude of average avalanche

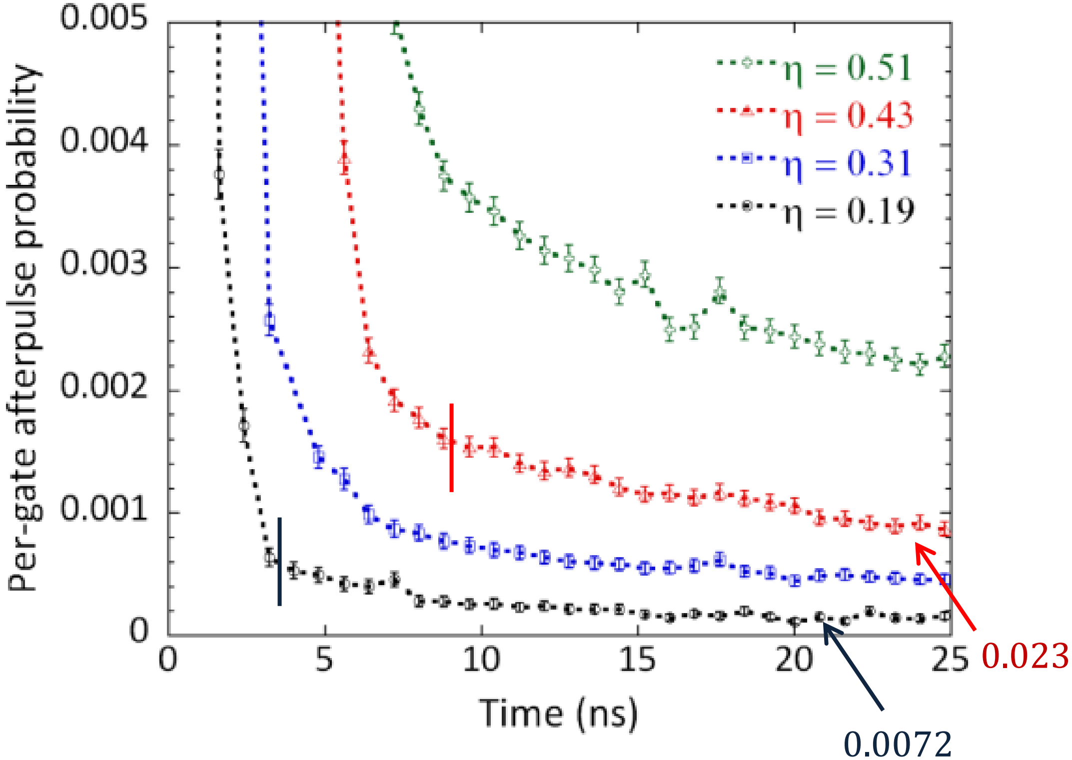
➔ Threshold = (7.4 ± 1) fC

Afterpulsing & Count rate

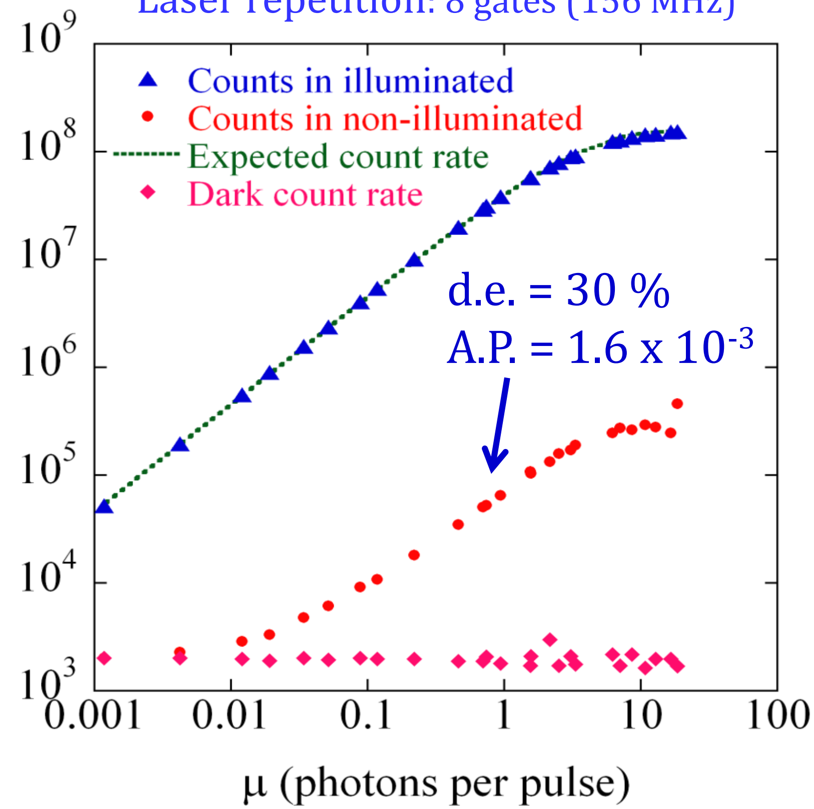




Laser repetition: 32 gates (39 MHz)
Count rate = 2 MHz
280 ps gate (two harmonics)



Laser repetition: 8 gates (156 MHz)



Summary & Outlook

Demonstrated new technique for high-speed periodic gating
- Stabilized with threshold ≈ 7 fC

Highest efficiency observed in GHz gated InGaAs, approaching device saturation

Low afterpulsing, consistent with exponential scaling

Low-noise counting > 10^8 s^{-1}

Suitable for testing other detectors, e.g. silicon

Further improvement projected with shorter gates

If you think this work is interesting, send your CV. We are always looking for good post-docs!
bienfang@nist.gov

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Thank you !

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Technology Administration, U.S. Department of Commerce