A Longitudinal Density Monitor for LHC

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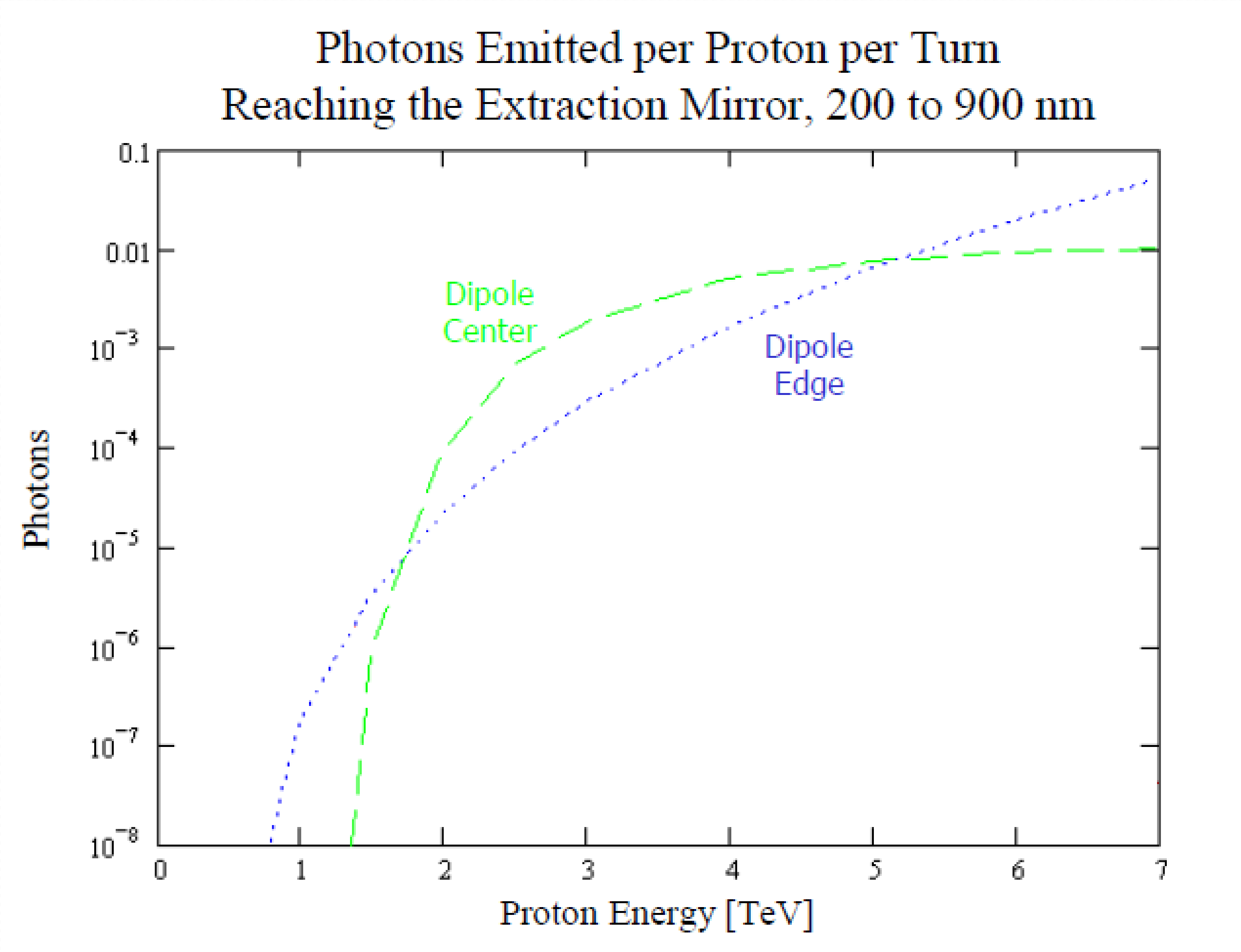
Contents

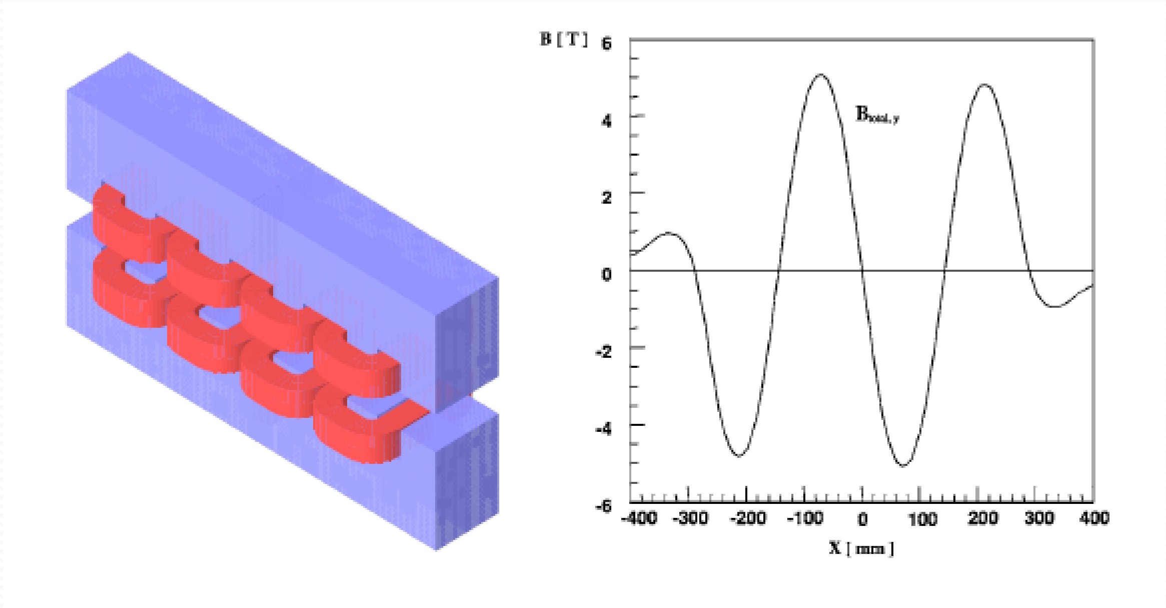
- Synchrotron light monitors at the LHC
  - Production of sync light
  - Optical arrangements
- LDM specifications
- Photon counting
  - Corrections needed
  - Dynamic range limit
- LDM design

- D3 (RF separation dipole) chosen as main source

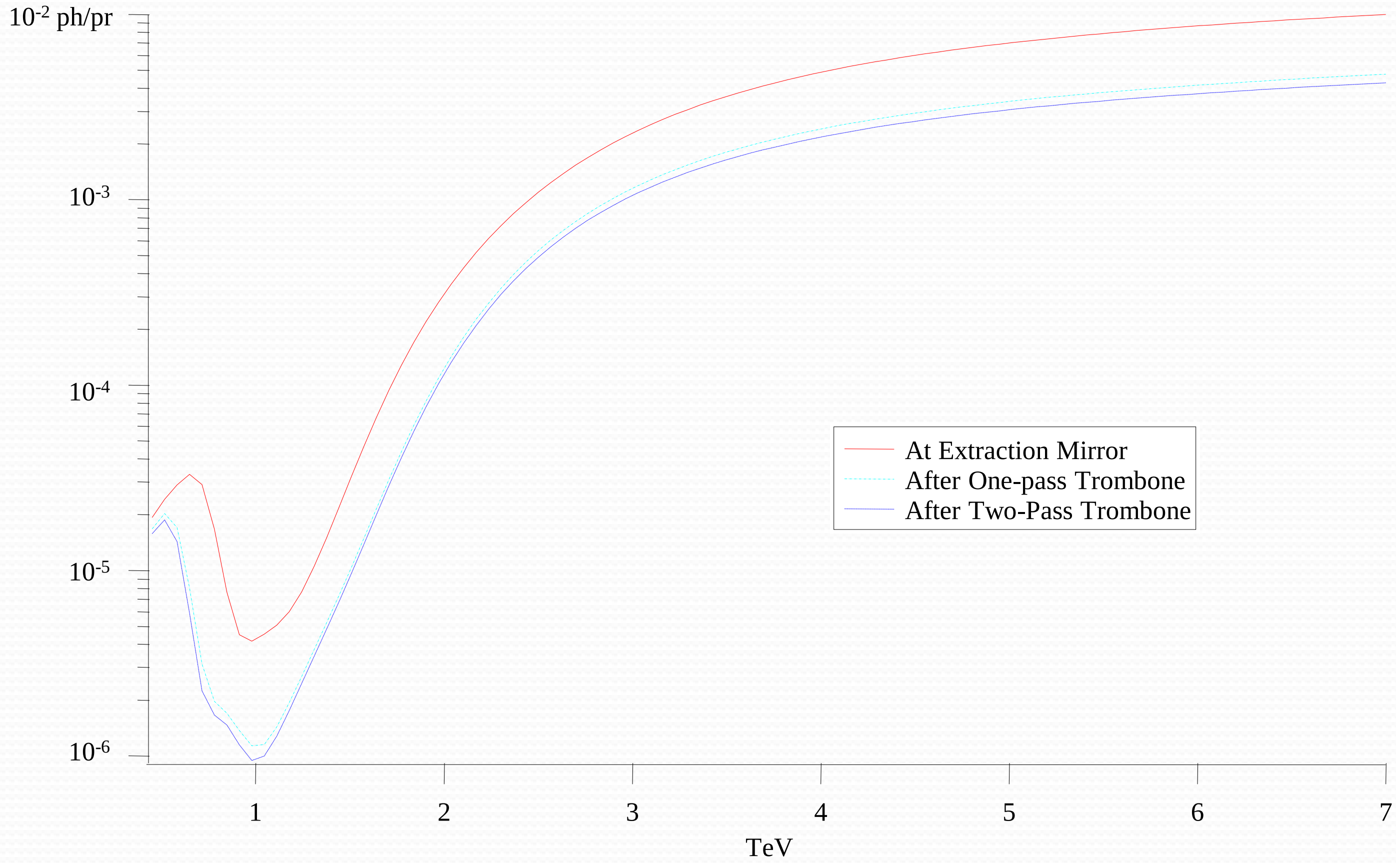


- Need to be able to monitor the beam at all energies.

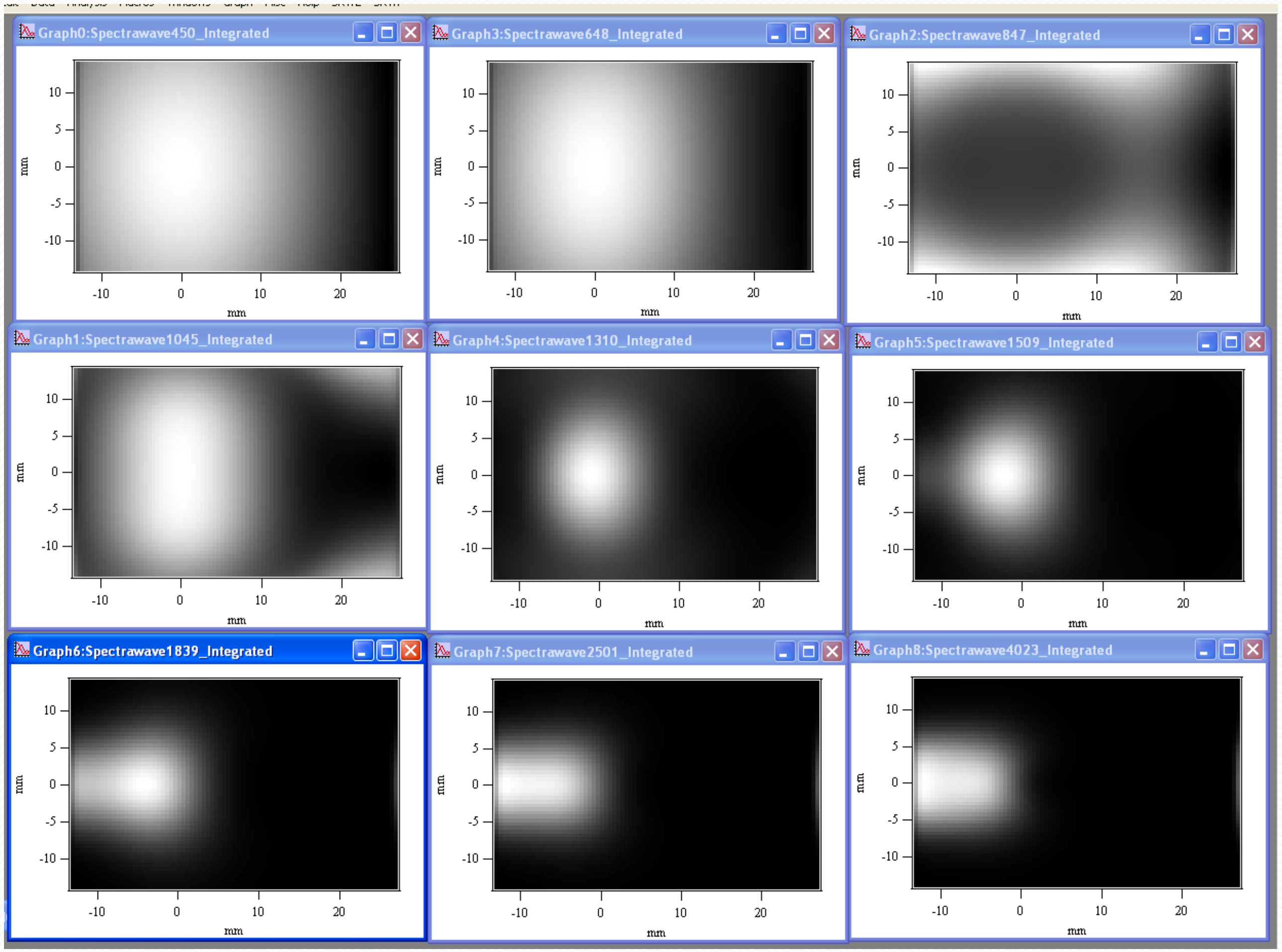
- Solution: Add an undulator to increase the amount of radiation at low beam energy.

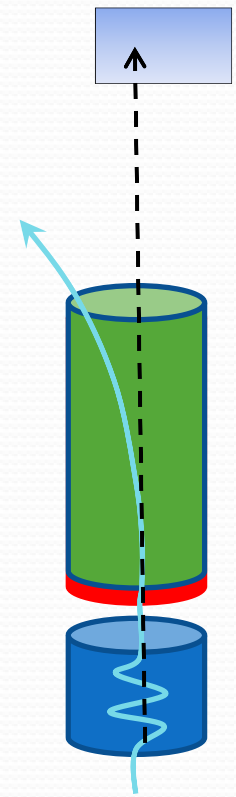


Total visible flux per proton



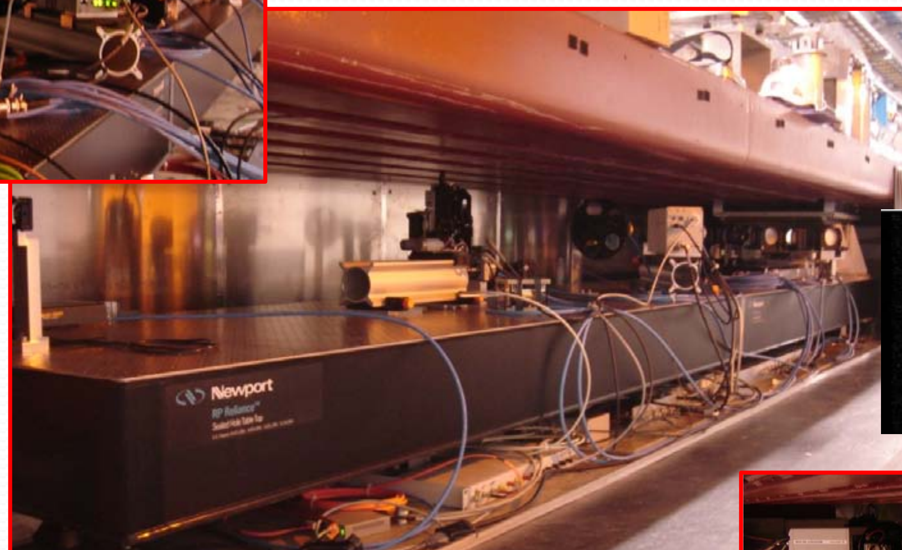
- Light at the extraction mirror:

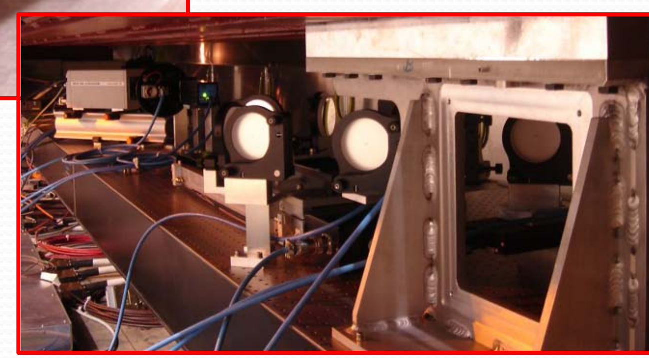




(anticlockwise beam)

LHC synchrotron light monitors





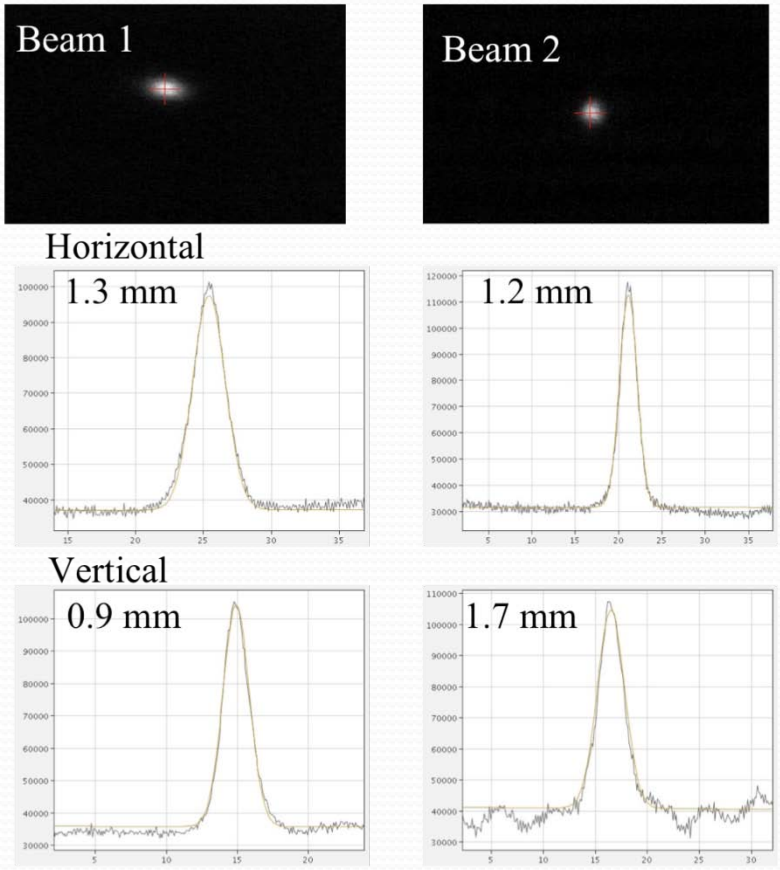
- Implemented:
  - Abort Gap monitor
  - Slow and Fast cameras for transverse profile
- In design:
  - Longitudinal density monitor

Optical arrangement

- A 4.8m optical table containing
  - One motorized steering mirror
  - Two spherical focusing mirrors
  - Motorized optical delay line to select light source
- Cameras get 90% of the light
  - Beam splitter separates 10% for abort gap monitor
  - Second splitter to separate 10% of this for LDM
- Identical arrangement for each beam

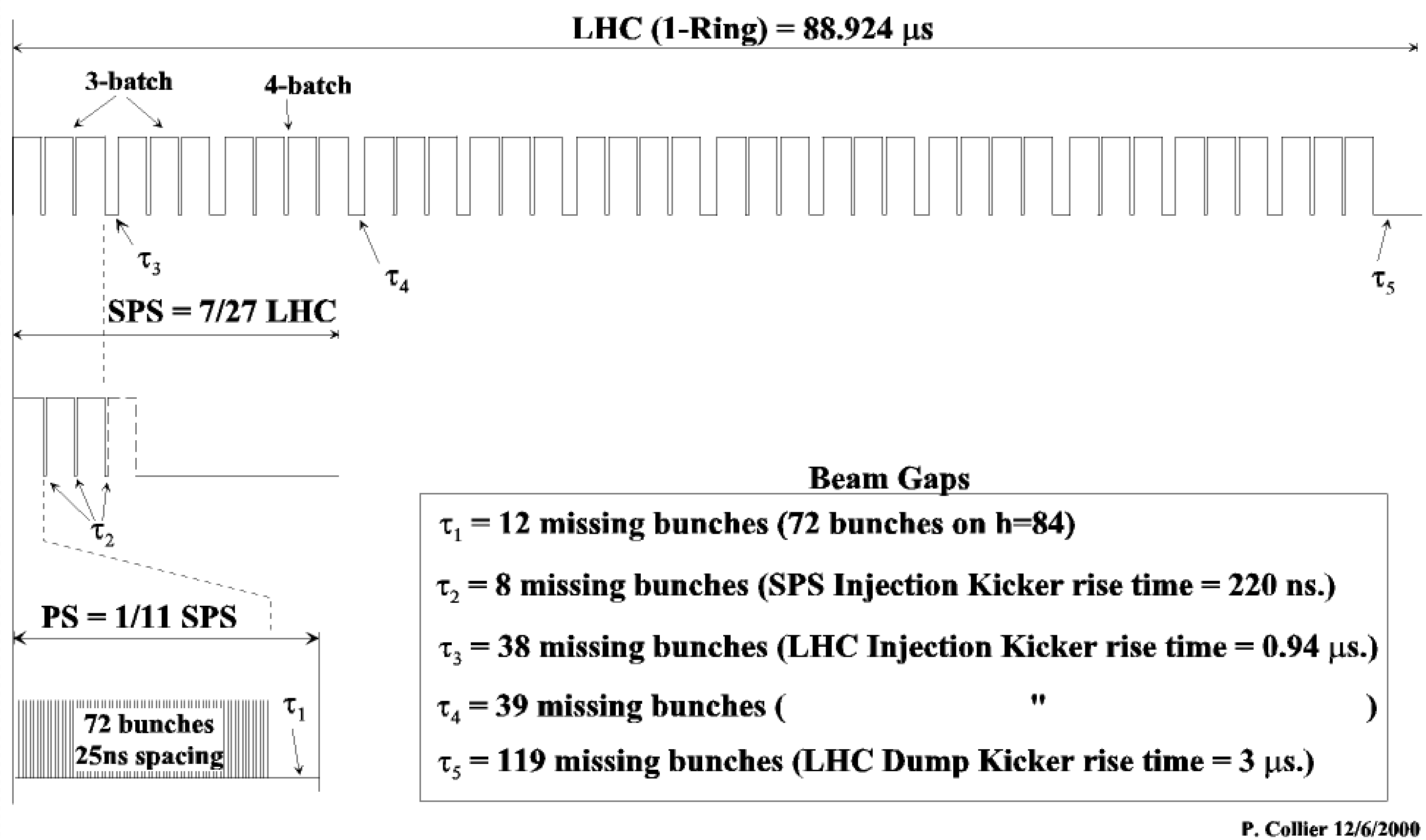
BSRT

- Intensified CCD camera can image a single pilot bunch
- Fast gated camera for bunch-by-bunch measurements
- Generally good agreement with wire scanners



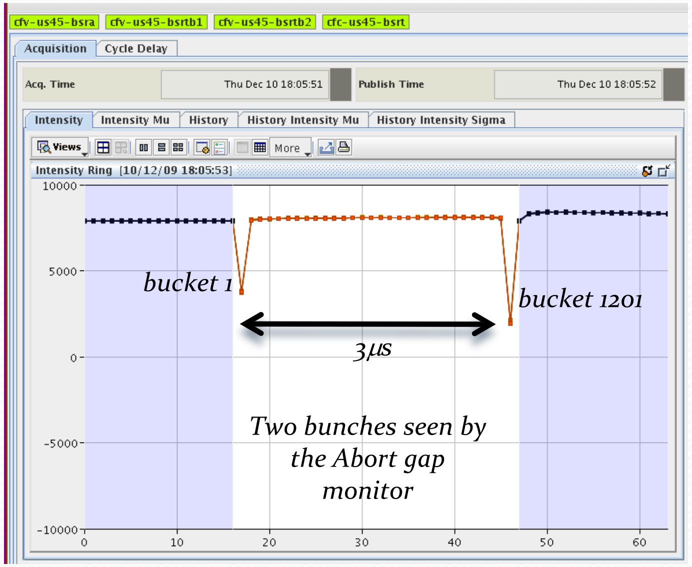
LHC bunch structure

- Bunch length 300-600 ps RMS
- Bunch separation 25ns



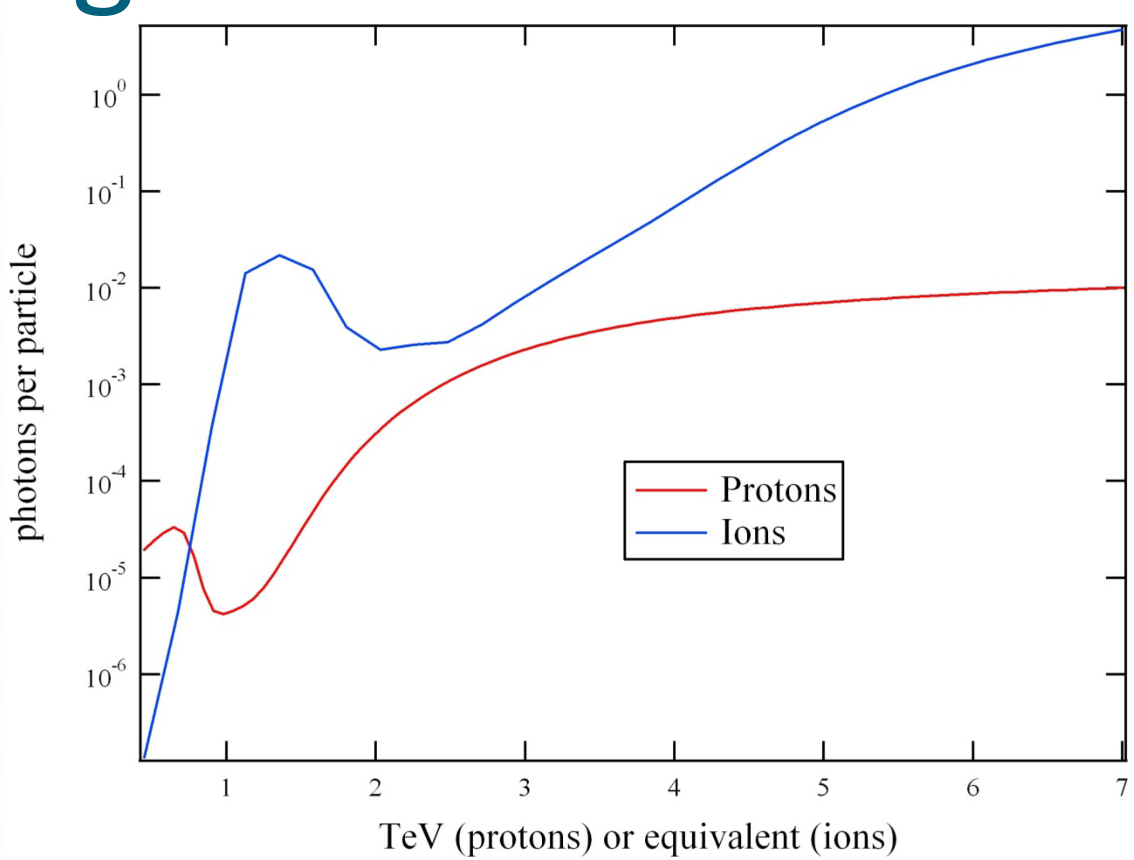
Abort Gap Monitor

- Particles occupying the 3μs abort gap would receive a partial deflection by the abort kicker.
- The population gap must be monitored and compared to magnet quench thresholds
- A gated PMT is used
- Sensitivity ~10^7 protons / 100ns at 3500 GeV



Synchrotron light with ions

- Lead ion run planned for next year
- γ scales by 82/208 compared to photons so undulator radiation in IR at injection
- Coherent sync radiation increases emission at higher energy
- Also smaller bunches.



⇒ sync light monitoring severely limited for ions at injection

What's needed:

- Photon detector for longitudinal profile.
- Measure proton density as a function of time with 50ps resolution.
- Measure the bunch parameters (shape, length, density) with 1ms integration
- Sensitive to $5x10^5$ protons in the bunch tails or in ghost bunches, ie 1/30000 of the main bunch, with 10s integration

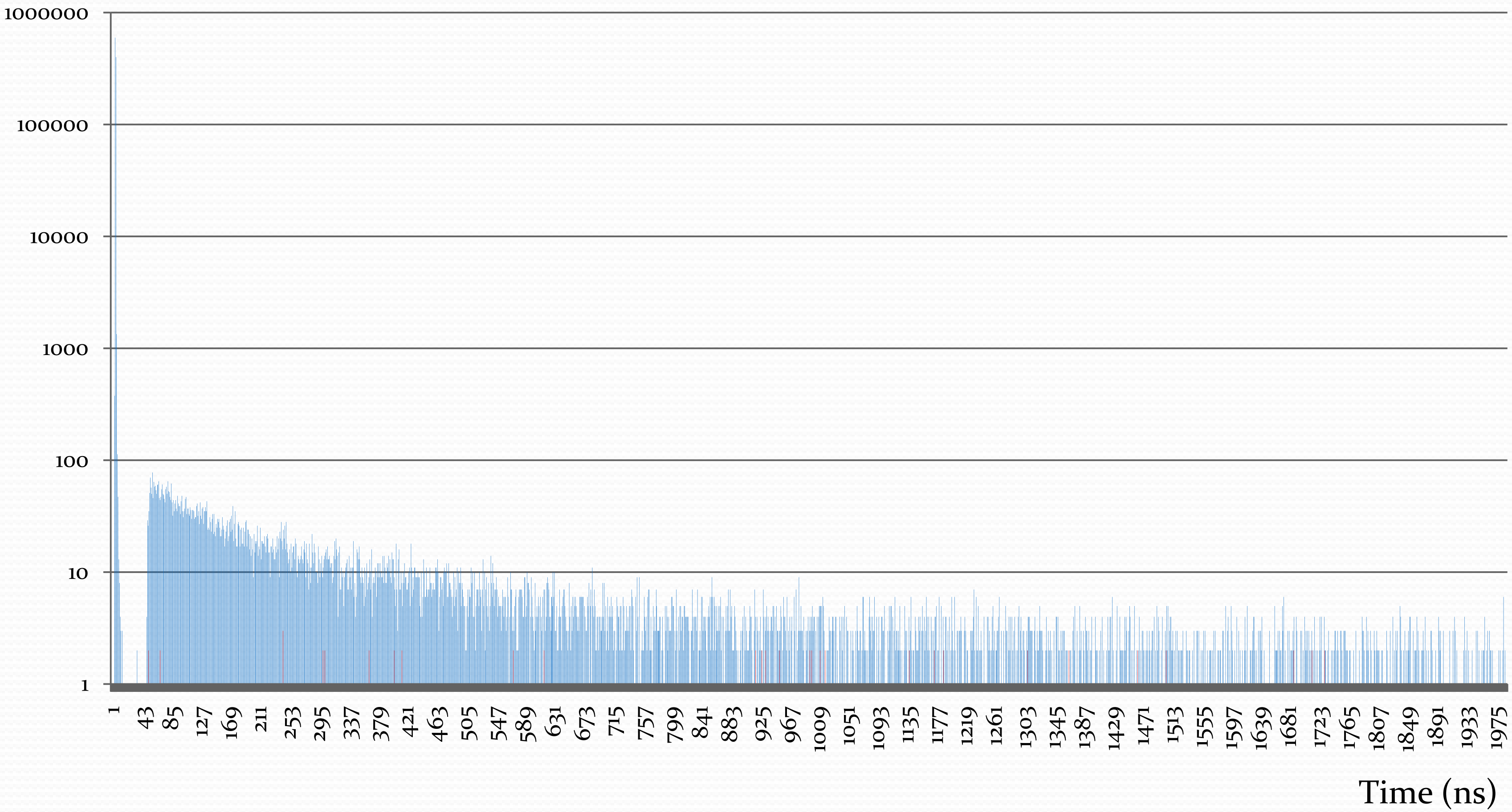
What's available:

- Abort gap monitor gets 10% of the incoming light
- I can get 10% of that
- So maximum available is 1 photon per 10^8 protons at 1TeV
- Which means ~1500 photons for a full bunch – plenty!
- But only 1 photon every 200 turns at the maximum sensitivity.

Proposal:

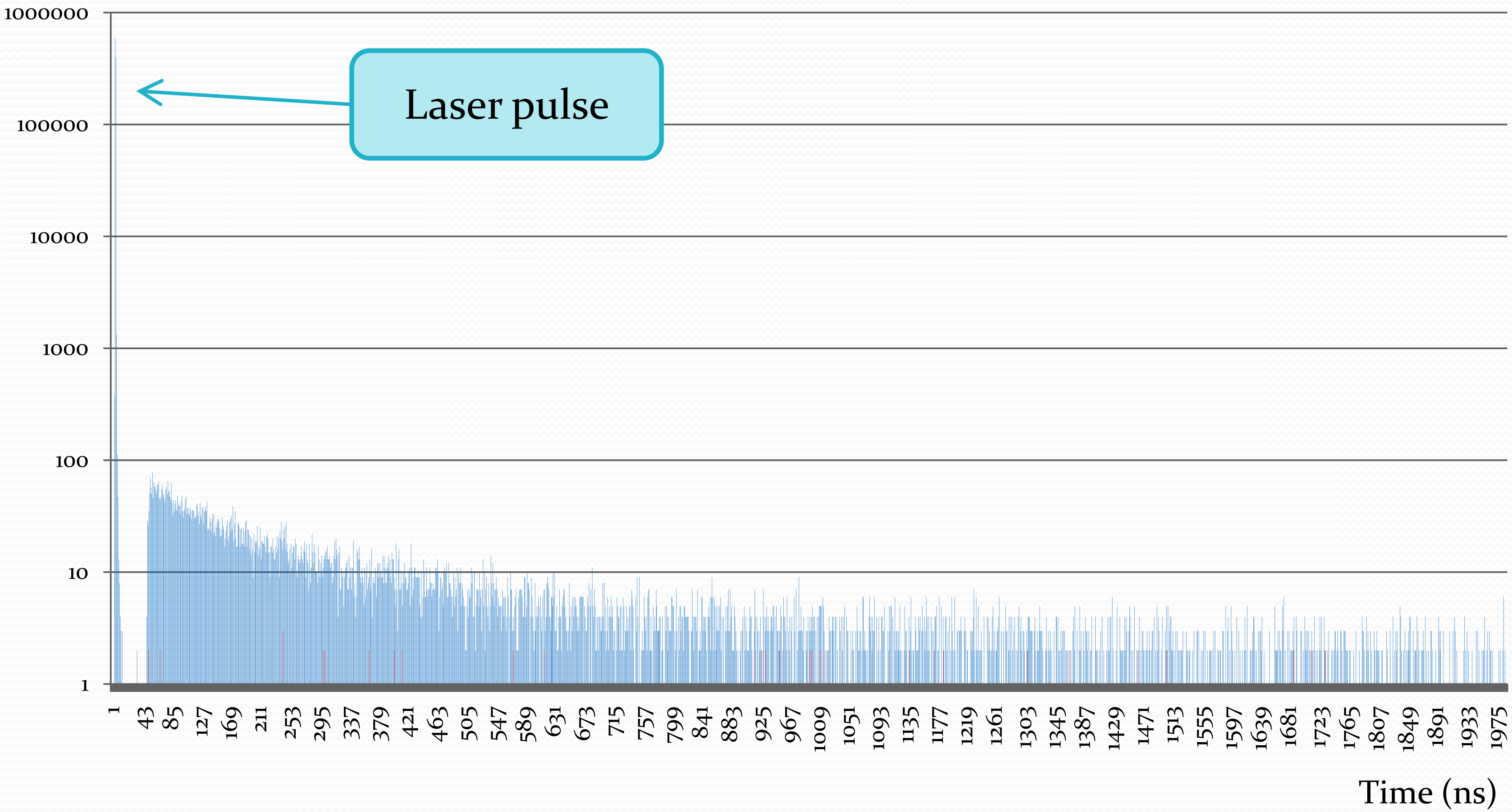
- Photon counting with Geiger-mode Avalanche Photo-Diode (APD)
- Photon arrival times collected in Time-to-Digital converter card synchronised to bunch clock
- Integration over many turns to build up profile

APD response – id100



- Afterpulsing decays slowly

APD response – id100



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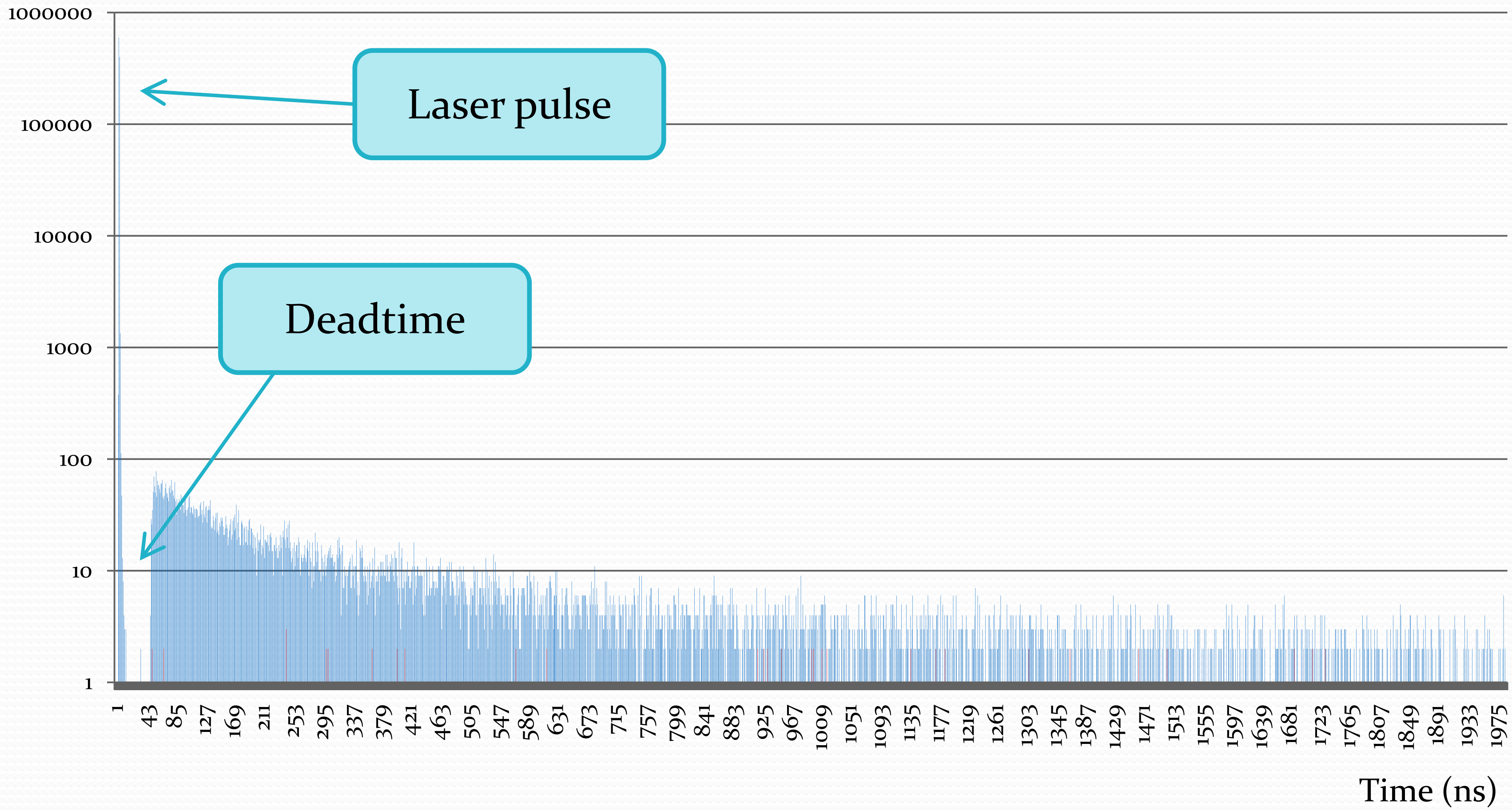

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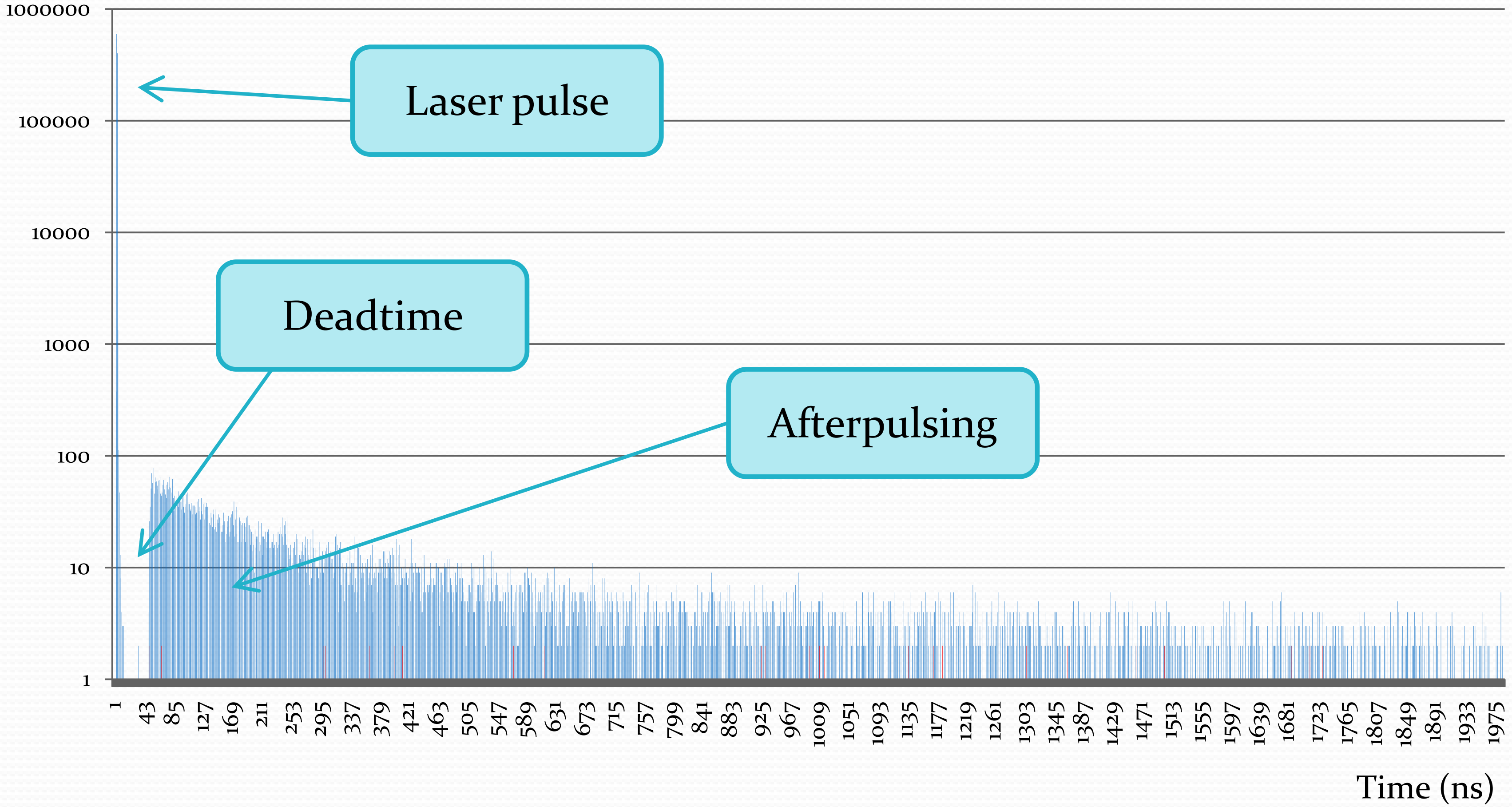
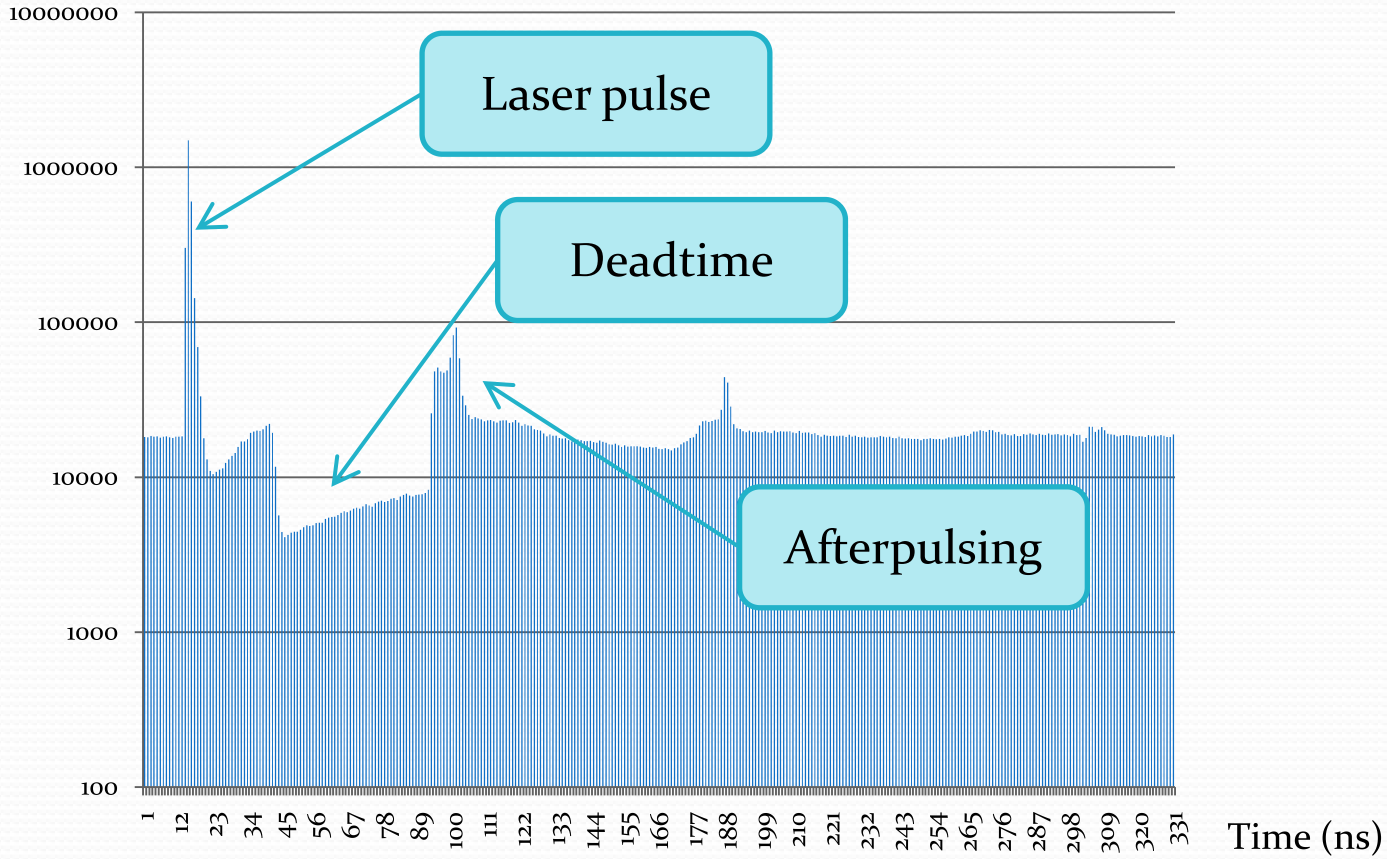
APD response – id100



- Afterpulsing decays slowly

APD response - MPD

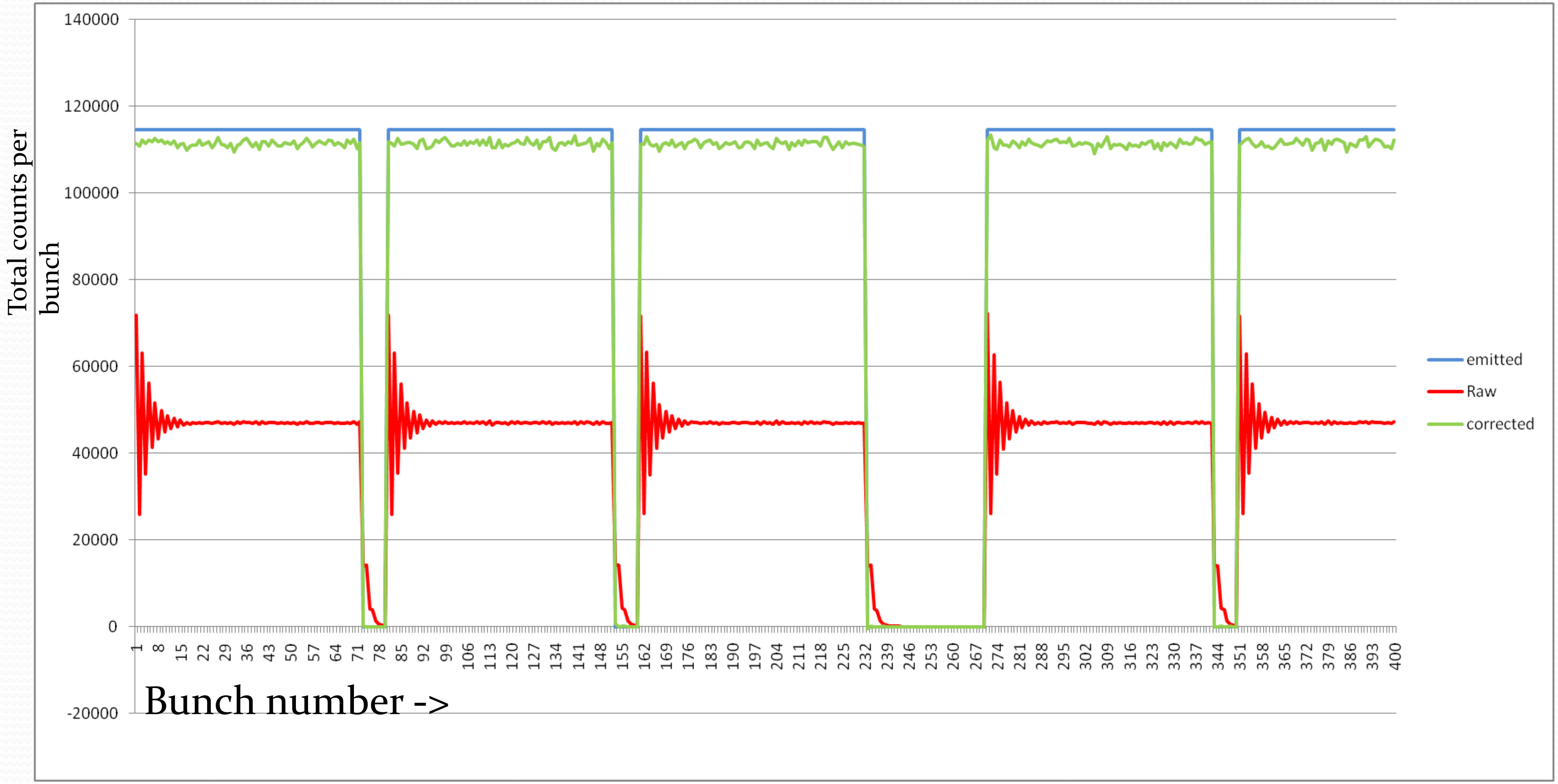


- Sharp afterpulsing – easier to correct for

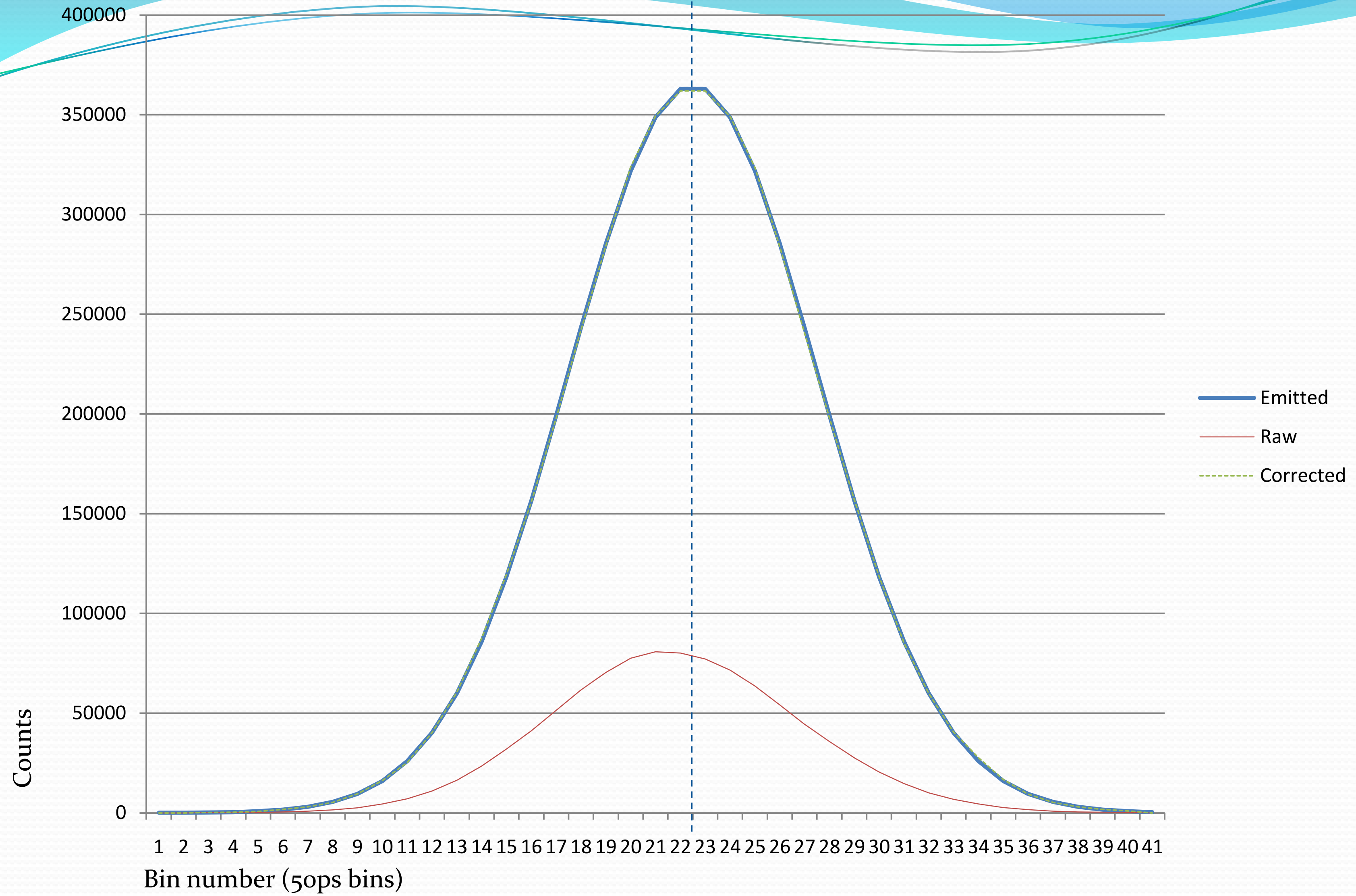
Signal correction

- Must take into account:
  - Skewing due to deadtime
  - Afterpulsing
  - Pile-up

Bunch-by-bunch



- Bunch current for first few PS batches. Raw counts fluctuate since deadtime > bunch spacing.



- 0.5 photons per bunch, 195ns deadtime

Correction

- How many photons does the detector miss?
  - Sum the counts over the previous *d* bins, where *d* is the deadtime
  - Divide by the total number of passes to obtain the probability that the detector was unavailable.

- An 'ideal' detector would count

$$C_i = \frac{x_i}{P(up)_i} = x_i \frac{N}{N - \sum_{j=i-d}^{i-1} x_j}$$

N= number of passes, x=actual counts, C= corrected counts

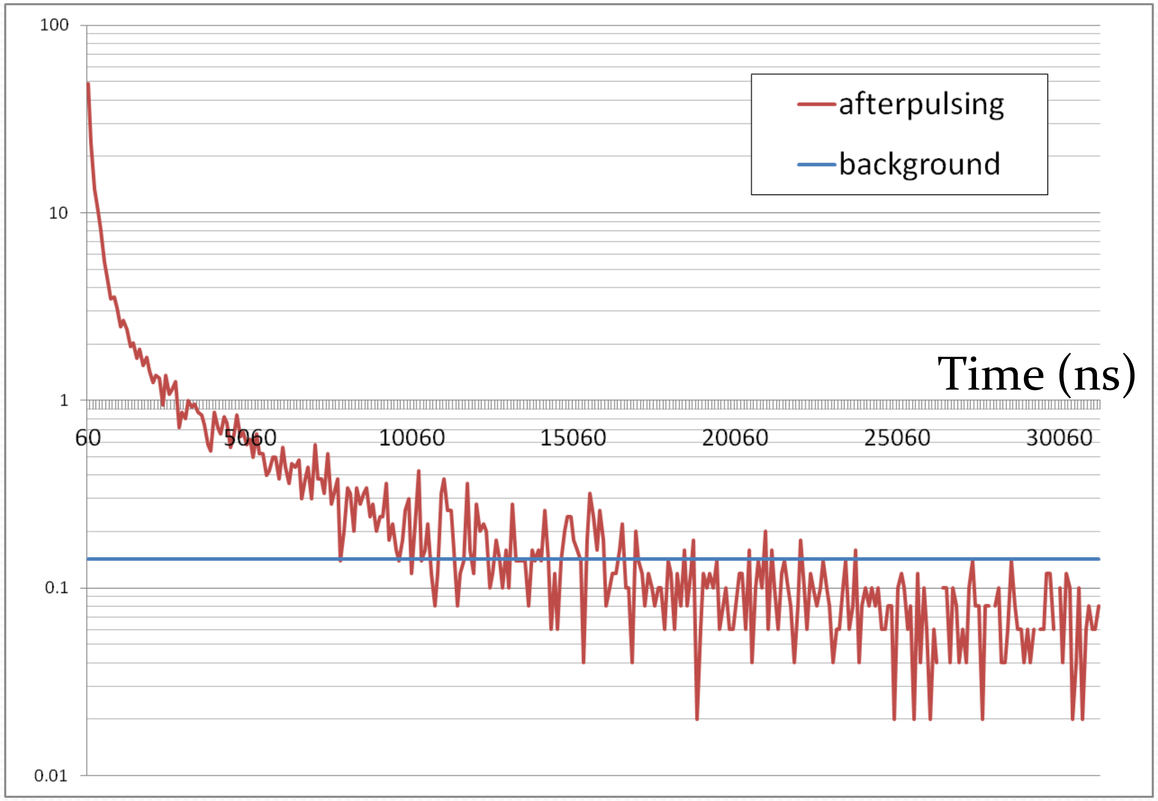
Optimum photon rate

Too few photons → Noisy profile Or → Long integration time

Too many photons → Almost always in deadtime → Noisy correction

Best profile with 1 photon per deadtime period

Afterpulsing



- Long-lasting effect
- Can remove by deconvolution
- Major source of noise

Pile-Up

- Possibility of two photons arriving at the same time.
- Large number of particles, small chance of emitting a photon: Poissonian distribution.
- If the number of counts expected in a particular bin (given the proton density) is λ, then the probability of having a given number k of photons emitted is

$$p(k) = \frac{\lambda^k e^{-\lambda}}{k!}$$

- If C_i/N is the probability that the ideal detector would see at least one photon then

$$p(0) = 1 - C/N = e^{-\lambda}$$

- The expected number of photons, which is now directly proportional to the proton density, is then given by

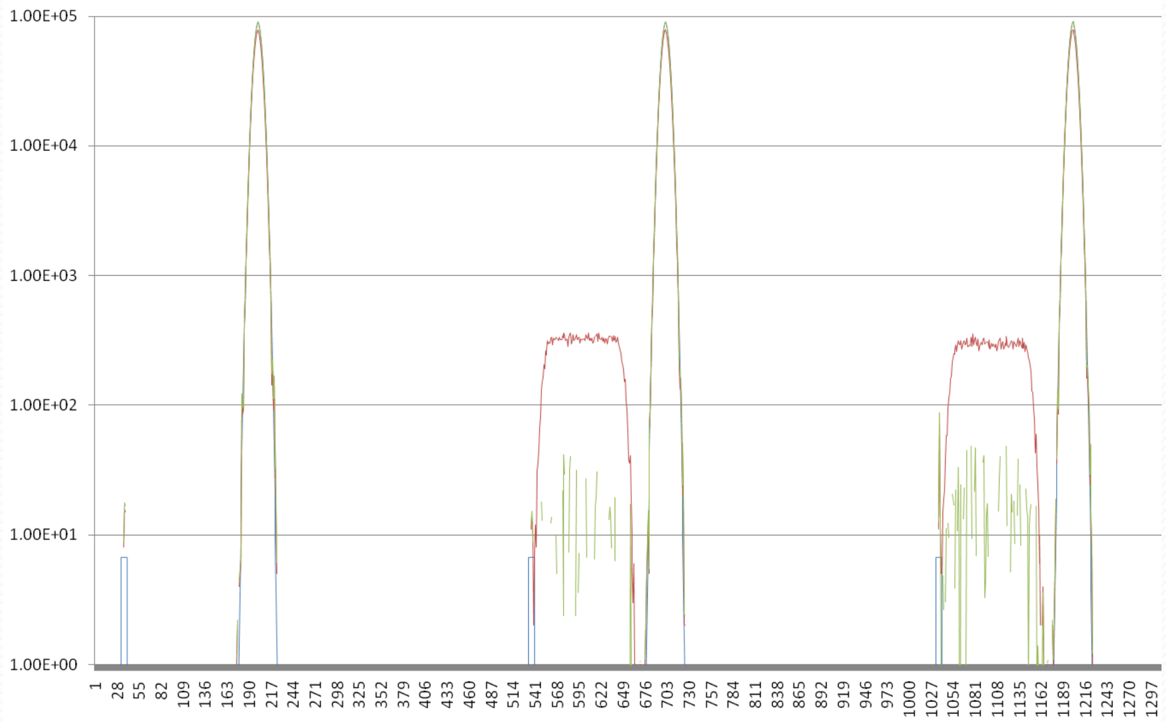
$$\lambda = -\ln(1 - C/N)$$

Limited dynamic range

- Theoretical limit due to masking of ghost bunches by deadtime
- Increasing integration time should increase dynamic range
- In fact, it increases only slowly, due to afterpulsing

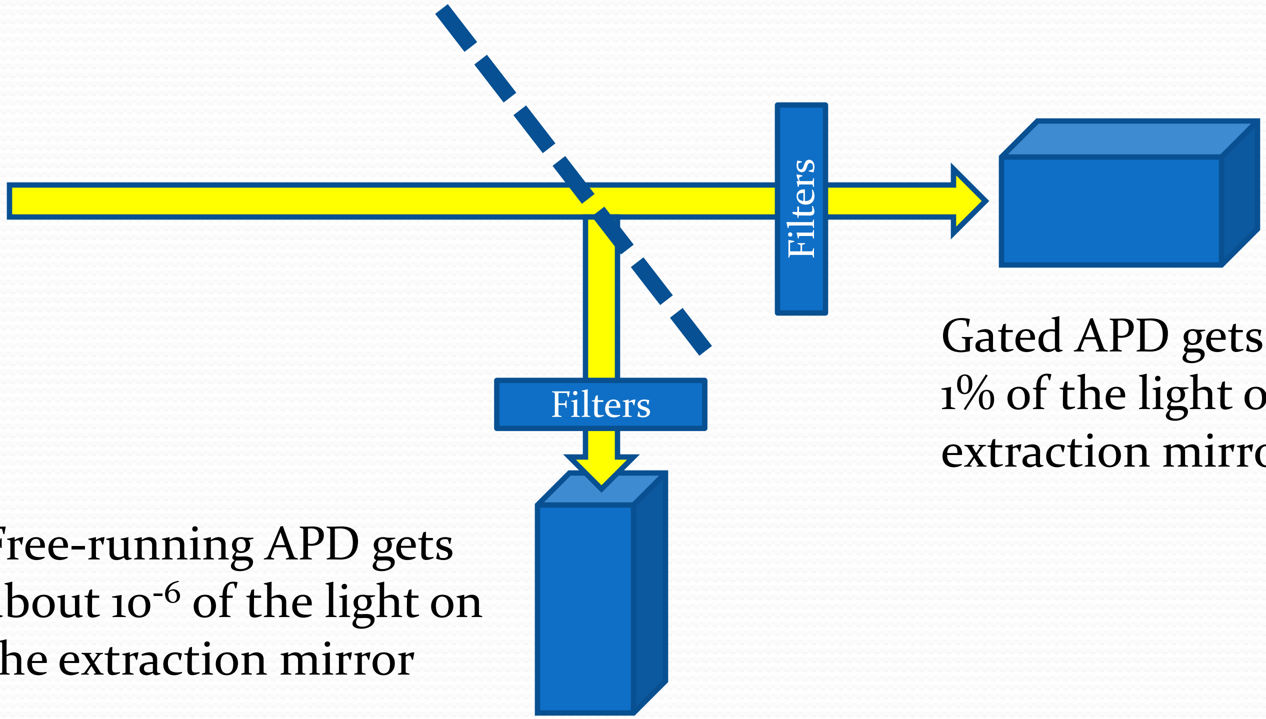
Limited dynamic range

- Main limiting factor is noise due to afterpulsing



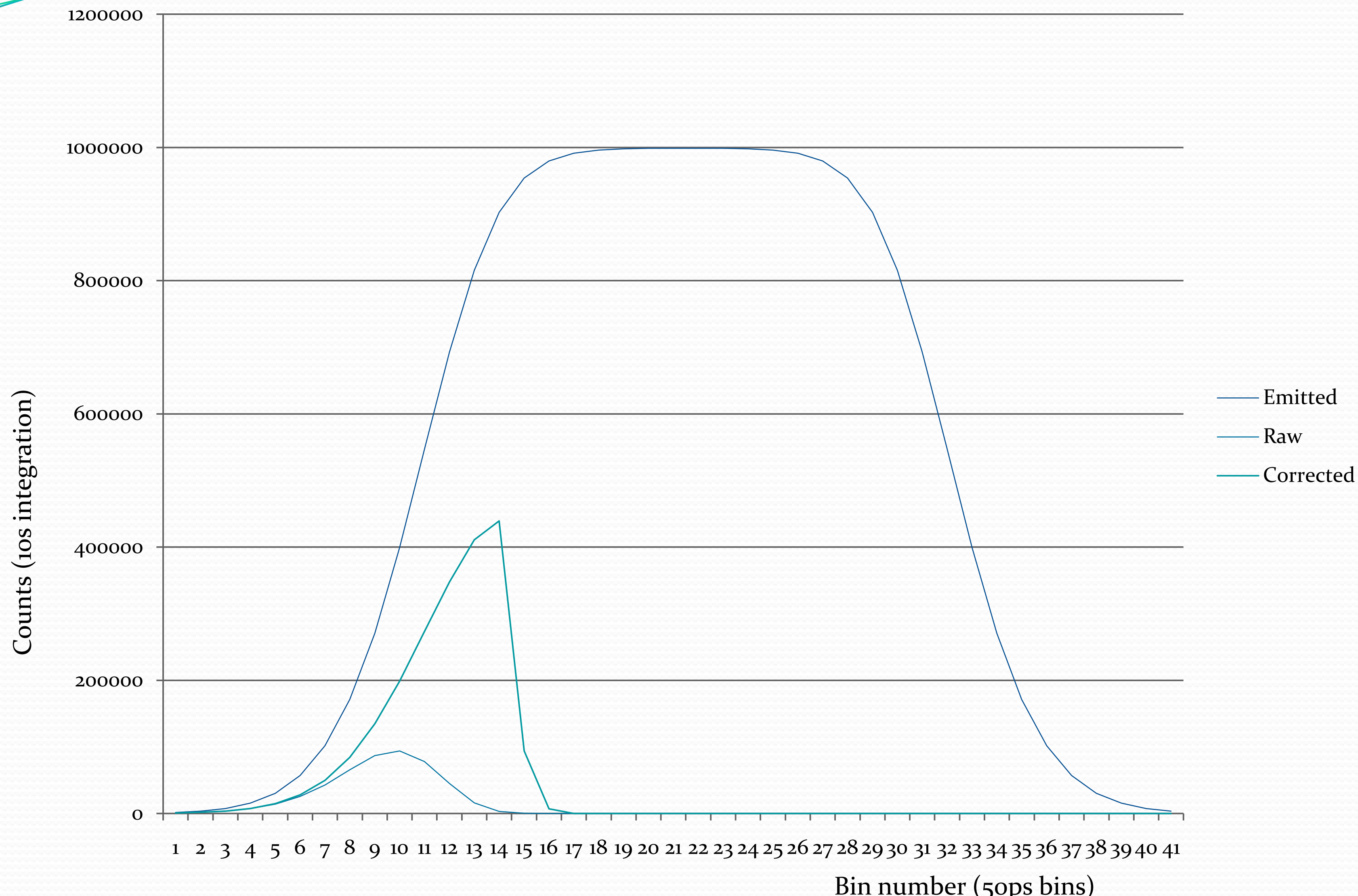
Example: 1000 sec integration, 3% afterpulsing

The solution

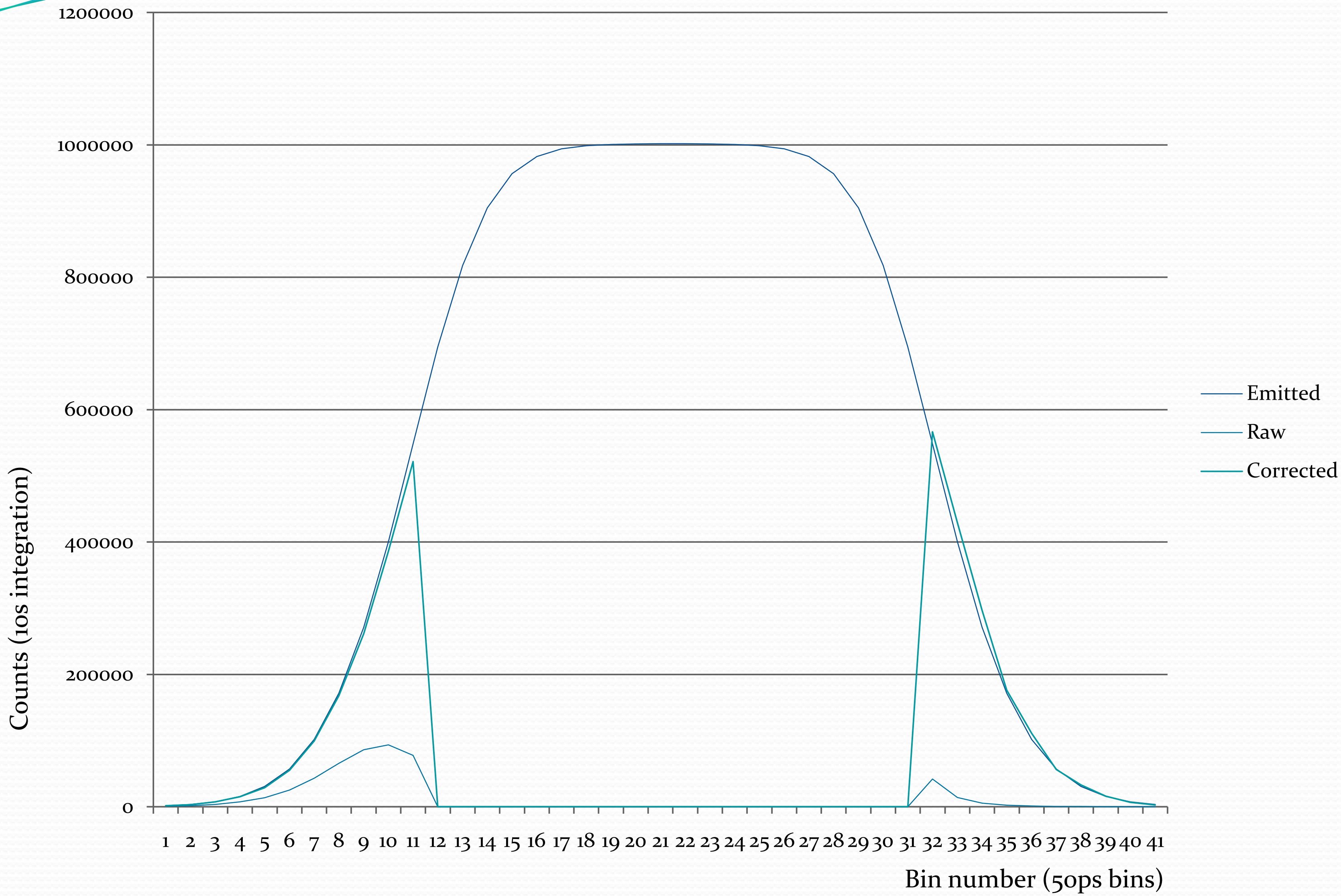


Gated APD gets about 1% of the light on the extraction mirror

Free-running APD gets about 10^{-6} of the light on the extraction mirror

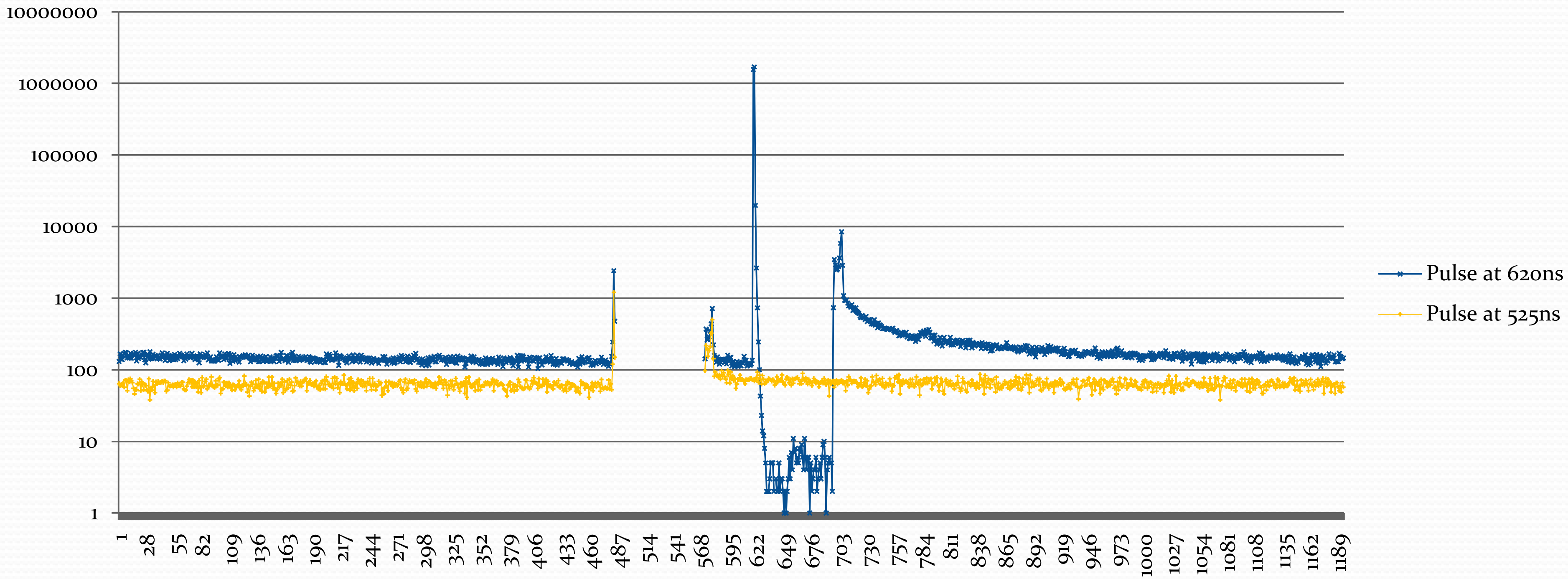


- 90 photons per bunch

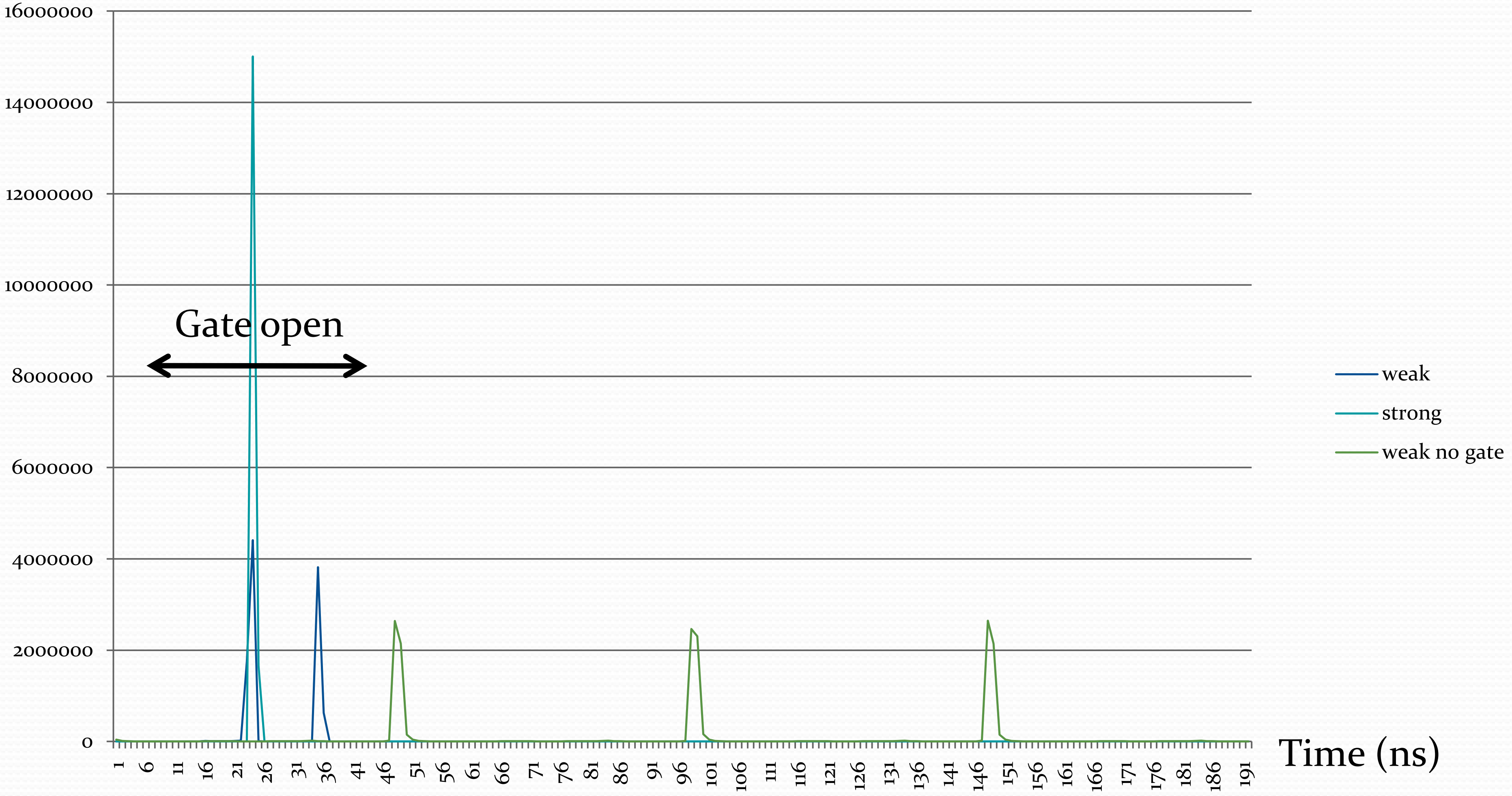


- 90 photons per bunch, with gating

Gated APD - low rate

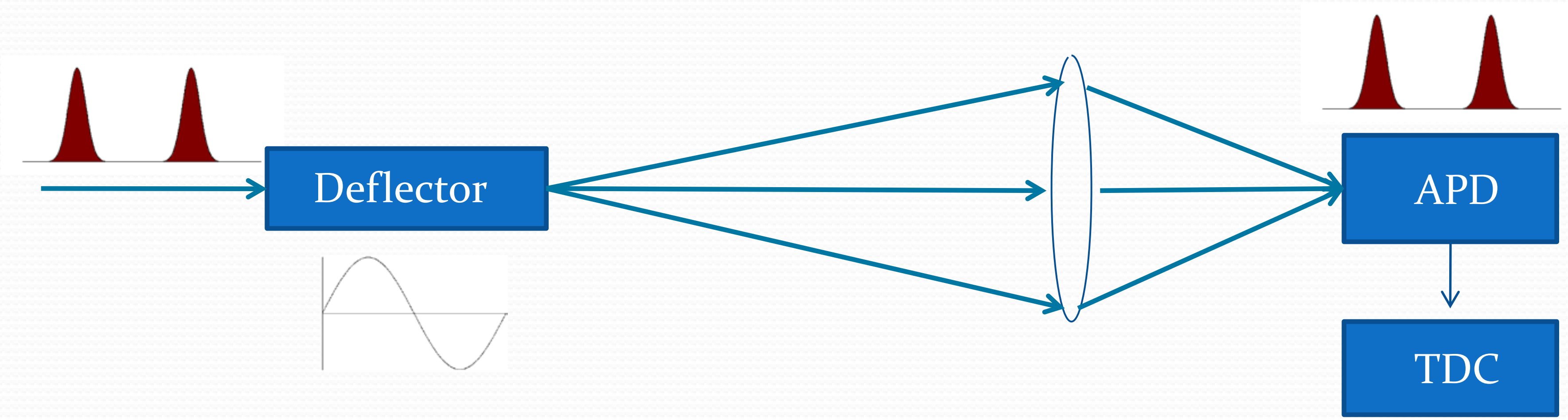


- Pulse is completely hidden, no effect on count rate



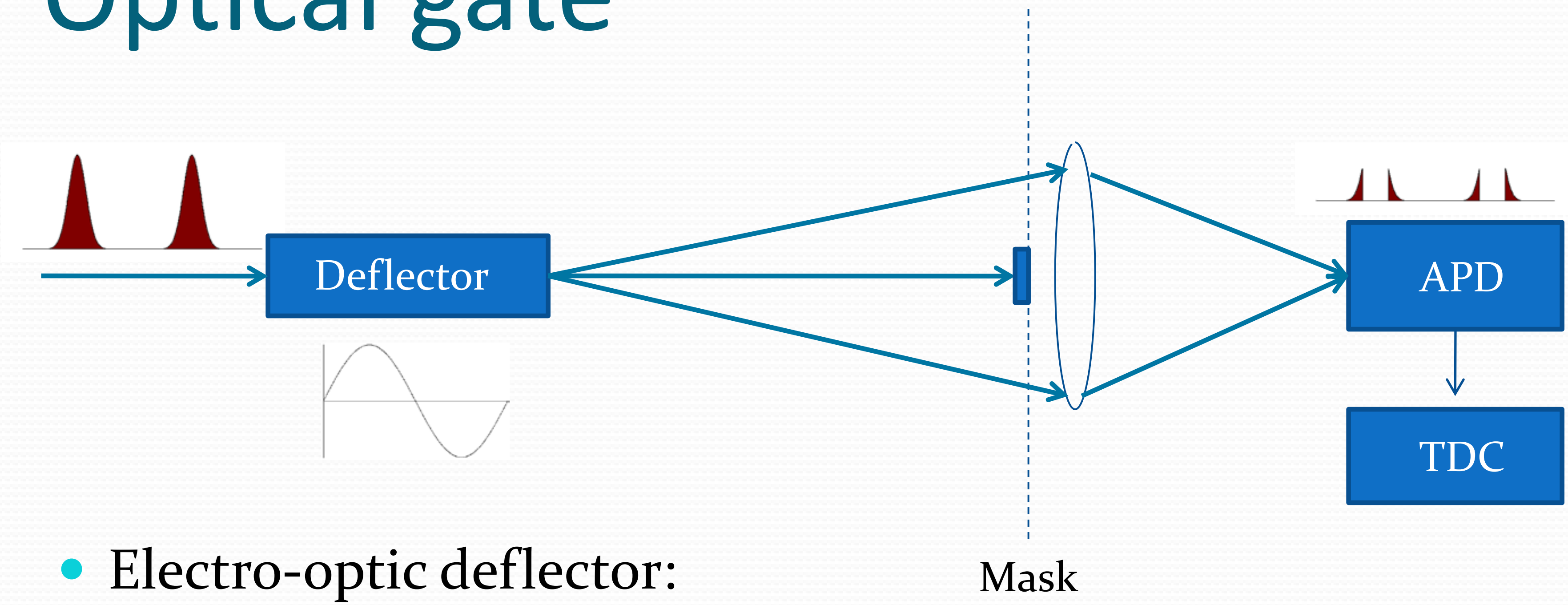
- Not so good with faster gate
- Strong pulses completely destroy gate information

Optical gate



- Electro-optic deflector:
  - High speed
  - High extinction ratio
  - No wavelength dependence
  - Reliability – no moving parts
  - No HV pulse needed

Optical gate



- Electro-optic deflector:
  - High speed
  - High extinction ratio
  - No wavelength dependence
  - Reliability – no moving parts
  - No HV pulse needed

Detector location

- Weak deflection -> need long gap between deflector and mask/lens.
- Need to collimate and polarize before entering deflector

>>> Deflector on the optical table

- Uncertain of APD performance with radiation
- Keep APDs in the electronics rack

>>> Couple light into optical fibers

Conclusions:

- A longitudinal profile of the LHC beams can be taken in the specified integration times
  - Average bunch length in 1 ms
  - Full bunch-by-bunch profile in 10 s
- Suitable correction algorithms can compensate for the detector imperfections
- An optical gate is necessary to achieve high dynamic range

Thanks!

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What next:

- Lab test the optical gate
- Prototype system ready soon
- Can't do individual bunch lengths in 1 ms – might be possible with APD array?
- A (partial?) system will be installed this year

Consider a main bunch which emits an average of A photons every time it passes the detector. This is immediately followed by a ghost bunch whcih emits B photons per pass, B<<A. Then for each pass:

$$\text{counts}_B := P(B)\cdot P(\text{notA})$$

The probabilities follow a Poisson distribution so the probability that the bunch does not emit is

$$P(\text{notA}) := e^{-A}$$

And the probability that the ghost emits at least one photon is

$$P(B) := 1 - e^{-B}$$

The dynamic range of the detector is d, where B is the smallest detectable ghost and A=dB. Then

$$\text{counts}_B := e^{-d\cdot B}\cdot\left(1 - e^{-B}\right)$$

This is a maximum when dB = 1, in other words when the main bunch emits an average of 1 photon per pass. The number of counts from the ghost bunch can then be estimated for various d:

$$\text{counts}_B(d) := e^{-1}\cdot\left(1 - e^{\frac{-1}{d}}\right)\cdot\frac{10}{89\times 10^{-6}}$$

where the last term is the number of passes in one 10 second integration period (ignoring missed passes through detector deadtime).

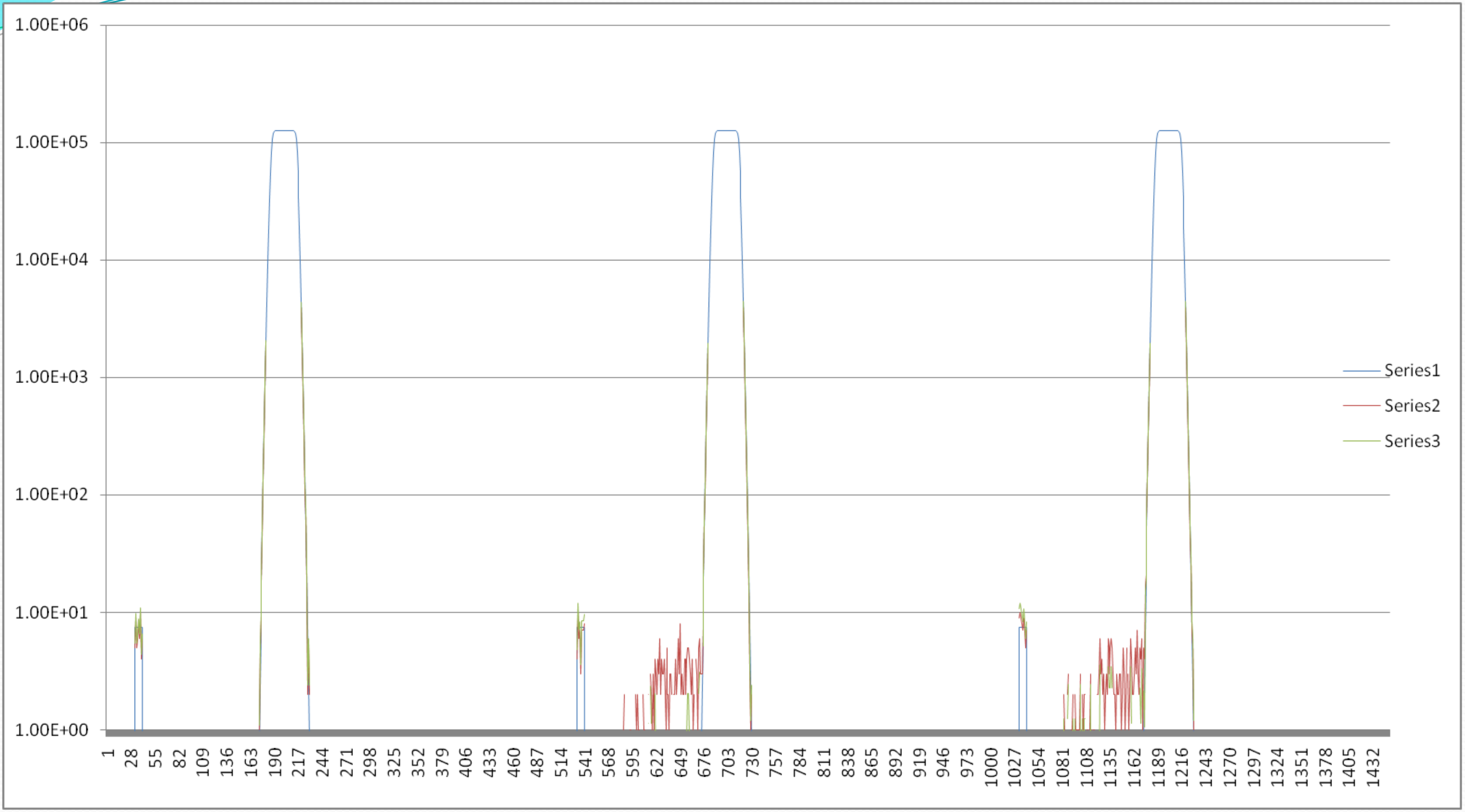
$$\text{counts}_B(1000) = 41.314$$

$$\text{counts}_B(10000) = 4.133$$

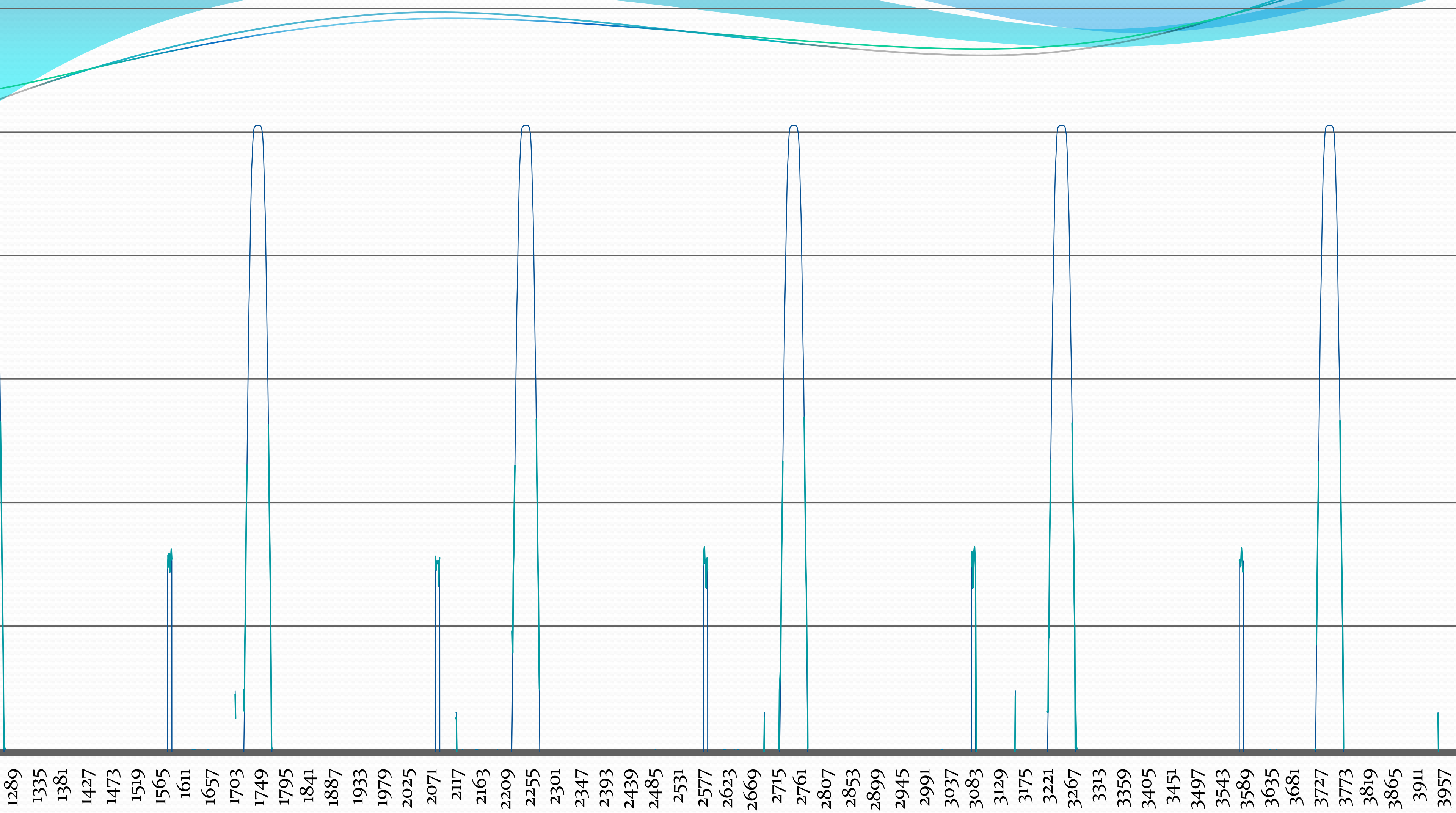
$$\text{counts}_B(40000) = 1.033$$

So even with no noise the maximum dynamic range is 40,000

This treatment ignores the possibility of the detector coming up between the bunch and the ghost. In practice therefore this is only true for the case where the ghost immediately follows the main bunch. As the time between the two increases the detector becomes more sensitive.



- Realistic case with gating and smallest detectable ghost bunch



- Increased gate-off width -> increased sensitivity