Noise Effects on Emittance Blow-up and Luminosity Degradation in HL-LHC

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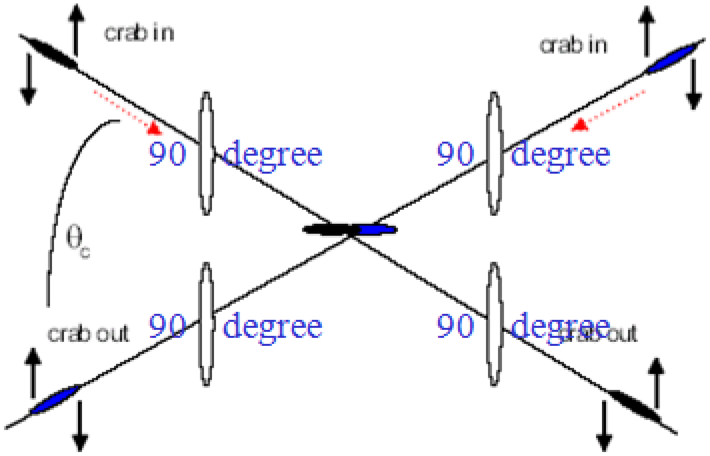
Introduction

- High energy collider, LHC, needs large luminosity

$$L(d_x, \phi_y, \sigma_x, \sigma_y, \sigma_s) = L_0 \frac{e^{-\frac{d_x^2}{4\sigma_x^2}}}{\sqrt{1+\zeta^2}}$$

$$L_0 = \frac{N^2 n_b f_0}{4\pi\epsilon\beta^*} \qquad \zeta = \frac{\phi}{2}\frac{\sigma_s}{\sigma_x}$$

- LHC beam collides with an crossing angle to reduce the long-range beam-beam effects
- Crab cavity compensates the luminosity loss due to crossing angle



crabcavity RF voltage :

$$V = \frac{cE_s \tan(\frac{\theta_c}{2})}{\omega\sqrt{\beta_{x,crab}\beta_x^*}}$$

RF Noise in the Crab Cavity Causes Emittance Growth and Luminosity Degradation

$$x_i \propto V_{cc} \sin(kz_i + \delta\varphi)$$

0th order error (phase error): $\delta X = -\frac{c}{\omega_{cc}} \tan\left(\frac{\theta}{2}\right) \delta\varphi$

1st order error (voltage error): $\delta x_i \propto \delta V_{cc} \sin(kz_i) \approx \delta V_{cc} k z_i$

white noise offset collision drives emittance growth

$$\frac{\delta\varepsilon}{\varepsilon} \approx \frac{K}{\left(1 + \frac{G}{2\pi|\xi|}\right)^2} \frac{\delta x^2}{\sigma_x^2}$$

$$G = 1/\tau$$

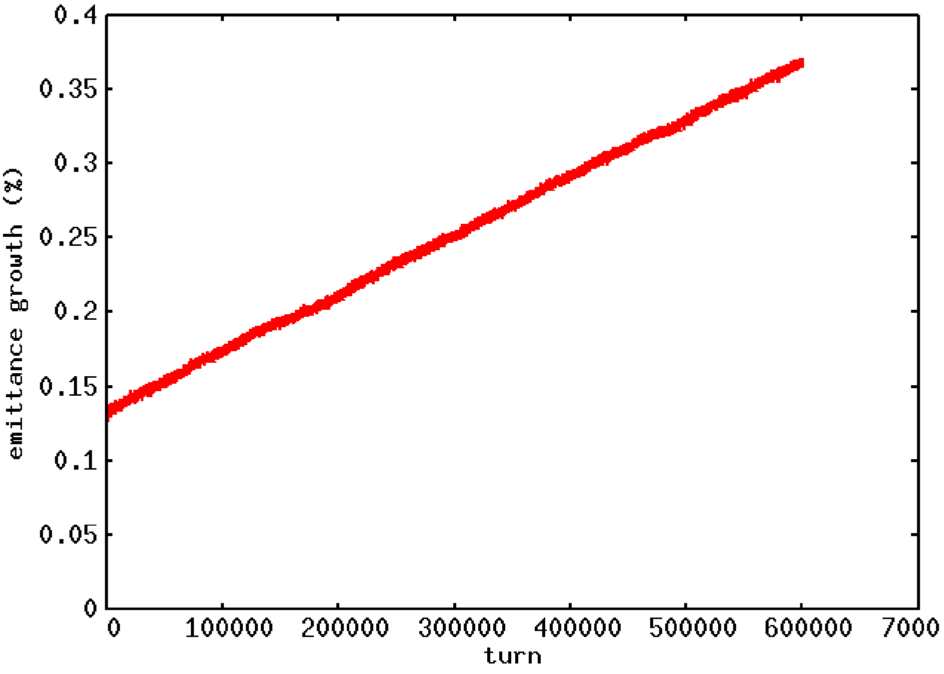
$$\Delta x^2 = \frac{\delta x^2}{2G}$$

$$\frac{\Delta L}{L} = 10.8\left(\xi \frac{\Delta x}{\sigma}\right)^2$$

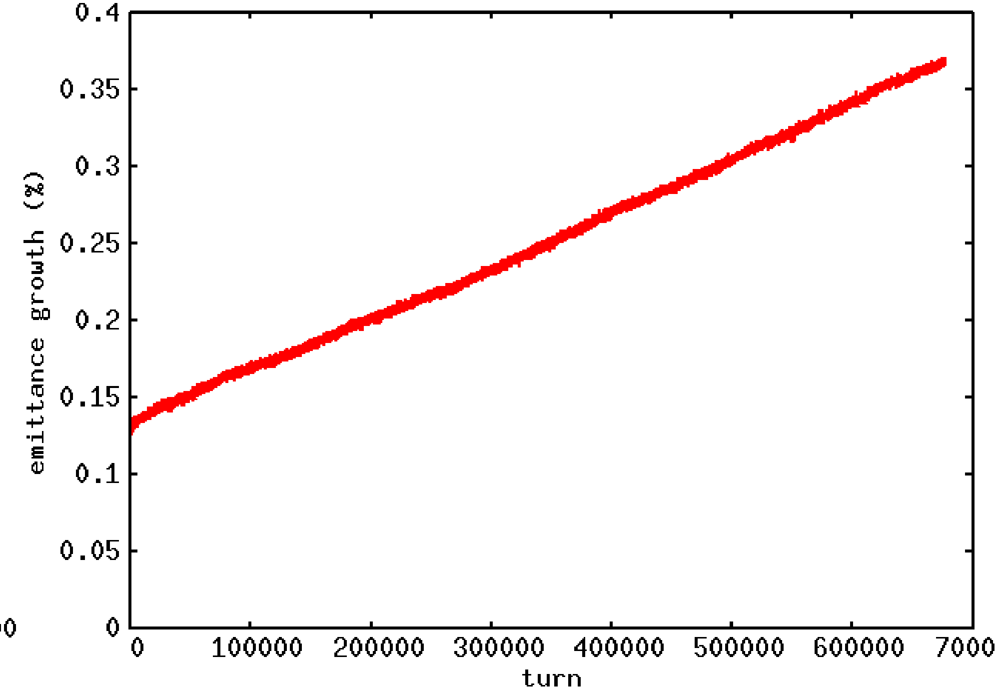
G. Stupakov, SSC-560 (1991).
T. Sen and J. Ellison, PRL 77, 1051 (1996)
Y. Alexahin, NIM A391,73 (1996)
K. Ohmi, in Proc. Beam-Beam 2013 workshop.

Emittance Blow-up due to Phase or Voltage White Noise

emittance blow-up from phase error

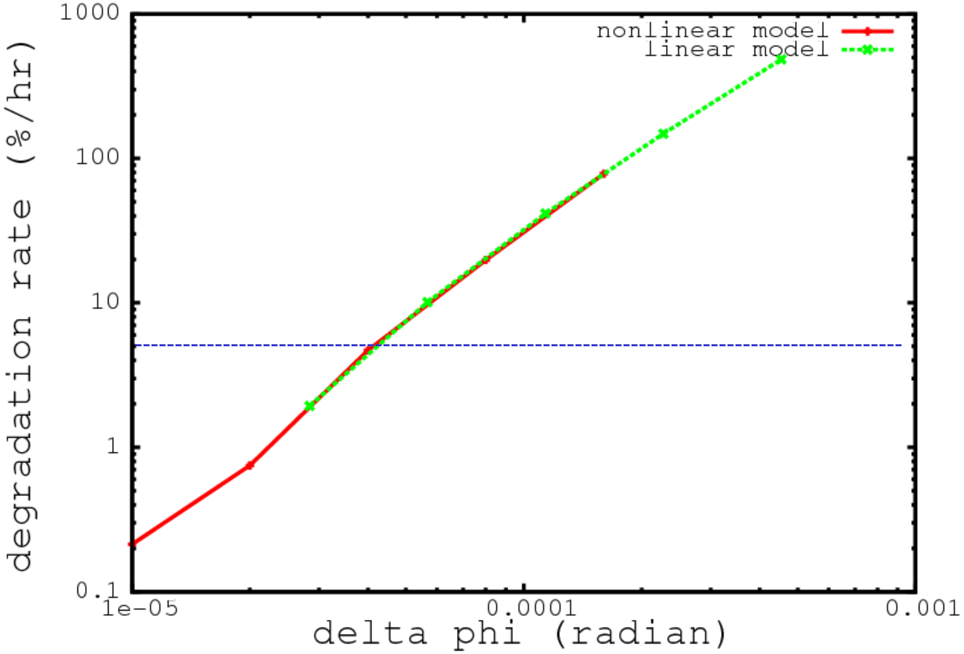


emittance blow-up from voltage error.

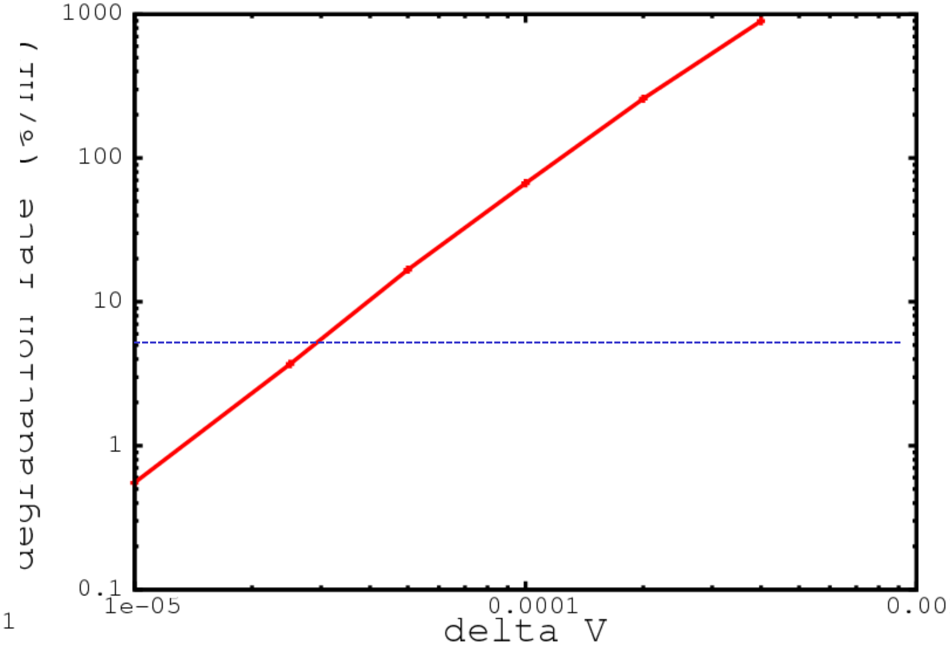


Luminosity Degradation due to Phase or Voltage White Noise

degradation rate vs. phase noise amp.



degradation rate vs. voltage noise amp.

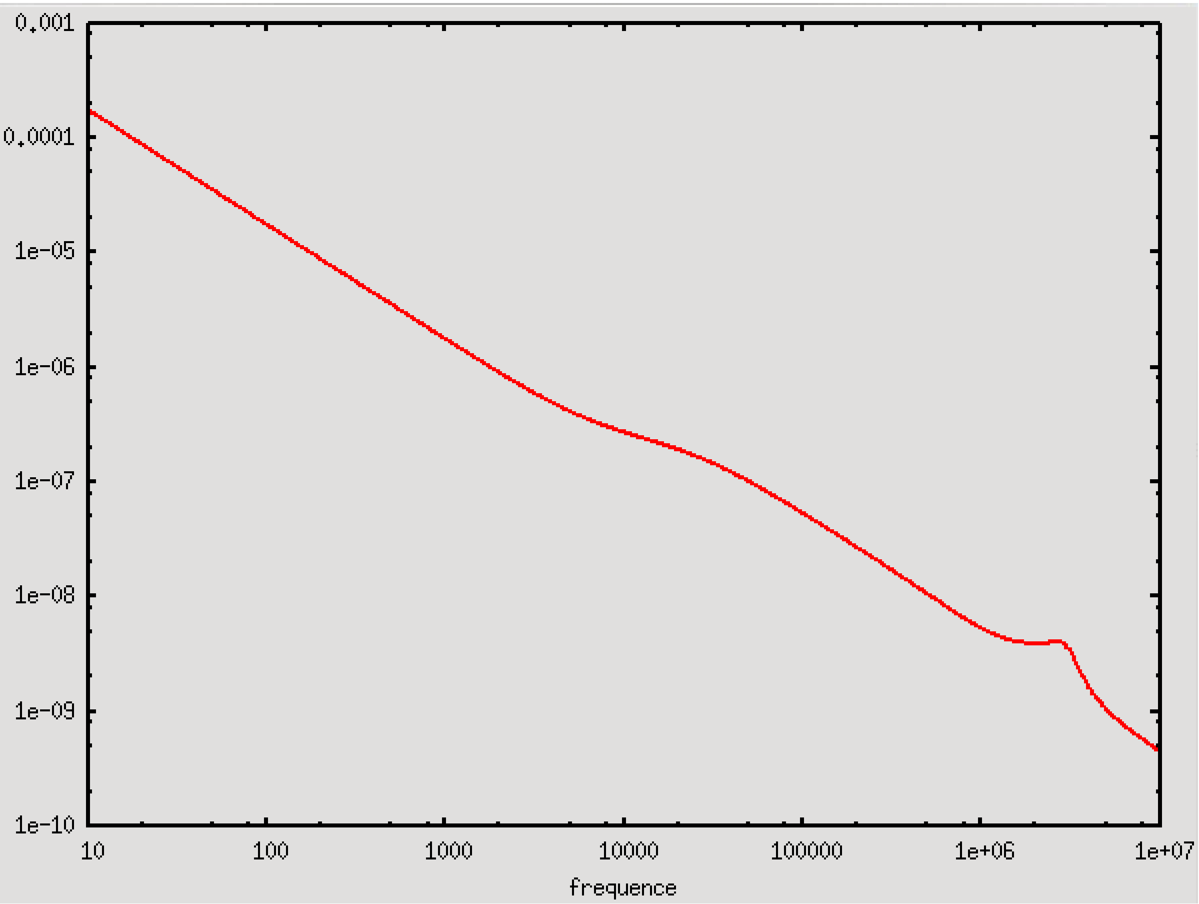


In order to have a good luminosity lifetime ~ 20 hours,
the noise amplitude needs to be kept below the level of a few 10^{-5}.

J. Qiang et al., in Proc. IPAC2015.

Frequency-Dependent Crab Cavity Noise Power Spectrum

(dBc/Hz)



frequency (Hz)

Courtesy of T. Mastori

BeamBeam3D: Parallel Strong-Strong / Strong-Weak Simulation

- Multiple-slice model for finite bunch length effects
- New algorithm -- shifted Green function -- efficiently models long-range parasitic collisions
- Parallel particle-based decomposition to achieve perfect load balance
- Lorentz boost to handle crossing angle collisions
- Arbitrary closed-orbit separation (static or time-dep)
- Independent beam parameters for the 2 beams
- Multiple bunches, multiple collision points
- Linear transfer matrix + one turn chromaticity
- Conducting wire, crab cavity, e-lens compensation model

Computational Model Used in the Simulation

- Strong-Strong beam-beam forces with soft-Gaussian approximation
- Two IPs per turn
- Use both ideal feedback model and a damper feedback model
- Local crab-cavity correction (4 CCs per beam)
- Frequency dependent crab cavity phase errors and voltage errors
- Phase errors amplitude ~ voltage errors amplitude
- 8 slices per beam
- 1 million macroparticles per beam

Some Physical Parameters Used in the Simulations

Physical parameters	
ε	0.335 nm
pick-up gain	0.05
Tunes Chromaticity	62.31/60.32 0 – 4
β^* Θ	15-60 cm 0.59 mrad
ξ N IPs	0.011 - 0.022 1.1 - 2.2x10^{11} 2

Procedure to Generate Turn-Dependent Noise Used in the Simulation Using Frequency-Dependent Noise Spectrum

1) noise errors in each crab cavity are independent of each other;

2) to get the noise error vs. turn, assume 256 samplings per turn (to reach MHz in frequency domain), and for 131072 turns, generate a random white Gaussian noise by sampling a random Gaussian distribution (0,1) using 131072 x 256 data points;

3)FFT the random Gaussian sampling data and extract the frequency dependent data;

4)multiply that frequency dependent data with the spectral data after taking (Sqrt(10^(data/10)));

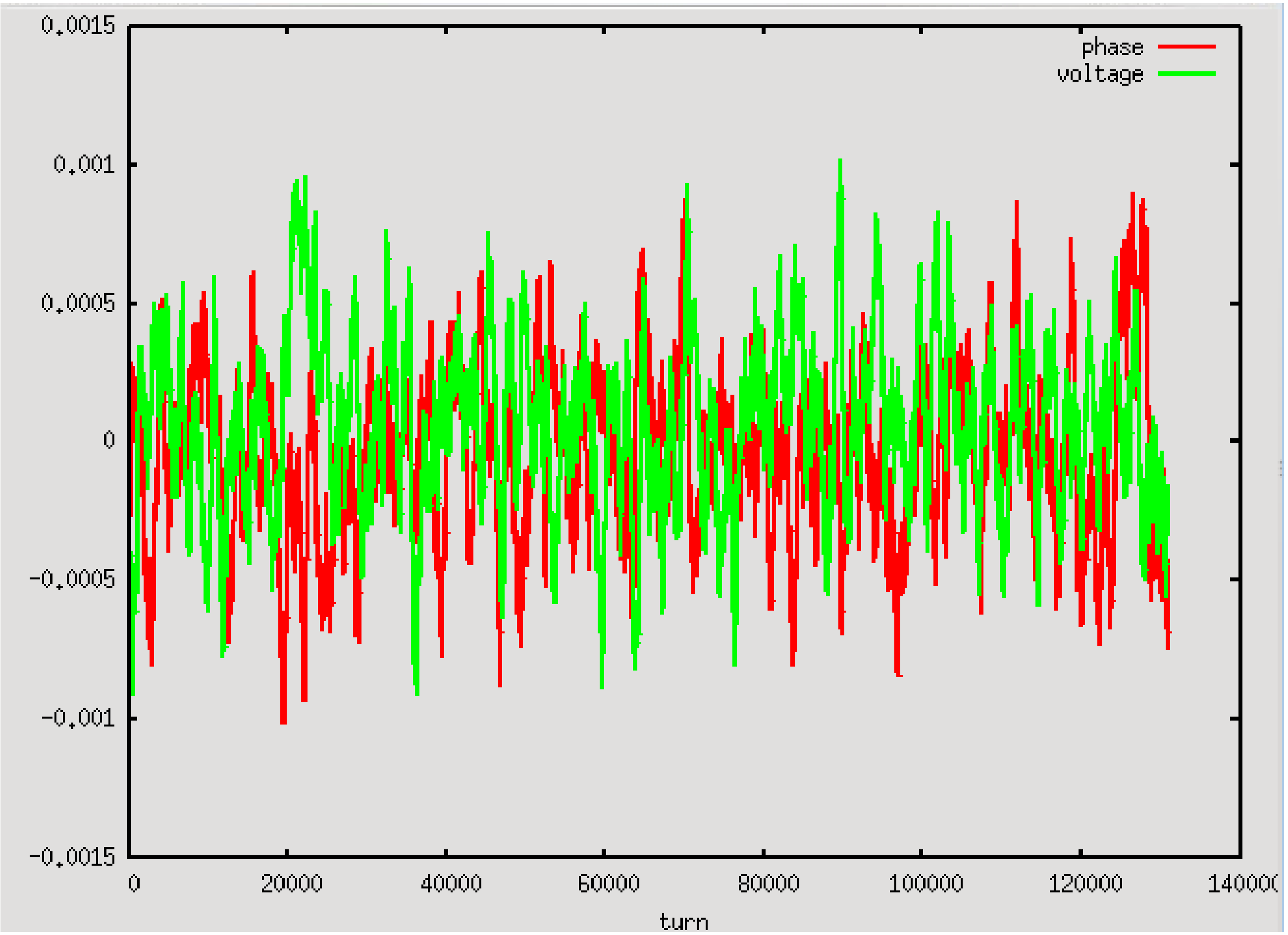
5) take an inverse FFT of the signal and back to time domain;

6)for every 256 data points, select only 1 point to obtain the turn-dependent signal to be used in the crab cavity beam-beam simulation.

7)scale the turn-dependent noise to the nominal rms noise amplitude ~3×10^{-4}.

Crab Cavity Noise in Time Domain

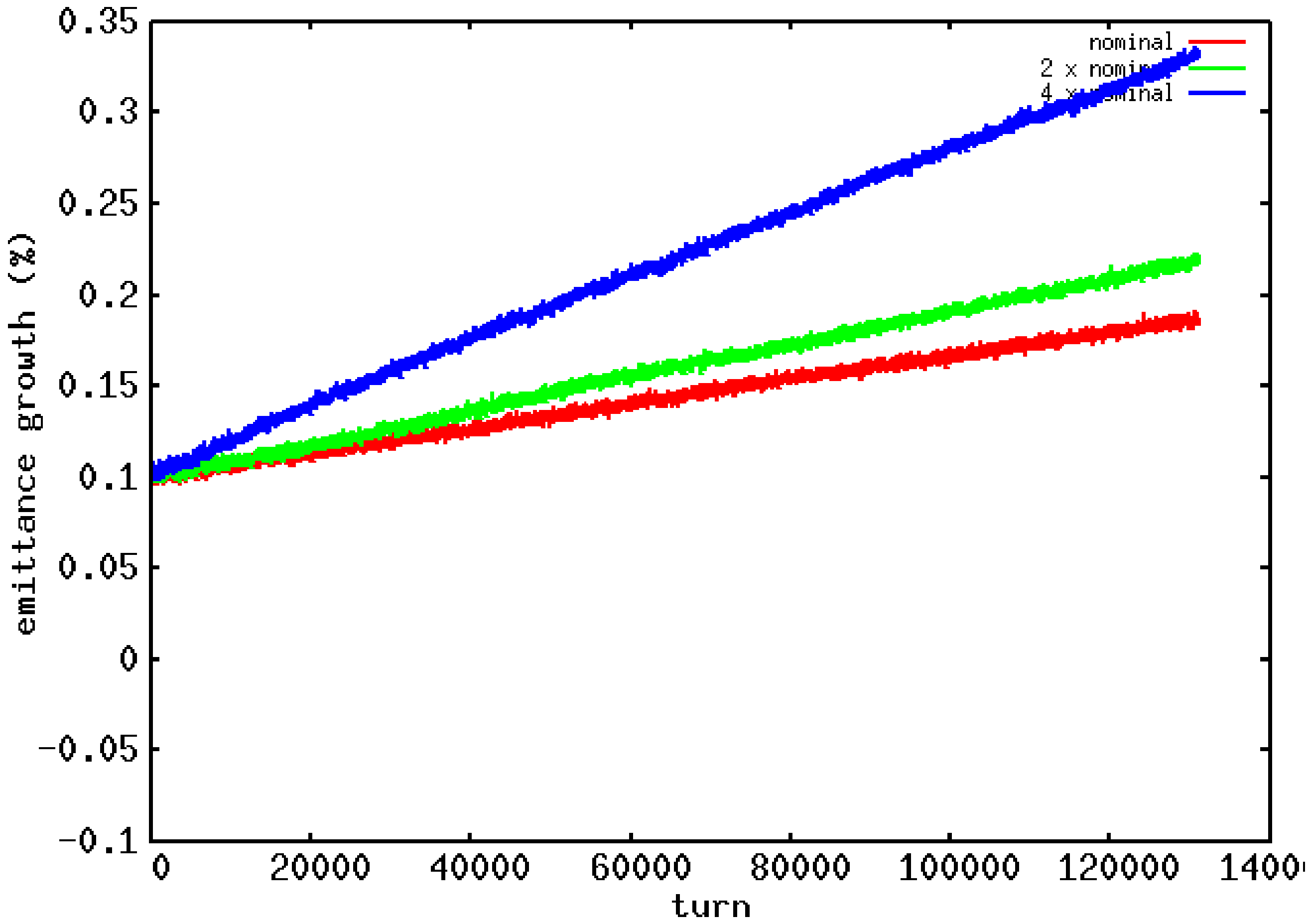
Nominal RMS Amplitude ~ $3x10^{-4}$



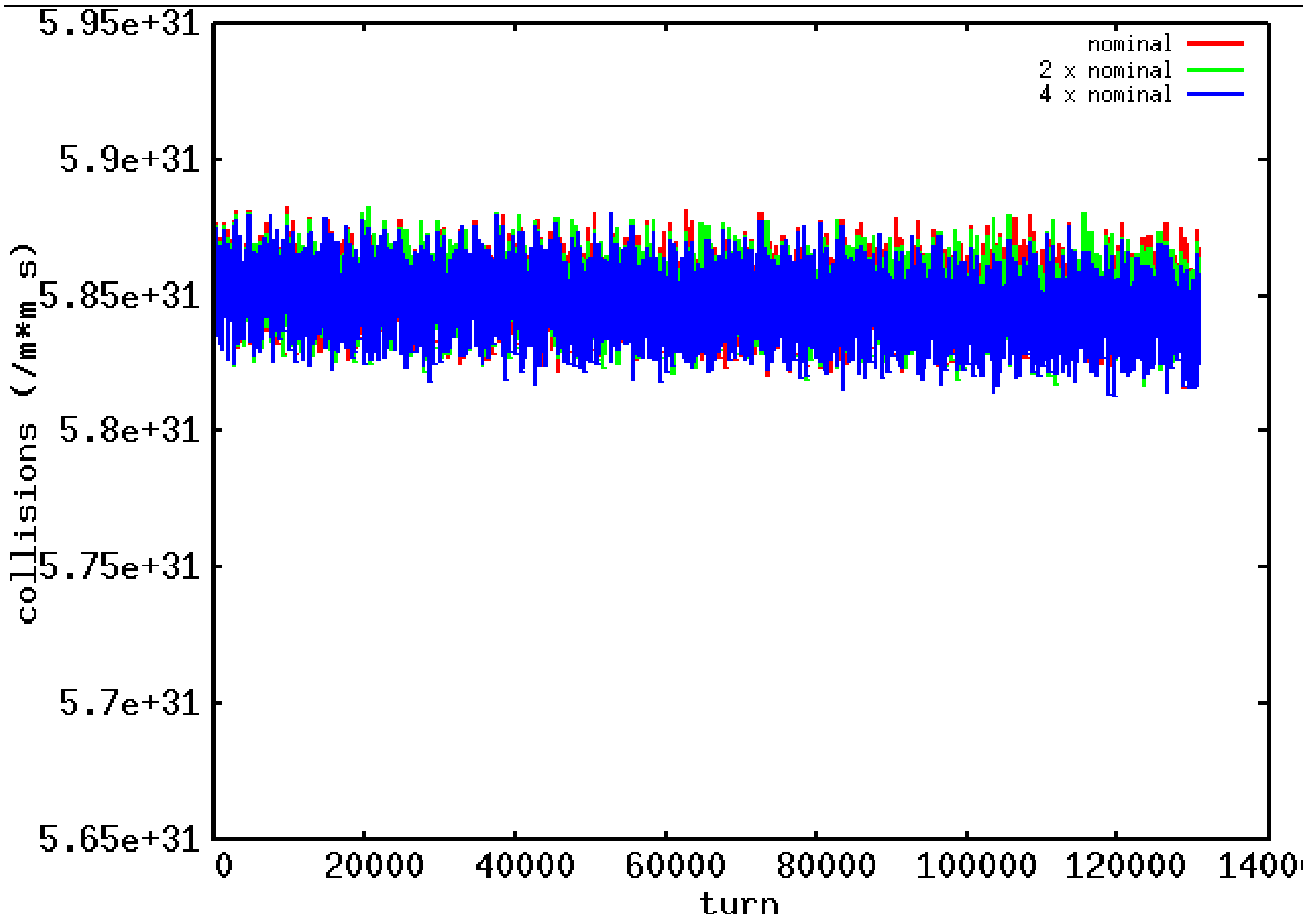
turn

there are additional 14 turn-dependent noise similar to the above ones

RMS Emittance Evolution with Different Noise Amplitudes

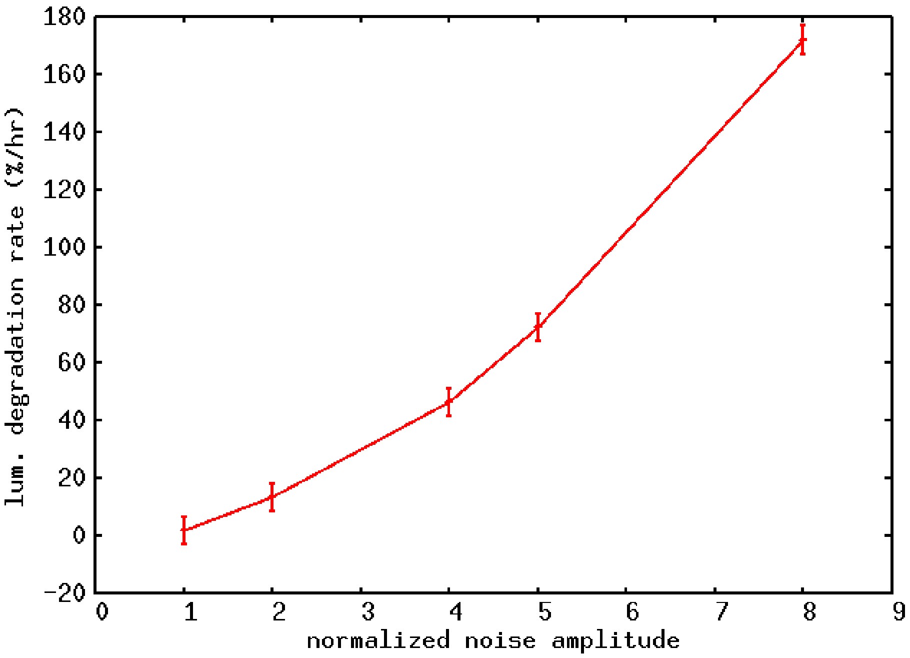


Peak Luminosity Evolution with Different Noise Amplitudes

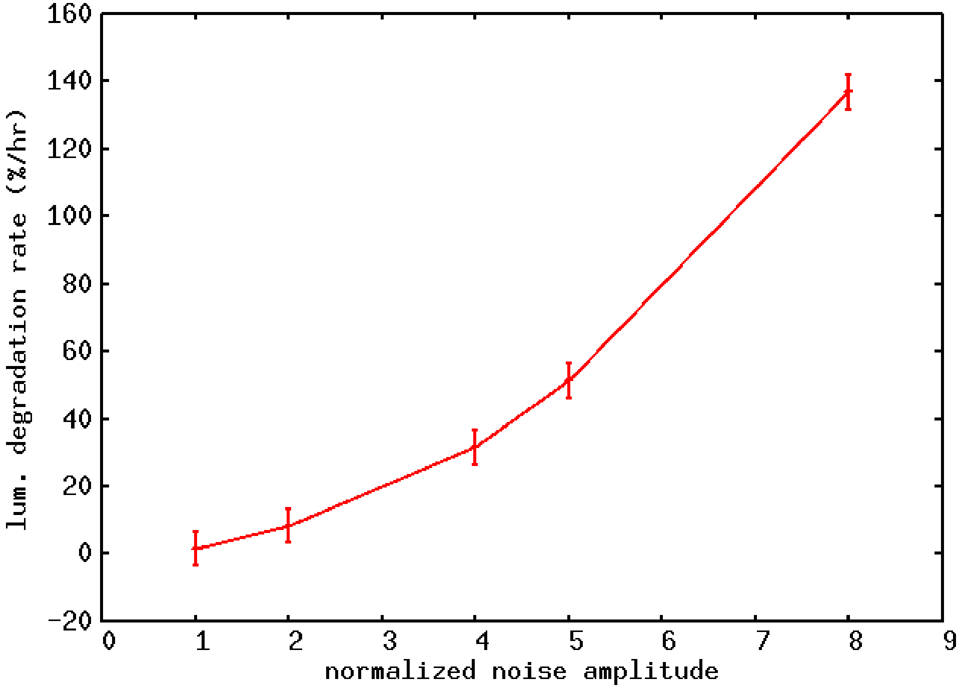


CC Noise Induced Lumi. Degradation
Np = 2.2 x 10^{11}, beta* = 0.15 m

damper feedback model

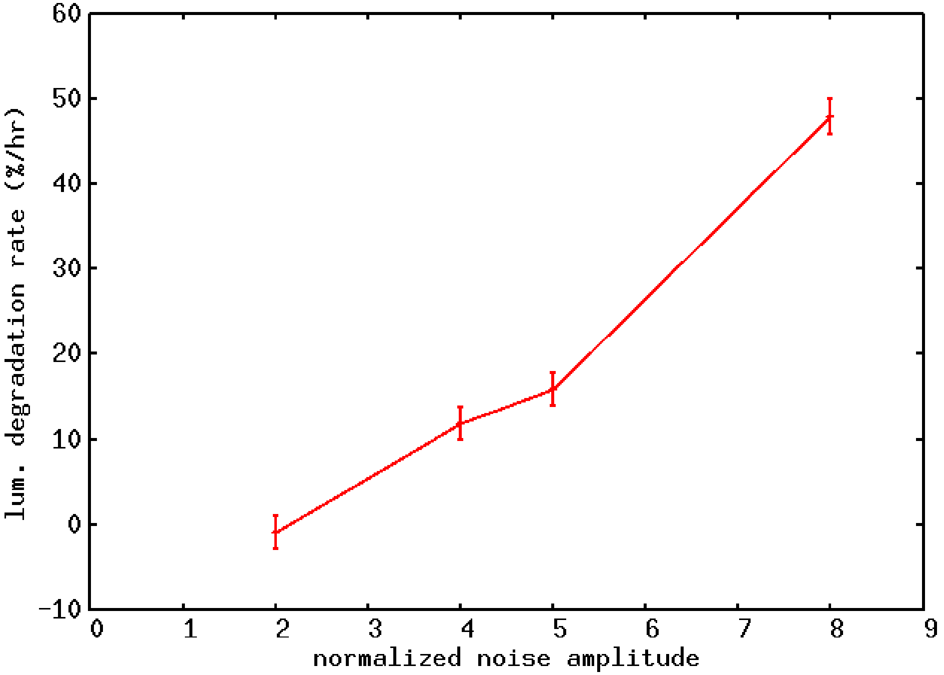


ideal feedback model

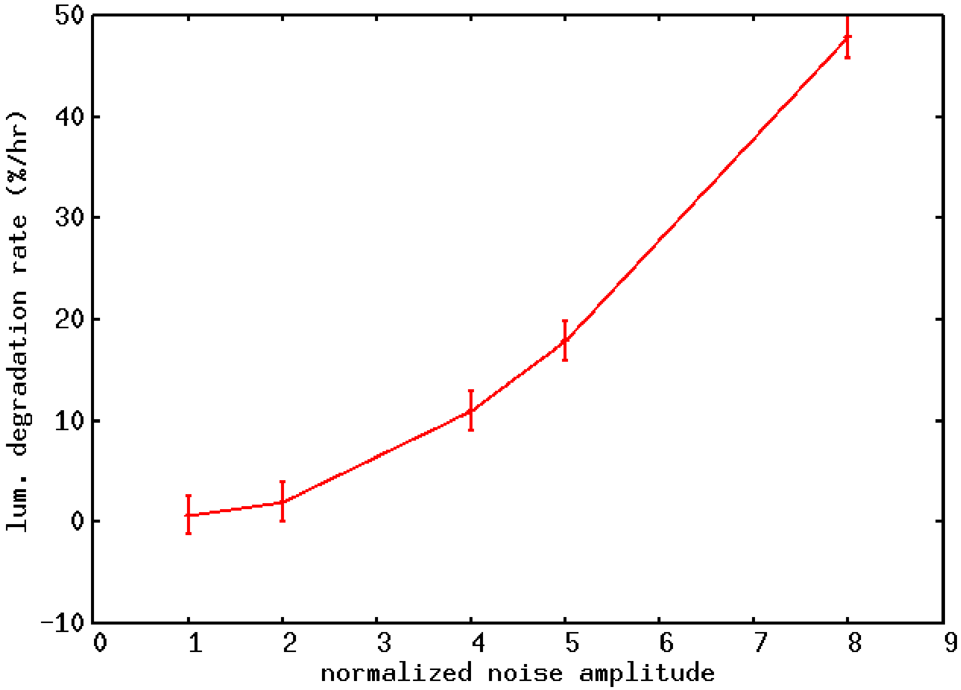


CC Noise Induced Lumi. Degradation
Np = 2.2 x 10^{11}, beta* = 0.49

damper feedback model

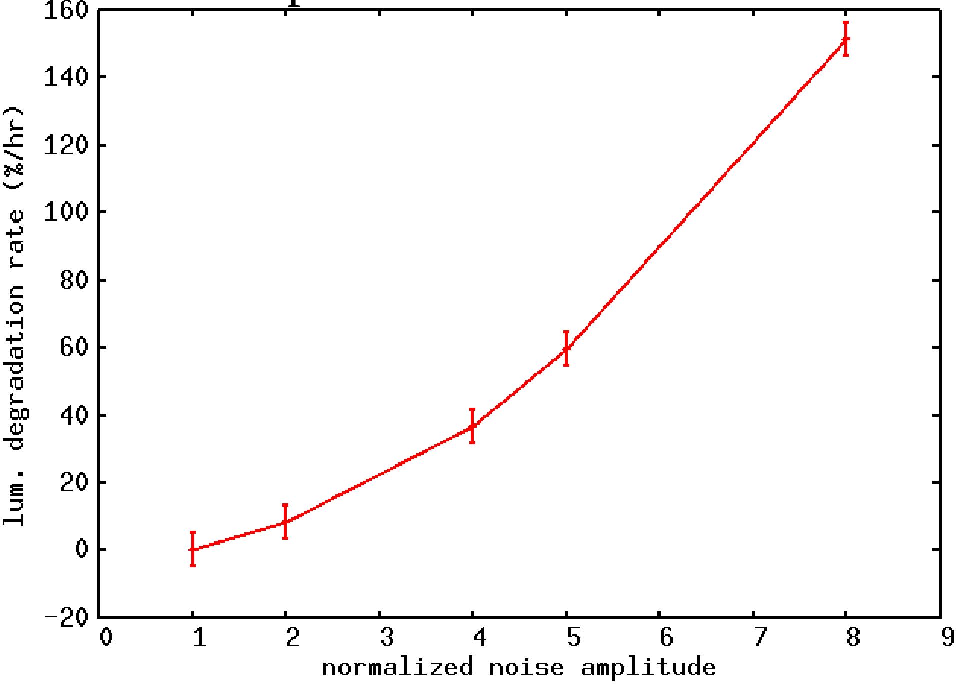


ideal feedback model

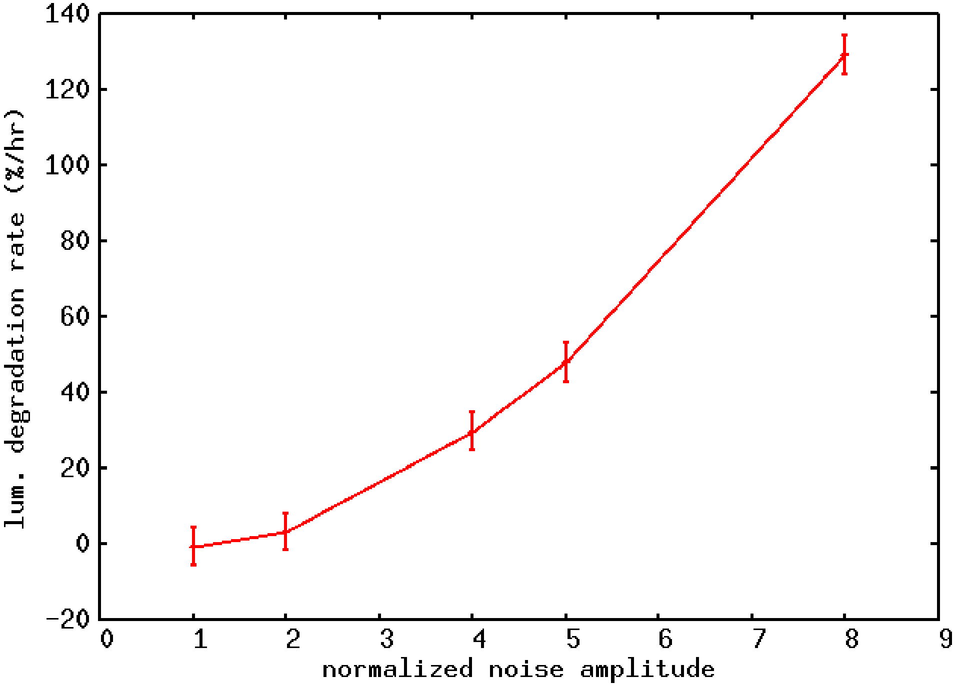


CC Noise Induced Lumi. Degradation
$N_p = 1.1 \times 10^{11}$, beta* = 0.15 m

damper feedback model

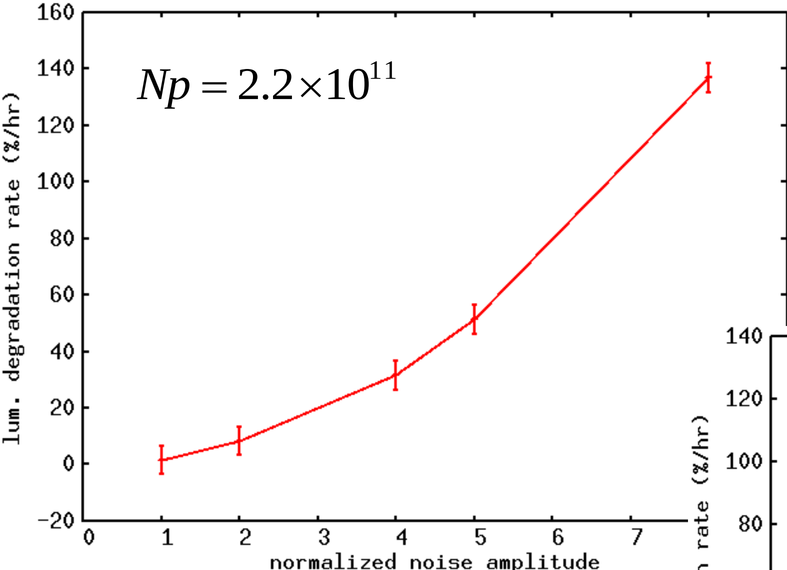


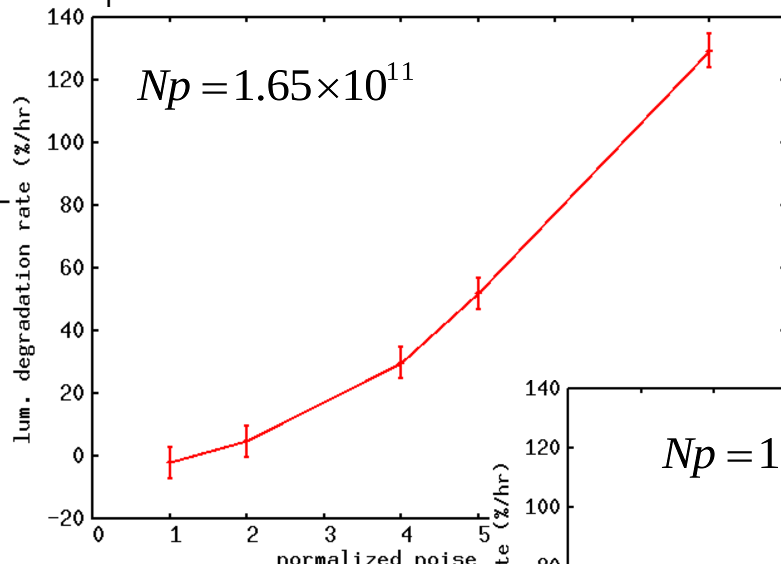
ideal feedback model

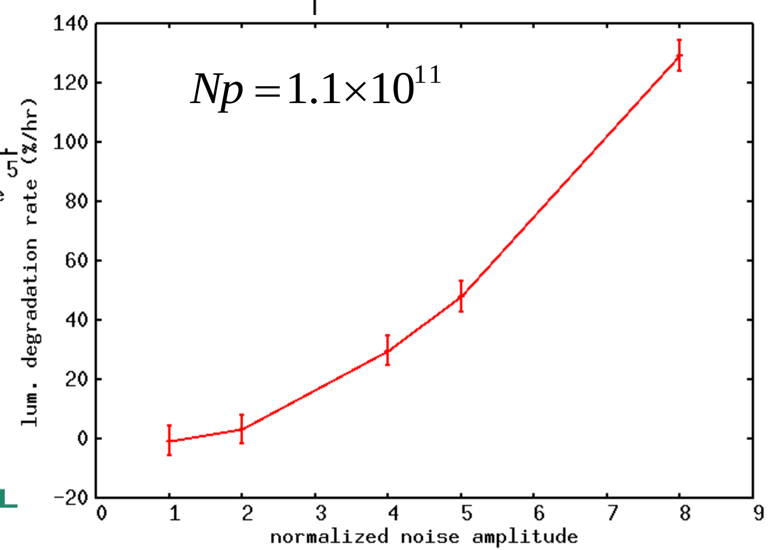


- Damper feedback model and ideal feedback model show similar degradation rate
- A factor of two of the nominal noise amplitude might be acceptable for good luminosity lifetime

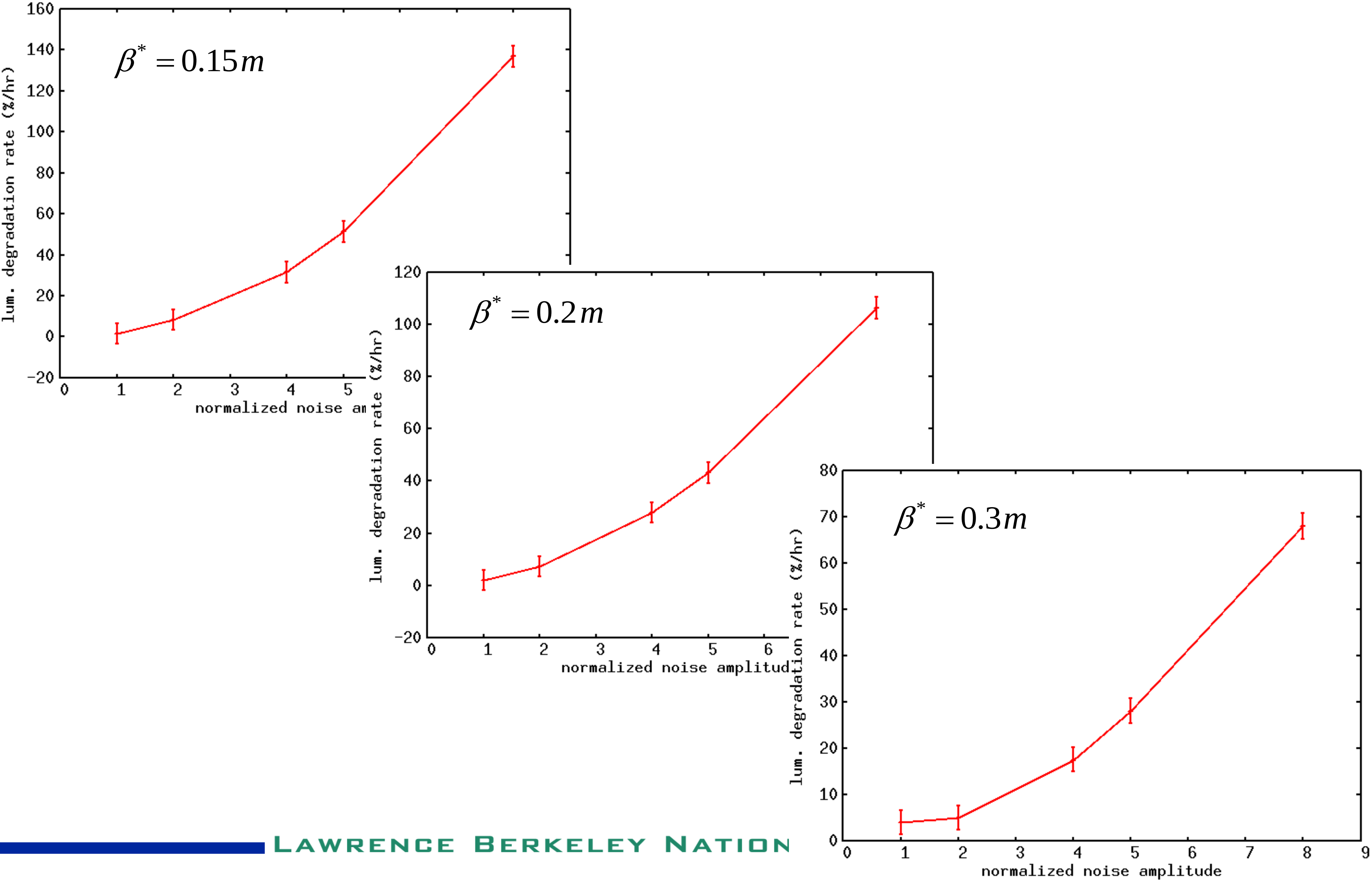
CC Noise Induced Lumi. Degradation with Different Intensities
beta* = 0.15 m



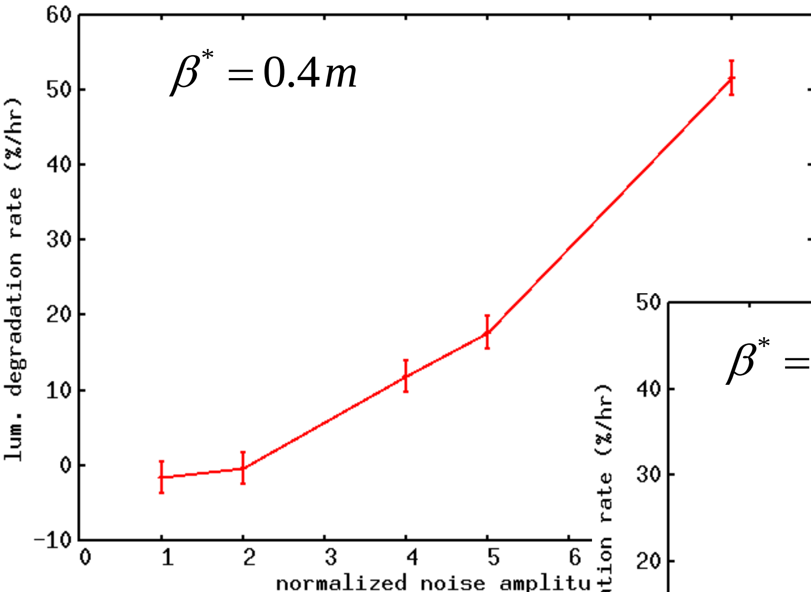


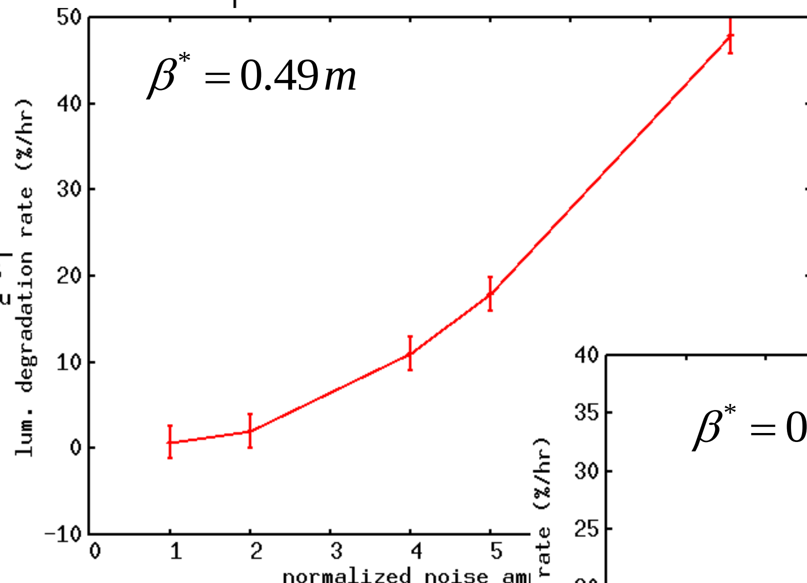


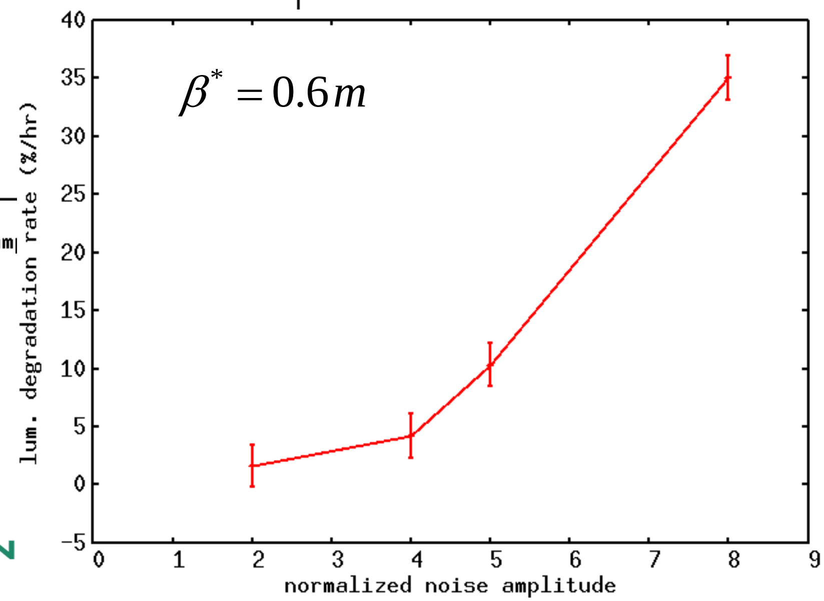
CC Noise Induced Lumi. Degradation with Different beta*
Np = 2.2 x 10^{11}



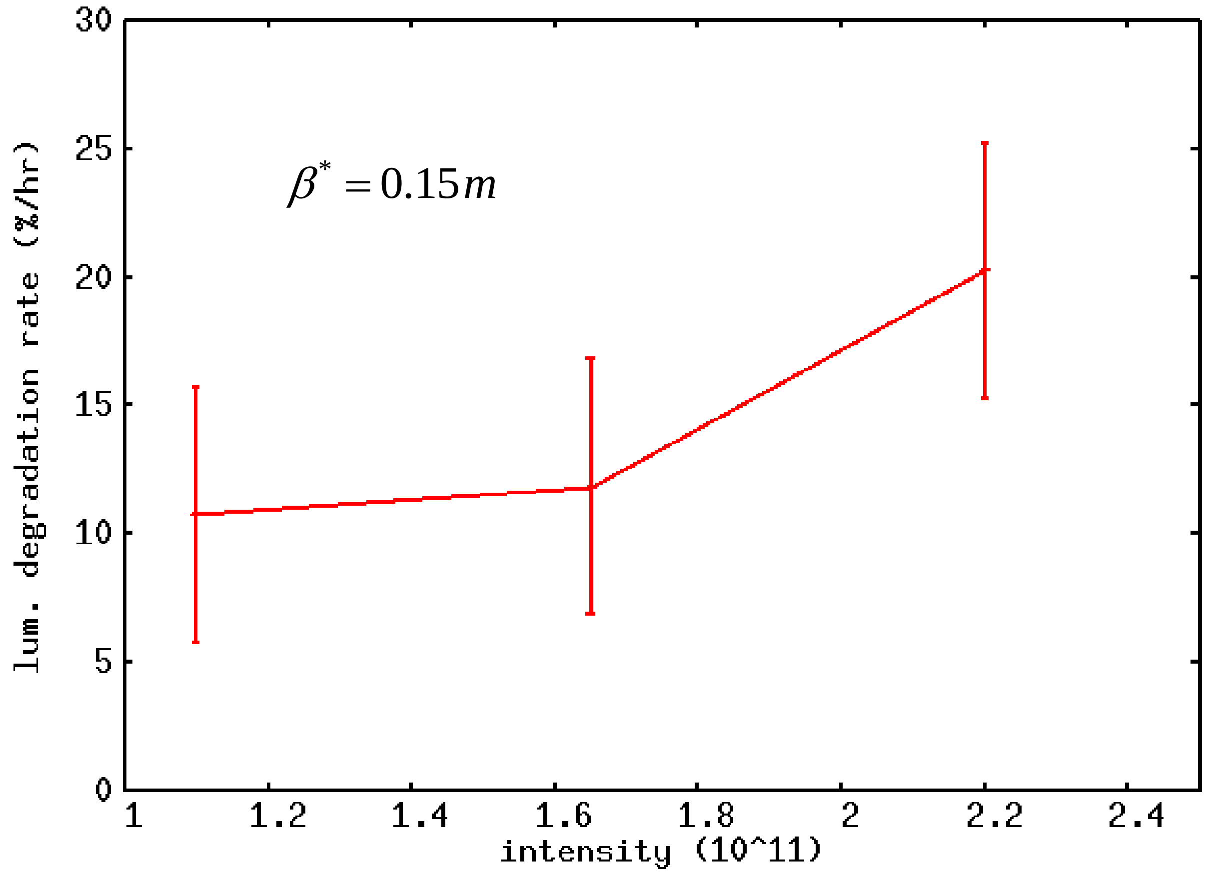
CC Noise Induced Lumi. Degradation with Different beta*
Np = 2.2 x 10^{11}







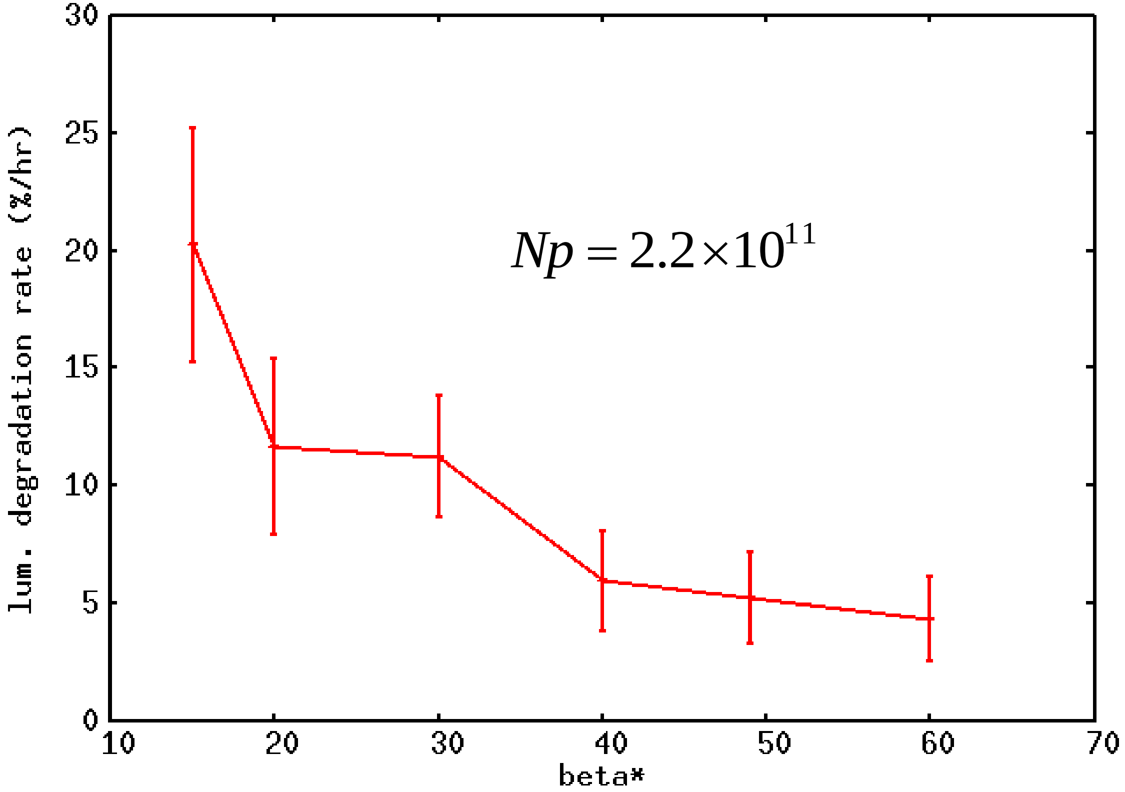
CC Noise Induced Lumi. Degradation with vs. Intensity (with nominal noise amplitude)



qualitatively agrees with the analytical model based on white noise but much weaker scaling

$$\frac{\Delta L}{L} = 10.8\left(\xi \frac{\Delta x}{\sigma}\right)^2$$

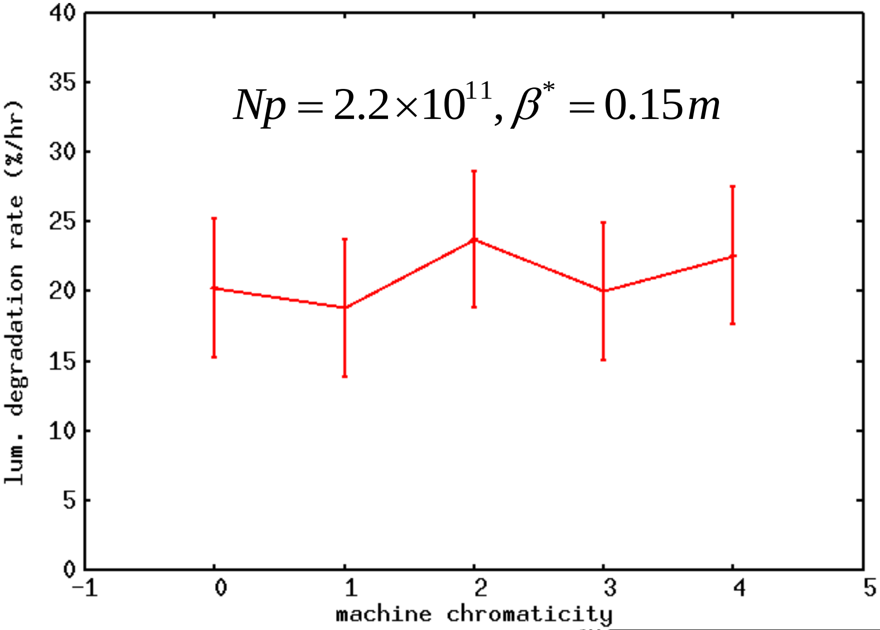
CC Noise Induced Lumi. Degradation with vs. beta* (with nominal noise amplitude)

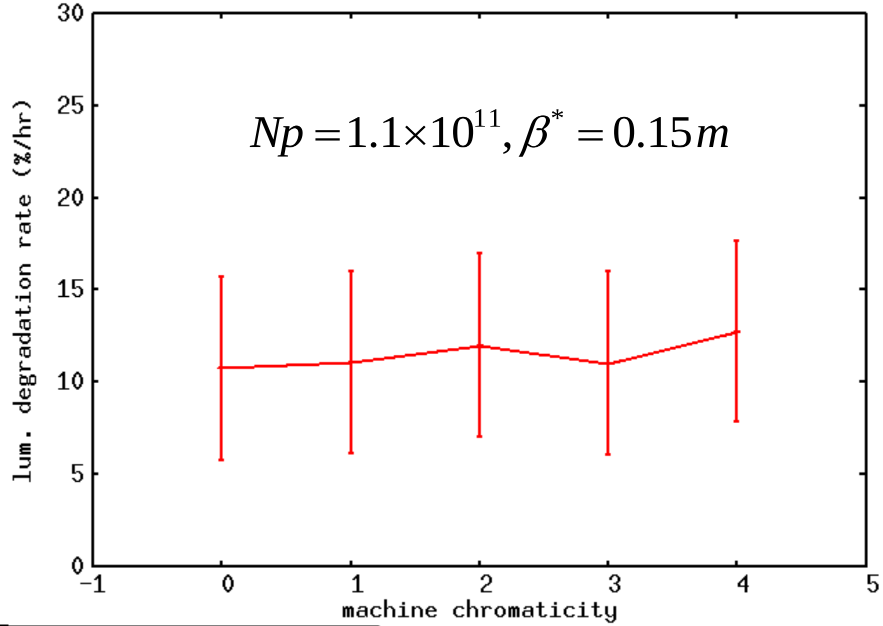


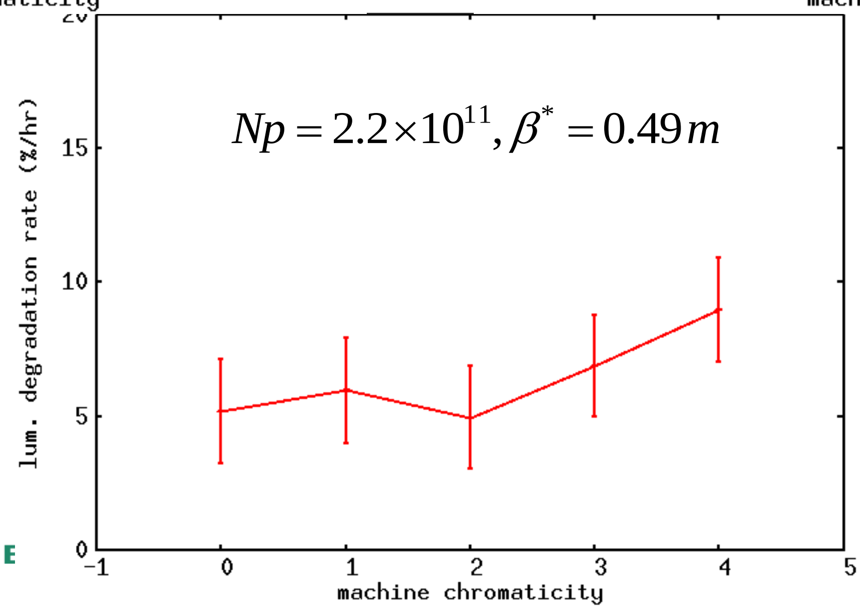
qualitatively agrees with the analytical model based on white noise

$$\frac{\Delta L}{L} = 10.8\left(\xi\frac{\Delta x}{\sigma}\right)^2$$

Lumi. Degradation with Different Chromaticities (and with nominal CC noise amplitude)

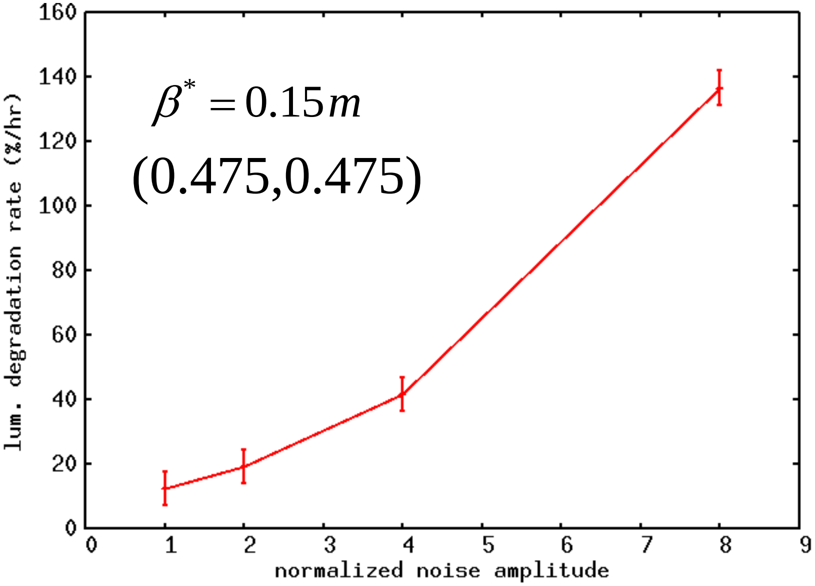


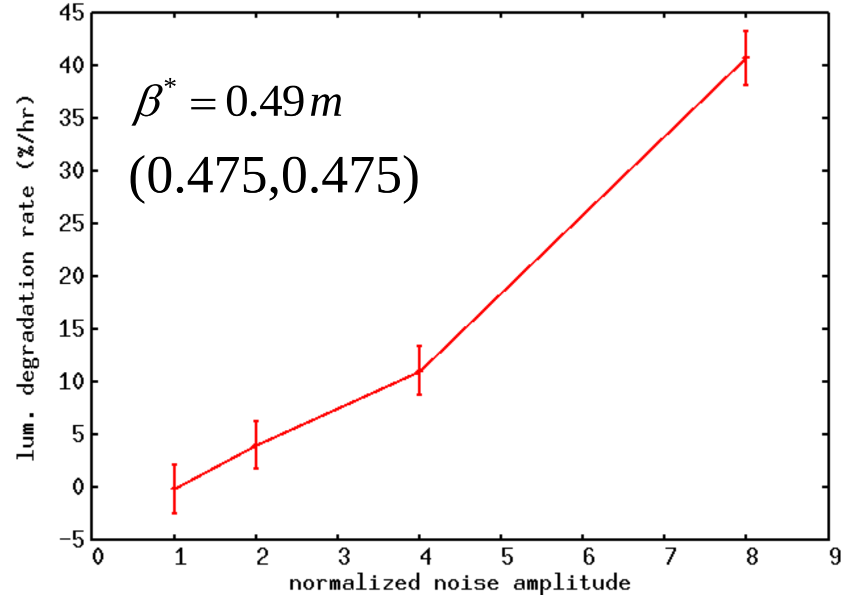


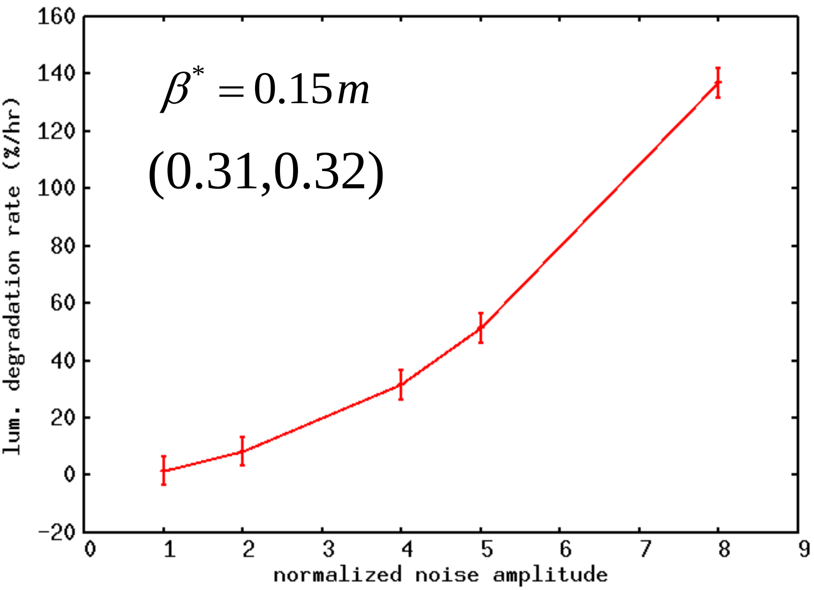


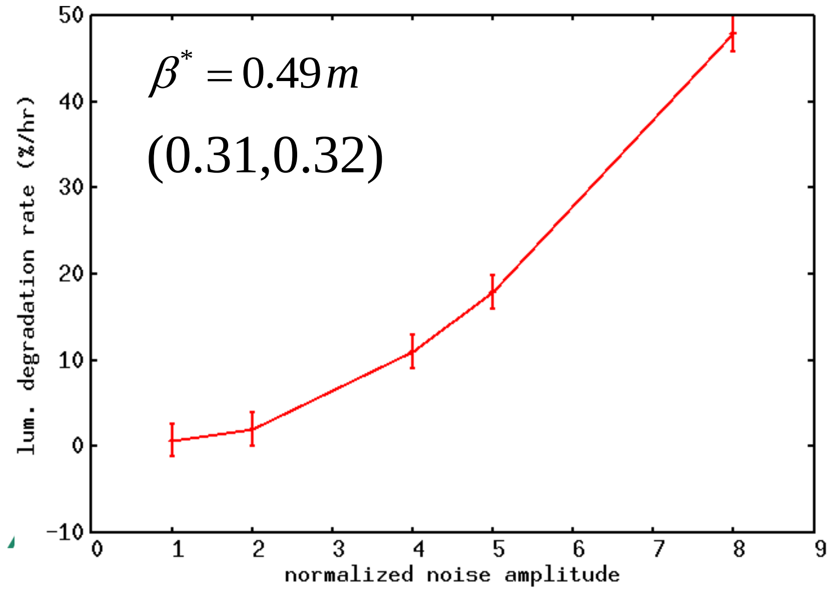
CC Noise Induced Lumi. Degradation with Different Working Points

$Np = 2.2\times10^{11}$ (0.475,0.475) vs. (0.31,0.32)









Conclusions

- Frequency-dependent noise error shows larger error tolerance than the white noise error for luminosity lifetime.
- Nominal 3×10^{-4} frequency-dependent phase and voltage noise rms amplitude will not cause significant luminosity lifetime degradation during beta* leveling.
- Luminosity degradation rate decreases with the increase of the beta*.
- Luminosity degradation rate increases with the increase of the bunch intensity.
- Luminosity degradation rate is not sensitive to the machine chromaticity and tune working point.