Models and Evidence of Shot Noise Reduction and Amplification

Daniel Ratner, SLAC

May 24, 2012

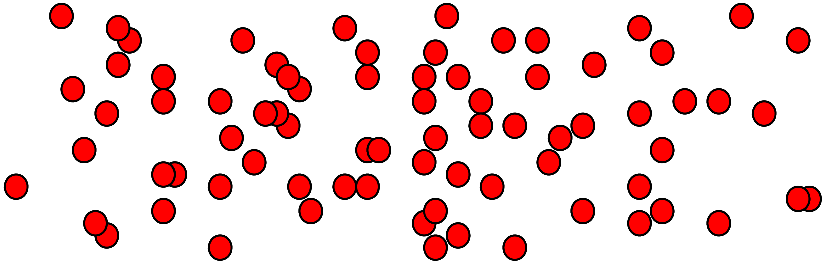
IPAC '12, New Orleans

Shot Noise Reduction and Amplification

1. Motivation for studying shot noise in accelerators

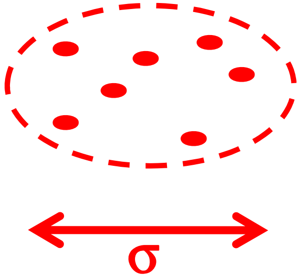
2. Model for shot noise reduction and amplification

3. Experimental evidence of shot noise reduction



Electron Microbunching

Shot Noise



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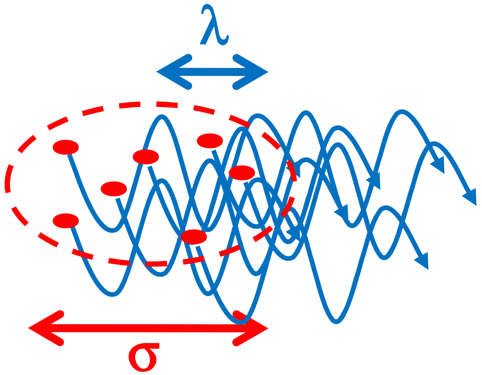
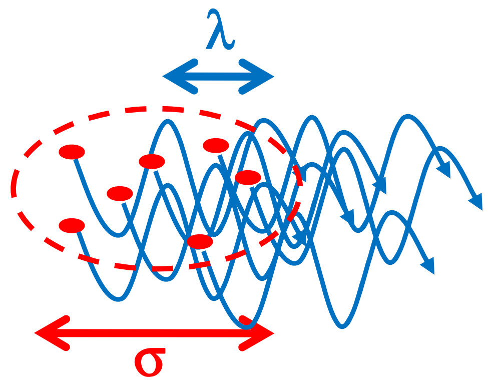


Number of electrons

$$P_{rad}(\lambda) \propto N_e$$

Electron Microbunching

Shot Noise



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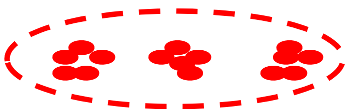

Shot Noise Reduction

Electron Microbunching

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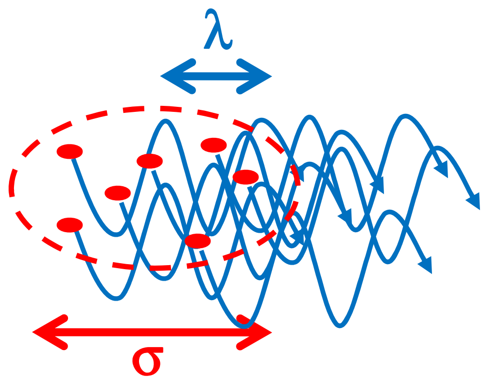

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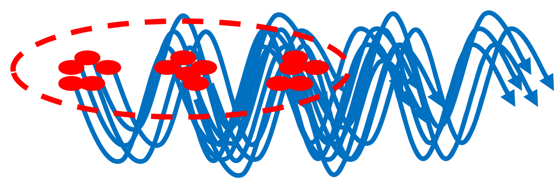
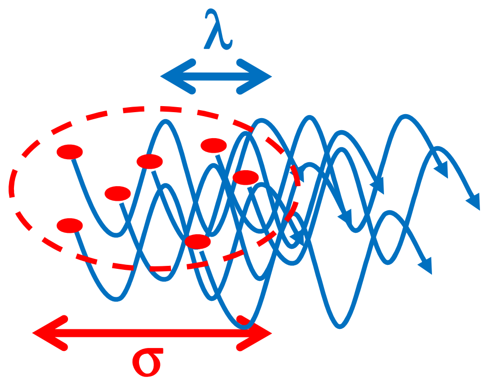


$$P_{rad}(\lambda) \propto N_e^2$$

Electron Microbunching

Shot Noise



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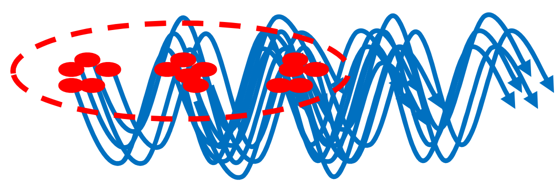

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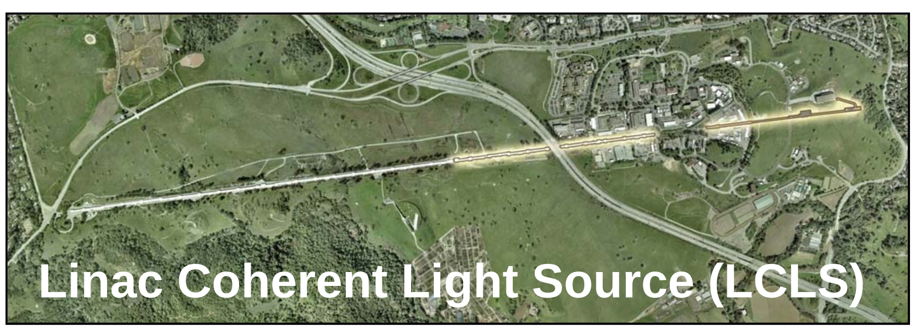

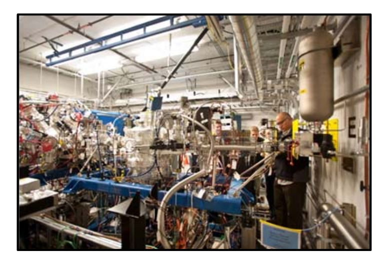

Electron Microbunching

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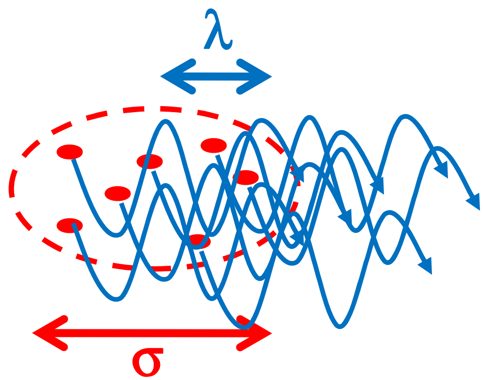

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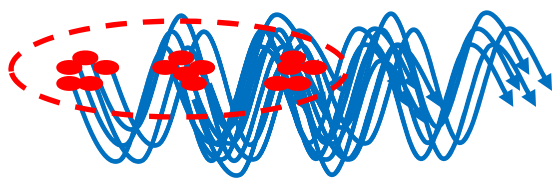
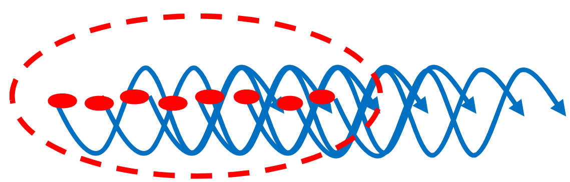


$$P_{rad}(\lambda) \propto N_e^2$$

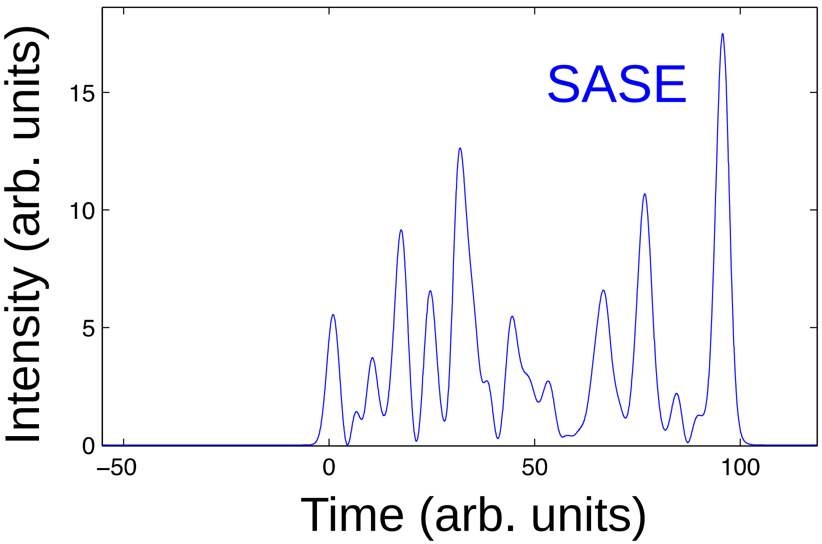
Noise Reduction



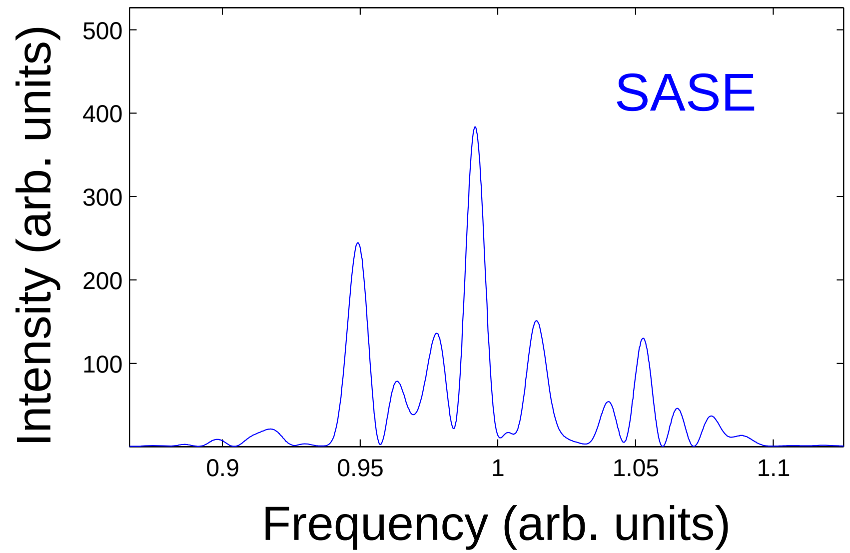
$$P_{rad}(\lambda) \rightarrow 0$$

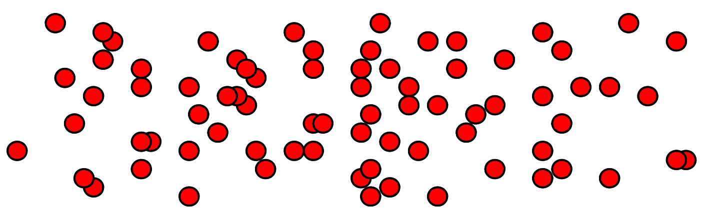
Motivation: Seeded FELs

Time Domain



Frequency Domain





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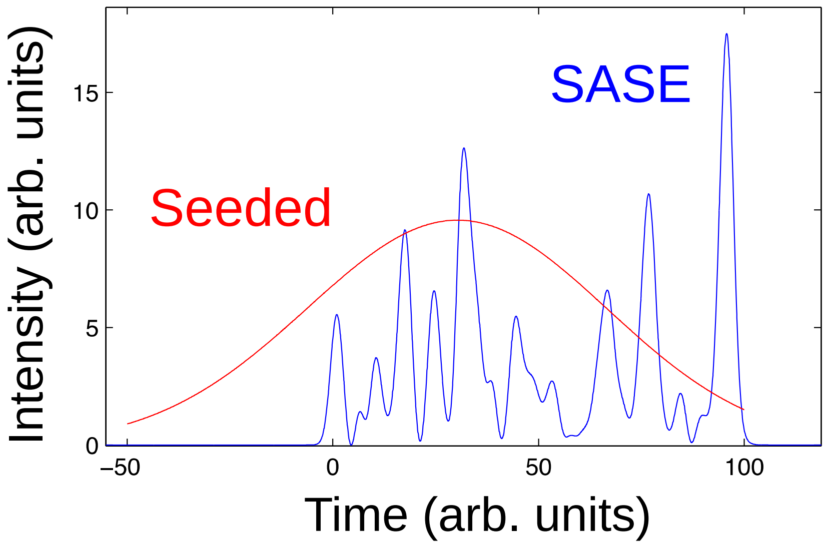

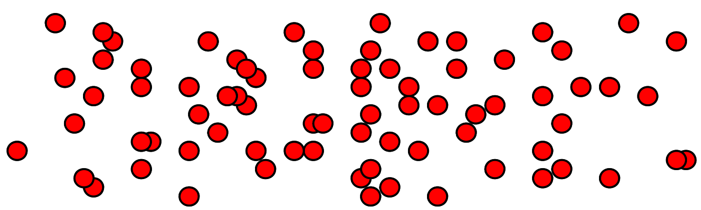

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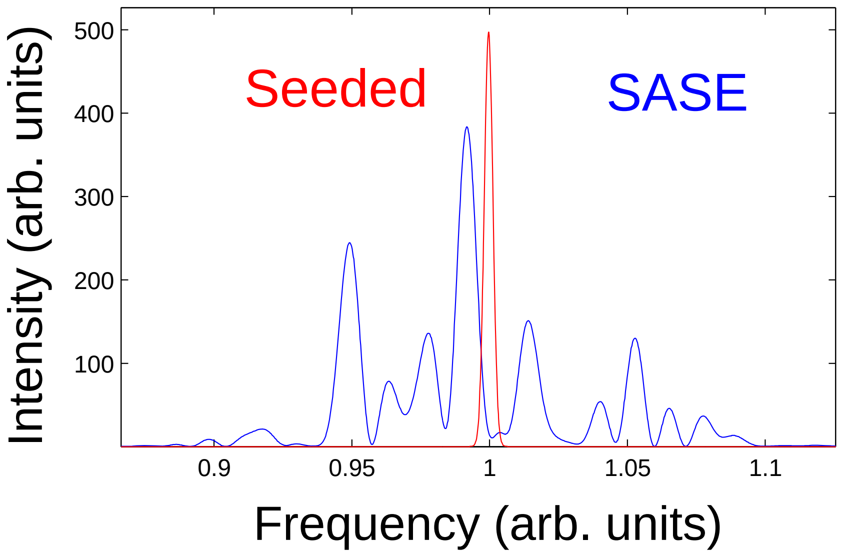

Theoretical Models

PRL **102,** 154801 (2009) PHYSICAL REVIEW LETTERS week ending 17 APRIL 2009

Collective-Interaction Control and Reduction of Optical Frequency Shot Noise in Charged-Particle Beams

A. Gover and E. Dyunin

Proceedings of FEL2009, Liverpool, UK TUOB05

SUPPRESSING SHOT NOISE AND SPONTANEOUS RADIATION IN ELECTRON BEAMS*

Vladimir N. Litvinenko, BNL, Upton, USA#

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14,** 060710 (2011)

Analysis of shot noise suppression for electron beams

Daniel Ratner

Department of Applied Physics, Stanford University, Stanford, California 94305, USA

Zhirong Huang and Gennady Stupakov

Theoretical Models

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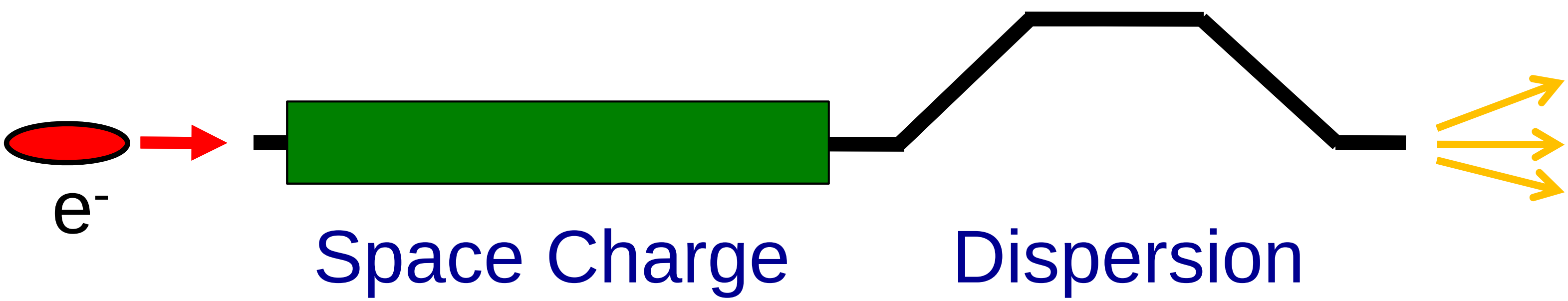
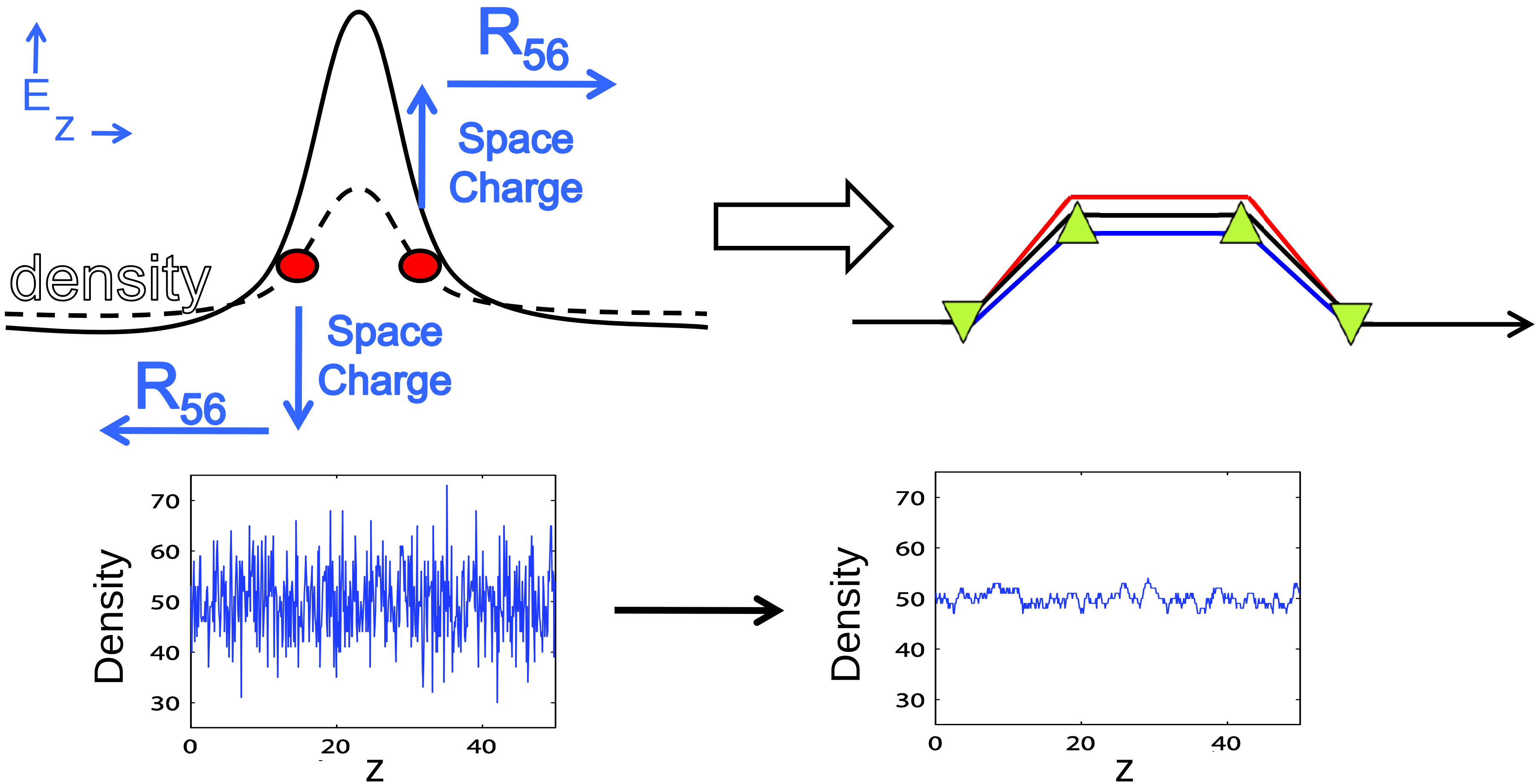


Physical Picture



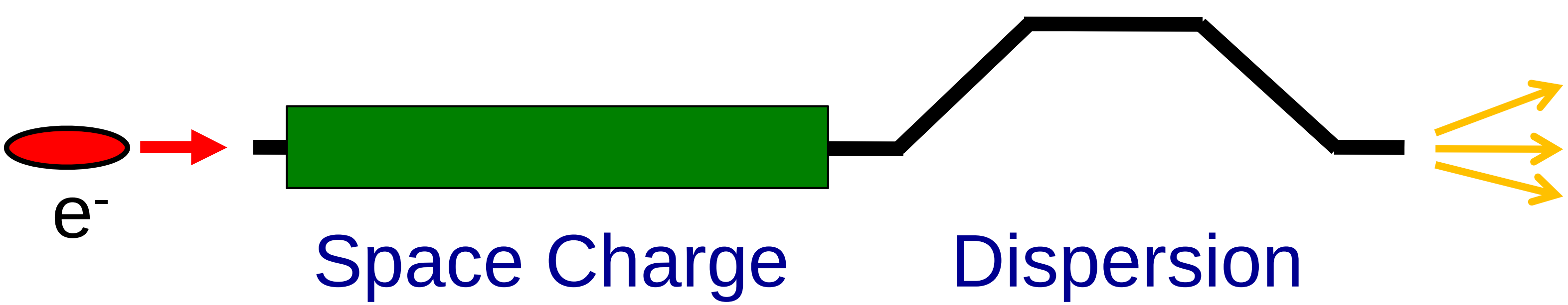
Model radiation from beam:

$$\left(\frac{d^2 I}{d\omega d\Omega}\right)_{\text{tot}} = \left(\frac{d^2 I}{d\omega d\Omega}\right)_1 |N b(\vec{k})|^2$$

e.g. for optical transition radiation

$$\left(\frac{d^2 I}{d\omega d\Omega}\right)_1 \propto \frac{\gamma^4(\theta_x^2 + \theta_y^2)}{\left[1 + \gamma^2(\theta_x^2 + \theta_y^2)\right]^2}$$

energy γ, observation angle θ



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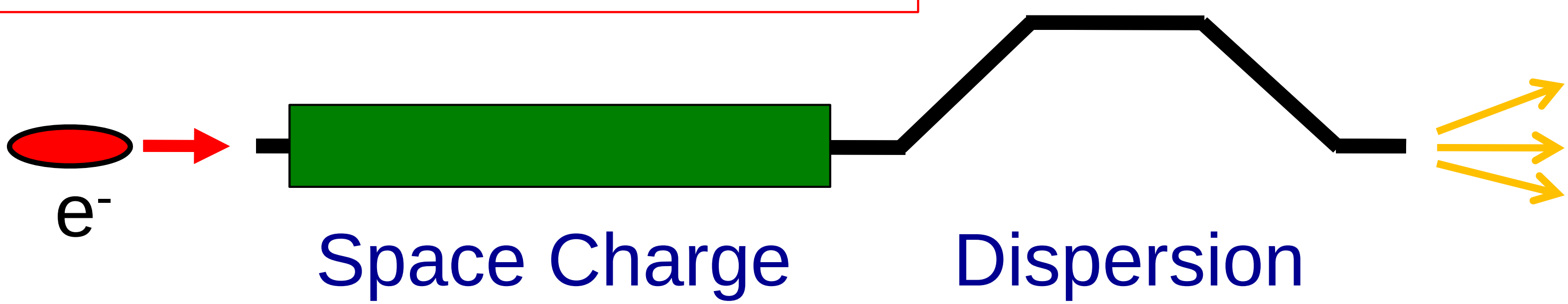
energy γ, observation angle θ

$$b(\vec{k}) = \frac{1}{N}\sum_j^N \exp\left[-i\tilde{K}X_j\right]$$

$$\tilde{K} \equiv [k\theta_x \ 0 \ k\theta_y \ 0 \ k \ 0]$$

$$k = 2\pi/\lambda$$

N particles with coordinates X_j



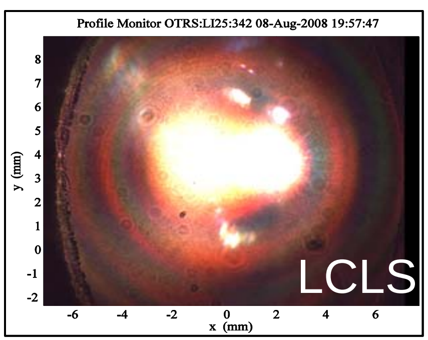
Solve bunching in 1D Limit

$$N\left\langle \left| b(\vec{k}) \right|^2 \right\rangle \approx (1-\Upsilon)^2$$

$$\Upsilon \equiv n_0 R_{56} A$$

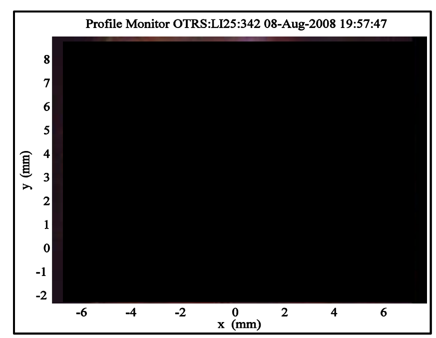
Charge density, n_0, dispersion R_{56}, space charge strength, A

Noise Amplification:
Y >>1

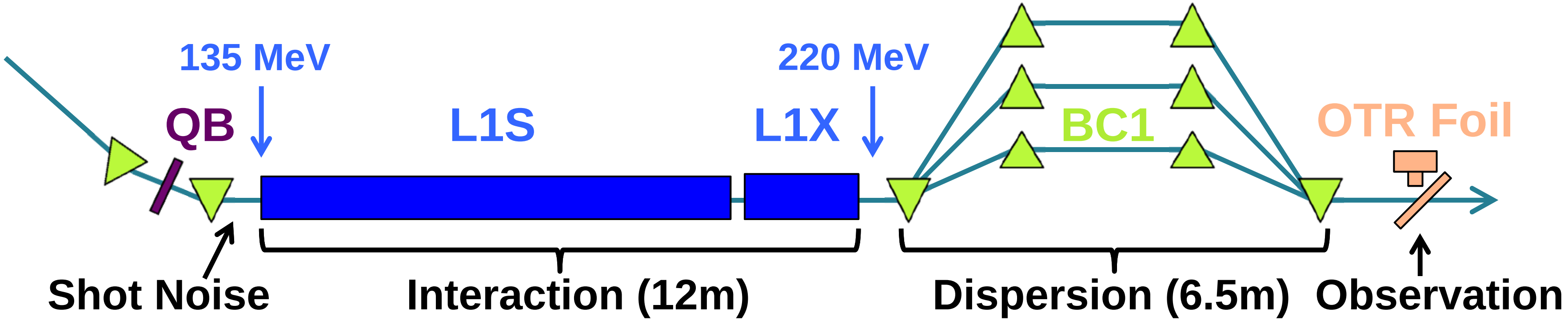


E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 13(2010)110701

Noise Reduction:
Y ~ 1



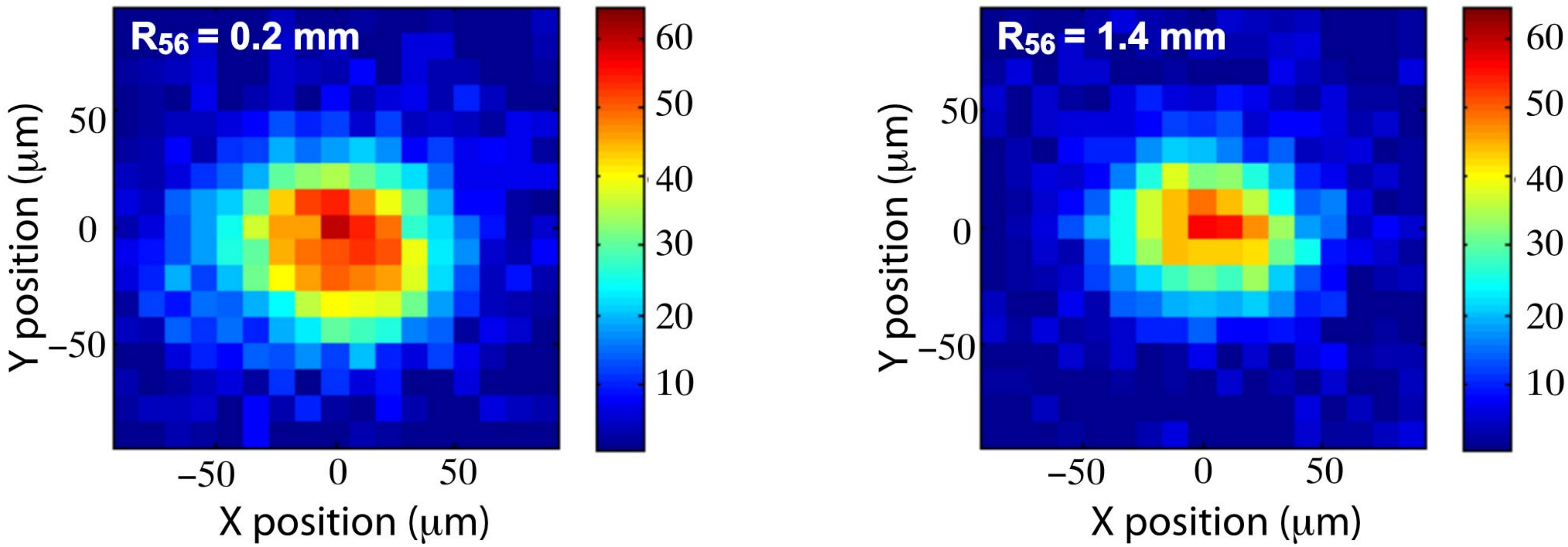
Experimental Schematic

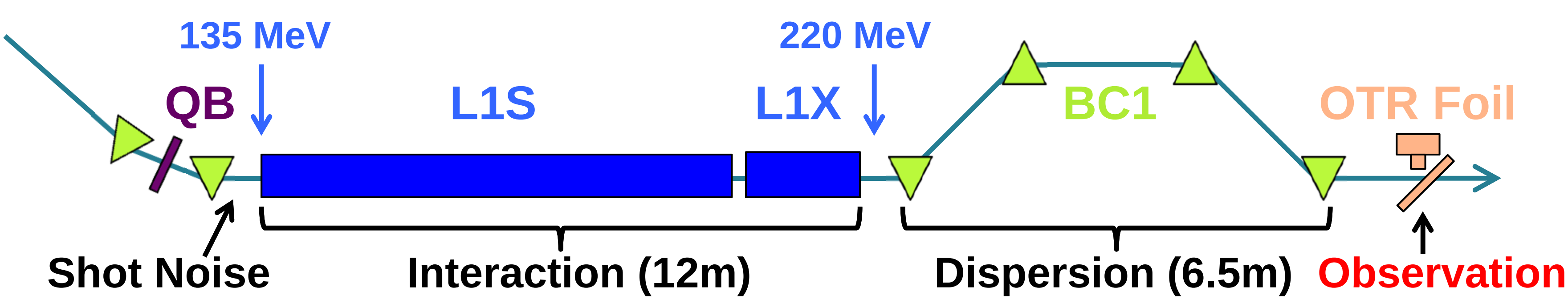


$$N \left\langle \left| b(\vec{k}) \right|^2 \right\rangle \approx (1 - \Upsilon)^2$$

$$\Upsilon \equiv n_0 R_{56} A$$

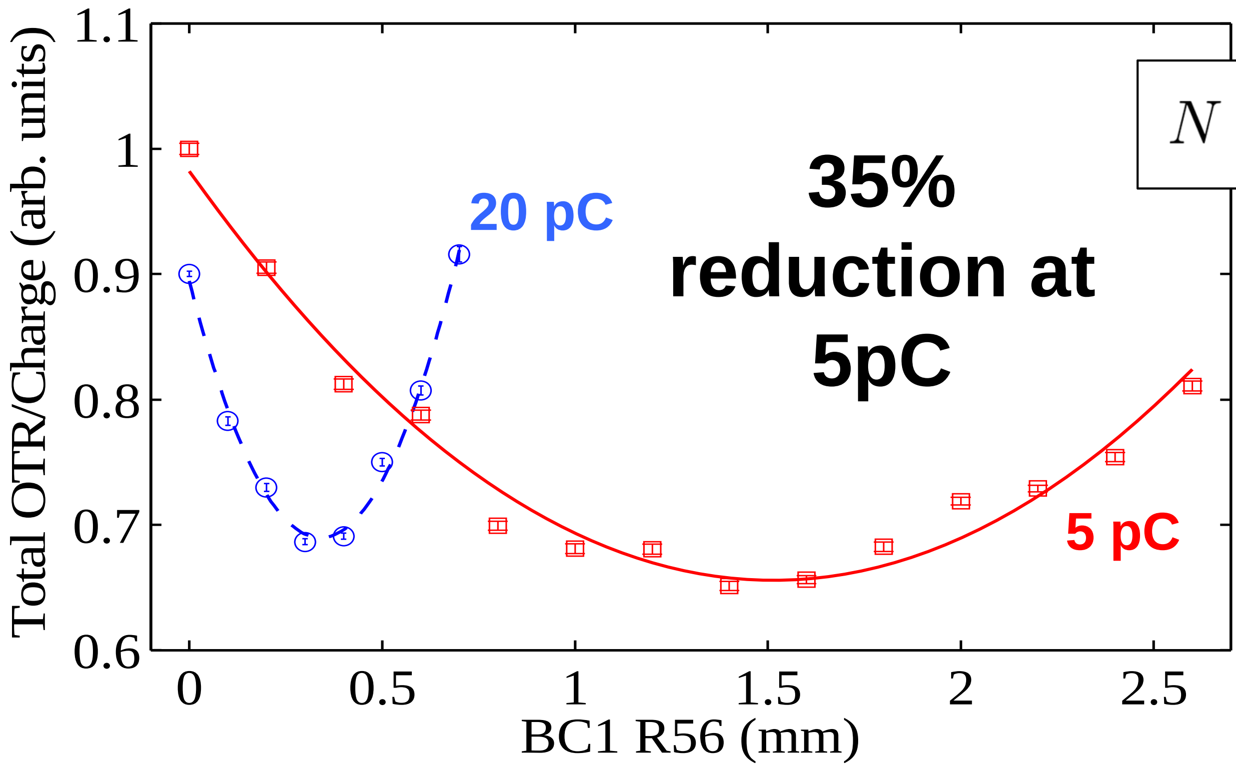
OTR Reduction





Experimental Data

OTR Reduction



$$N \left\langle |b(k)|^2 \right\rangle = (1 - \Upsilon)^2$$

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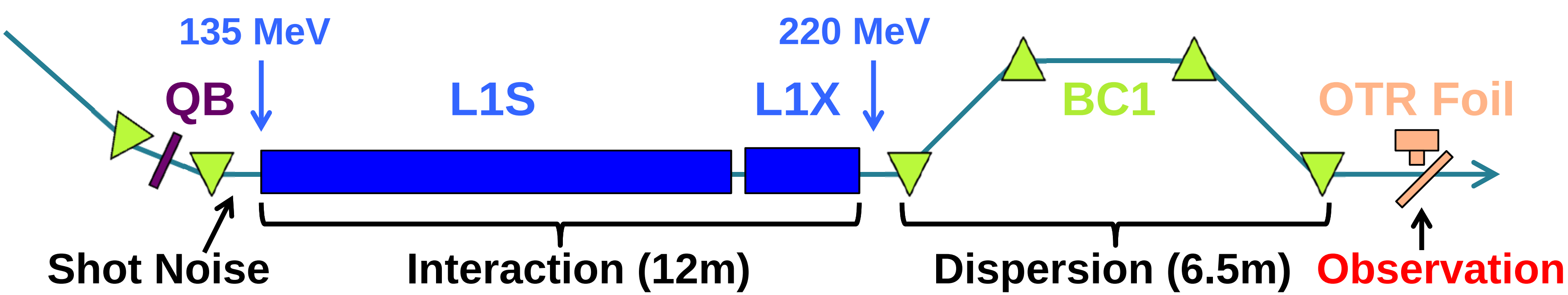
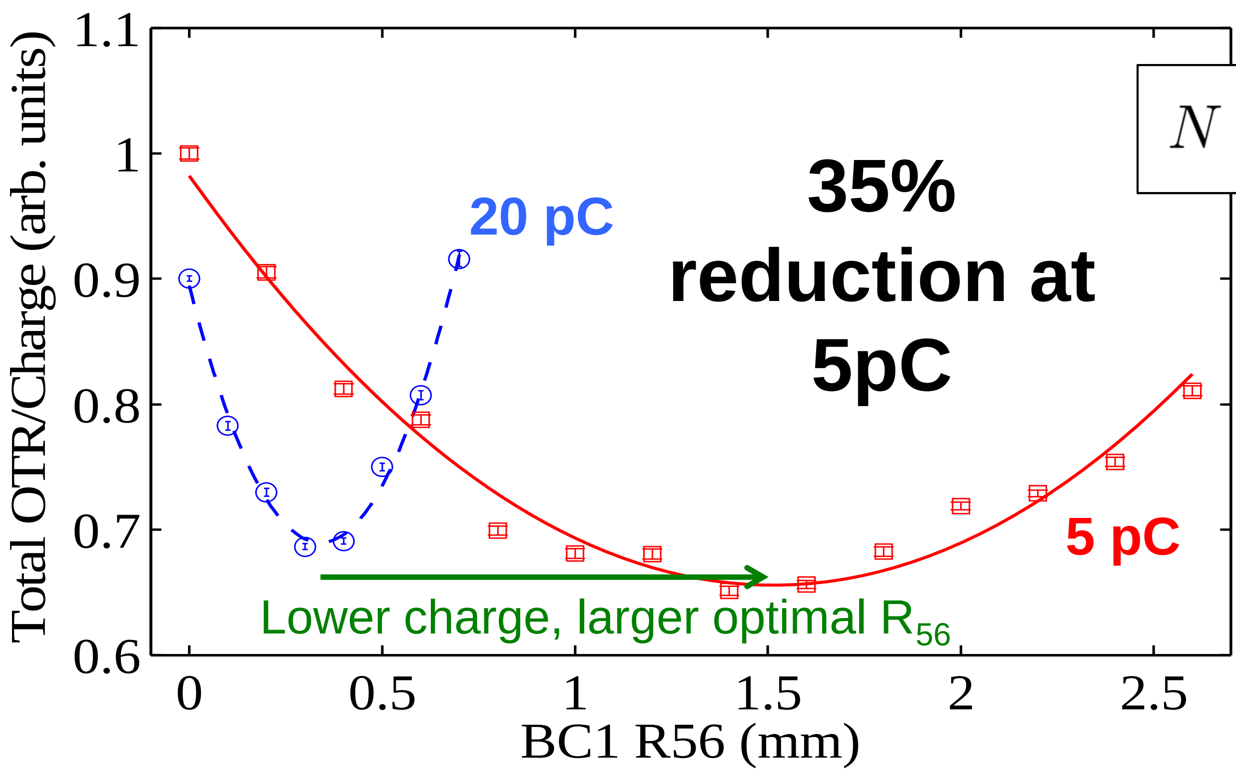


OTR Reduction



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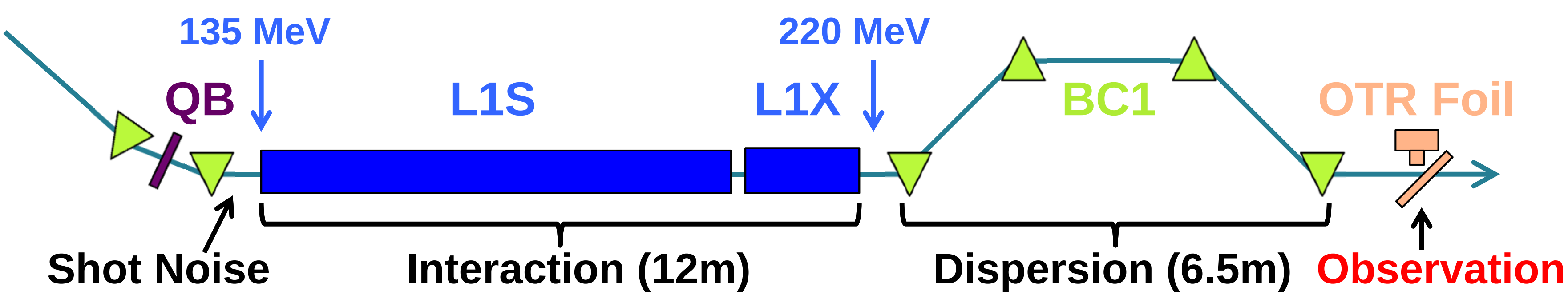
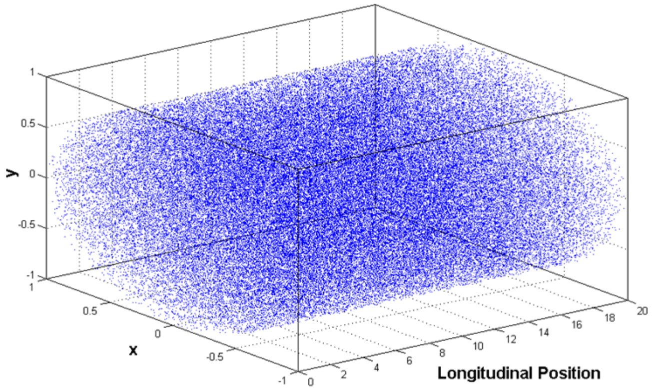


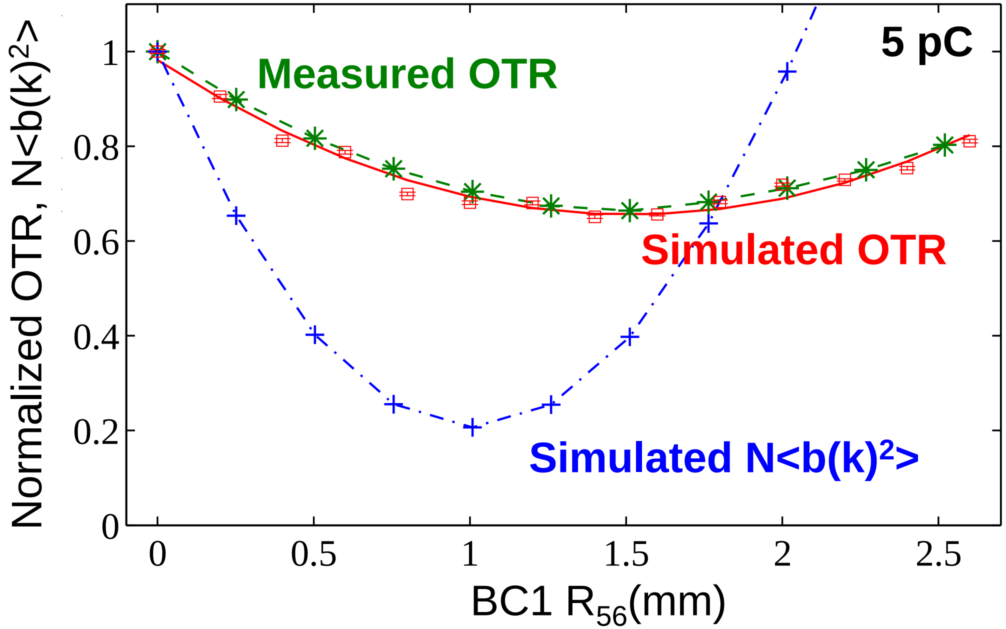
Transverse Effects

1. Longitudinal bunching factor: $N\left\langle |b(\vec{k})|^2 \right\rangle \propto \left| \sum^{i=1..N} e^{ikz_i} \right|^2$
2. 3D OTR calculation: $OTR(k) \propto \left| \sum^{i=1..N} \int d\theta e^{ik(r_i\theta + z_i)} \frac{\theta}{\theta^2 + 1/\gamma^2} \right|^2$

3D simulations

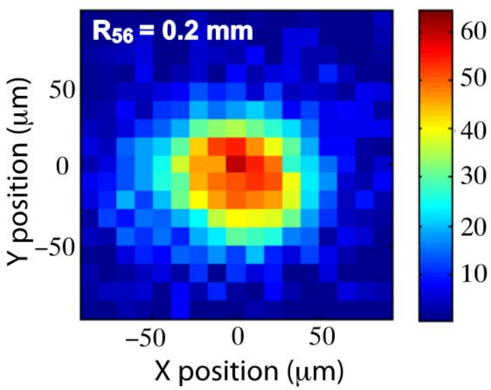


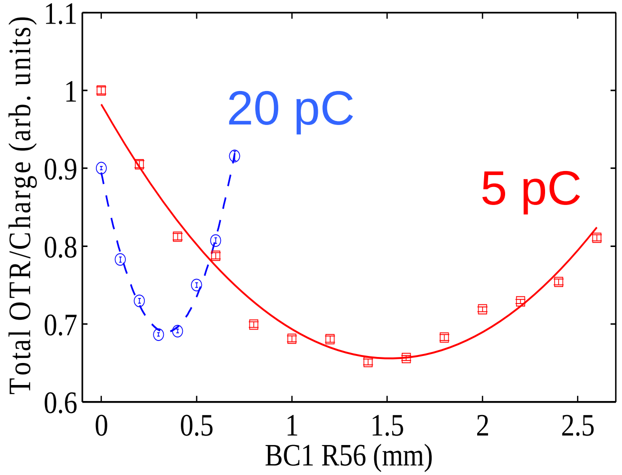
Fit average density to match optimal R_{56}

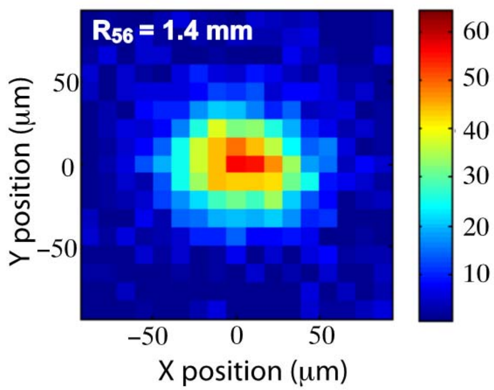


Conclusions

1. 1D/3D model of noise amplification and suppression
2. Broad-bandwidth noise reduction feasible
3. Experimental observation of optical shot noise reduction
4. Continuing studies of noise reduction and amplification







Questions?

Thanks to help from:

Franz-Josef Decker, Yuantao Ding, Paul Emma, Zhirong Huang, Henrik Loos, Agostino Marinelli, Yuri Nosochkov, Ji Qiang, Gennady Stupakov, Juhao Wu