Dispersive Noise Suppression: Models, Evidence and Applications

FEL 13, New York

D. Ratner

Aug. 26, 2013

U.S. DEPARTMENT OF ENERGY
Office of Science

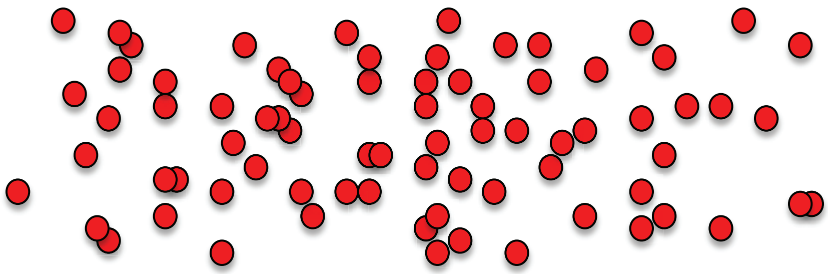
SLAC NATIONAL ACCELERATOR LABORATORY

Dispersive Shot Noise Suppression
Models, Evidence and Application

1. Model for dispersive noise reduction

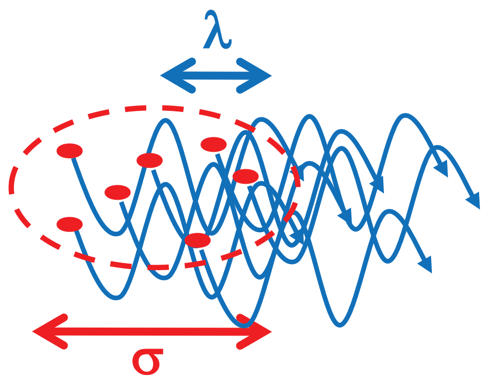
2. Experimental evidence of dispersive noise reduction

3. Applications: FEL seeding and hadron cooling



Microbunching and Noise Suppression

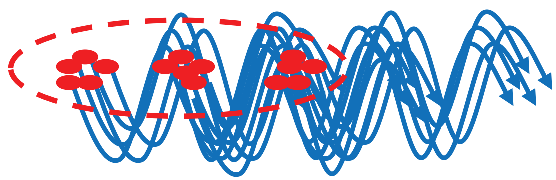
Shot Noise



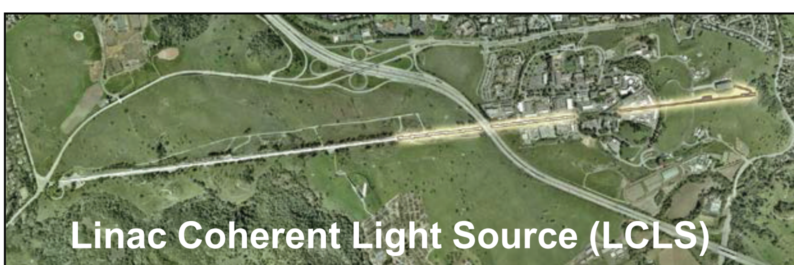
Number of electrons

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

Microbunching



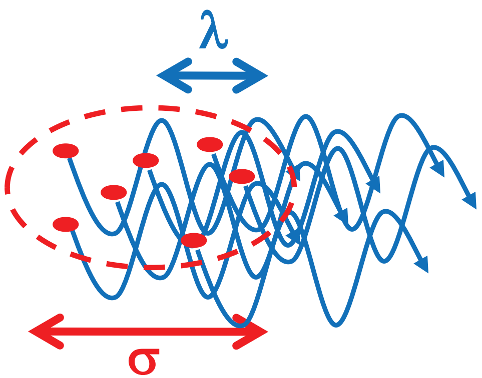
$$P_{rad}(\lambda) \propto N^2$$



Microbunching and Noise Suppression

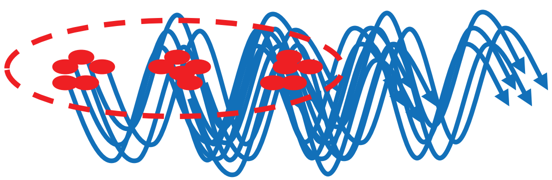
Number of electrons

Shot Noise



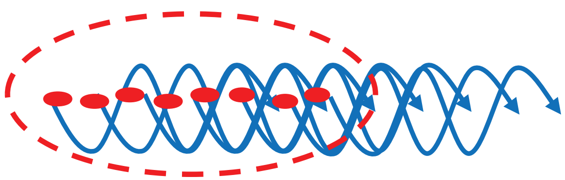
$$P_{rad}(\lambda) \propto N$$

Microbunching



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

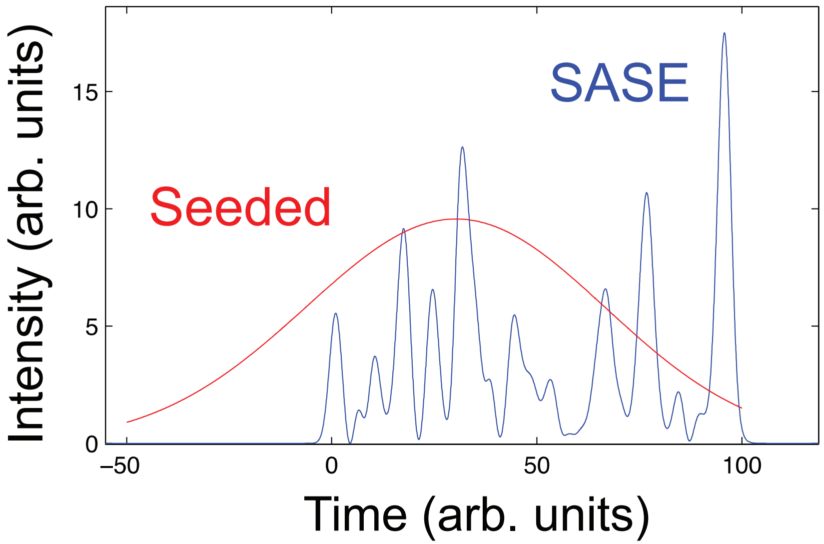
Noise Suppression



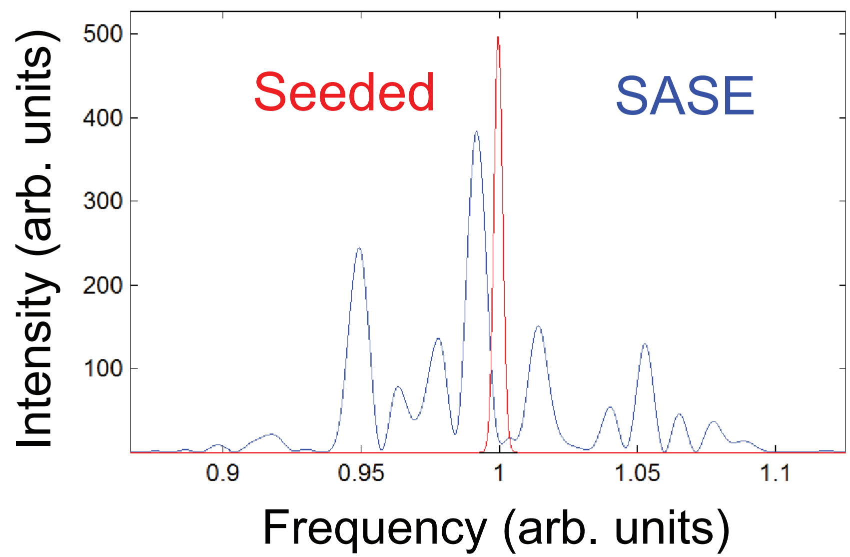
$$P_{rad}(\lambda) \rightarrow 0$$

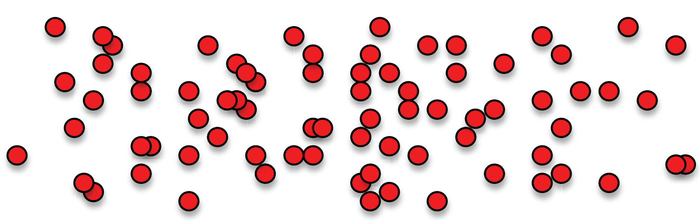
Motivation: Seeded FELs

Time Domain



Frequency Domain





Shot Noise Reduction

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#

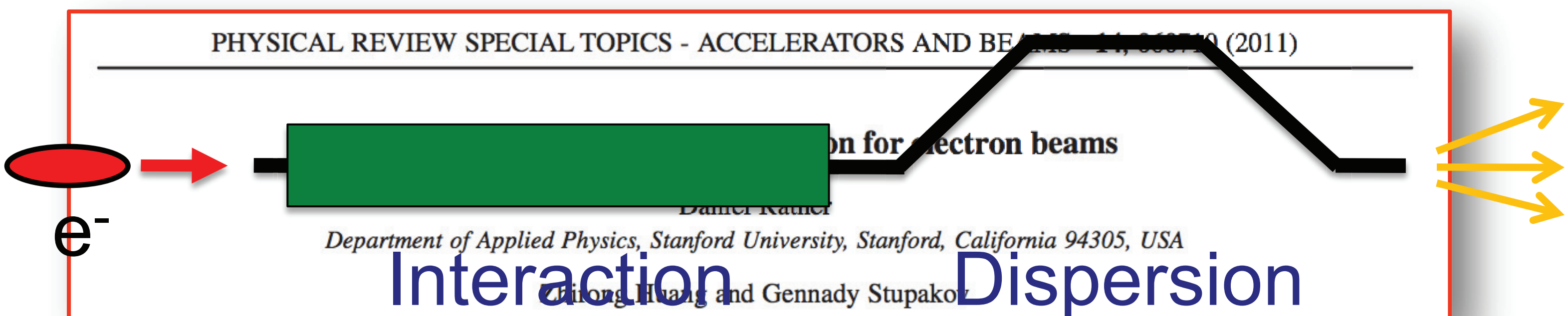
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14,** 060710 (2011)

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

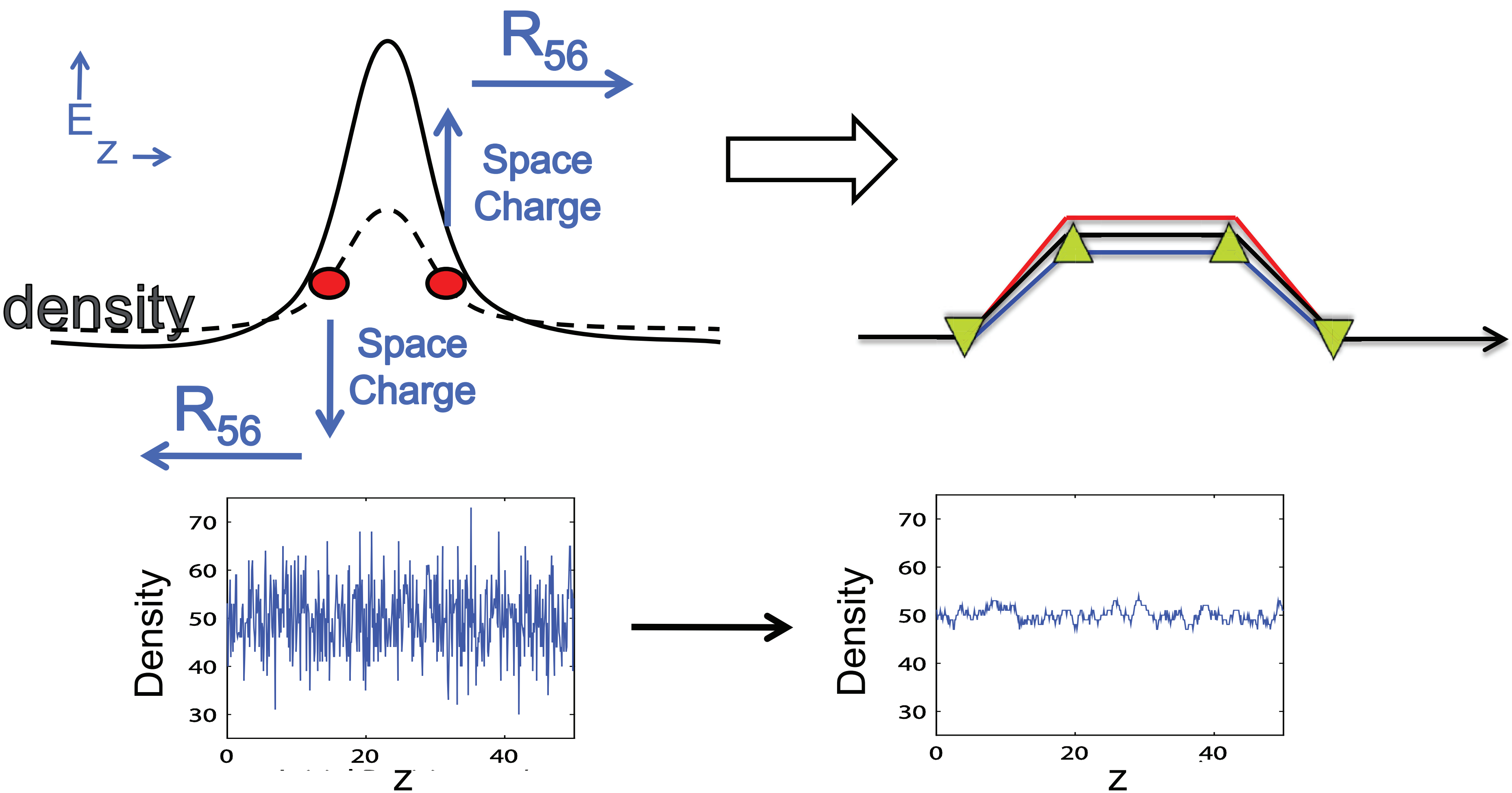
Dispersive noise suppression



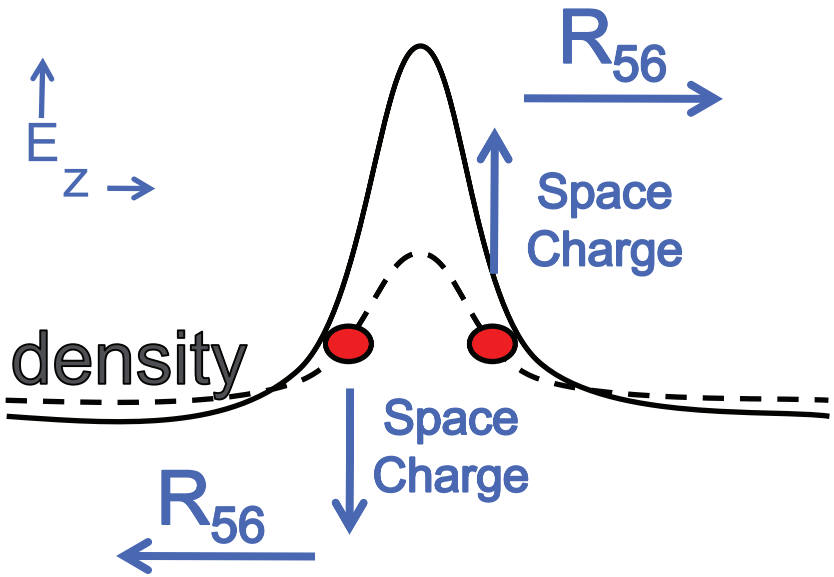
Particles frozen longitudinally

No interaction

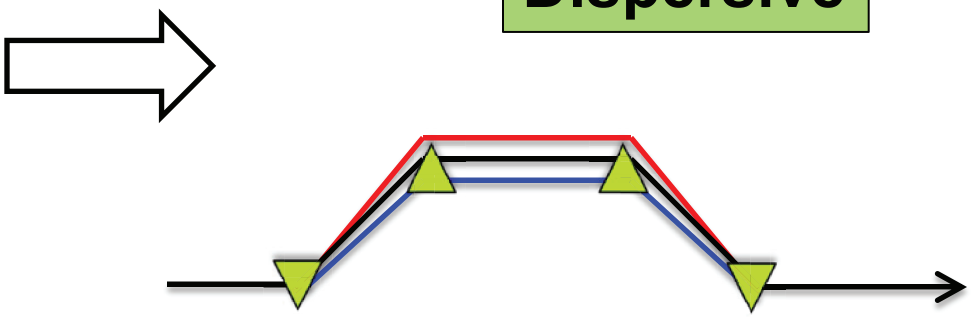
Physical Picture



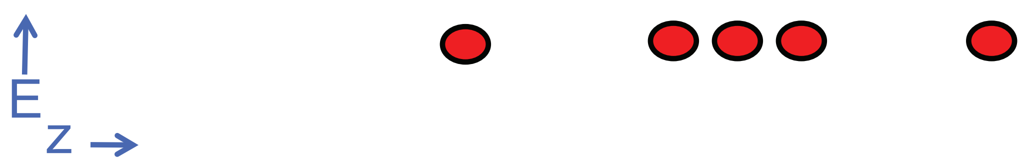
Physical Picture



Dispersive



Plasma Oscillation



Model radiation from beam:

$$\left(\frac{d^2 I}{d\omega d\Omega}\right)_{\mathrm{tot}} = \left(\frac{d^2 I}{d\omega d\Omega}\right)_1 N F(k)$$

e.g. for optical transition radiation

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

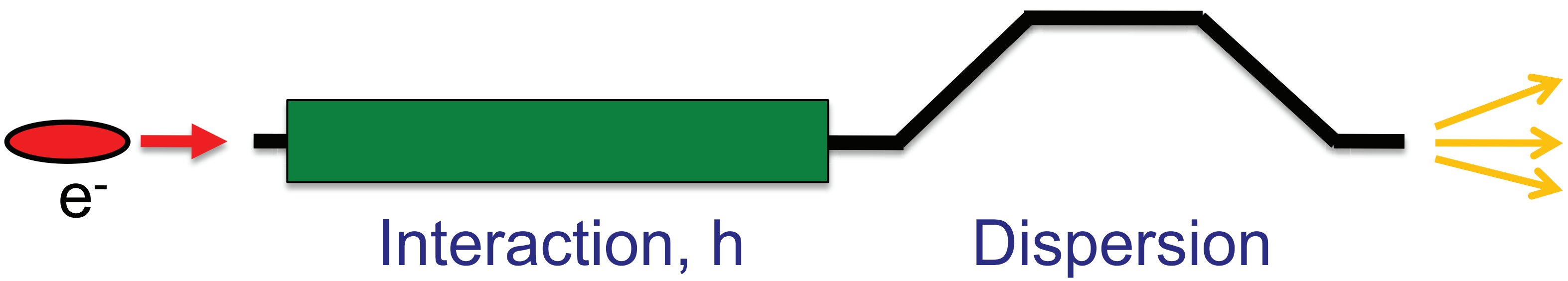
energy γ, observation angle θ

$$F(k) = \frac{1}{N}\left|\sum_j^N \exp\left[-i\tilde{K}X_j\right]\right|^2$$

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

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

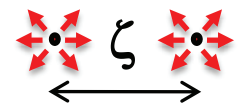
N particles with coordinates X_j



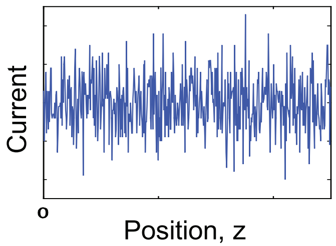
Shot Noise Reduction

SLAC

Noise Factor: $F(k) = \frac{1}{N}\left|\sum_j^N \exp\left[-i\tilde{K}X_j\right]\right|^2$



$\boxed{\zeta \equiv z_1 - z_2}$



Weak interaction, 1D:

$$\langle F(k)\rangle \approx \boxed{1} + n_0 e^{\cancel{-k^2R_{56}^2\sigma_\eta^2}} \int_{-\infty}^{\infty} d\zeta e^{ik\zeta}\left[\boxed{\Gamma_1(\zeta)} + \boxed{\Gamma_2(\zeta)}\right]$$

Shot Noise

Linear term: $\boxed{\Gamma_1(\zeta) \approx ikR_{56}\left[h(\zeta) - h(-\zeta)\right]}$ Noise Supp.

Quadratic term: $\boxed{\Gamma_2(\zeta) \approx n_0k^2R_{56}^2 \int_{-\infty}^{\infty} d\tau\left[h(-\tau+\zeta)h(-\tau) - h(-\tau)^2\right]}$ MBI

longitudinal density, n_0 arbitrary particle interaction $h(\zeta)$

Drop energy spread term:

$$\langle F(k)\rangle \approx (1-\Upsilon)^2$$

$$\Upsilon \equiv n_0\cancel{k}R_{56}\mathrm{Im}\left[\tilde{h}(\cancel{k})\right]$$

Only constraint on *h(z)*: Step function interaction!!!

Noise Factor 1D Limit, Space Charge

$$\langle F(k) \rangle \approx (1-\Upsilon)^2$$

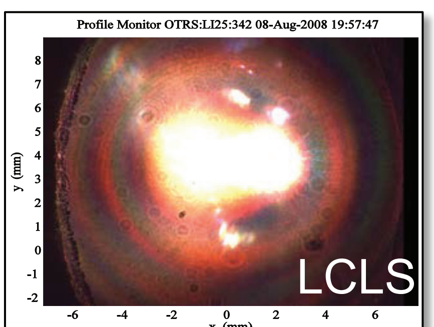
$$\boxed{\Upsilon \equiv n_0 R_{56} A}$$

$$\left(\frac{d^2 I}{d\omega d\Omega}\right)_{\mathrm{tot}} = \left(\frac{d^2 I}{d\omega d\Omega}\right)_1 N F(k)$$

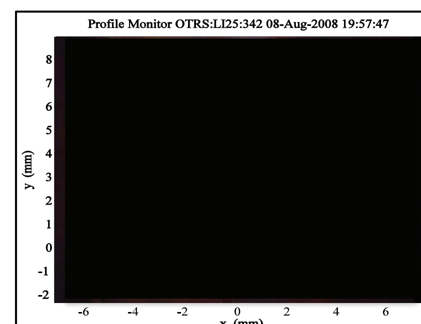
$$A = \frac{r_e L_a}{\beta \varepsilon}$$

Charge density, n_0, dispersion R_{56}, interaction length L_a, emittance ε, classical e- radius r_e

Noise Amplification:
Y >>1

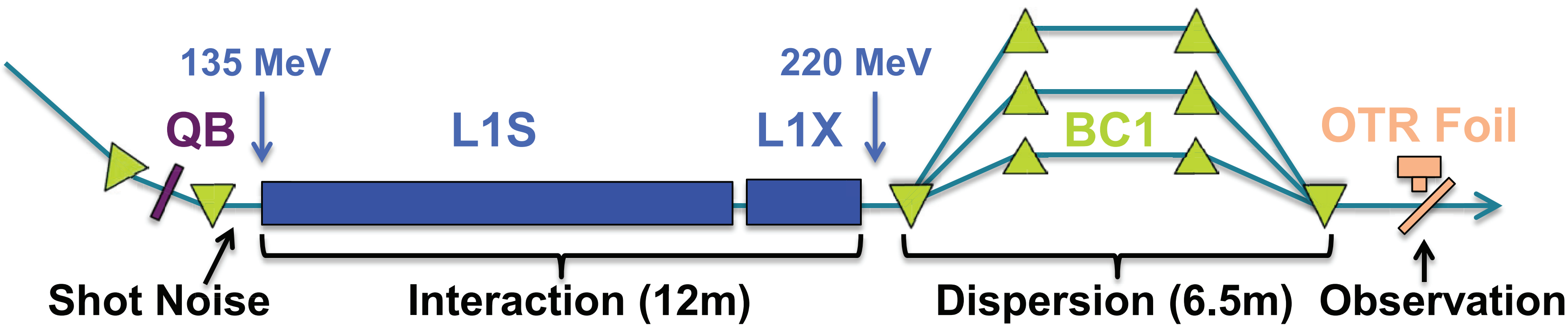


Noise Reduction:
Y ~ 1



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

Experimental Schematic
LCLS



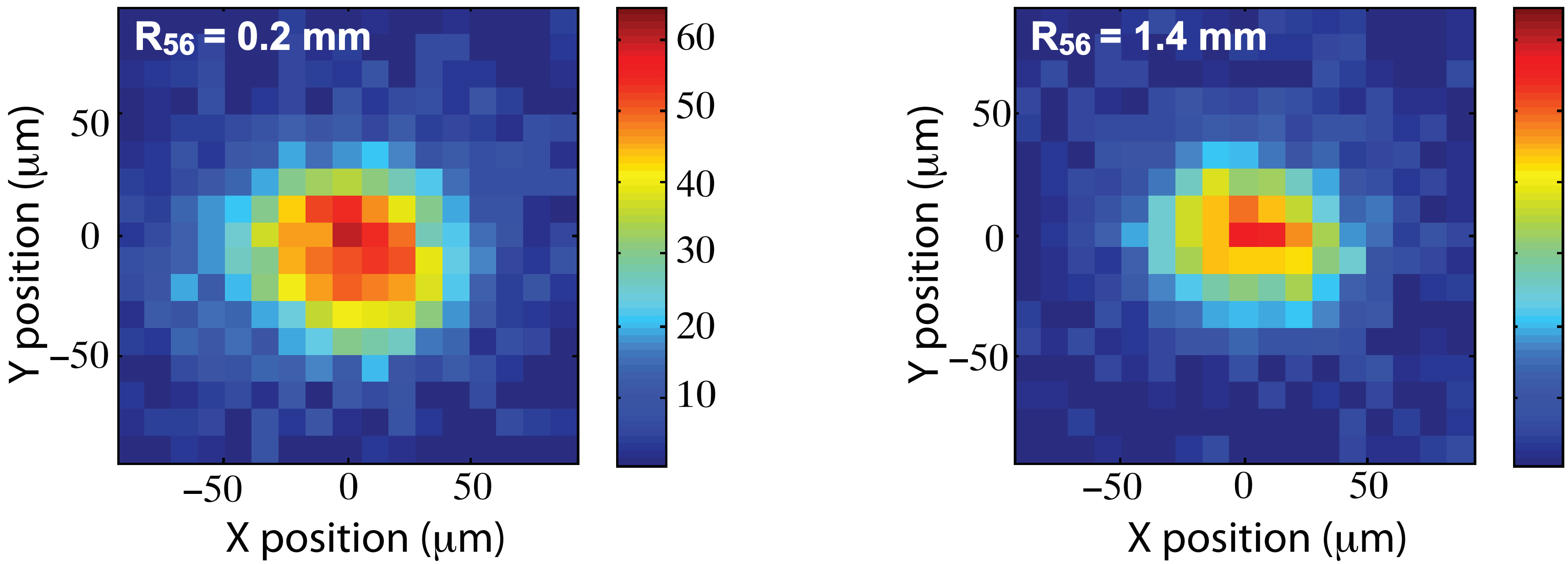
$$\frac{dI}{d\omega} \propto (1 - \Upsilon)^2$$

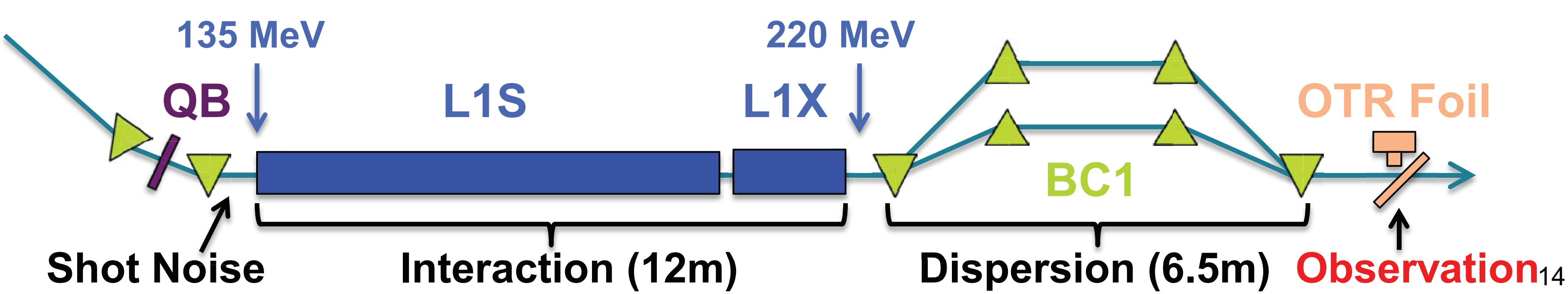
$$\boxed{\Upsilon \equiv n_0 R_{56} A}$$

Experimental Data

SLAC

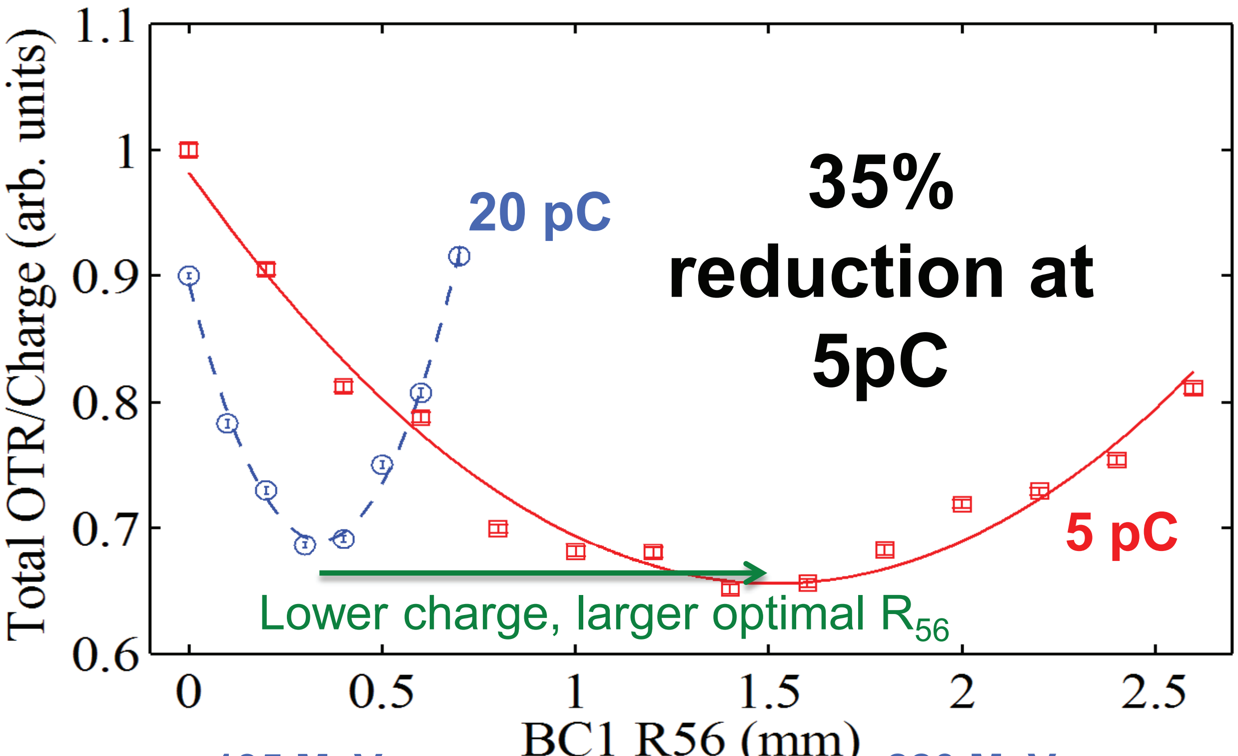
OTR Reduction





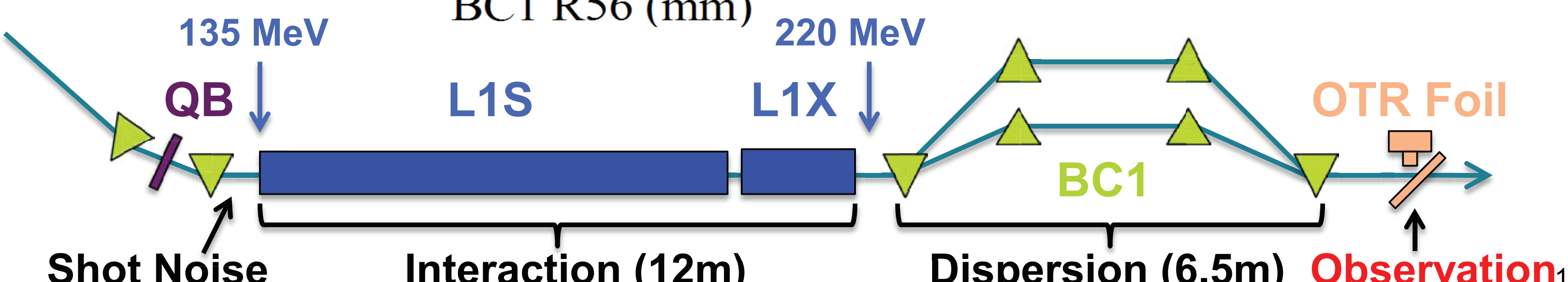
Experimental Data

OTR Reduction



$$\frac{dI}{d\omega} \propto (1-\Upsilon)^2$$

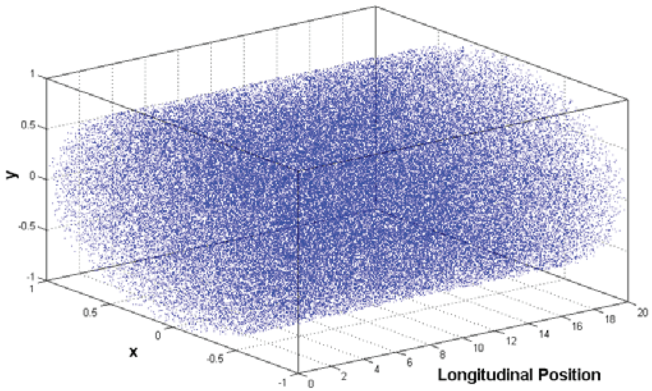
$$\Upsilon \equiv n_0 R_{56} A$$



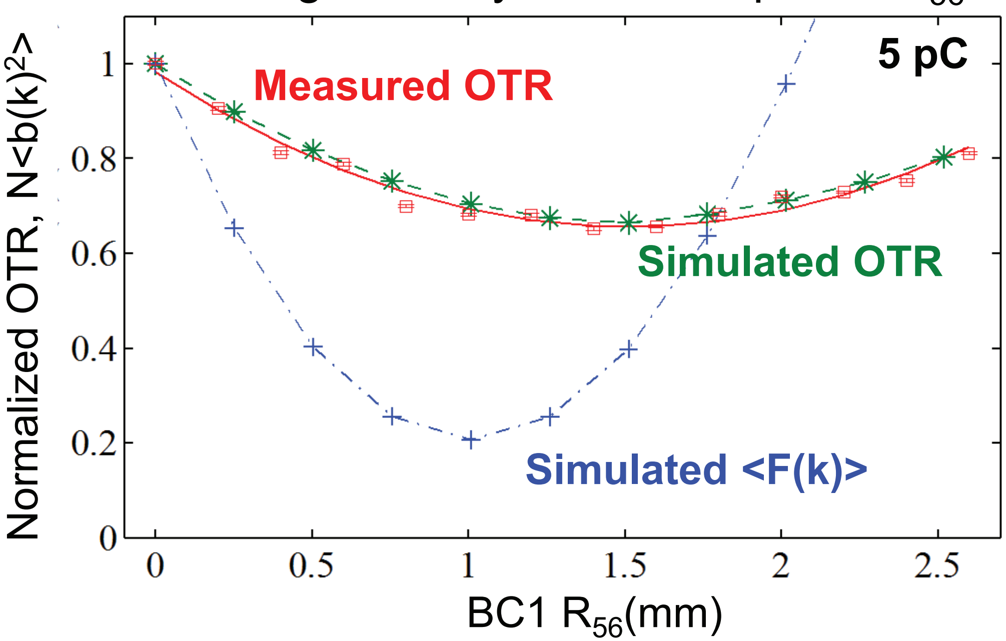
Transverse Effects

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

3D simulations



Fit average density to match optimal R_{56}

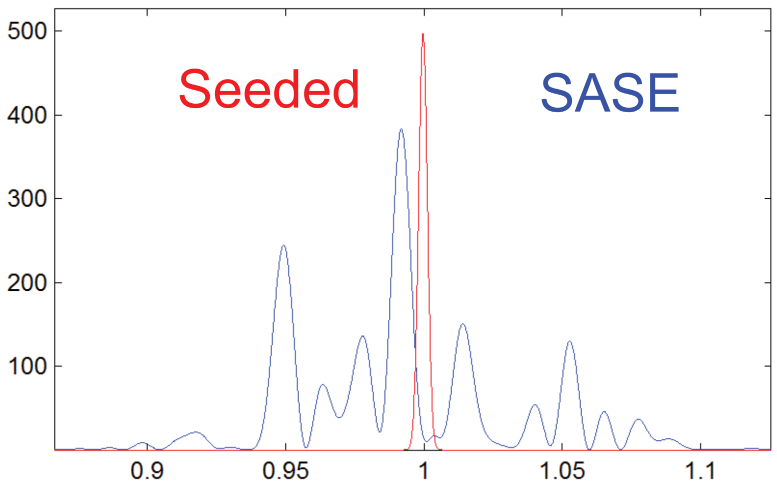


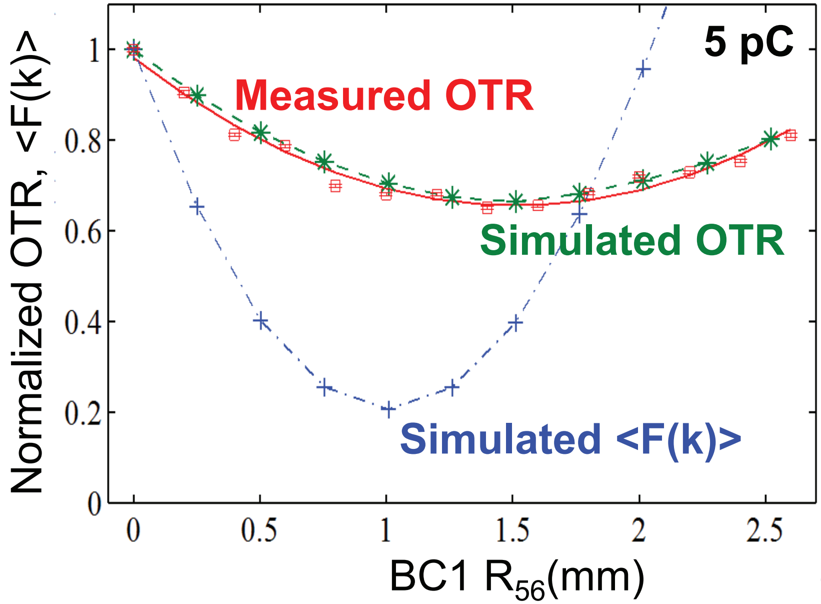
Application 1: Noise Suppression for FEL Seeding

1D FEL gain:

$$\tilde{a}(\bar{z}) \approx \frac{1}{3}\left(\boxed{\tilde{a}(0)} - i\cancel{\frac{b(0)}{\mu_3}} - \boxed{iP(0)\mu_3}\right) e^{-i\mu_3 \bar{z}}$$

Seed radiation **Density modulation** **Energy modulation**





Application 1: Noise Suppression for FEL Seeding

COLLECTIVE AND INDIVIDUAL ASPECTS OF FLUCTUATIONS IN RELATIVISTIC ELECTRON BEAMS FOR FREE ELECTRON LASERS*

K.-J. Kim† and R. R. Lindberg‡, ANL, Argonne, IL 60439, USA

FEL11

Shot noise:

$$\mathcal{S}_k(0) = N_e \left(1 + \left|\frac{\mu\sigma_\eta}{\rho}\right|^2\right) \sim N_e$$

Density modulation

Energy modulation

After ¼ plasma period:

$$\mathcal{S}_k(\Lambda_p/4) = N_e \left((k\lambda_D)^2 + \left|\mu\frac{\sigma_\eta}{\rho}\frac{1}{k\lambda_D}\right|^2\right) \sim N_e/2$$

Density << 1

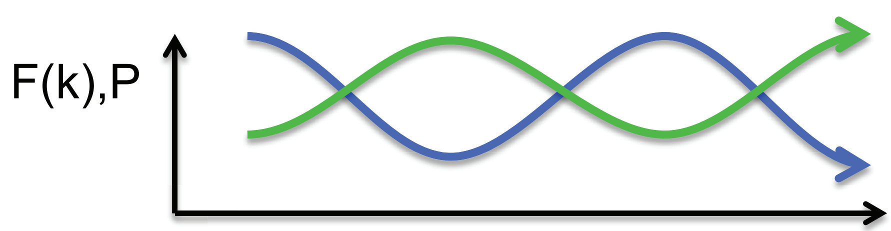
Energy ~ 1

Application 1: Noise Suppression for FEL Seeding

COLLECTIVE AND INDIVIDUAL ASPECTS OF FLUCTUATIONS IN RELATIVISTIC ELECTRON BEAMS FOR FREE ELECTRON LASERS*

K.-J. Kim† and R. R. Lindberg‡, ANL, Argonne, IL 60439, USA

FEL11



Minimize F(k) ➔ Maximize P

After ¼ plasma period:

$$\boxed{S_k(\Lambda_p/4) = N_e\left((k\lambda_D)^2 + \left|\mu\frac{\sigma_\eta}{\rho}\frac{1}{k\lambda_D}\right|^2\right)} \sim N_e/2$$

Density << 1

Energy ~ 1

Application 2: Electron cooling of hadrons

Proceedings of FEL2009, Liverpool, UK TUOB05

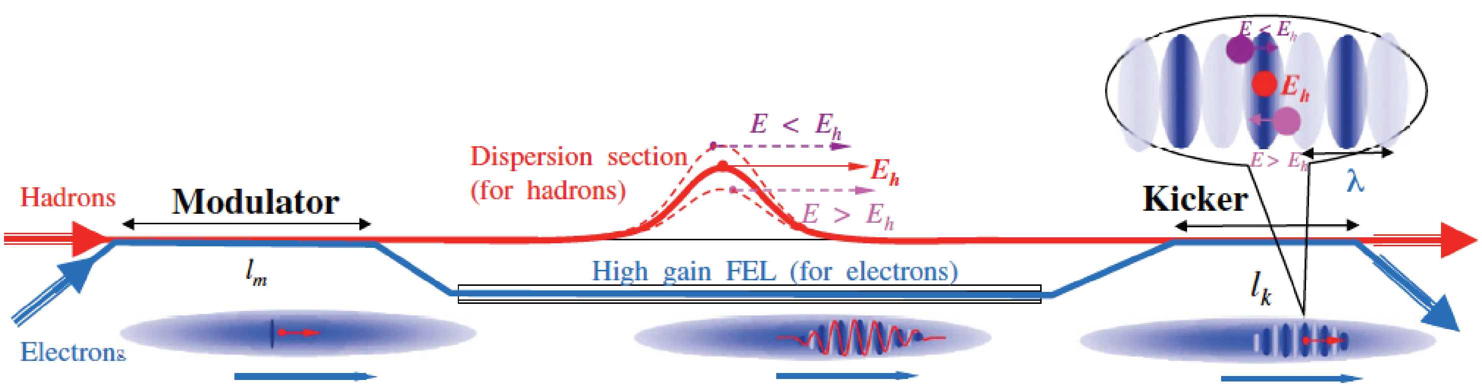
SUPPRESSING SHOT NOISE AND SPONTANEOUS RADIATION IN ELECTRON BEAMS*

Vladimir N. Litvinenko, BNL, Upton, USA#

PRL **102,** 114801 (2009) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2009

Coherent Electron Cooling

Vladimir N. Litvinenko[1,*] and Yaroslav S. Derbenev[2]



SLAC

Application 2: Electron cooling of hadrons

PRL **111,** 084802 (2013) PHYSICAL REVIEW LETTERS week ending 23 AUGUST 2013

Microbunched Electron Cooling for High-Energy Hadron Beams

D. Ratner*

Poster today: MOPS067

1. Ion Imprints on Electrons

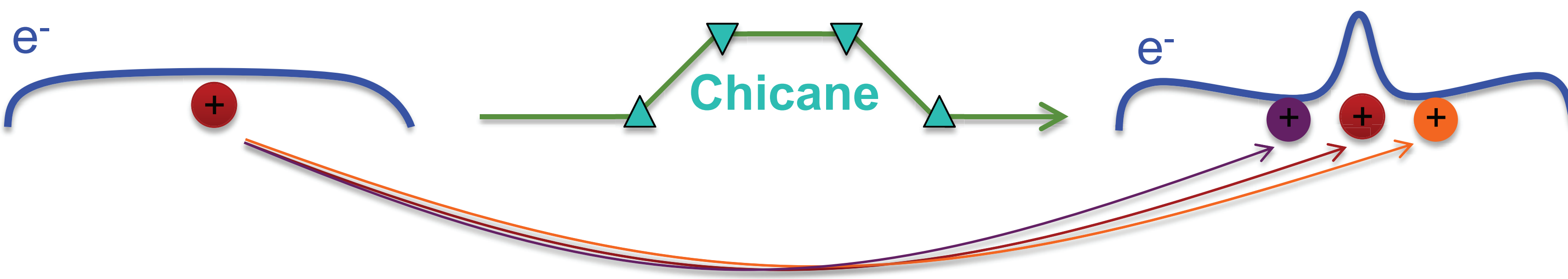
2. Bunching mechanism

3. Energy Correction

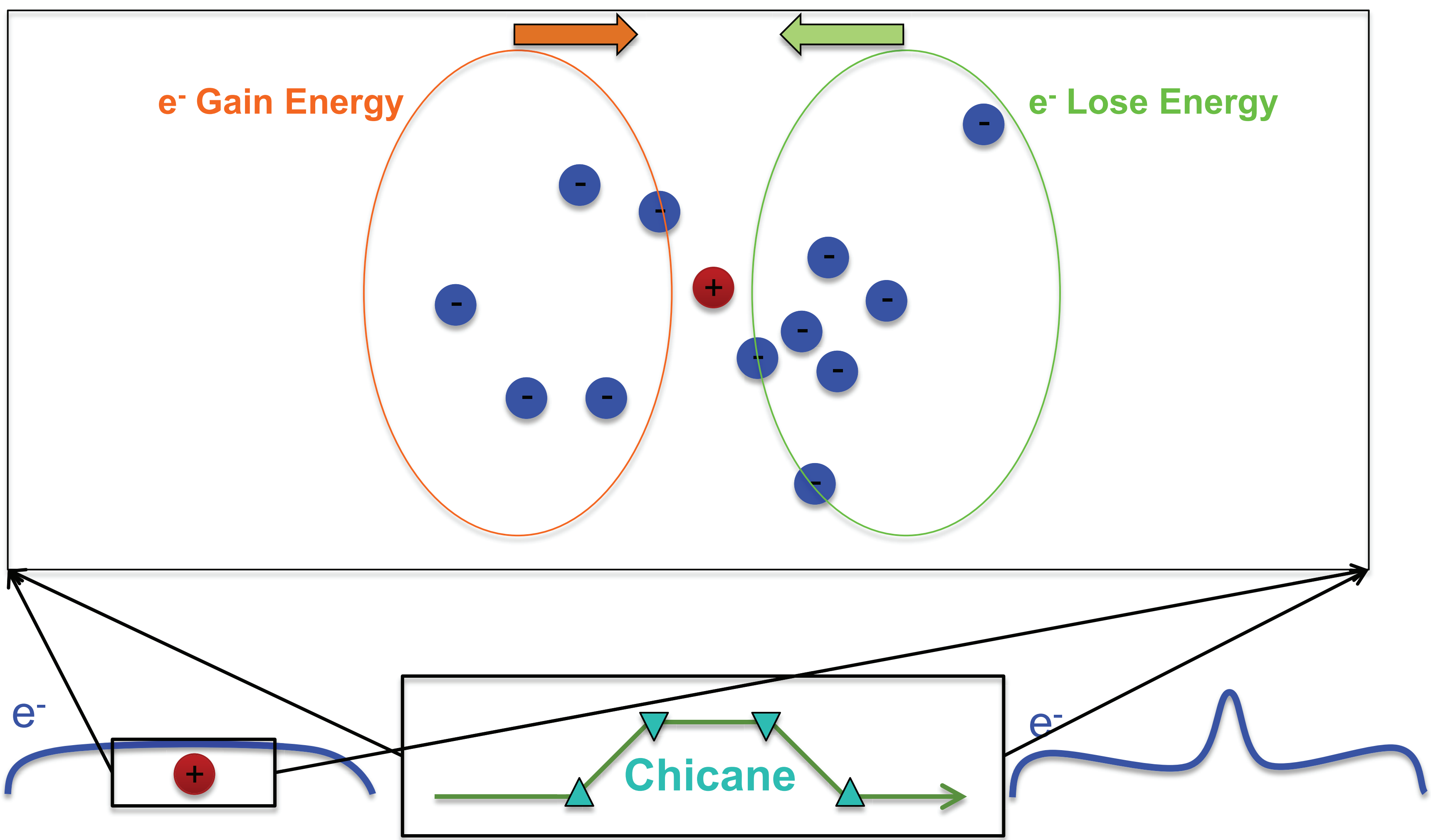
Modulation of Electrons by Space Charge

Dispersion

Modulation of Ions by Space Charge

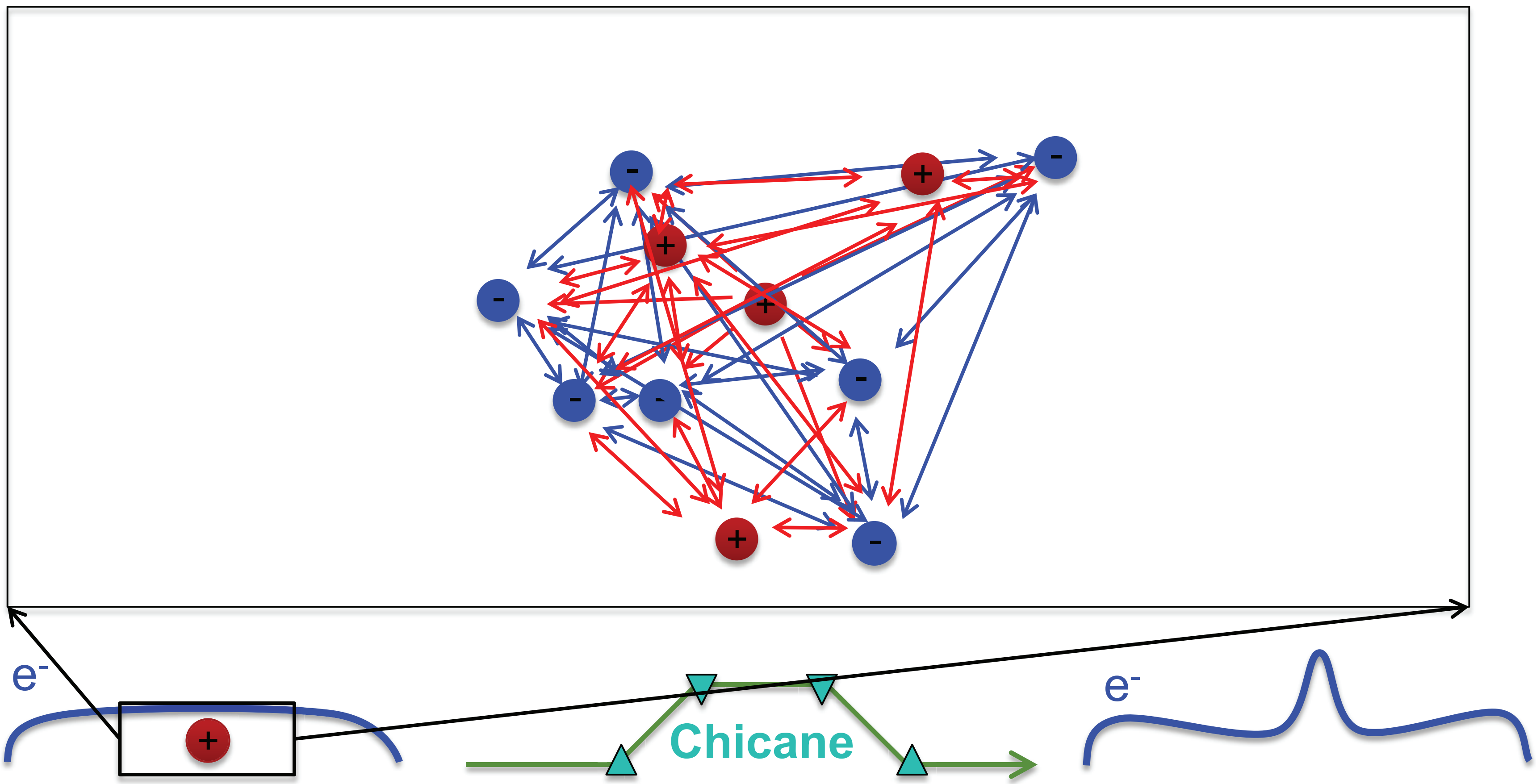


Energy Modulation



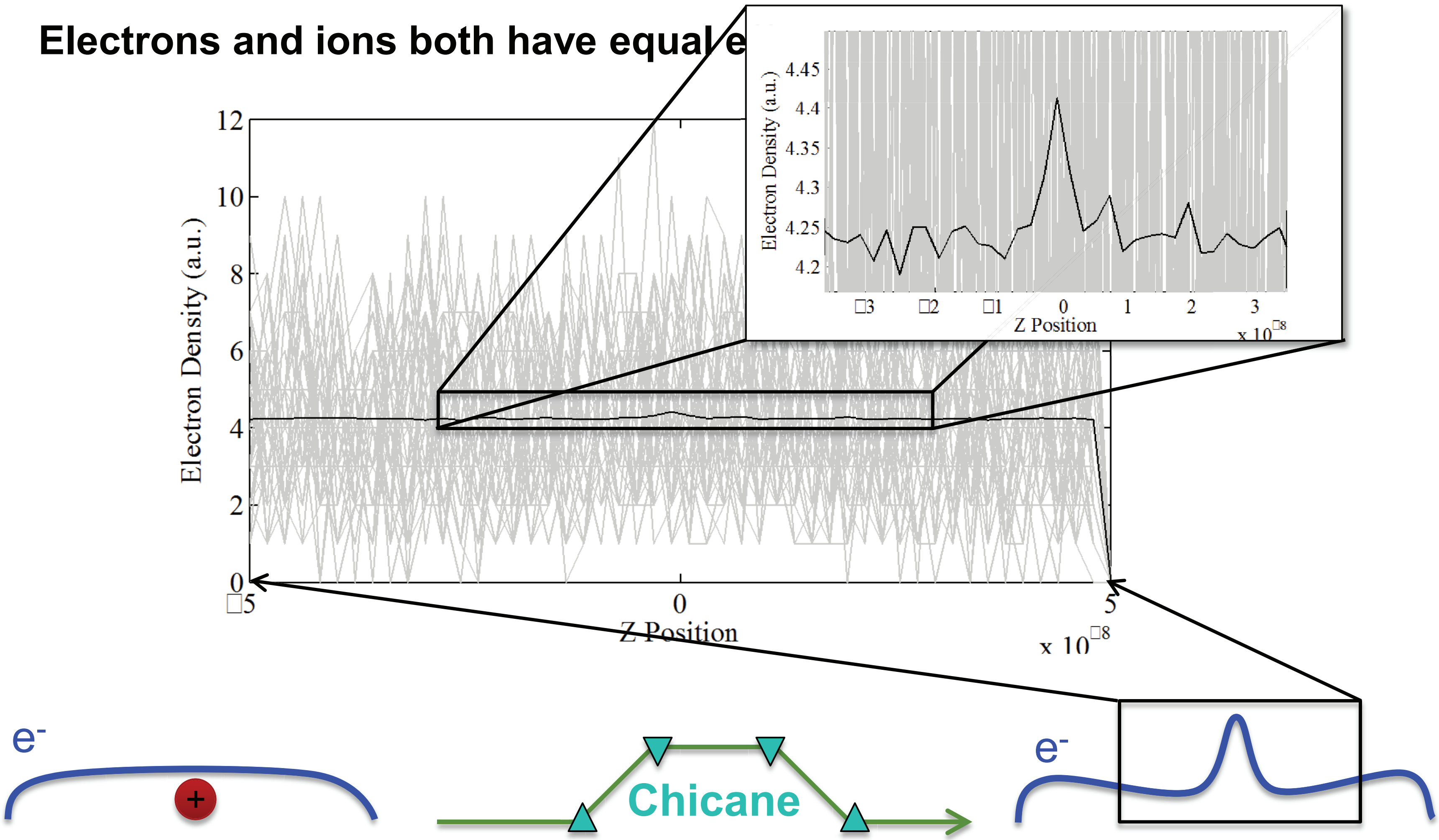
Shot Noise

Electrons and ions both have equal effect on electron modulations

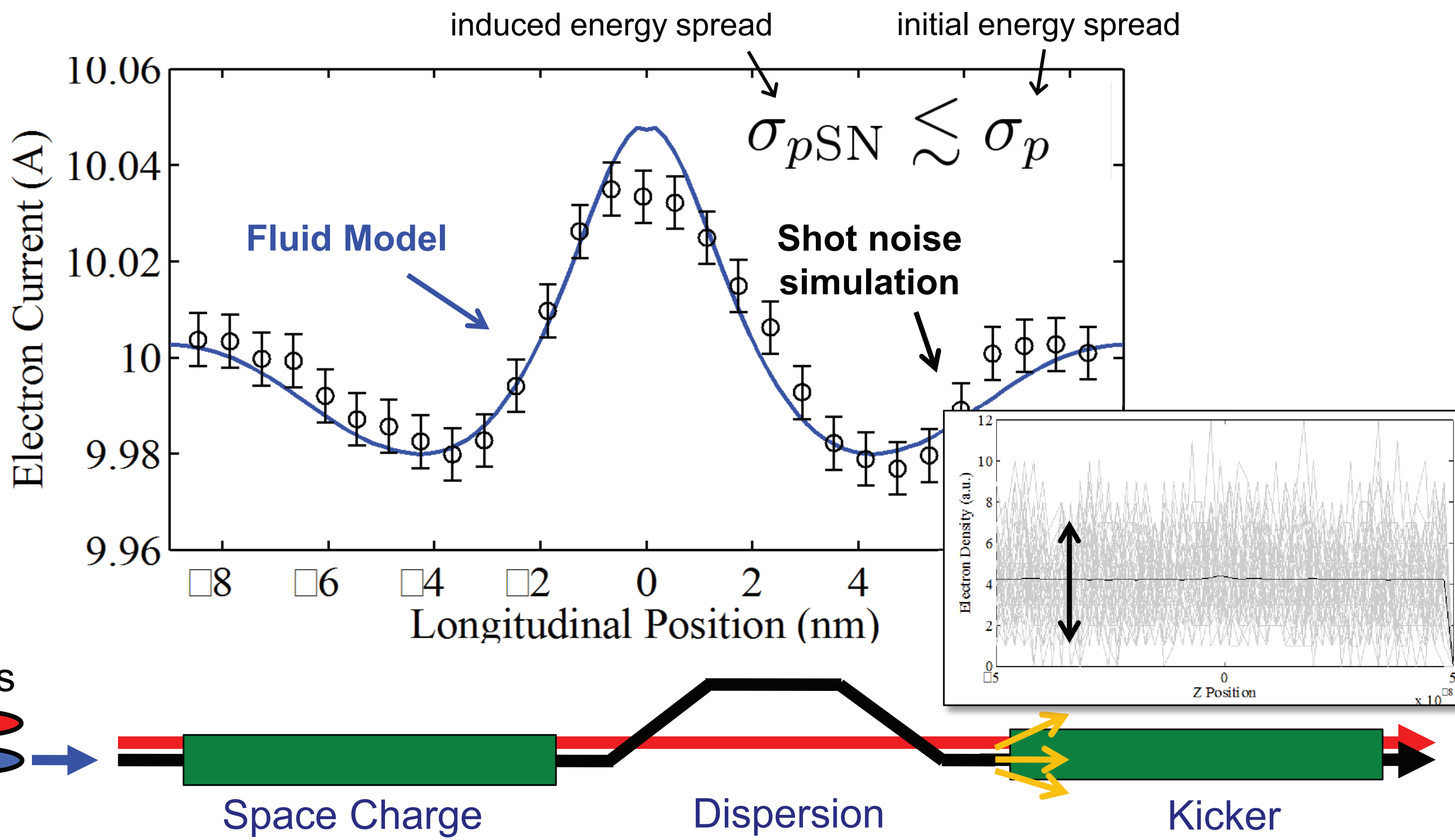


Shot Noise

Electrons and ions both have equal e

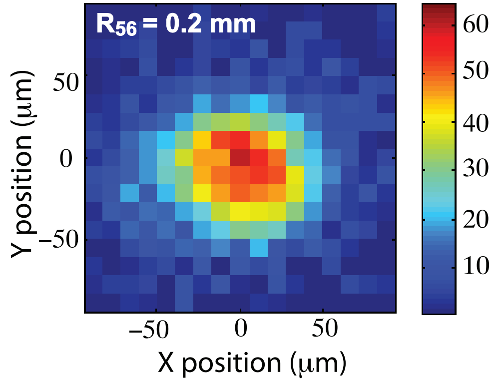


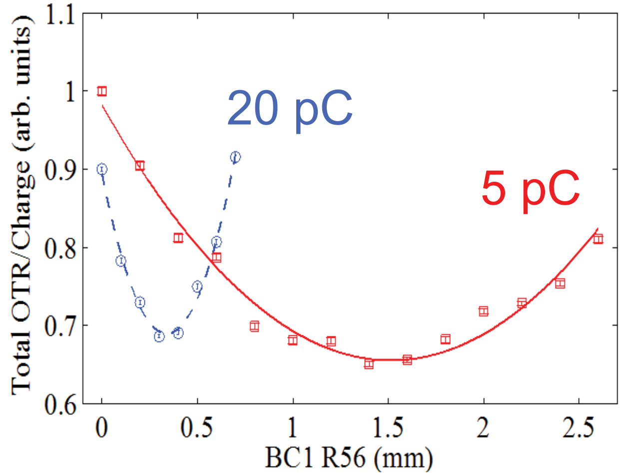
Full Shot Noise Simulations

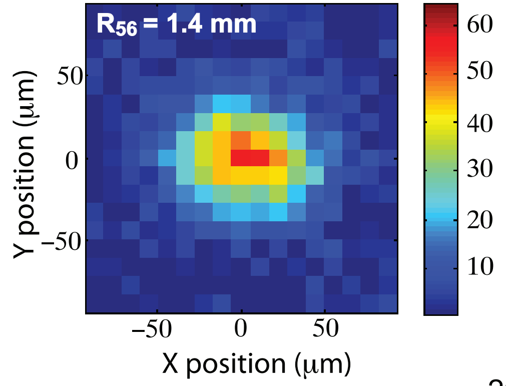


Conclusions

1. Simple model of dispersive noise suppression
2. Broad-bandwidth noise reduction feasible
3. Experimental observation of optical shot noise reduction
4. Continuing studies of short wavelength reduction in undulator radiation for seeding



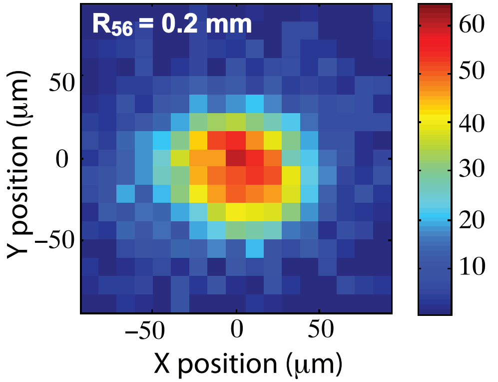


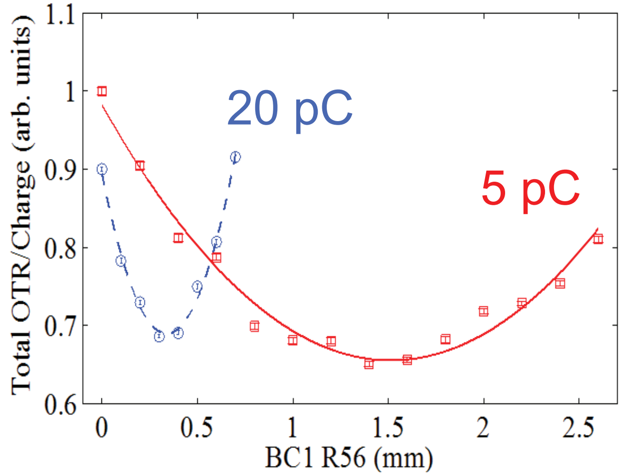


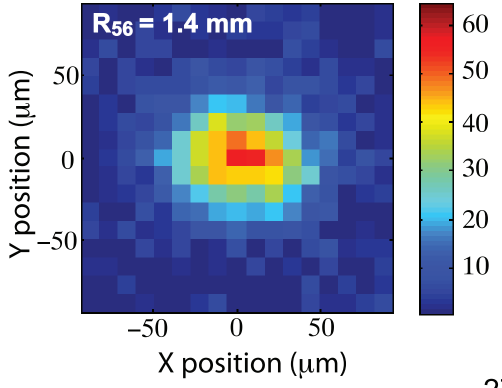
Questions?

Thanks to help from:

F.-J. Decker, Y. Ding, P. Emma, G. Wang, Z. Huang, H. Loos, V. Litvinenko, A. Marinelli, Y. Nosochkov, J.Qiang, G. Stupakov, J. Wu



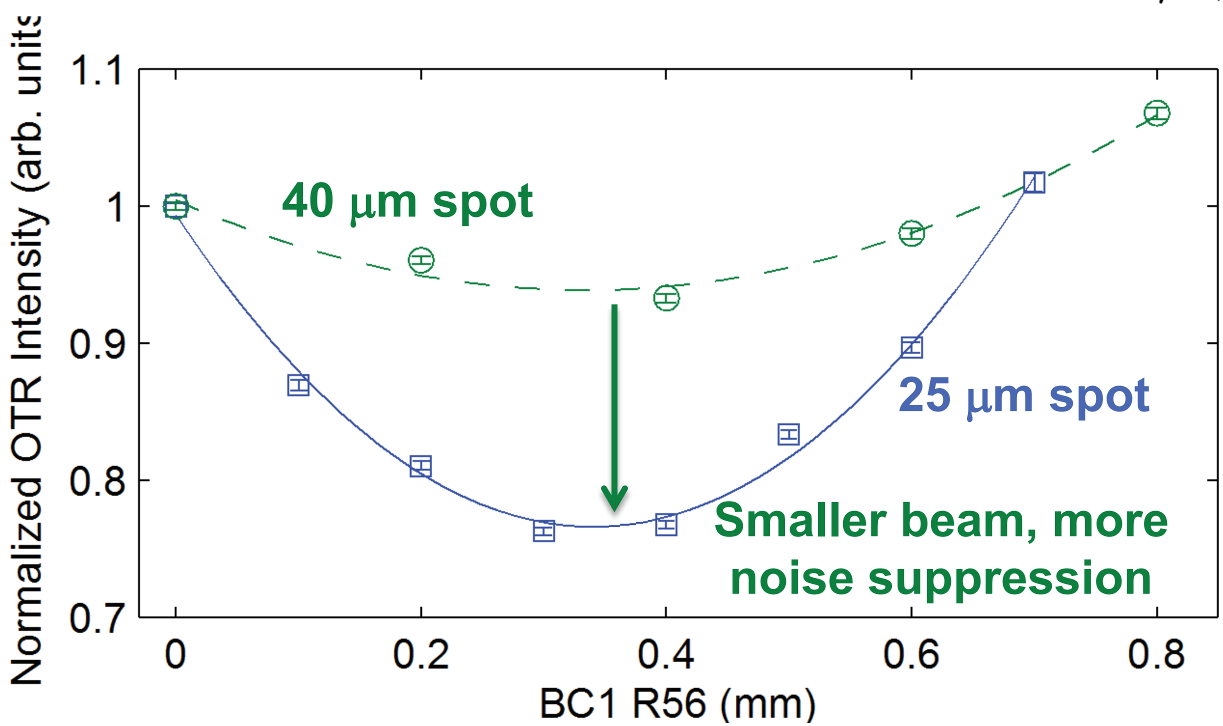




OTR has Angular Dependence

require rθ < λ

$$OTR(k) \propto \left| \sum^{i=1..N} \int d\theta e^{ik(r_i\theta + z_i)} \frac{\theta}{\theta^2 + 1/\gamma^2} \right|^2$$



Experimental Data

QB at 10.3 kG