Beating the Shot-Noise Limit: Collective Interaction Optical Noise Suppression in Charged Particle Beam

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Carried out under the supervision of
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Publications

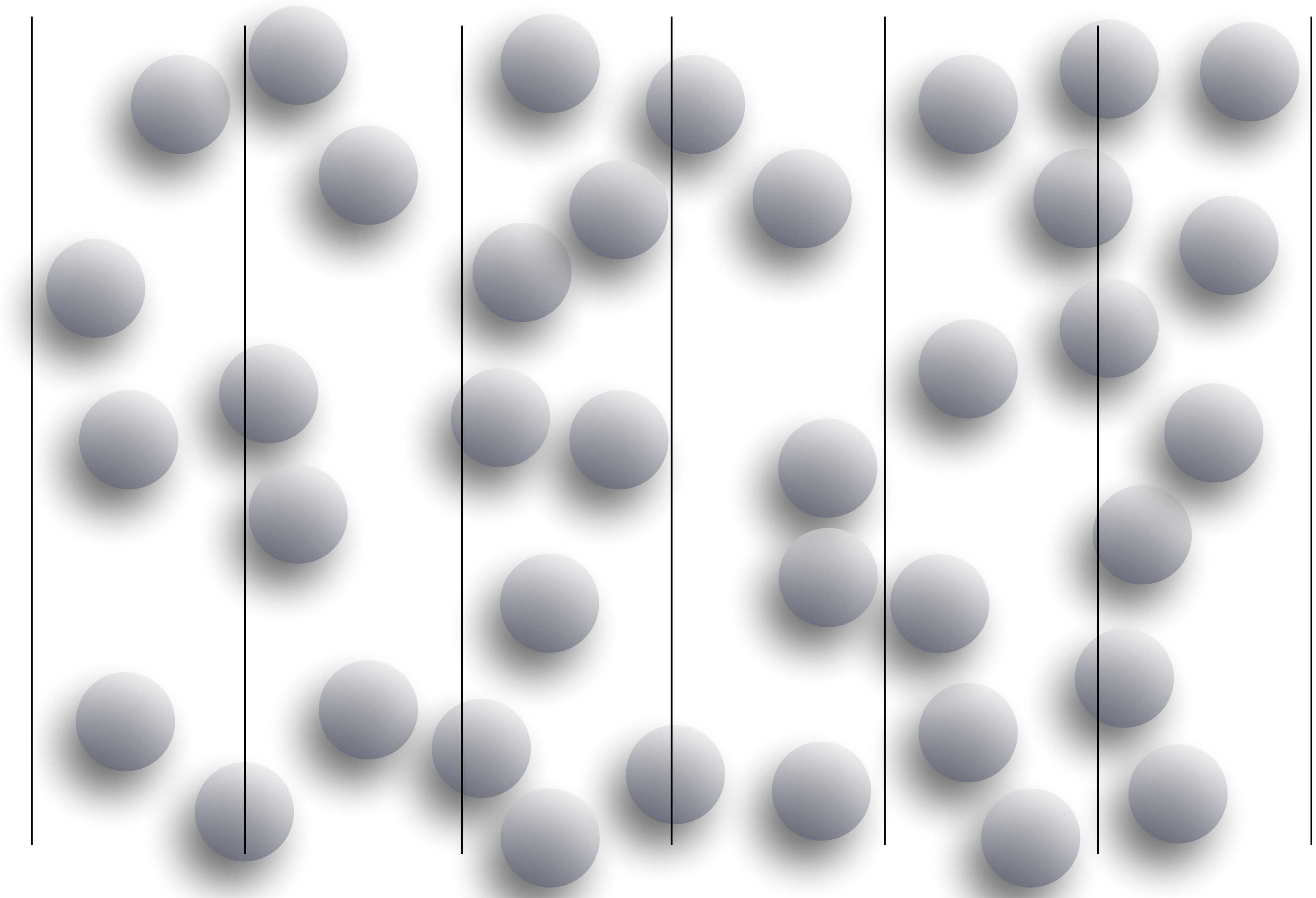
- A. Gover, E. Dyunin, "Collective interaction control of optical frequency shot-noise in charged particle beams". Phys. Rev. Lett. 102, 154801 (2009).
- A. Nause, E. Dyunin, A. Gover, "Optical frequency Shot- Noise suppression in electron beams: 3-D analysis". .J. of Appl. Phys. 107, 103101 (2010).
- A. Gover, E. Dyunin, T. Duchovni, A. Nause (2011) Collective micrody- namics and noise suppression in dispersive electron beam transport, Phys. of Plasmas , 18, 123102.
- E. Dyunin, A. Nause, A. Gover (2011) Suppression of Current Shot Noise and of Spontaneous Radiation Emission in Electron Beams by Collective Coulomb Interaction, IEEE transactions on Plasma Sciences, 39, 10.
- **A. Gover, A. Nause, E. Dyunin, M. Fedurin, "Beating the Shot-noise limit". Nature Phys. 1745-2481 (2012).**

Introduction

Is it possible to suppress the beam current noise below the known Shot-noise level (eI)?

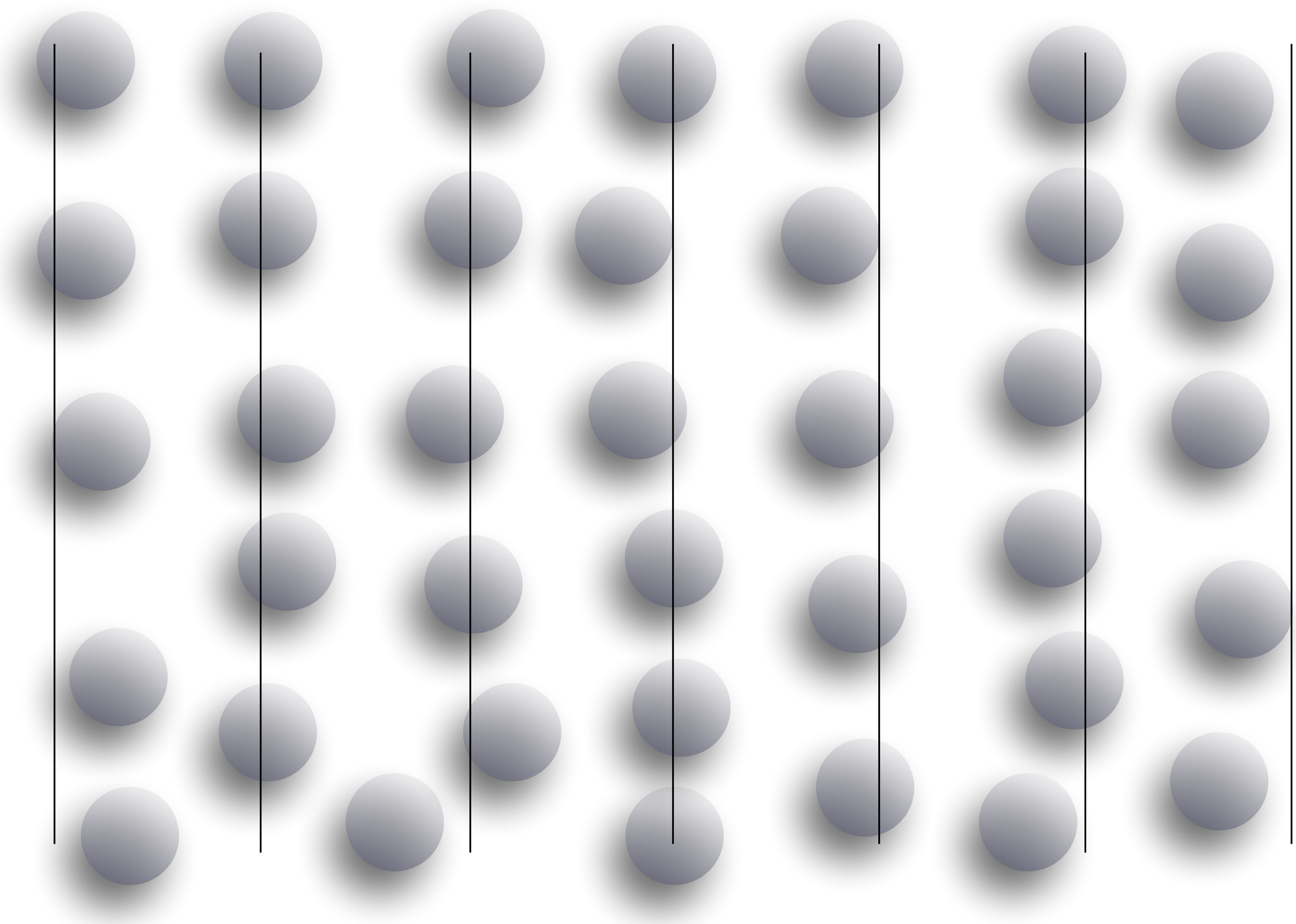
Shot Noise

$$\overline{|\breve{i}(0,\omega)|^2} = eI_b$$

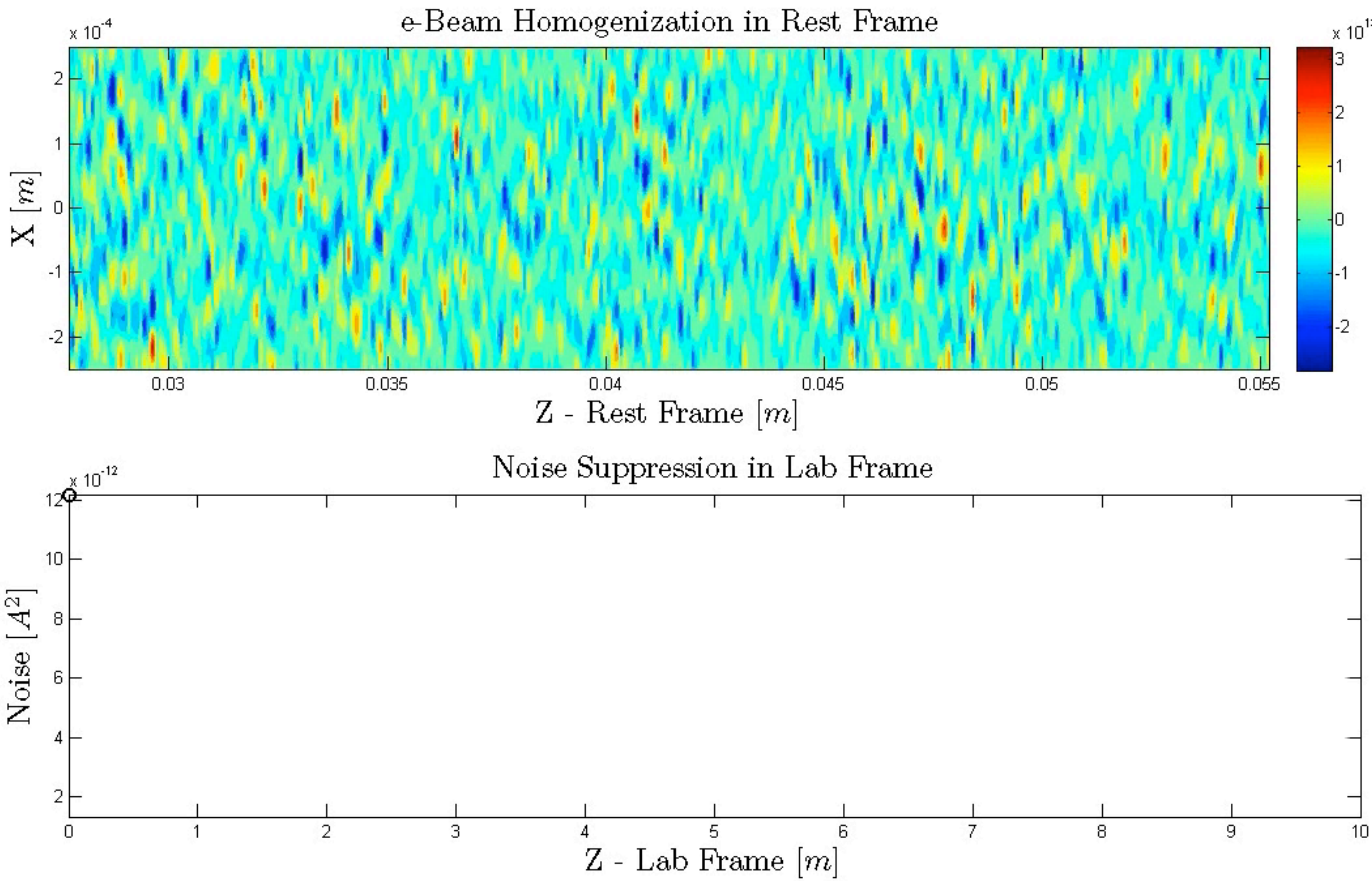


Shot Noise

$$\overline{|\breve{i}(L_d,\omega)|^2} << eI_b$$



What does the noise suppression and homogenization process looks like?



What is it good for?

- Noteworthy demonstration of a fundamental physical process.
- Suppress spontaneous and SASE emission in any free electron radiation device, including Undulators and FELs.
- Help controlling beam instability in transport of intense high quality beams.

Scientific Background

1-D Model Analysis

In a free drift beam transport section with **uniform** beam parameters

$$\breve{i}(z,\omega) = [\cos\phi_p \breve{i}(0,\omega) - i(\sin\phi_p/W_d)\breve{V}(0,\omega)]e^{i\phi_b(z)}$$

$$\breve{V}(z,\omega) = [-iW_d \sin\phi_p \breve{i}(0,\omega) + \cos\phi_p \breve{V}(0,\omega)]e^{i\phi_b(z)}$$

$$\phi_b = \frac{\omega}{v_z}z,\ \phi_p = \theta_{pr}z,\ \theta_{pr} = r_p\frac{\omega_p^{'}}{v_0},\ \omega_p^{'} = (\frac{e^2 n_0}{m\epsilon_0\gamma^3}),\ W_d = \sqrt{\mu_0/\epsilon_0}/k\theta_{pr}A_e$$

$$\breve{V}(\omega) = -\gamma_o^3 v_o(m/e)\breve{v}(\omega)$$

1-D Model

In the condition for dominant Shot-noise: $\overline{|\breve{i}(0,\omega)|^2} \gg \overline{|\breve{V}(0,\omega)|^2}/W_d^2$

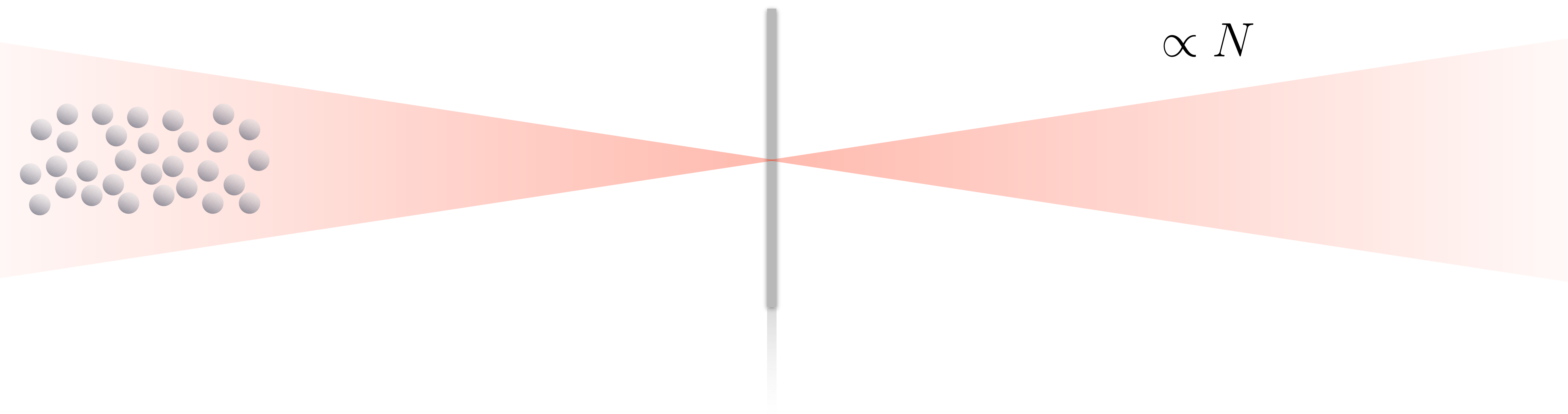
and at a distance of quarter plasma oscillation $\phi_p = \theta_p L_d = \pi/2$

we obtain full transformation of current noise to velocity noise and vice versa:

$$\overline{|\breve{i}(L_d,\omega)|^2} = \overline{|\breve{V}(0,\omega)|^2}/W_d^2$$

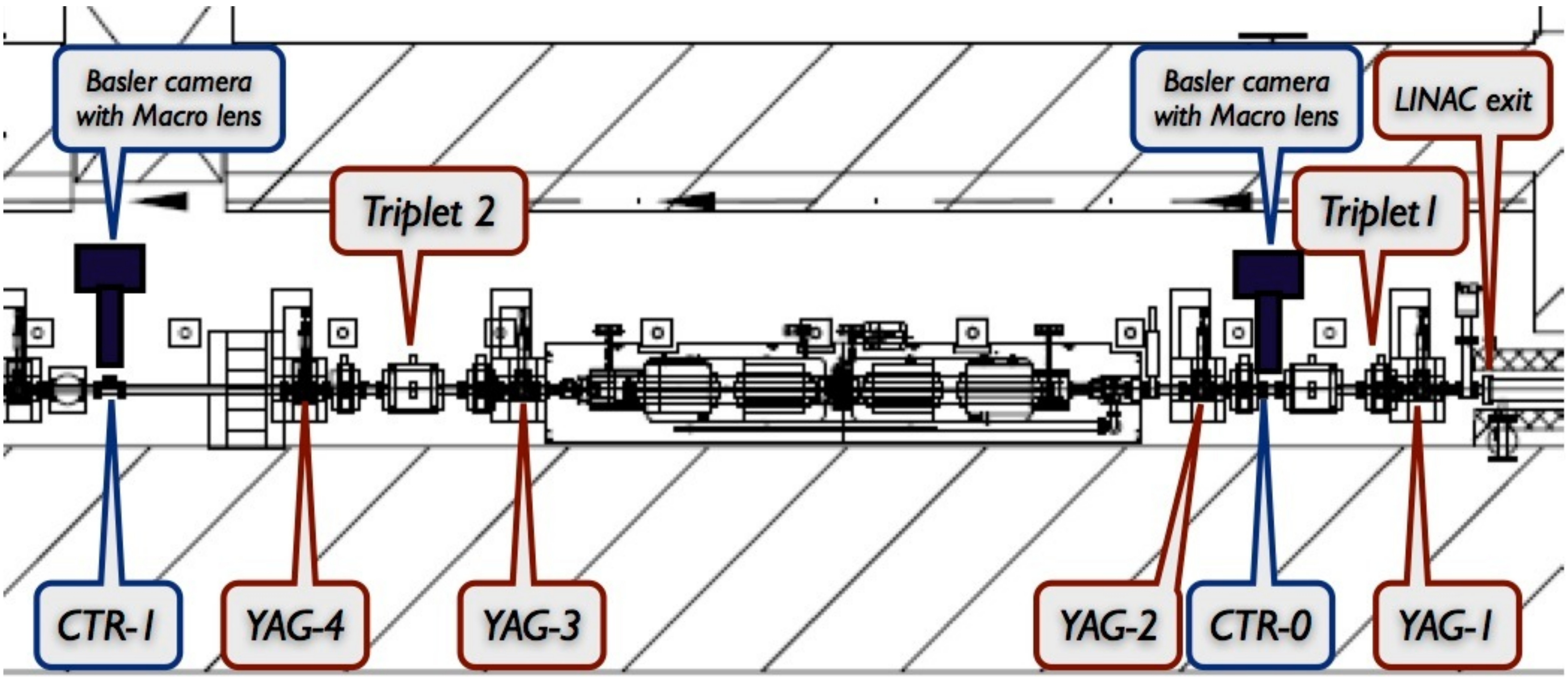
$$\overline{|\breve{V}(L_d,\omega)|^2} = \overline{|\breve{i}(0,\omega)|^2} W_d^2$$

OTR From an Electron Pulse

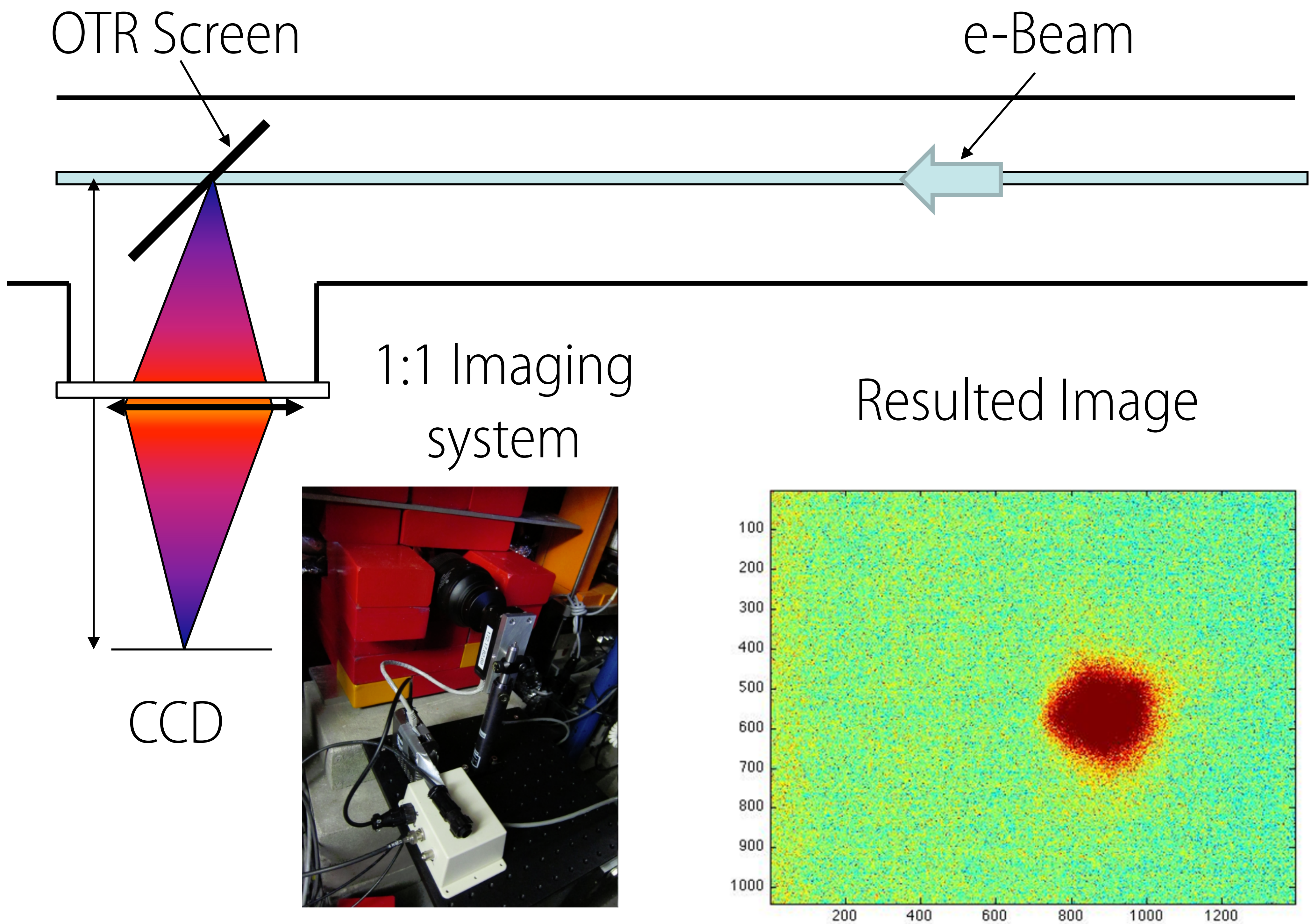


Experimental Concept

ATF Facility (Brookhaven National Lab)

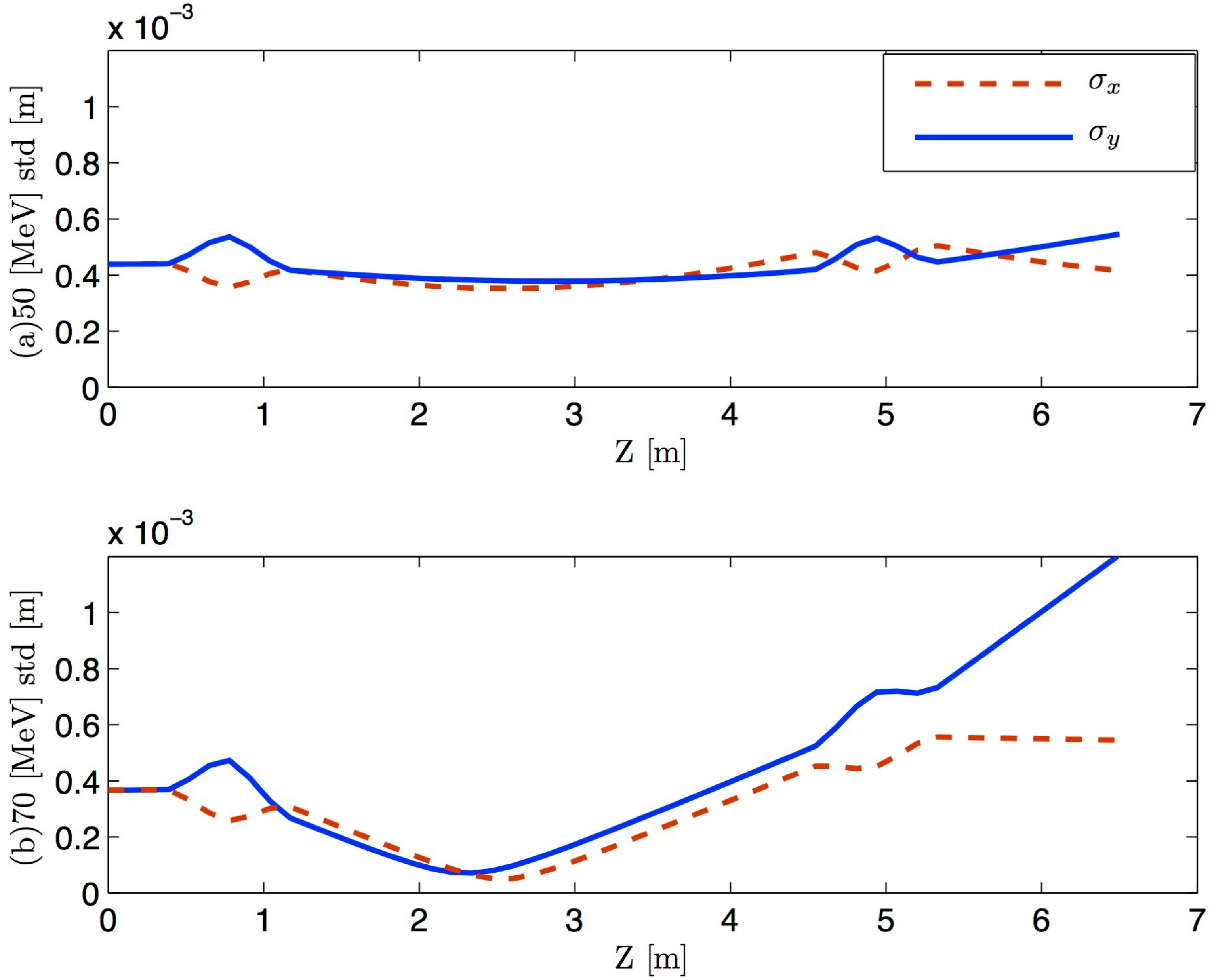


Experimental Setup



Theoretical Predictions

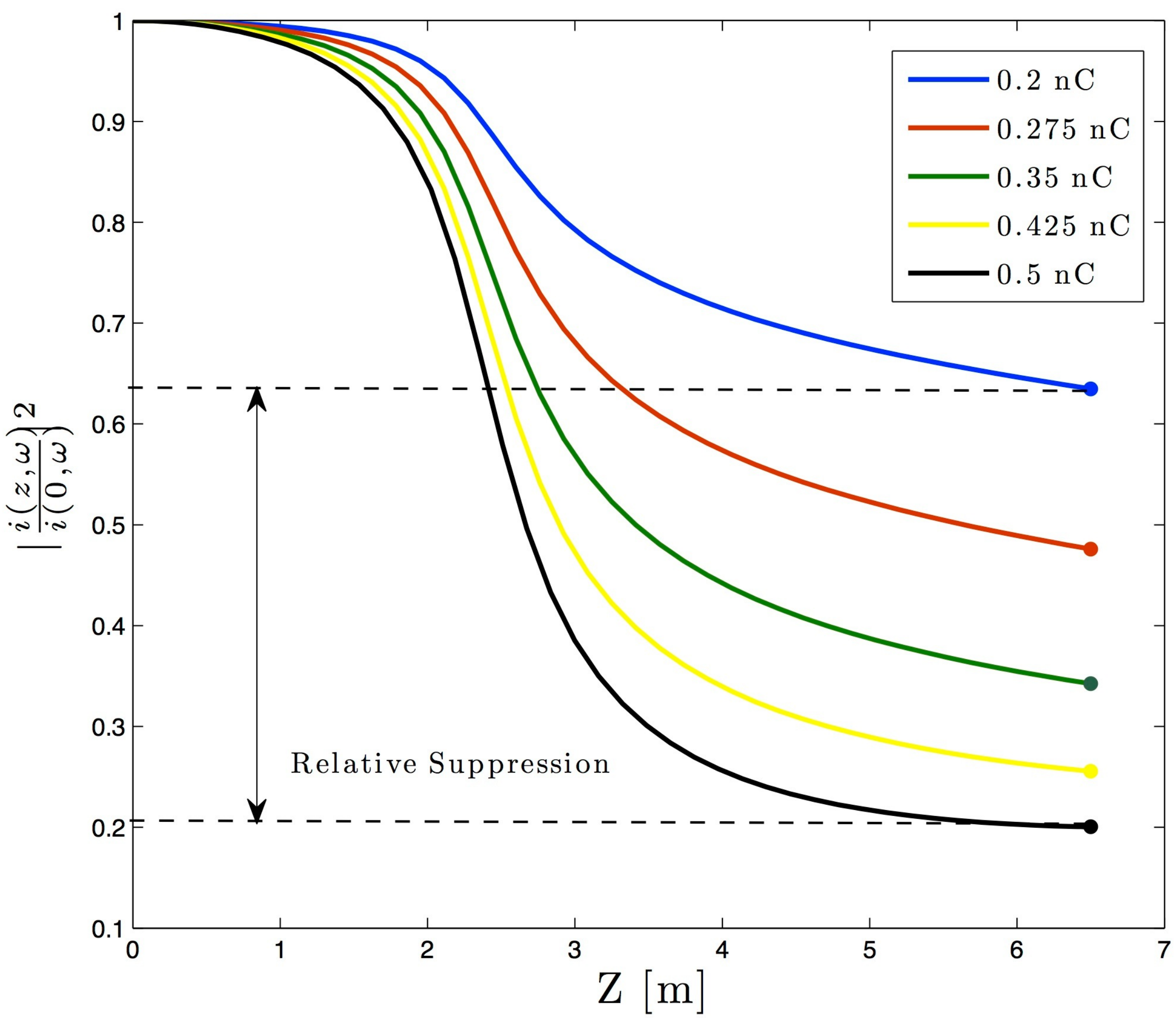
Beam Profile (GPT-General Particle Tracer)



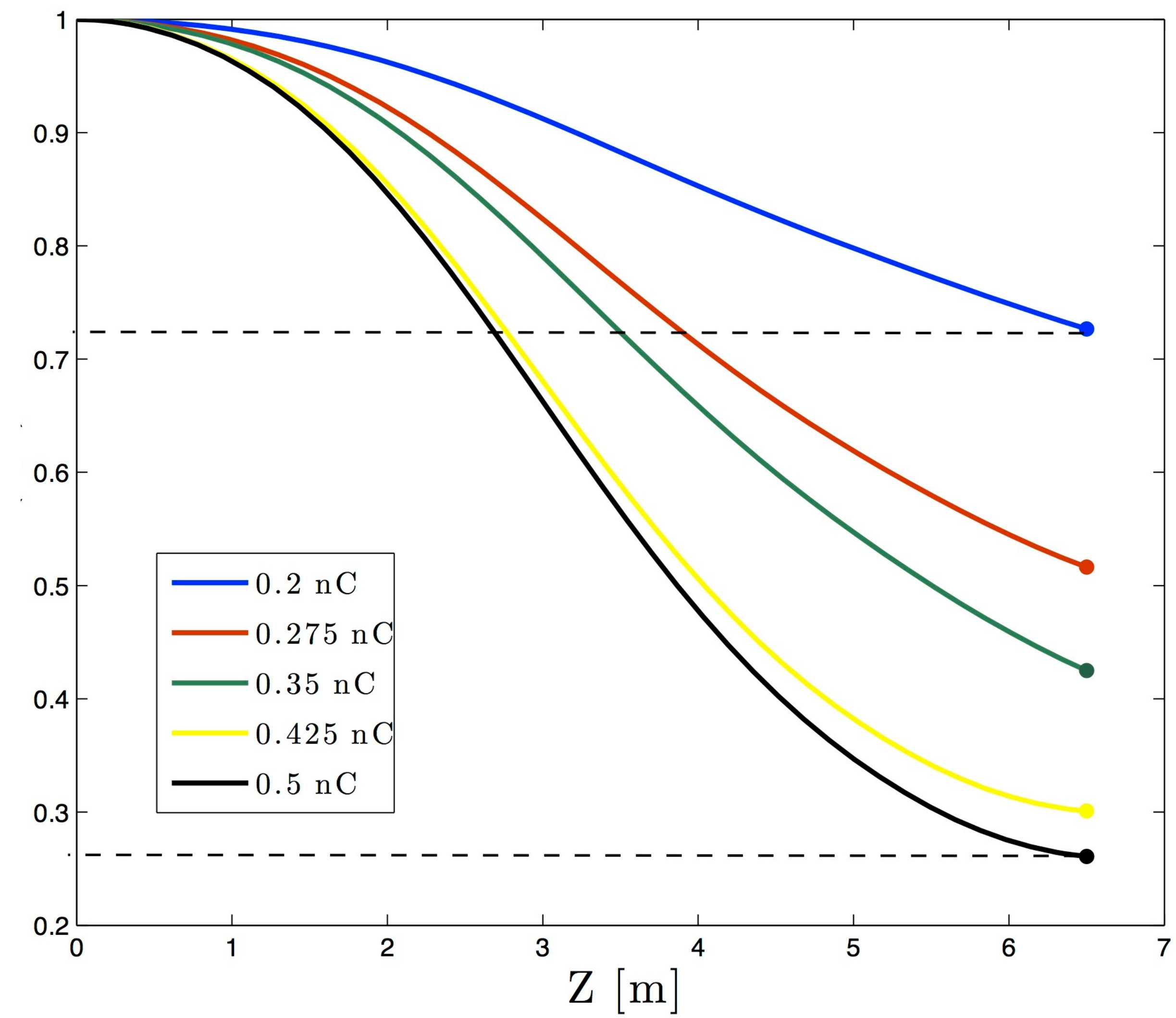
Theoretical Predictions

Noise dynamics during drift (ATF)

70 MeV

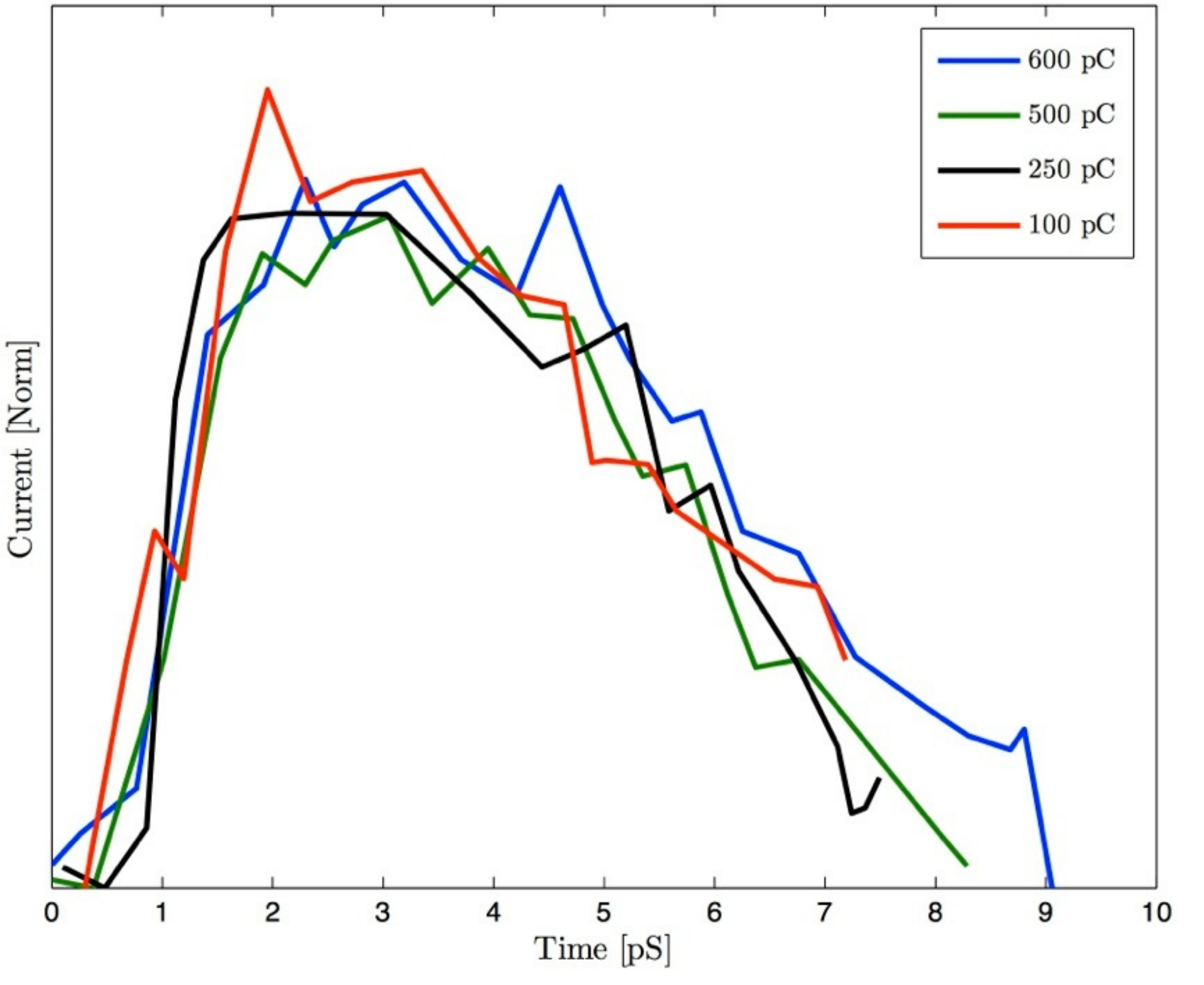


50 MeV



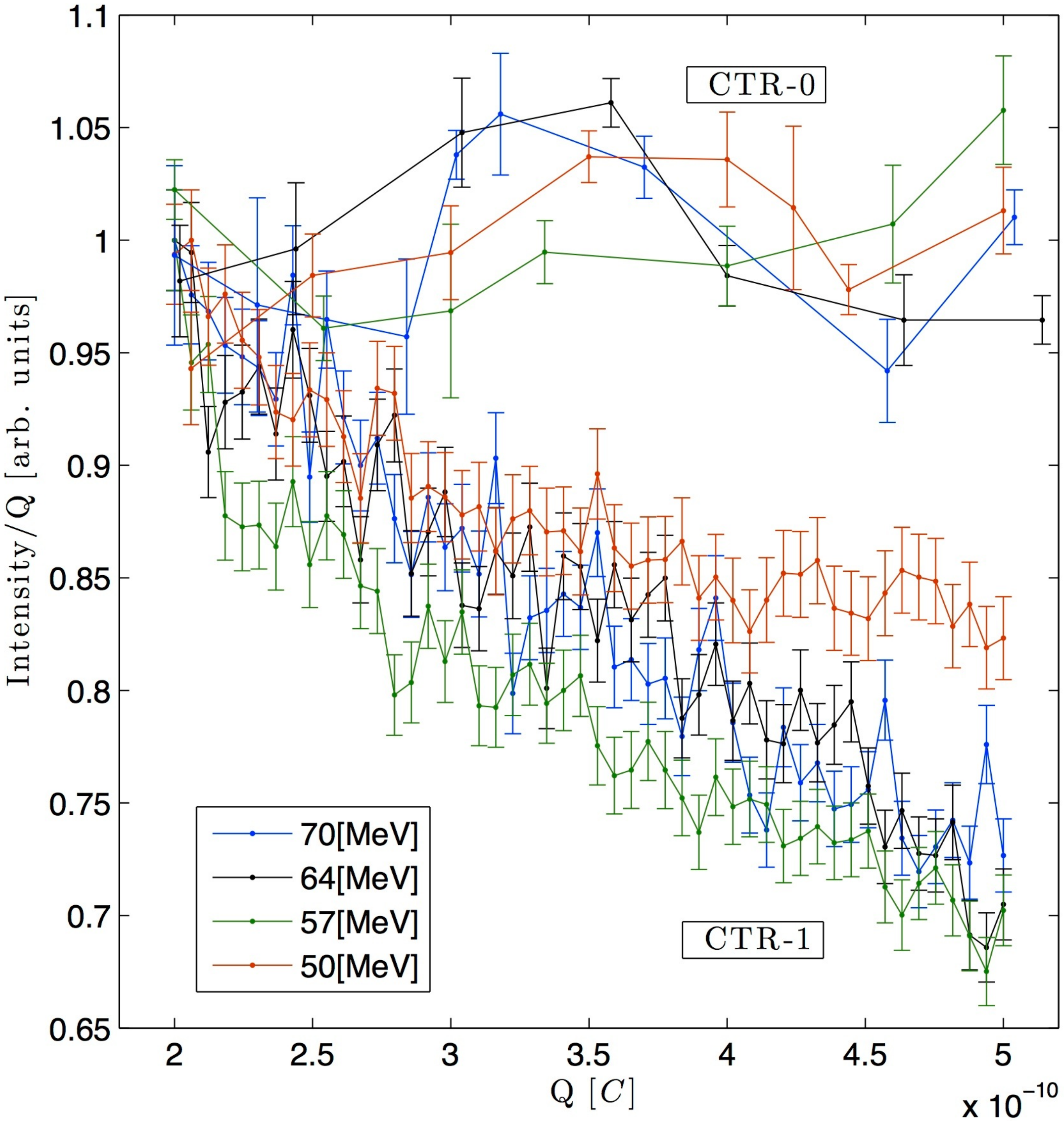
Operating Parameters

- Pulse Length: 5 pS
- Beam Energy: 50-70 MeV
- Beam Current: 40-100 A
- Normalized Emittance: ~3 mm-mrad
- Initial Beam Size: 400-500 um
- Acceleration Phase: On crest
- Copper OTR Screen

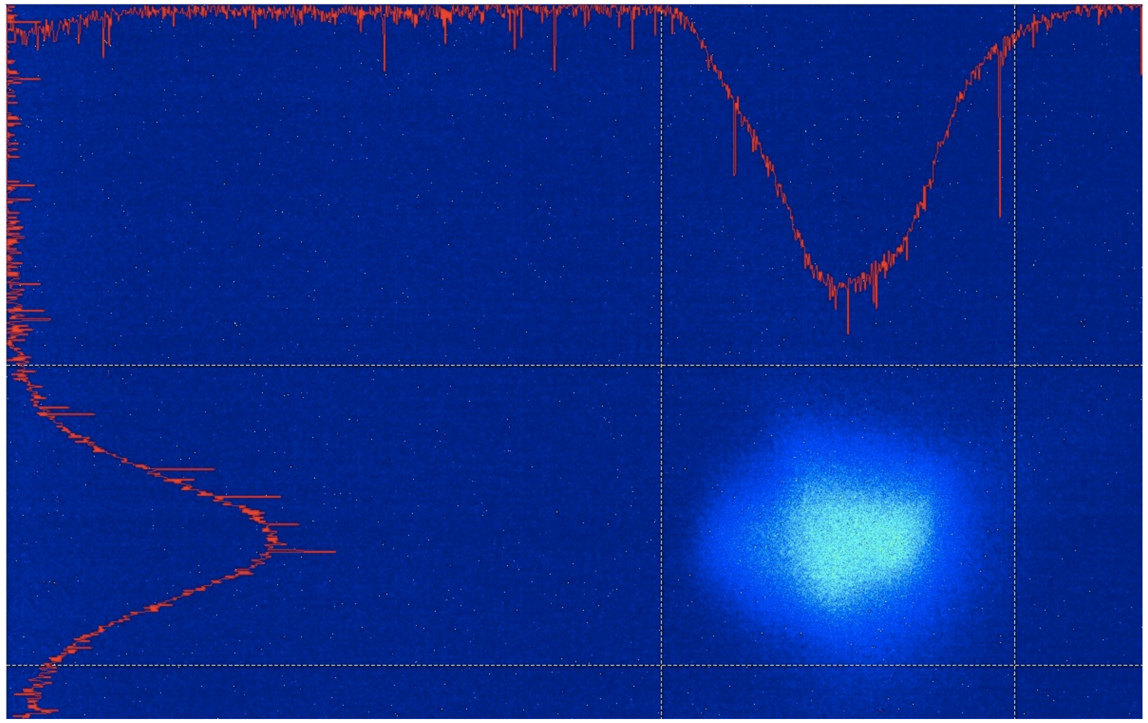


- Basler CCD camera equipped with a Nikkor Macro lens (100 mm)
- Camera Sensitivity: 0.4-1 um

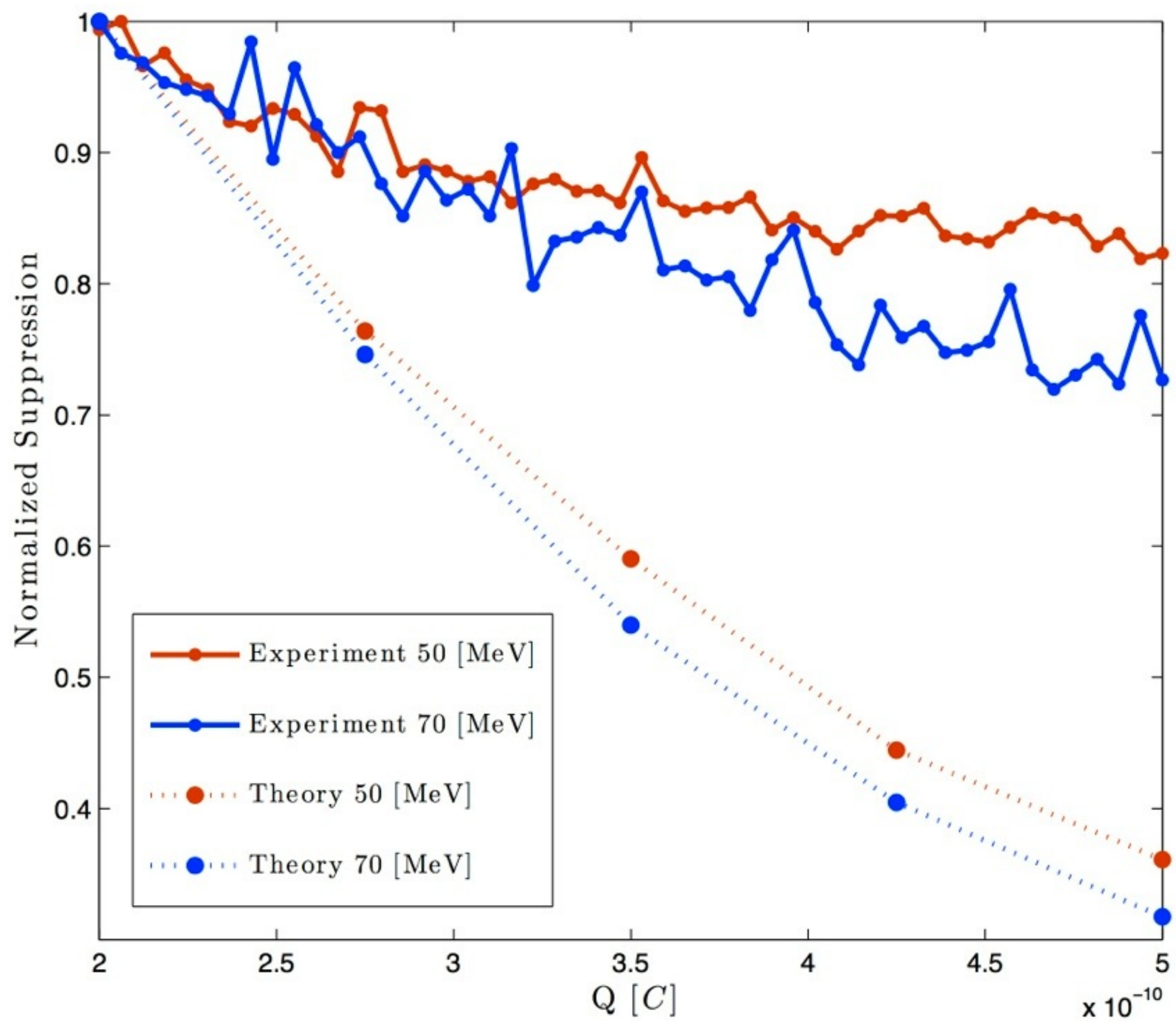
Experimental Results



ATF/BNL - October 2011



Experimental Results VS Theory



Conclusions

- It is possible to adjust the e-beam current shot-noise level by controlling the longitudinal plasma oscillation dynamics.
- We have demonstrated for the first time such noise suppression at optical frequencies.
- Implication to coherence enhancement of seeded-FELs, controlling micro-bunching instabilities and COTR effects.

Thanks