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

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Publications


Introduction

Is it possible to suppress the beam current noise below the known Shot-noise level ($eI$)?
In a free drift beam transport section with uniform beam parameters, this relativistically extended theory results in the following dynamic equations for the spectral noise parameters:

\[
\begin{align*}
\ddot{i}_{s}z, & \quad t = \cos p \dot{i}_{s0}, t \\
\frac{\ddot{\imath}}{\dot{\imath}} & = e I_b(z)
\end{align*}
\]

where

\[
\dot{\imath} = \frac{\vec{v} z}{\dot{p} z} \frac{\vec{v} z}{\dot{p} z} \frac{\vec{v} z}{\dot{p} z} = r \vec{v} z \vec{v}_0 \vec{v}_0 \vec{v}_0 \\
\mu_0 & = \frac{\vec{v} z}{\dot{p} z} \vec{v}_0 \\
\vec{E}_c & = \text{longitudinal energy spread in the beam}
\]

These are the well-known plasma oscillation equations of a space charge column as viewed in the laboratory frame when the plasma is drifting. The initial current and kinetic voltage modulation amplitudes are not known when they are generated by a random process of electrons injection into the drift section at random energies within a given range of small energy spread \(\vec{E}_c\) around the center energy. From the classical one-dimensional shot noise theory:

\[
|\dot{i}(0, \omega)|^2 = e I_b
\]

Here \(\vec{E}_c\) is the longitudinal energy spread in the beam. In low noise vacuum tube guns, it is ideally limited by the cathode temperature \(\vec{E}_c\), but it is significantly increased during the acceleration processes in an RF gun injector and acceleratory. The statistical averaging symbol corresponds to averaging over the initial entrance times of the electrons and their velocity distribution.

This model is essentially a modified one-dimensional longitudinal model of interaction. It applies to an ex-beam with finite cross-section area.
In a free drift beam transport section with uniform beam parameters, this relativistic theory results in the following dynamic equations for the spectral noise parameters:

\[
\dot{\mathbf{v}}_s(z, t) = \left[ \cos \hat{p}, \sin \hat{p} \right] \mathbf{V}_s, \quad \dot{\mathbf{v}}_s \left( z, t \right) = \mathbf{e}^i \mathbf{b}(z)
\]

where

\[
\hat{p} = \int v_z(z) \, dz
\]

These are the well-known plasma oscillation equations of a space charge column as viewed in the laboratory frame when the plasma is drifting. The initial current and kinetic voltage modulation amplitudes are not known when they are generated by a random process of electrons injection into the drift section at random energies within a given range of small energy spread \( \Delta E \) around the center energy \( E_0 \).

From the classical one-dimensional shot noise theory [1]:

\[
|\dot{i}_{Ld, \omega}|^2 \ll eI_b
\]

Here

\[
\Delta E = k_B T_c\Delta z
\]

is the longitudinal energy spread in the beam. In low noise vacuum tube guns, it is ideally limited by the cathode temperature \( T_c \), but it is significantly increased during the acceleration processes in an RF gun injector and acceleratory. The statistical averaging symbol corresponds to averaging over the initial entrance times of the electrons and their velocity distribution.

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What does the noise suppression and homogenization process look 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.
In a free drift beam transport section with uniform beam parameters

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

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

\[ \phi_b = \frac{\omega}{v_z} z, \phi_p = \theta_{pr} z, \theta_{pr} = r_p \frac{\omega_p}{v_0}, \omega_p = \left( \frac{e^2 n_0}{m e_0 \gamma^3} \right), \quad W_d = \sqrt{\mu_0/\varepsilon_0/k \theta_{pr} A_e} \]

\[ \ddot{V}(\omega) = -\gamma_0^3 v_0 (m/e) \ddot{v}(\omega) \]
1-D Model

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

and at a distance of quarter plasma oscillation

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

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

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

$$\phi_p = \theta_p L_d = \pi / 2$$
Shotnoise is a noise resulting from the granular nature of the space-charge in an electron beam. The discreteness of the particles and the randomness of electrons emission from the cathode causes time dependent fluctuations of the charge and current density at any cross section along the beam transport line. This noise was first reported in 1918 by Schottky who made experiments in vacuum tubes. Noise is best characterized in terms of the Fourier transform of the time-varying fluctuations in electric current, namely, by its spectral density. The scientific hypothesis underlying this research proposal is that it is possible to observe and control optical frequency energy and current shot noises fluctuations in a dense relativistic charged particles beam. Moreover, at certain conditions, when the dominant noise in the beam is current shot noise and density fluctuations, it is possible to reduce significantly the beam noise by virtue of a collective interaction process along an interaction length corresponding to a quarter period longitudinal plasma oscillation in the beam. This means that the charge distribution in the beam can be homogenized in this process. This remarkable optical scale "self ordering" process in a commonplace relativistic charged particles beam is quite unexpected and still controversial although similar effects were observed in the microwave frequency regime 6 years ago. It should be stressed that this hypothesis does not violate any thermodynamics principles. When the beam density homogenizes, the current shot noise transforms into energy noise. The question is whether technological limitations of beam acceleration and transport limit the process from taking place, and in what frequency range. In recent years, there has been great advance in the technological improvement of the quality parameters, e.g., energy spread, emittances of accelerated high current density electron beams.
Experimental Concept

ATF Facility (Brookhaven National Lab)
Experimental Setup

OTA Screen

1:1 Imaging system

CCD

e-Beam

Resulted Image
Theoretical Predictions

Beam Profile (GPT-General Particle Tracer)
Theoretical Predictions

Noise dynamics during drift (ATF)

70 MeV

50 MeV

Relative Suppression
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

![Graph showing experimental results vs. theory. The x-axis represents Q [C] and the y-axis represents normalized suppression. The graph includes lines for Experiment 50 [MeV], Experiment 70 [MeV], Theory 50 [MeV], and Theory 70 [MeV].]
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