FIRST OBSERVATION OF OPTICAL CURRENT NOISE SUPPRESSION BELOW THE SHOT-NOISE LIMIT

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Abstract

In this paper we present experimental results that demonstrate noise suppression in the optical regime, for a relativistic e-beam, below the well-known classical shot-noise limit. Shot-noise amplitude is linear to the e-beam current due to the random nature of particles emission (Poisson statistics) from the cathode. Plasma oscillations driven by collective Coulomb interaction during beam drift between the electrons of a cold intense beam are the source of this phenomenon [1]. The effect was experimentally demonstrated by measuring Optical Transition Radiation (OTR) power per unit e-beam pulse charge. The noise suppression effect implies beam charge homogenization (sub-Poissonian particle number distribution) and therefore the spontaneous radiation emission from such a beam would also be suppressed (Dicke's subradiance [2]). This can be utilized to suppress SASE radiation emission in FEL [3],[4]) and enhance the coherence [5] of seed-injected FELs [6] beyond the classical coherence limits.

MAIN

Current shot-noise suppression in an electron beam in the optical frequency regime is an effect of particle self-ordering and charge homogenization on the scale of optical wavelengths [7], which statistically corresponds to the exhibition of sub-Poissonian electron number statistics (similarly to photons in squeezed light [8]). A dispute over the feasibility of this effect is resolved in the experiment reported here [9]. We have evidence for e-beam noise suppression from measurement of the Optical Transition Radiation (OTR) power emitted by a beam upon incidence on a metal screen. The OTR emission is proportional to the current shot noise of the incident beam.

In a randomly distributed stream of particles that satisfies Poison statistics, the variance of the number of particles that pass through any cross section at any time period T is equal to the number of particles N_T that pass this cross section during the same time T, averaged over different times of measurements. Consequently, the current fluctuation is $I = e\sqrt{N_T}/T = e\sqrt{I_b T e}/T = \sqrt{eI_b T}$. When formally calculated, the average beam shot-noise spectral power $(-\infty < \omega < \infty)$ is:

$$\overline{|\breve{I}(\omega)|^2} = eI_b \quad (1)$$

here $I(t)$ is the beam current modulation, and the Fourier Transform is defined as $\breve{I}(\omega) = \int_{-\infty}^{\infty} e^{i\omega t} I(t)dt$.

In RF accelerators it is usually assumed that collective inter-particle interaction is negligible during beam acceleration and transport, and the shot-noise limit 1 applies. However, with recent technological advances in RF accelerators, and in particular the development of photocathode guns [10], high quality cold and intense RF- LINAC-accelerated electron beams are available, and the neglect of collective micro-dynamic interaction effects in the transport of such electron beams is no longer justified. Effects of coherent OTR emission and super-linear scaling with I_b of the OTR emission intensity were observed in SLAC 's LCLS injector [11] and other labs [12]. These effects, originally referred to as "unexplained physics" [13], are now clearly recognized as the result of collective Coulomb micro-dynamic interaction and establishment of phase correlation between the electrons in the beam. In these cases, however, the collective interaction led to shot-noise and OTR power enhancement (gain), and not to suppression. Collective effects were shown to be responsible also for beam instabilities (micro-bunching instability) which were observed in dispersive e-beam transport elements [14],[15] Recently Musumeci et al demonstrated in Pegasus collective microdynamic evolution of 1THz coherent single-frequency current modulation [16], but no stochastic optical noise suppression effect could be observed.

While noise gain due to collective interaction has been demonstrated in numerous labs, the notion of beam noise suppression at optical frequencies1 has been controversial (though analogous effects were known in non-relativistic microwave tubes [17]). To explain the physics of the noise suppression, we point out that in the e-beam frame of reference the effect of noise suppression comes into expression as charge homogenization. A simple argument shows that the space-charge force, which is directed to expand higher density charge bunches, has a dominant effect over the randomly directed Coulomb repulsion force between the particles (see Fig. 1).

Assume that in some regions of the beam, there is higher particle-density bunching. Encompassing such a bunch within a sphere of diameter d'. The excess charge in this sphere is $e\Delta N'$, and the potential energy of an electron on the surface of the sphere is $\epsilon_{sc} = e^2\Delta N'/(2\pi\epsilon_0 d'$. This potential energy turns in time into kinetic energy of electrons, accelerated in the direction of bunch expansion (homogenization). At the same time, the electron also possesses an average potential energy due to the Coulomb interaction with neighbor electrons at an average distance ${n'_0}^{-1/3}$ (n'_0 is the average density in the beam frame). This potential energy $\epsilon_{Coul} = e^2(4\pi\epsilon_0 {n'_0}^{-1/3}$ turns into kinetic energy of electrons that are accelerated in random directions. In a randomly distributed electron beam that satisfies

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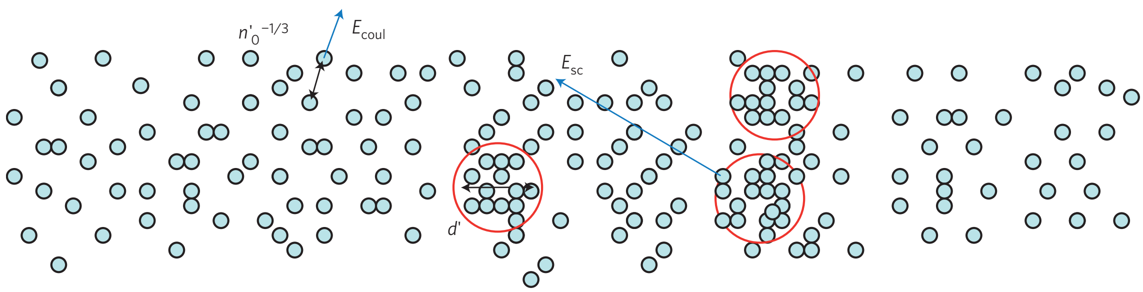

Figure 1: Random distribution in an electron beam, as viewed in the beam reference frame. The expansion-directed space charge force, exerted on electrons on the boundaries of a higher density bunch, exceeds the random inter-particle Coulomb force.

Poisson statistics $\Delta N' = N'^{1/2}$, $N' = \pi d'^3 n_0'/6$. Therefore, the condition for domination of the directed space-charge energy over the random energy is

$$\frac{\epsilon_{sc}}{\epsilon_{Coul}} = \left(\frac{2\pi}{3}\frac{d'}{n_0'^{-1/3}}\right)^{1/2} > 1 \qquad (2)$$

We conclude that a random cold beam of density n_0' always tends to homogenize in any spatial scale larger than the average inter-particle distance: $d' > n_0'^{-1/3}$. The expansion trend of a dense bunch would clearly tend to homogenize the charge distribution of an initially cold e-beam "plasma". The time scale for the homogenization process can only be connected to the plasma frequency - the fundamental collective excitation in the beam, namely: $\sim \pi/\omega_{po}'$, where $\omega_{po}' = (e^2 n_0'/m\epsilon_0)^{1/2}$.

In electron beam transport under appreciable space-charge conditions, the microdynamic noise evolution process may be viewed as the stochastic oscillations of Langmuir Plasma waves [1]. In the linear regime, the evolution of longitudinal current and velocity modulations of a beam of average current I_b, velocity βc and energy $E = \gamma mc^2$, can be described in the lab frame by [18]:

$$\begin{aligned} \frac{d}{d\phi_p}\breve{i}(z,\omega) &= -\frac{i}{W(z)}\breve{v}(z,\omega) \\ \frac{d}{d\phi_p}\breve{v}(z,\omega) &= -iW(z)\breve{i}(z,\omega) \end{aligned} \qquad (3)$$

where $\breve{i}(\omega) = \breve{I}(\omega)e^{i?z/\beta c}$, $\breve{v}(\omega) = \breve{V}(\omega)e^{i?z/\beta c}$, $\breve{I}(\omega)$, $\breve{V}(\omega)$ are the respective Fourier components of the beam current and kinetic-voltage modulations. The kinetic voltage modulation is related to energy and velocity modulations: $\breve{V} = -(mc^2/e)\breve{\gamma} = -(mc^2/e)\gamma^3\beta\breve{\beta}$, $\phi_p(z) = \int_0^z \theta_{pr}(z')dZ'$, is the accumulated plasma phase, $W(z) = r_p^2/(\omega A_e \theta_{pr}\epsilon_0)$ is the beam impedance, A_e is the effective beam cross section area, $\theta_{pr} = r_p\omega_{pl}/\beta c$ is the plasma wavenumber of the Langmuir mode, $r_p < 1$ is the plasma reduction factor, $\omega_{pl} = \omega_{p0}/\gamma^{3/2}$ is the longitudinal plasma frequency in the lab frame.

The single frequency Langmuir plasma wave model expression 3 can be solved straightforwardly in the case of uniform drift transport. After employing an averaging process, this results in a simple expression for the spectral parameters of stochastic current and velocity fluctuations (noise) in the beam [1], [18]:

$$\begin{aligned} \overline{|\breve{i}(L,\omega)|^2} &= \overline{|\breve{i}(0,\omega)|^2}\cos^2\phi_p(L) \\ &+(\overline{|\breve{v}(0,\omega)|^2}/W^2)\sin^2\phi_p(L) \end{aligned} \qquad (4)$$

The beam current noise evolution is effected by the initial axial velocity noise through the parameter $N^2 = \overline{|\breve{v}(0,\omega)|^2}/W^2\overline{|\breve{i}(0,\omega)|^2} = (\omega/c\beta k_D)^2$, where $k_D = \omega_{pl}/c\sigma_\beta$ is the Debye wavenumber. Eq. 4 suggests that current noise suppression is possible if the beam is initially cold - $N^2 < 1$, and if plasma phase accumulation of $\phi_p(L) \sim \pi/2$ is feasible. This condition also assures that Landau damping is negligible [19].

The noise suppression demonstration experiment was conducted on the 70MeV RF-LINAC of ATF (Fig. 2). The beam current noise measurement was made by recording the OTR radiation emitted from a copper screen placed L=6.5m away from the accelerator exit. Keeping the camera and screen CTR1 position fixed, the practical way to control the plasma phase ϕ_p was to vary the beam pulse charge (200-500pC) (as in [16]) and the beam energy $E = (\gamma - 1)mc^2$ (50 to 70MeV). The quad settings were readjusted for each beam acceleration energy, and the beam spot sizes σ_x,σ_y were measured at four points (YAG1-YAG4) along the beam transport line (Fig. 2). For reference, the OTR signal was measured independently also on a screen CTR-0 preceding the drift section.

The measured signal S_{OTR} was the integrated charge accumulated in all the pixels of a CCD camera exposed to the OTR emission upon the incidence of single micro-bunch e-beam pulses on the screen. The measured data of S_{OTR}/Q_b in CTR-0 and CTR1 is shown in Fig. 3 as a function of the varied bunch charge Q_b in the range 200-500pC. The pulse duration in all experiments remained approximately the same (5pS) corresponding to average current 40-100A. In a shot-noise dominated beam, in the absence of collective microdynamics, the current noise and consequently SOTR are proportional to I_b (1). Our measured data of S_{OTR}/Q_b in CTR-0 lies approximately

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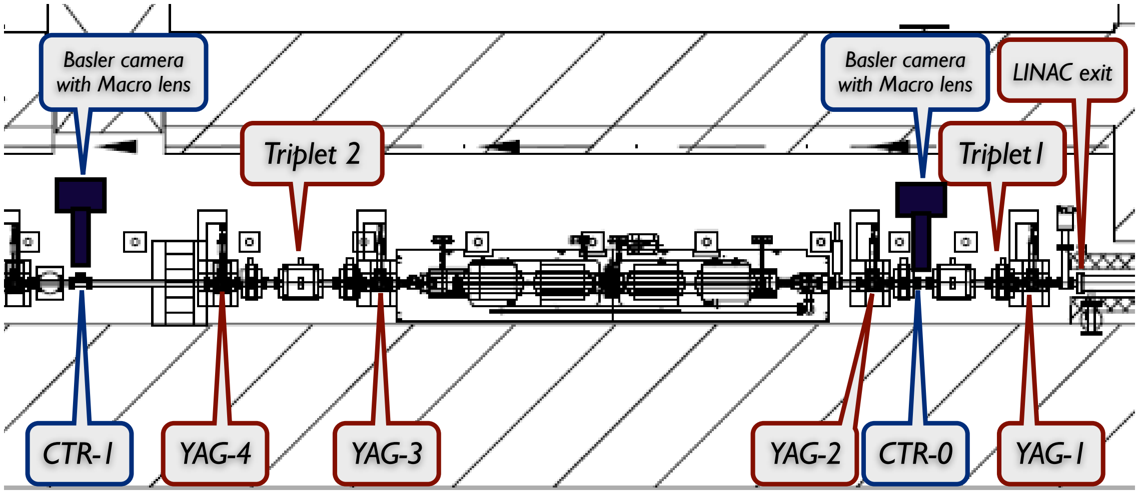

Figure 2: The experimental set-up. The ATF e-beam transport set-up is shown from the injector RF-LINAC exit to the OTR viewer site (CTR-1). The accelerated beam energy was varied from 50MeV to 70MeV and the beam charge was varied from 200pC to 500pC. The beam spot dimensions were measured at four locations using fluorescent screens (YAG-1 to YAG-4). The beam envelope was kept nearly uniform, except in the center section between quadruple lenses TRIPLET-1 and TRIPLET 2 where it was focused to a narrow waist in the free drift section between the triplets (the chicane in the drawing was turned off). An electronic signal proportional to the photon number of integrated OTR emission from CTR-1 was measured using a CCD camera. Independently, similar reference measurement was carried out at CTR-0 prior to the collective interaction region.

on a horizontal line, indicating absence of collective microbunching and noise suppression before this point. On the other hand, the data measured on CTR-1 displays systematic drop as a function of charge (200-500pC) for all beam energies (50-70MeV).

Since the measurement conditions at the two measurement positions and at different energies could not be made identical, the absolute suppression level could not be determined. The normalized data for all experiments depicted in Fig. 2 shows the scaling with charge of the noise per unit charge for all energies. The displayed data demonstrates attainment of 20-30% relative noise suppression, and confirms the predicted effect of collective microdynamic noise suppression process in the drift section.

Beyond observation of noise suppression, interpreting the measured data and the noise suppression rate in terms of a simple theoretical model as presented by Eq. 4 would be very crude. For $N^2 \ll 1$ Eq. 4 predicts maximum suppression by a factor N^2 at $\phi_p = \pi/2$. In the present transport configuration the beam was focused to a tight waist in the section between triplet 1 and triplet 2 (the location of a turned-off chicane). According to a theorem of Gover and Dyunin [1] a plasma phase increment $\phi_p = \pi/2$ is accumulated along a beam waist, but this applies only if the beam transport is fully space-charge dominated. This is not the case when the beam angular spread due to emittance and beam focusing is significant, which compromises the collective microdynamic noise suppression process. Solution of the more general equation (3) under conditions of varying beam cross-section and finite angular spread shows

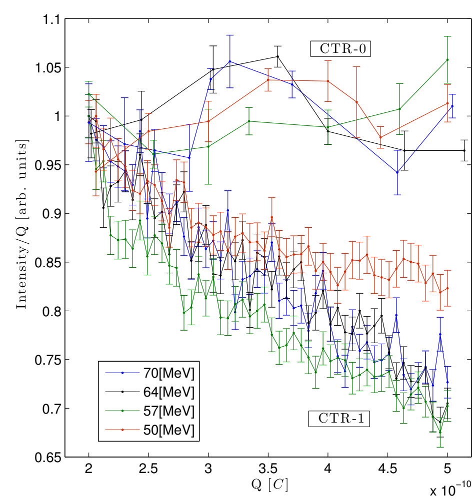

Figure 3: Integrated OTR intensity measurement signals divided by the electron pulse charge. The CTR-1 data corresponds to OTR measurement from a screen, intercepting the e-beam 6.5m away from the LINAC exit. The curves negative slope indicates relative current shot-noise suppression of 20-30% as the beam charge varies from 0.2nC to 0.5nC at different beam energies (50-70MeV). The CTR-0 data corresponds to OTR measurement right after the LINAC exit. Used for reference, its horizontal slope (linear scaling of SOTR on beam charge) indicates that there was no charge suppression prior to the collective microdynamic process in the subsequent drift section.

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that the noise suppression expected in a model configuration similar to the present experimental configuration is smaller than anticipated in the uniform beam model (4). This model calculation also shows that the observed weak dependence of the relative suppression rate on the beam energy is consistent with the experimental conditions (the down scaling of ω_{pl} with $\gamma^{3/2}$ is offset by the increased current density) and with a point of view that in the beam rest frame the beam envelope expansion and the charge homogenization effects are related [1]. Other reasons that can reduce the collective microdynamic suppression rate may be 3-D effects and excitation of higher order Langmuir plasma waves of different wavenumber values θ_{pr} [7],[20]. These and other deviations from ideal conditions can explain why the relative noise suppression effect in the range of charge variation (200-500pC) is quite modest (20-30%).

The first observation of current shot noise suppression at optical frequencies, though small, is of interest from the fundamental and applications points of view. The electron beam shot-noise expression (1) is widely considered to be an absolute limit, and the experiment demonstrates that at least at optical frequencies this is not the case. The suppression of OTR emission is a vivid demonstration of spontaneous emission sub-radiance in Dickes sense [2] in the classical limit. It is attributable to the uniform rate of incidence of electrons on the screen, an effect that would suppress spontaneous and SASE emission in any free electron radiation device, including undulators and FELs [5], as was first suggested in [23]. Furthermore, microdynamic control over electron beam noise may also help to control beam instability in transport of intense high quality beams.

Theory predicts that much bigger factors of shot noise suppression are possible in more favorable configurations, and schemes have been suggested for producing the noise suppression process in shorter lengths using dispersive transport [20],[21] (dispersive transport noise suppression has just been demonstrated experimentally in LCLS [22]). While we demonstrated here the noise suppression effect at optical frequencies (that are four orders of magnitude higher than the previous microwave noise suppression works), further research and beam quality improvements are required in order to determine the short wavelength limits of applicability of this process [24], a limit that is ultimately bound at X-Ray wavelengths by the beam charge granularity inter-particle spacing limit (2).

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