First Demonstration of Optical Frequency Shot-Noise Suppression in Relativistic Electron-Beams and implications to FEL Coherence Enhancement

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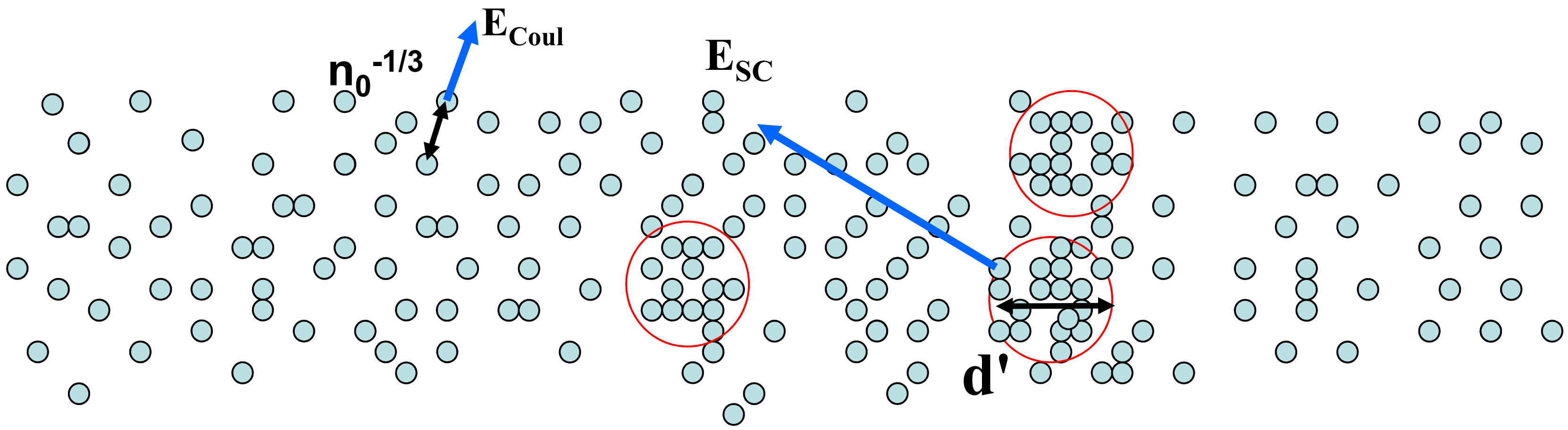
Physics of Collective Micro-Dynamics in a Charged Particle Beam: Homogenization trend

In the beam rest frame:

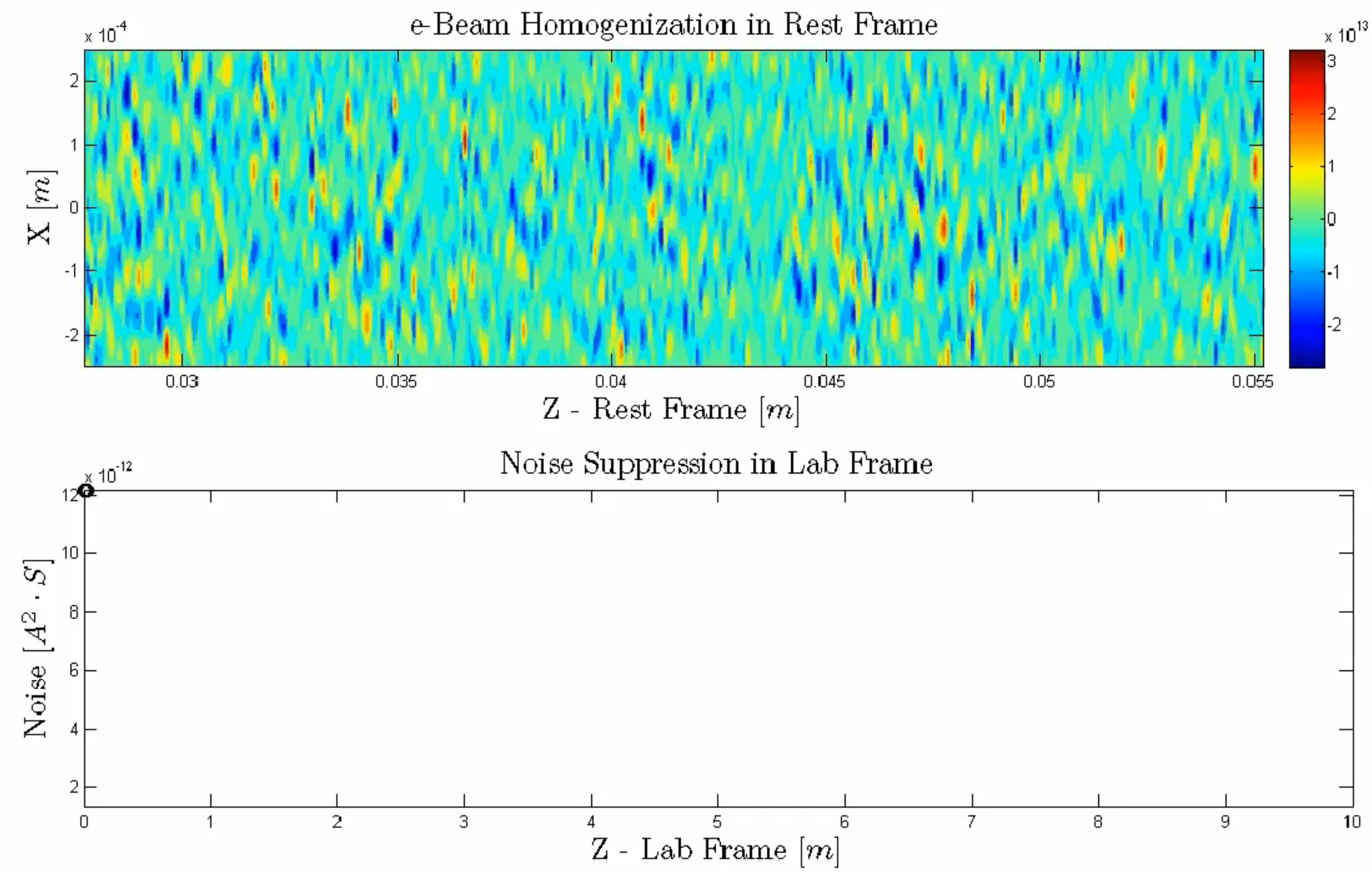
When $\varepsilon_{sc} > \varepsilon_{coul}$?

Answer: $d' > n_0^{-1/3}$



HOMOGENIZATION (λ=5-10 μm)

Density
In beam
frame



$$\frac{\overline{\left|\breve{I}(z,\omega)\right|^2}}{\overline{\left|\breve{I}(0,\omega)\right|^2}}$$

Nause, A. Dyunin, E. Gover, A. Optical frequency Shot- Noise suppression in electron beams: 3-D analysis. *.J. of Appl. Phys*. **107,** 103101 (2010).

ANALYTICAL FLUID-PLASMA LINEAR MODEL

[H. Haus and F. N. H. Robinson, Proc. IRE 43, 981 (1955)]

[A. Gover, E. Dyunin, PRL 102, 154801 (2009)]

Plasma Oscillation in a Uniform e-Beam Drift Section

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

$$\breve{V}(L_d,\omega)=\left[-i\breve{i}(0,\omega)W_d \sin\phi_p + \breve{V}(0,\omega)\cos\phi_p\right] e^{i\phi_b(L_d)}$$

Kinetic voltage:
(axial velocity modulation)

$$\breve{V}(z,\omega)\propto\breve{\gamma}(z,\omega)\propto\breve{v}_z(\omega)$$

Optical phase:

$$\phi_b=\frac{\omega}{v_z}L_d$$

Plasma phase:

$$\phi_p=\theta_{pr}L_d \qquad \theta_{pr}=r_p\frac{\omega_{pL}}{v_0} \quad , \quad \omega_{pL}=\left(\frac{e^2 n_0}{m\varepsilon_0\gamma^3}\right)^{1/2}$$

CURENT SHOT-NOISE SUPPRESSION

$$gain = \frac{\overline{\left|\breve{i}(L_d,\omega)\right|^2}}{\overline{\left|\breve{i}(0,\omega)\right|^2}} = \cos^2\phi_p + N^2\sin^2\phi_p$$

$$N^2 = \frac{\overline{\left|\breve{V}(0,\omega)\right|^2}}{W_d^2\overline{\left|\breve{i}(0,\omega)\right|^2}} = \left(\frac{\lambda_D}{\lambda}\right)^2$$

$$\left(k_D = \frac{2\pi}{\lambda_D} = \frac{\omega_{pL}}{\delta v_z} \right)$$

$$\Rightarrow \quad gain(\phi_p = \pi/2) = N^2$$

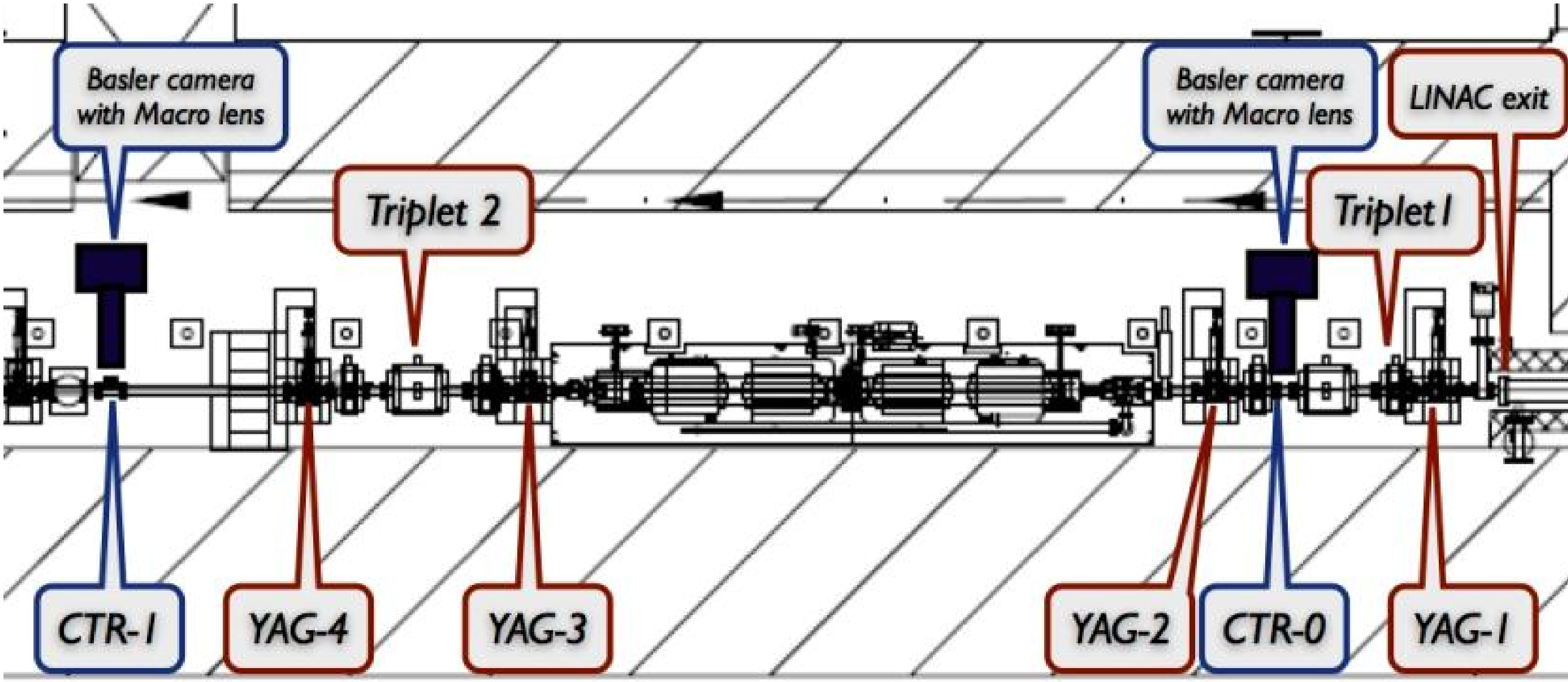
$\langle\langle 1$ **For current noise dominated beam.**

For LCLS (δE=3keV): $N^2 = 2.5\times10^{-5}$

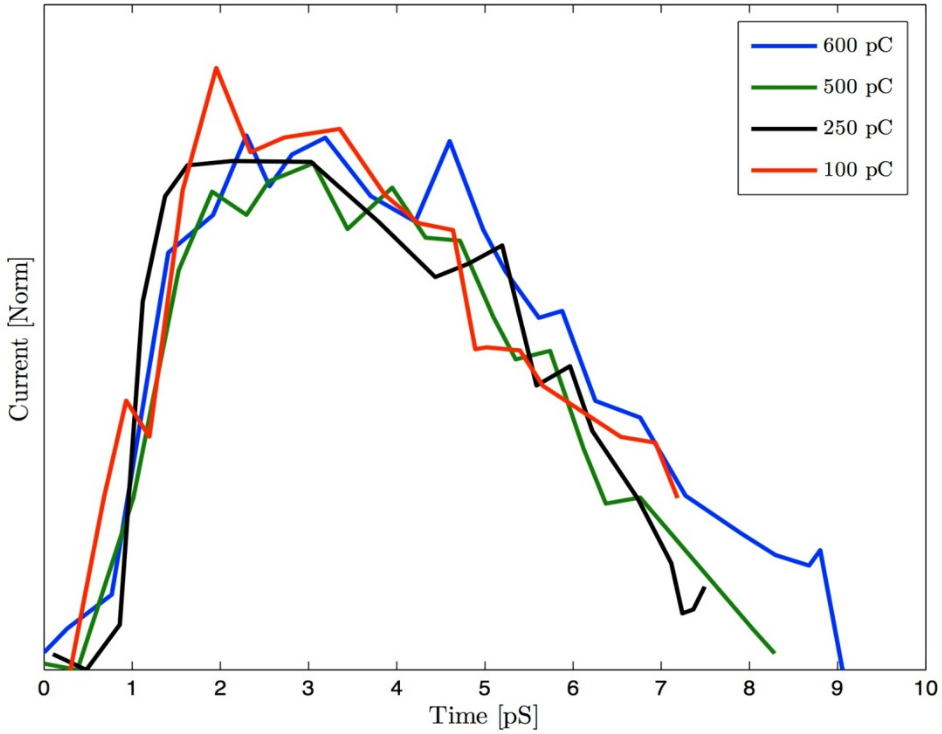
NOISE SUPPRESSION EXPERIMENT IN ATF

ARIEL NAUSE - OCTOBER 2011

Experiment Layout



Operating Parameters



Pulse length: 5 ps

Beam energy: 50 – 70 MeV

Beam current: 40-100 A

Emittance: ~3 mm-mrad

Initial beam size: 400-500 μm

Convergence: ~2 mrad

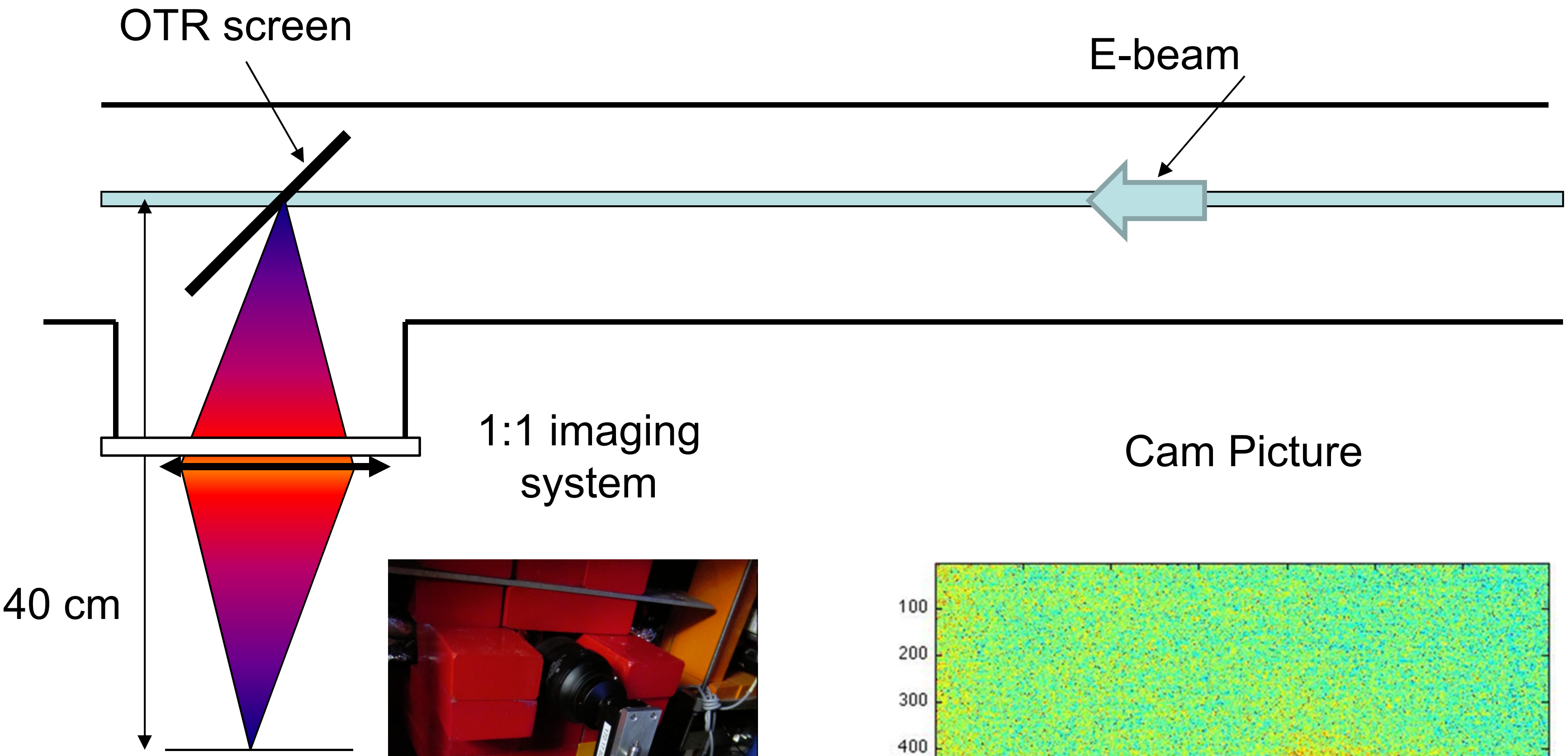
Acceleration phase: on crest

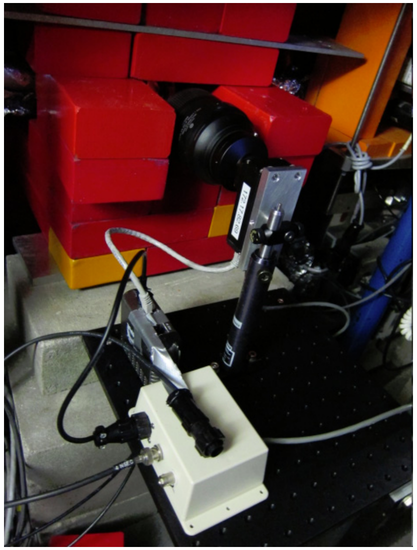
Copper OTR screen

Basler CCD camera equipped with a Nikkor macro lens (100 mm)

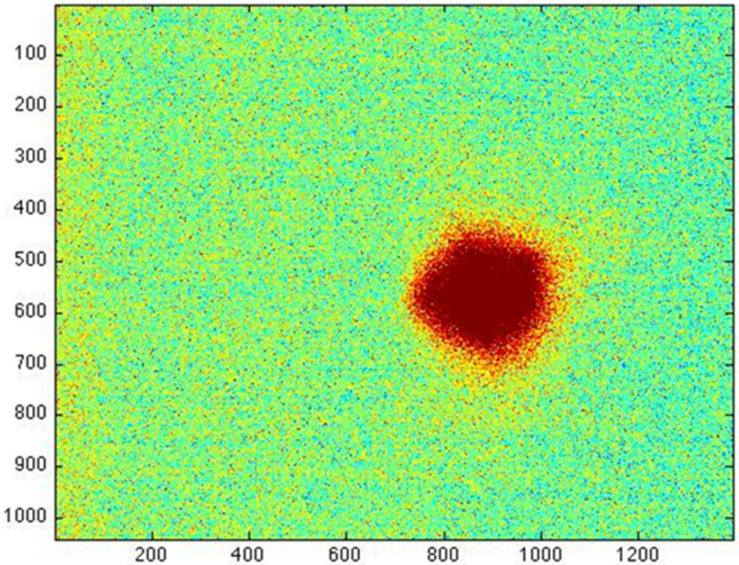
Cam sensitivity: 0.4 – 1 μm

OTR Measurement

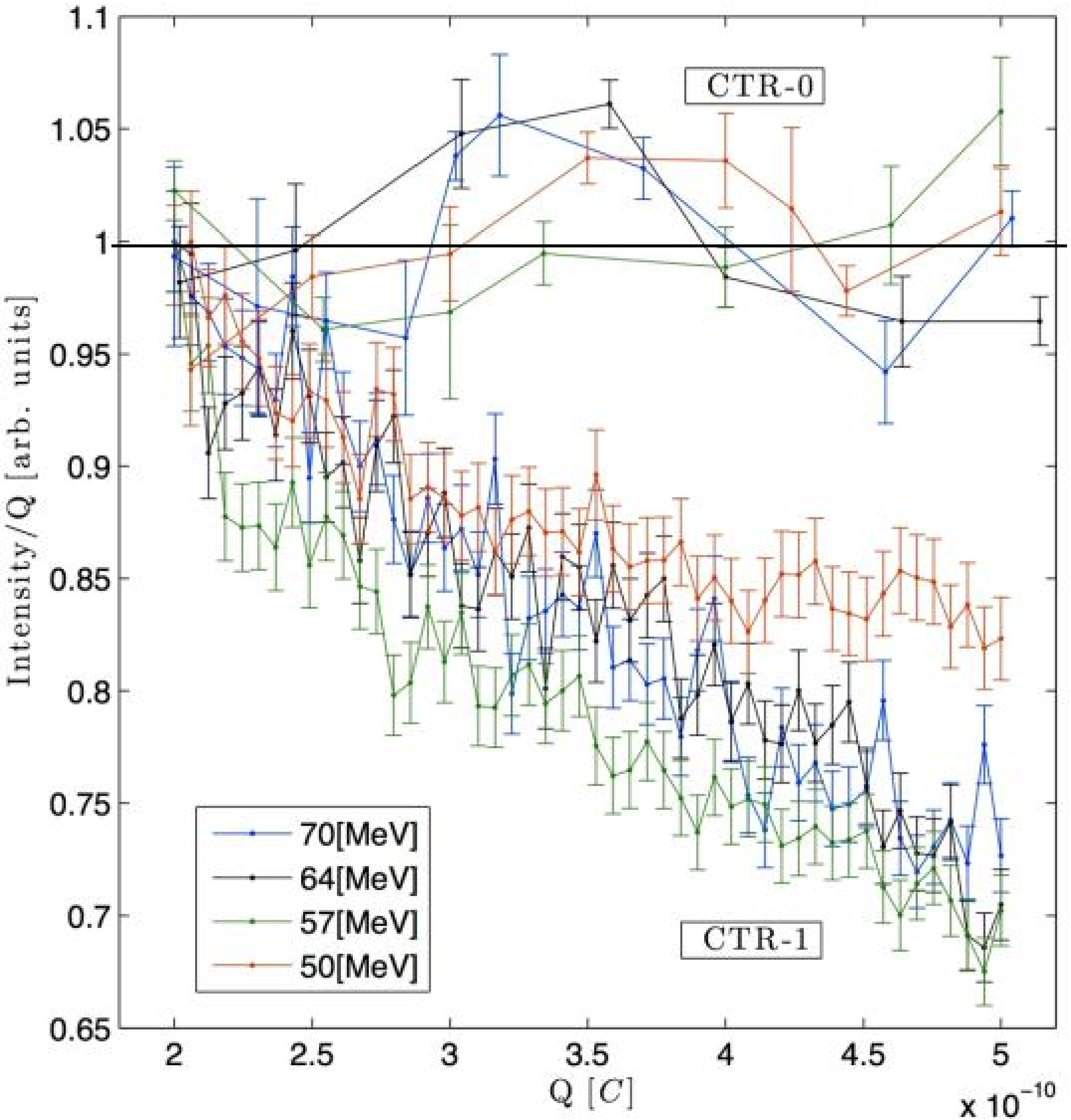




Cam Picture



Measured OTR Signal per unit charge



Before drift: linear dependence on Q

After drift: sub-linear dependence on Q

GENERAL LINEAR COLLECTIVE MICRODYNAMICS EQUATIONS FOR A BEAM WITH VARYING PARAMETERS

$$\frac{d}{d\phi_p}\breve{i}(z,\omega) = -\frac{i}{W(z)}\breve{V}(z,\omega)$$

$$\frac{d}{d\phi_p}\breve{V}(z,\omega) = -iW(z)\breve{i}(z,\omega)$$

$$W(z) = \frac{r_p\sqrt{\mu_0/\varepsilon_0}}{kA_e(z)\theta_p(z)}$$

Plasma-wave "transmission line" impedance

$$W = -i\frac{Z_{LSC}}{r_p\theta_p}$$

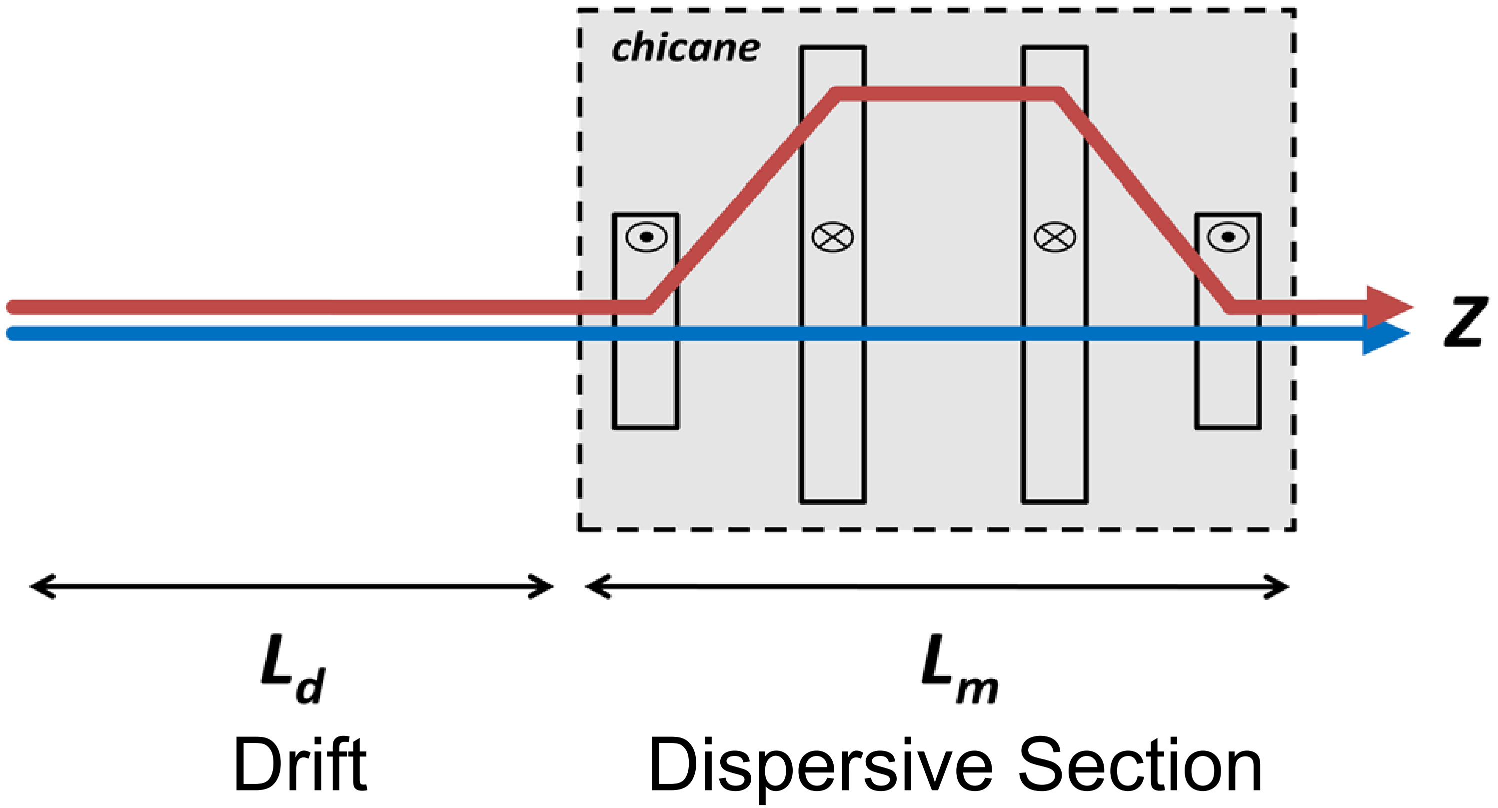
Z_{LSC} is the "conventional" beam impedance per unit length

$$\phi_p(z) = \int_0^z \theta_{pr}(z')dz'$$

$$\theta_p^2(z) = \frac{eZ_0 I_0}{mc^2 A_e(z)\gamma_0\gamma_{0z}^2(z)\beta_{0z}^3(z)}$$

A.Gover, E.Dyunin, T.Duchovni, A.Nause, *Phys. of Plasmas*, **18,** 123102 (2011).

DRIFT/DISPERSION TRANSPORT



D. Ratner Z. Huang G. Stupakov, Phys. Rev. ST-AB, **14**, 060710 (2011)
A.Gover, E.Dyunin, T.Duchovni, A.Nause, *Phys. of Plasmas*, **18,** 123102 (2011).
Experiment (35% suppression):
D. Ratner, G. Stupakov, Phys. Rev. Lett. 109, 034801 (2012)

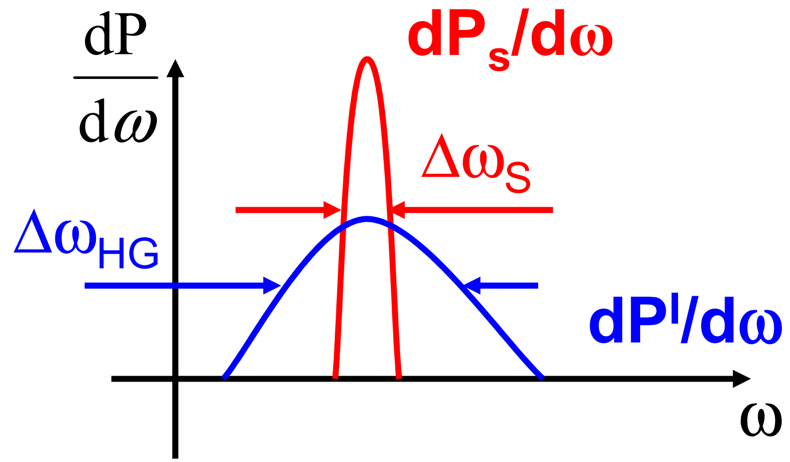
SASE SUPPRESSION

Effective Input noise (NEP)

$$\left(\frac{dP_{in}^{noise}}{d\omega}\right)_{eff} = \left(\frac{dP(L_w)}{d\omega}\right)_{incoh} \Big/ G(\omega)$$

Coherence condition

$$\left[P_s(0)\right]_{coh} >> \left(\frac{dP_{in}^{noise}}{d\omega}\right)_{eff} \Delta\omega$$



To dominate Current Shot-Noise:

$$\left[P_s(0)\right]_{coh} >> \frac{eI_b Z_0}{16\pi A_{em}}\left(\frac{a_w}{\gamma\beta_z\Gamma}\right)^2 \Delta\omega$$

(seed radiation injection)

$$\left|\tilde{i}_s(0)\right|^2 \gg eI_b\Delta\omega$$

(pre-bunching)

Conditions for **Radiation NOISE** suppression

A. Gover, E. Dyunin, “Coherence Limits of Free Electron Lasers”

IEEE J. Quant. Electron. **46**, 1511 (2010)

Residual Velocity Noise Contribution

Residual Current Noise Contribution

$$\left.\frac{dP_{SASE}}{d\omega}\right|_{\phi_{pd}=\frac{\pi}{2}-\frac{\sqrt{3}}{2}S} = \left(N^2 + \left(\frac{S}{2}\right)^2\right)\left.\frac{dP_{SASE}}{d\omega}\right|_{L_d=0}$$

SASE suppression factors: $S^2 = \left(\frac{\gamma_0}{\gamma_z}\frac{\theta_{pw}}{\Gamma}\right)^2 << 1$ $\quad N^2 = \left(\frac{\lambda_D}{\lambda}\right)^2 << 1$

$s^2 >> N^2$: SASE suppression limited by current shot-noise

$s^2 << N^2$: SASE suppression limited by velocity spread

Short wavelengths limits

For significant suppression

(and negligible Landau damping):

$$N = \frac{\lambda_D}{\lambda} = k\frac{\Delta\beta_z}{\theta_p} << 1$$

Ballistic condition

(same as Landau for $L_d=\pi/2\theta_p$):

$$\Delta\phi_p = kL_d\Delta\beta_z << 1$$

$$\Rightarrow \begin{cases} \dfrac{k}{\theta_p}\dfrac{\Delta\gamma}{\gamma^3} << 1 & \text{V} \\ \dfrac{k}{\theta_p}\left(\dfrac{\varepsilon_n}{\gamma\sigma_x}\right)^2 << 1 & \text{?} \end{cases}$$

Granularity condition:

$$n_0 A_e \lambda = \frac{I_0}{ec}\lambda \sim 10^4 >> 1 \quad \text{V}$$

Short wavelengths limit?

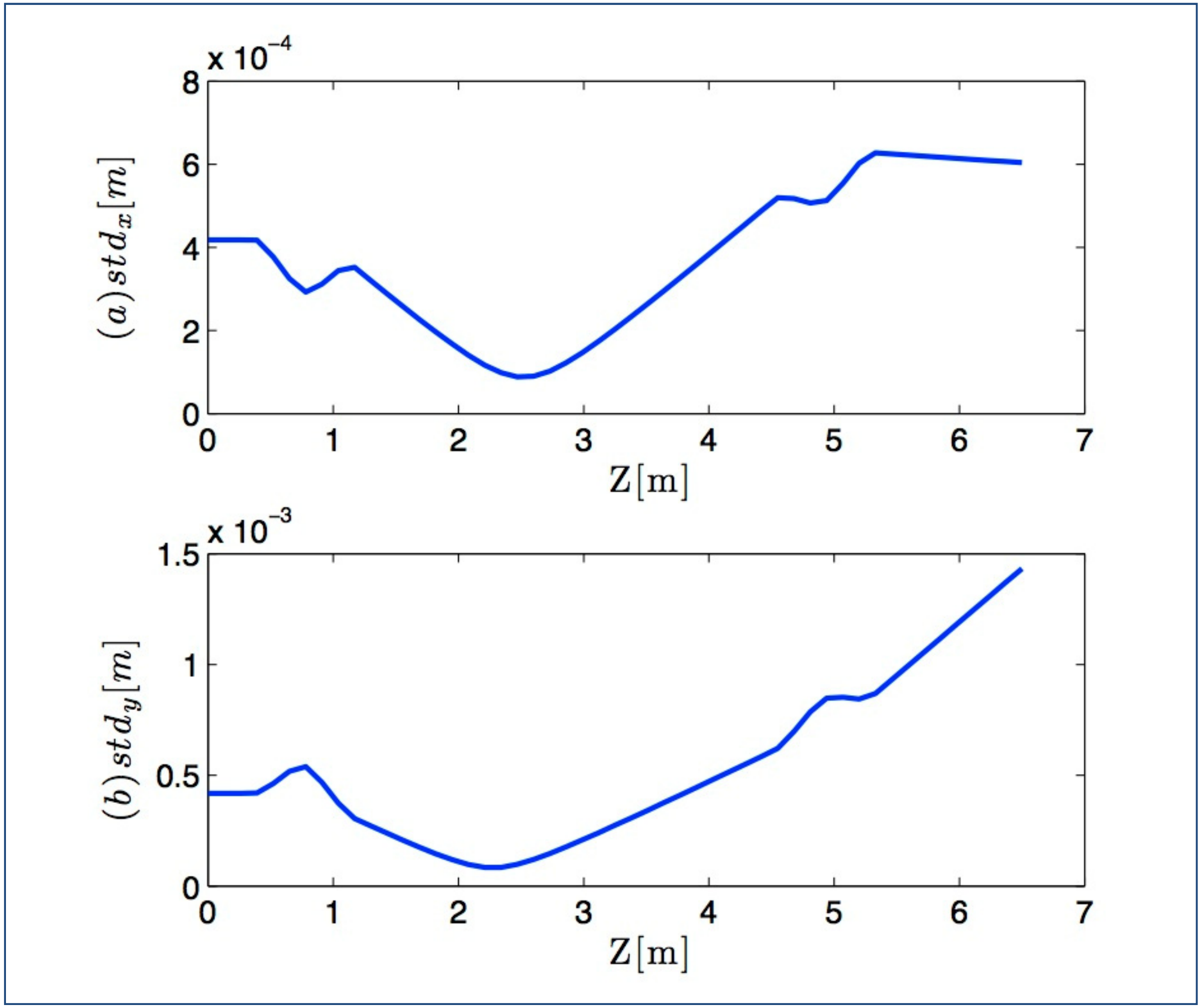
- First demonstrate in UV
- Improve beam parameters (emittance, energy spread) to satisfy N<<1
- Find optimal transport parameters.

CONCLUSION

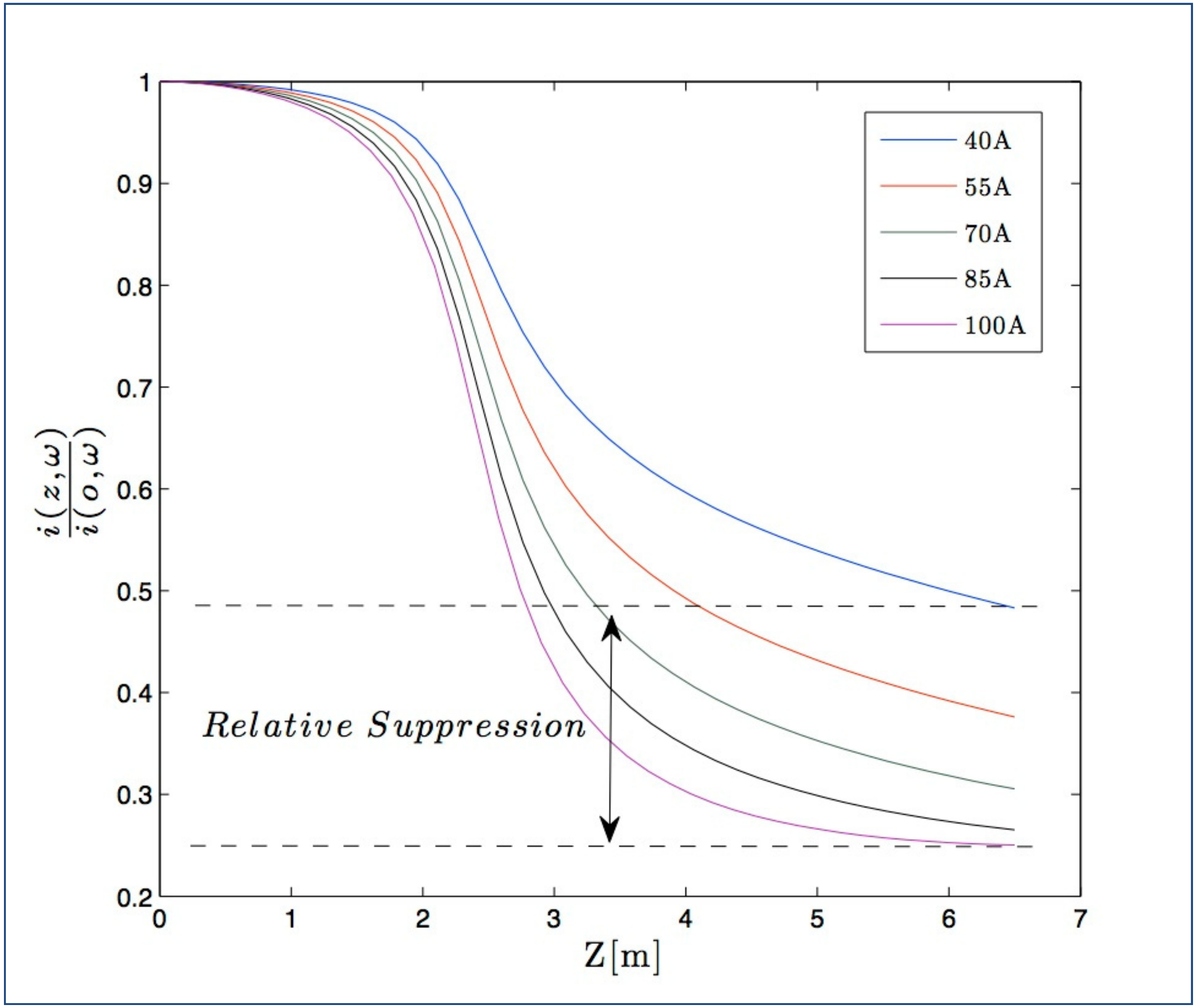
- It is possible to adjust the e-beam current shot-noise level by controlling the longitudinal plasma oscillation dynamics.
- We have demonstrated for the first time such noise suppression at optical frequencies.
- This can be used to enhance FEL coherence and relax seeding power requirement. Further studies will determine short wavelength limit needs
- After elimination of shot noise, IR/XUV FEL coherence is ultimately limited by the quantum input noise $dP / d\omega = \hbar \omega$.

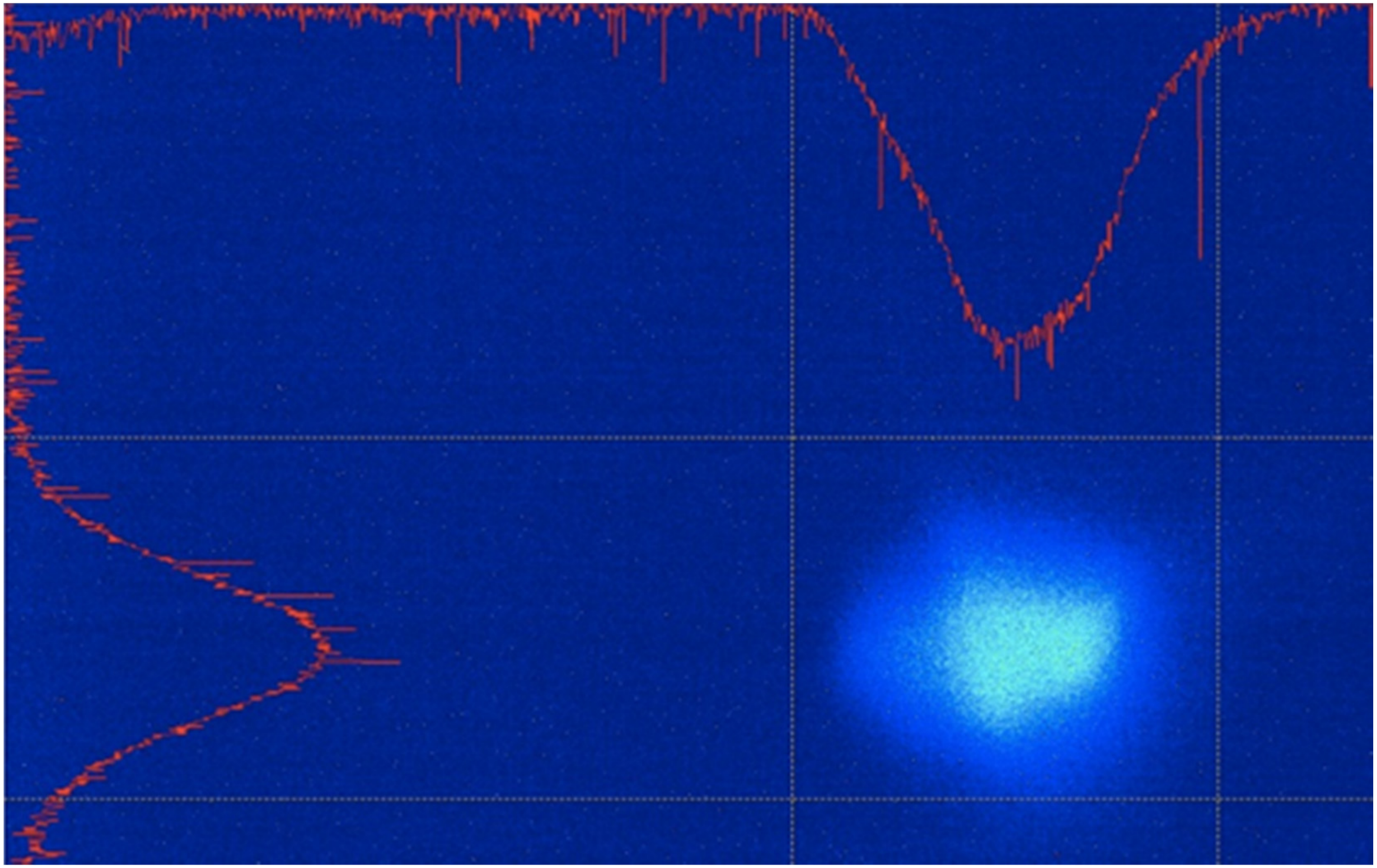
Reserve

Beam Profile Along Trajectory (GPT)



COMPUTATION OF NOISE SUPPRESSION WITH BEAM ANGULAR SPREAD





Fundamental "Schawlow-Townes" Coherence Limits (NEP)

e-Beam current noise + energy shot + radiation noise:

$$\left(\frac{dP_{in}}{d\omega}\right)_{\min} = A \bullet eI_b + B \bullet \delta E_c + \frac{\hbar\omega}{1+e^{-\hbar\omega/kT}}$$

Minimum (energy spread limited) e-beam noise:

$$\left(\frac{dP_{in}}{d\omega}\right)_{\min} = \frac{\delta E_c}{\pi} + \frac{\hbar\omega}{1+e^{-\hbar\omega/kT}}$$

Microwave/THz regime:

$$\left(\frac{dP_{in}}{d\omega}\right)_{\min} = \frac{\delta E_c}{\pi} + k_B T \qquad \left(\approx \frac{\delta E_c}{\pi} = \frac{k_B T_c}{\pi} > k_B T\right)$$

(Cathode temperature limited)

Optical/X-UV regime:

$$\left(\frac{dP_{in}}{d\omega}\right)_{\min} = \frac{\delta E_c}{\pi} + \hbar\omega \qquad (\approx \hbar\omega)$$

(Quantum limit)

3-D Numerical Simulations

A. Nause, E. Dyunin, A. Gover,
JAP 107, 103101 (2010).

100,000 particles over 2 pS duration to increase resolution,
70 MeV energy, 200pC charge

E-BEAM NOISE AND RADIATION SUPPRESSION THEORY

Microwave tube noise suppression (!)

H. Haus and F. N. H. Robinson, Proc. IRE 43, 981 (1955).

Optical noise suppression in a drifting relativistic beam:

Gover, Phys. Rev. Lett. 102, 154801 (2009),

Nause, JAP, 107, 103101 (2010)

Optical noise suppression with a dispersive section:

Rathner, PhysRevSTAB 14 060710 (2011)

Gover, Phys. Plasmas 18, 123102 (2011)

SASE noise suppression:

Gover, JQE46, 1511 (2010)

Short wavelength limit:

R. Bonifacio, Optics Communications 138 (1997) 99-100

K-J Kim, Shanghai FEL conférence 2011

3-D Homogenization Trend

A simple physical argument:

Inter-particle Coulomb force: $\varepsilon_{Coul} = e^2 / 4\pi\varepsilon_0 n'^{-1/3}_0$

Space-charge force: $\varepsilon_{sc} = e^2 \Delta N' / 2\pi\varepsilon_0 d'$

Poisson statistics: $\Delta N' = N'^{1/2}$ $\quad N' = \left(\pi d'^3 n'_0 / 6\right)^{1/2}$

When $\boldsymbol{\varepsilon_{sc} > \varepsilon_{coul}}$?

$$\frac{\varepsilon_{sc}}{\varepsilon_{Coul}} = \left(\frac{2\pi}{3} \frac{d'}{n'^{-1/3}_0} \right)^{1/2} \rangle 1$$

<u>Answer</u>: $\boldsymbol{d' > n_0^{-1/3}}$

<u>Note</u>: Process leads to velocity spread growth

At the Cathode (no-correlation point)

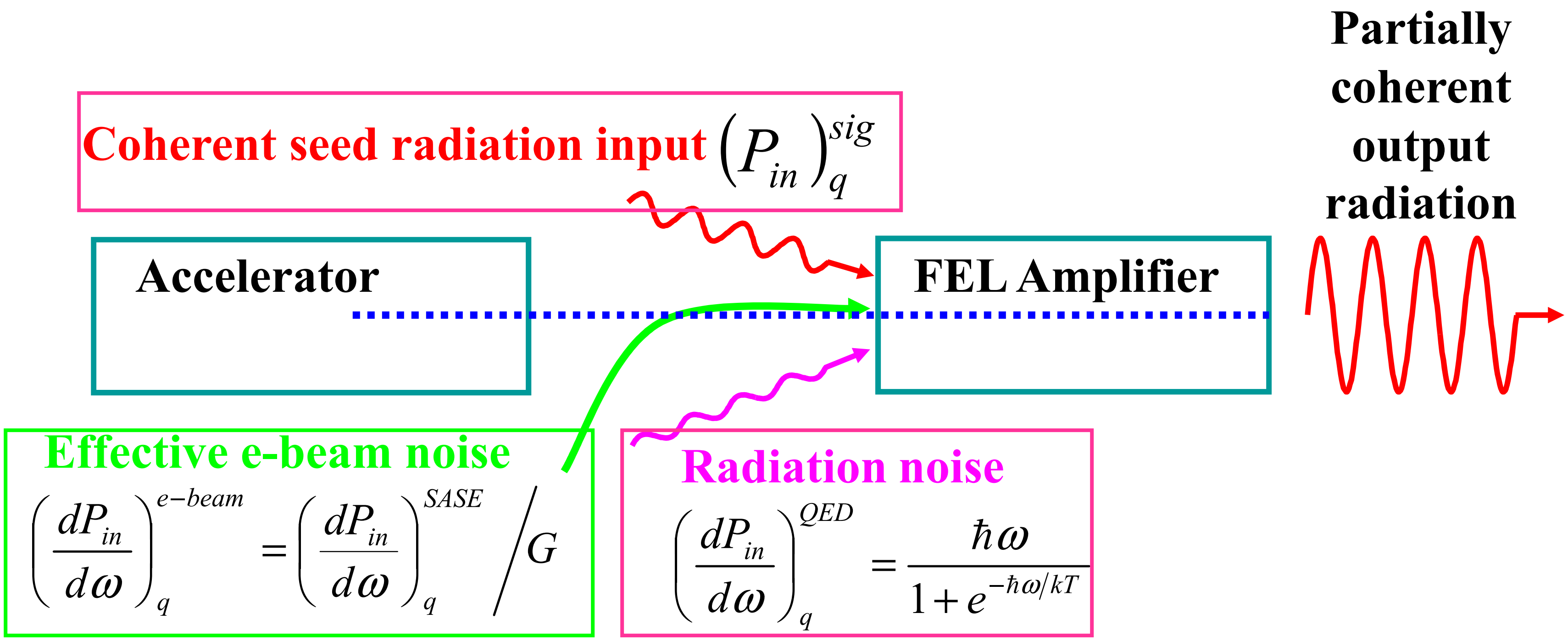
Current and velocity noise – uncorrelated:

$$\overline{\left|\breve{i}(\omega)\right|^2} = \frac{1}{T}\left\langle \left|\breve{i}(\omega)\right|^2 \right\rangle_{N_T} = eI_b$$

$$\overline{\left|\breve{v}(\omega)\right|^2} = \frac{1}{T}\left\langle \left|\breve{v}(\omega)\right|^2 \right\rangle_{N_T} = \frac{(\delta E_c)^2}{eI_b}$$

$$\left(\overline{\left|\breve{I}(\omega)\right|^2}\right)^{1/2}\left(\overline{\left|\breve{V}(\omega)\right|^2}\right)^{1/2} = \delta E_c$$

NOISE INPUTS INTO FEL AMPLIFIER
(NOISE EQUIVALENT POWER - NEP)



Fundamental Coherence Limits

A Conservative of motion in a non-dissipative e-beam transport section:

$$\overline{\left|\breve{i}_c\right|^2}\;\overline{\left|\breve{V}_c\right|^2} = (\delta E_c)^2$$

Minimum input noise:

$$\left(\frac{dP_{in}}{d\omega}\right)_{min} = \frac{\delta E_c}{\pi} + \frac{1}{1+e^{-\hbar\omega/kT}}$$

Microwave/THz regime:

$$\left(\frac{dP_{in}}{d\omega}\right)_{min} = \frac{\delta E_c}{\pi} + k_B T \qquad \left(\approx \frac{\delta E_c}{\pi} \geq \frac{k_B T_c}{\pi}\right)$$

(Cathode temperature limited)

Optical regime:

$$\left(\frac{dP_{in}}{d\omega}\right)_{min} = \frac{\delta E_c}{\pi} + \hbar\omega \qquad (\approx \hbar\omega)$$

(Quantum limit)