Spontaneous-Emission Sub-Radiance and Coherence Limits of FEL

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OUTLINE

Concepts

- Suppression of electron beam shot-noise
- Suppression of radiation spontaneous emission from e-beam

Fundamental Issues

- Shot-noise suppression and thermodynamics
- Sub-radiance (Dicke)
- Fundamental coherence limit (Schawlow-Townes limit for FEL)

Practical Issues

- e-beam quality requirements
- Dependence on radiation wavelength
- Implication to beam (micro-bunching) instability, diagnostics (COTR)
- Implication to coherence of seeded FEL

PHYSICAL REVIEW VOLUME 93, NUMBER 1 JANUARY 1, 1954

Coherence in Spontaneous Radiation Processes

R. H. DICKE
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received August 25, 1953)

IN the usual treatment of spontaneous radiation by a gas, the radiation process is calculated as though the separate molecules radiate independently of each other. To justify this assumption it might be argued that, as a result of the large distance between molecules and subsequent weak interactions, the probability of a given molecule emitting a photon should be independent of the states of other molecules.

This simplified picture overlooks the fact that all the molecules are interacting with a common radiation field and hence cannot be treated as independent. The model is wrong in principle and many of the results obtained from it are incorrect.

$dP_{in}/d\omega \propto N$ **Spontaneous emission (radiation noise)**

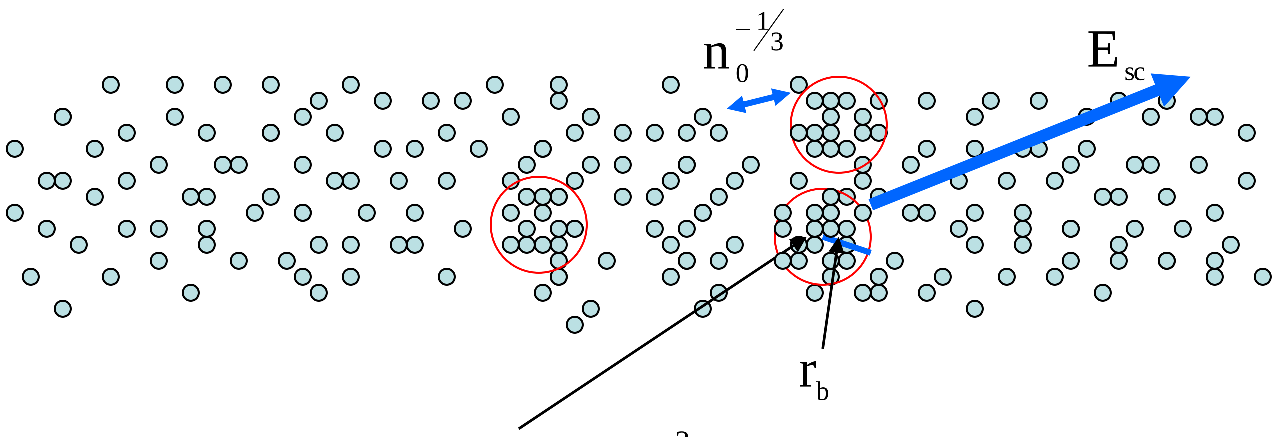
$dP_{in}/d\omega \rangle \alpha N \rightarrow N^2$ **Super-radiance (coherent emission)**

$dP_{in}/d\omega \langle \alpha N \rightarrow 0$ **Sub-radiance**

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

- Spatially coherent Coulomb interaction micro-dynamics.

- Yet unobserved effects of particle self-ordering and current shot noise suppression at optical frequencies.



$$N_b = K n_0 \cdot \frac{4\pi r_b^3}{3}$$

$$(K \rangle 1)$$

3-D Homogenization Trend

A simple physical argument:

Inter-particle Coulomb force:

$$F_{coul} = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{\left(n_0^{-1/3}\right)^2}$$

Space-charge force:

$$F_{sc} = e \cdot \frac{1}{4\pi\varepsilon_0} \frac{eN_b}{r_b^2} = \frac{e^2}{4\pi\varepsilon_0} \frac{Kn_0(4\pi r_b^3/3)}{r_b^2} = K\frac{e^2 n_0 r_b}{3\varepsilon_0}$$

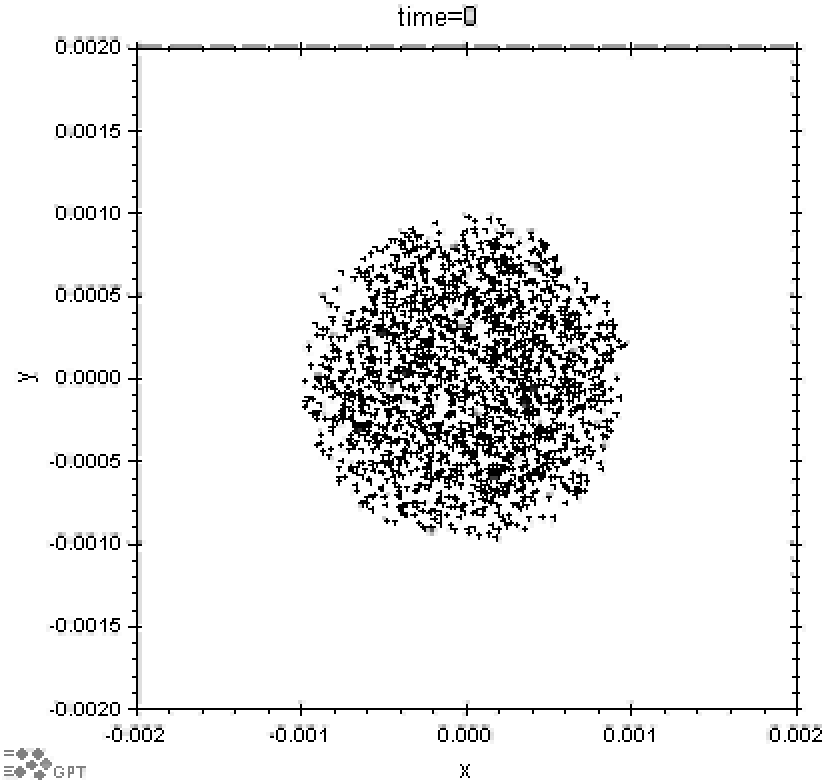
$$F_{sc}/F_{coul} \approx K\left(2r_b/n_0^{-1/3}\right) \rangle 1$$

When $F_{sc} > F_{coul}$? **Answer**: Always!

(if K > 1 in a sphere of diameter $2r_b > n_0^{-1/3}$)

Note: Process leads to velocity spread growth

Expansion of a Sphere Shaped Bunch of Uniformly Distributed Charges in Time Period $t = \pi / 2\omega_p$



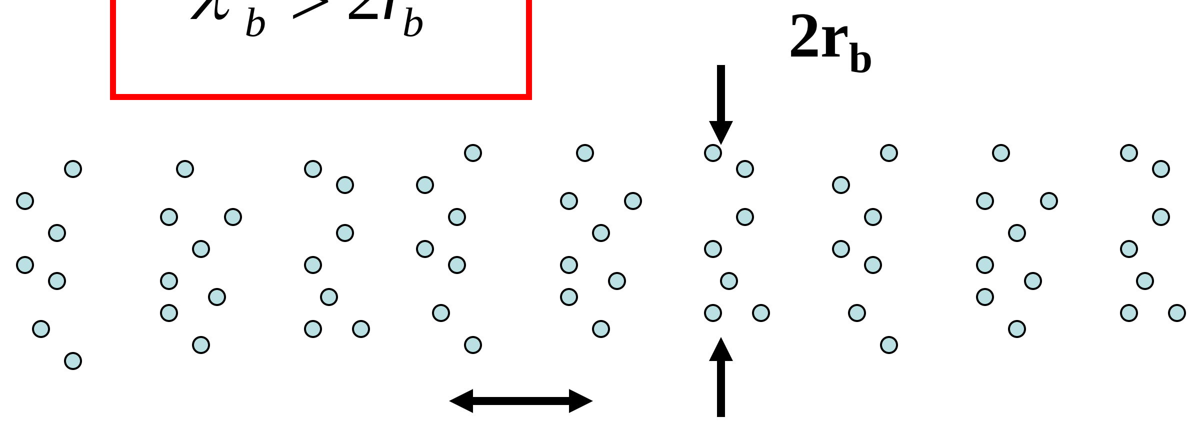
t=0[Sec], R=1[mm]

Conditions for a Charged-Particle Beam to Exhibit Spatially-Coherent Current Shot-Noise Suppression:

$$\left.\overline{\left|\breve{i}(\omega)\right|^{2}}\right|_{t\cong t_{\pi/2}} \langle \left.\overline{\left|\breve{i}(\omega)\right|^{2}}\right|_{t=0} = eI_b$$

1. **Cold beam: current shot-noise dominated (non-equilibrium plasma !)**
2. **Longitudinal interaction (single Langmuir mode)**

$$\lambda'_b > 2r_b$$



$$\lambda'_b = \lambda\gamma\beta$$

(Beam rest frame picture)

ANALYTICAL FLUID-PLASMA LINEAR MODEL

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

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

Coherent Plasma Oscillation in an e-Beam Drift Section

$$\breve{i}(t_d,\omega)=\left[\breve{i}(0,\omega)\cos(\omega_{pr}t_d)-i\frac{\breve{V}(0,\omega)}{W_d}\sin(\omega_{pr}t_d)\right]\cdot e^{i\omega t_d}$$

$$\breve{V}(t_d,\omega)=\left[-i\breve{i}(0,\omega)W_d\sin(\omega_{pr}t_d)+V(0,\omega)\cos(\omega_{pr}t_d)\right]\cdot e^{i\omega t_d}$$

$$\breve{V}(z,\omega)=-(mc^2/e)\breve{\gamma}(z,\omega)=-(mc^2/e)\gamma_0^3\beta_0\breve{\beta}(\omega)$$

(Chu's Relativistic Kinetic Voltage)

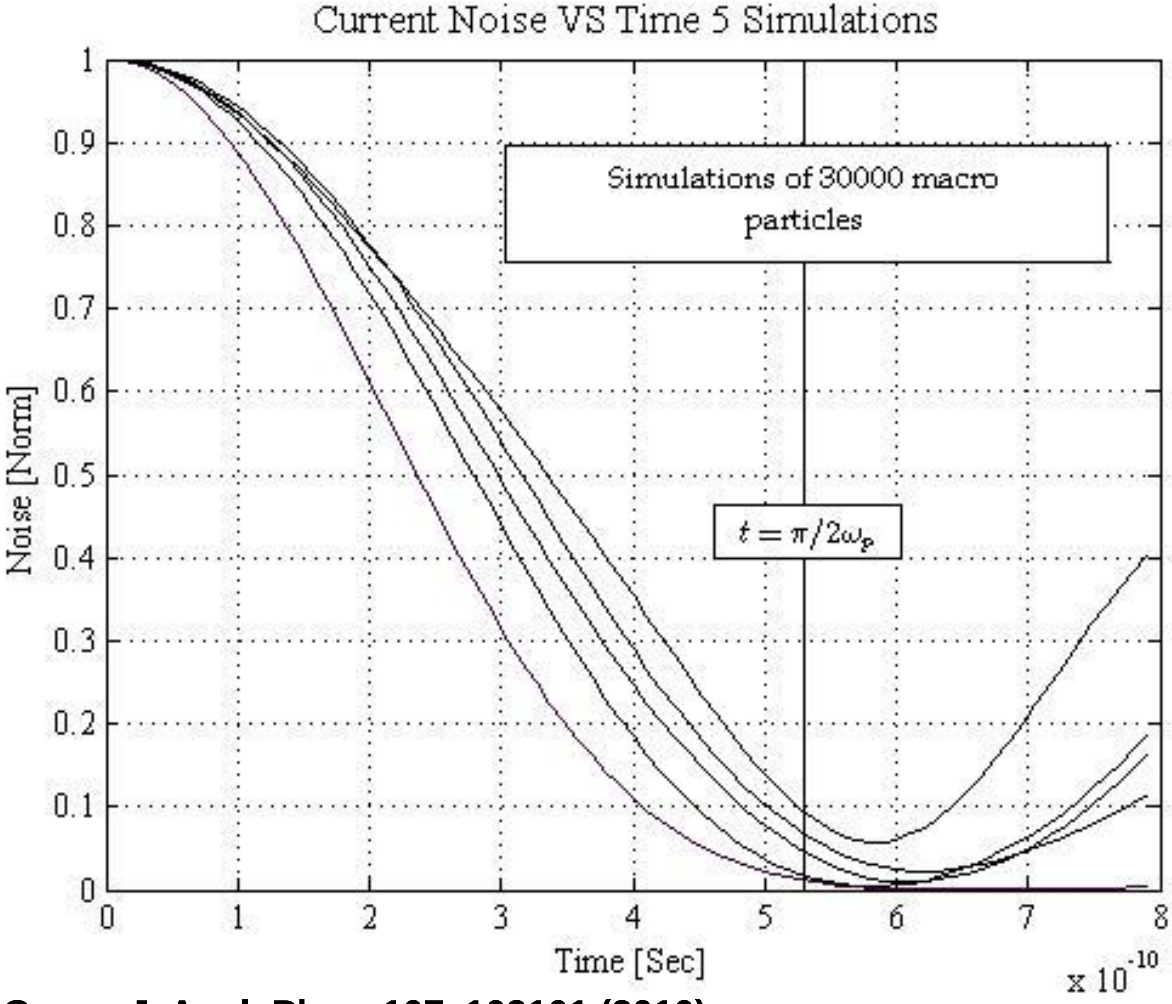
$$\mathrm{t_d}=\frac{\mathrm{L_d}}{\mathrm{v_z}} \qquad \omega_{pr}=r_p\left(\frac{e^2n_0}{m\varepsilon_0\gamma^3}\right)^{1/2} \qquad \theta_{pr}=\frac{\omega_{pr}}{v_0}$$

$$W_d=r_p^2\sqrt{\mu_0/\varepsilon_0}\,/k\theta_{pr}A_e$$

3D GPT Results of Simulations

Simulation Parameters (FERMI):

E= 100 [MeV], R=1 [mm], I = 80 [A]

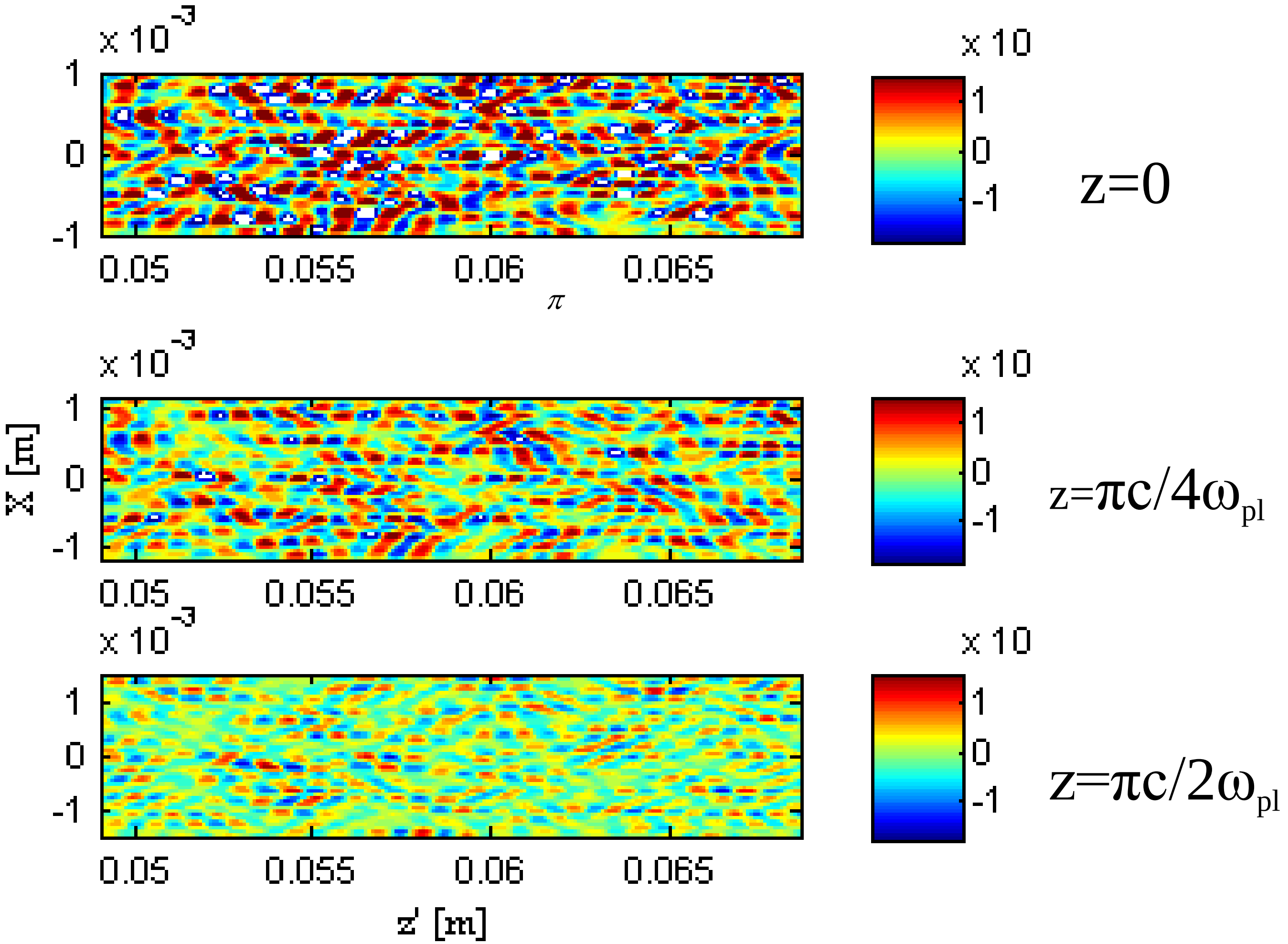


Nause, Dyunin, Gover, J. Appl. Phys. 107, 103101 (2010)

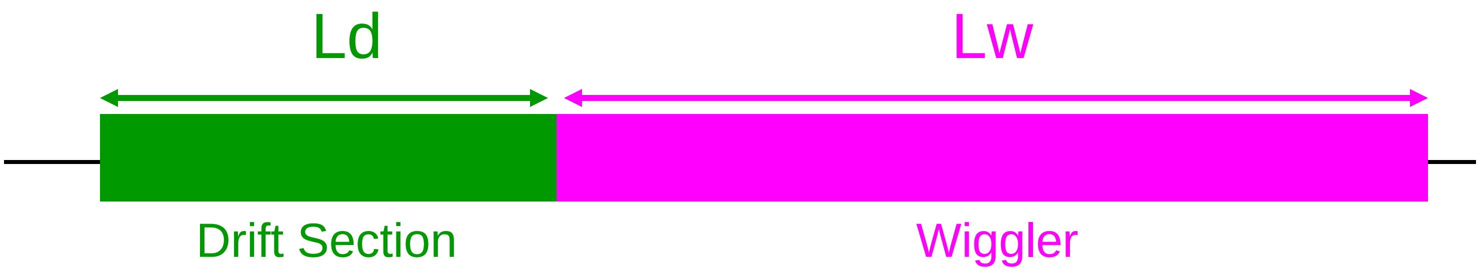
Charge Density Homogenization – Axially Filtered 5-10 [μm]

Simulation Parameters (FERMI 60k m.p):

E= 100 [MeV], R=1 [mm], I = 80 [A]



SASE Power Control

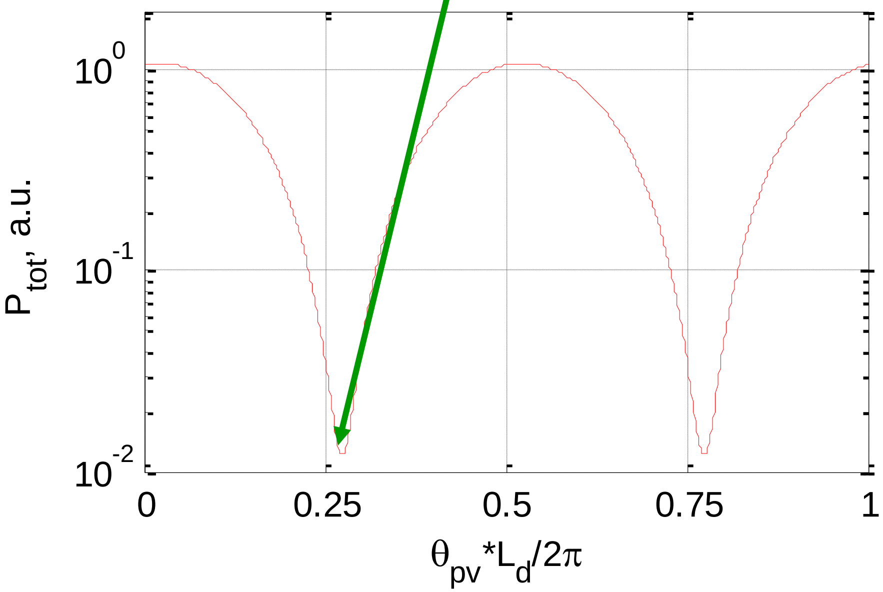


$$P_{tot} = \int \frac{dP}{d\omega} d\omega = \frac{2}{\pi}(eI_b)\int \left|H_{tot}^{Ei}(\omega)\right|^2 d\omega$$

(starting from current shot-noise at z=0, ΔE=0)

E. Dyunin, A. Gover, NIM **A 593**, 49 (2008)

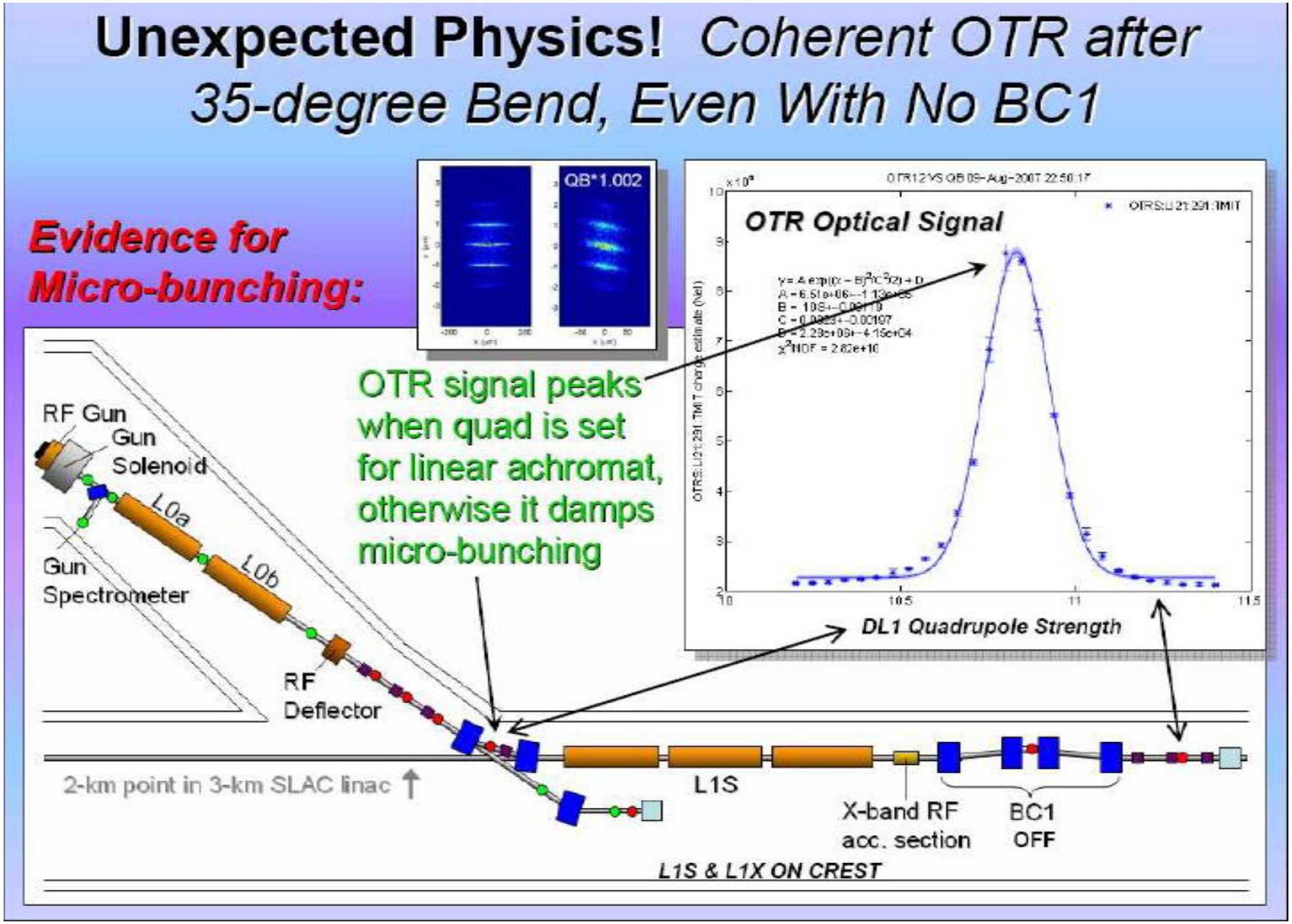
$Ld \sim \lambda_p/4 = \pi/2\theta_p$



Coherent Optical Transition Radiation in LCLS/SLAC

D. Dowell, FEL Frontiers conference (Italy, Sept. 9-13, 2007)

R. Akre et al, Phys. Rev. ST-AB, 11, 030703 (2008)



Initial condition: Current Noise Dominates Velocity Noise

$$N_n^2 = \frac{\overline{\left|\breve{V}(0,\omega)\right|^2}}{\overline{\left|\breve{i}(0,\omega)\right|^2} W_d^2} \ll 1 \quad \Rightarrow \quad \overline{\left|\breve{i}(L_d\omega)\right|^2} = N_n^2 \overline{\left|\breve{i}(0,\omega)\right|^2}$$

For LCLS injector parameters:

$$\mathrm{E} = 135\mathrm{MeV} \qquad r_b = 100\mu m$$

$$\mathrm{Q} = 0.5\mathrm{nc}/5\mathrm{pS} \qquad \lambda = 100nm - 1\mu m$$

$$\varepsilon_{\mathrm{n}} = 0.5\mu\mathrm{m} \qquad L_d = \pi/2\theta_{PL} = 4.4m$$

$$\Delta\mathrm{E} = 5\mathrm{keV} \qquad N_n = 9\times10^{-3}$$

Nause, Dyunin, Gover, Wu Poster WEPB21 Wed.

Fundamental "Schawlow-Townes" Coherence Limits of "Equivalent Radiation Noise Power" Input into SASE FEL

Current shot-noise dominated

$$\left(\frac{dP_{in}}{d\omega}\right)^{i} = (eI_b)\frac{\sqrt{\mu_0/\varepsilon}}{16\pi A_{em}}\left(\frac{a_w}{\gamma\Gamma}\right)^2$$

Suppressed current shot-noise:

$$\left(\frac{dP_{in}}{d\omega}\right)^{v} = N^2\left(\frac{dP_i}{d\omega}\right)^{i} \rightarrow \frac{\Delta E_c}{\pi}$$

Fundamental quantum limit $(\hbar\omega \rangle\rangle \Delta \mathrm{E}_c)$

$$\left(\frac{dP_{in}}{d\omega}\right)^{E} \rightarrow \hbar\omega$$

E. Dyunin, A. Gover, Accepted IEEE - JQE (2010)

Conclusions

- It is possible to adjust the e-beam current shot- noise level by controlling the longitudinal plasma oscillation dynamics.
- It may enable to control microbunching instability in transport line.
- It can be used to enhance FEL coherence and relax seeding power requirement.
- After elimination of shot noise, FEL coherence is limited by beam energy spread, and ultimately by quantum input noise: $dP/d\omega = \hbar\omega.$