Study of Collective Interaction Control over e-beam Current Noise

T. Shaftan on behalf of A. Gover, A. Nause, E. Dyunin
Tel-Aviv University

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Introduction

New Concepts and motivations:

- **Is it possible to reduce the beam current noise below the text-book shot-noise level (eI_b)?**
- **Is it possible to enhance the coherence of X-UV FELs by suppressing the input noise?**
- **What are the fundamental limits of FEL coherence?**
- **Notes:**
- In the art of microwave tubes, schemes for low-noise e-beam tube amplifiers were developed [H. Haus, 1950]. Seeded FEL [E. Dyunin, accepted JQE, 2010]
- Electron beam coherent collective micro-dynamics in the optical regime is the origin of COTR effects observed in LCLS, ALS, DESY, BESSY.

Electron beam fragmentation

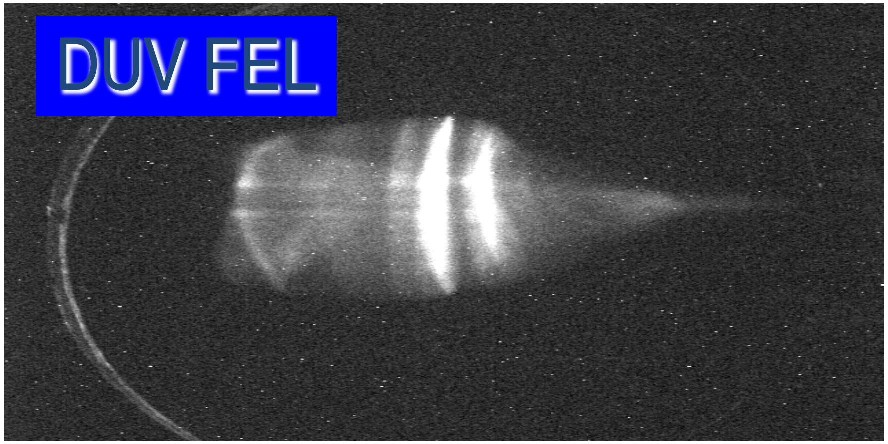
- “Zero-phasing” images from the spectrometer dipole revealed spiky structure with sub-picosecond period in the chirped beam energy spectrum

- Assuming that chirped bunch energy spectrum represents longitudinal density distribution → spikes could be treated as a spikes in the longitudinal bunch density (peak current)

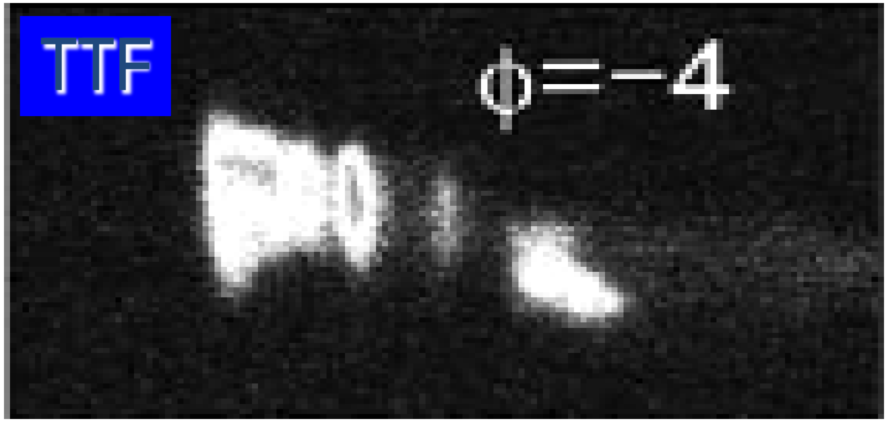
- Calculating FEL slippage length for lasing at 266 nm as 70 um , follows that the spike width is comparable or less than slippage length → must cause degradation of FEL performance

- Similar effect has been observed at TTF

W.S. Graves, et al., PAC 2001, p. 2860



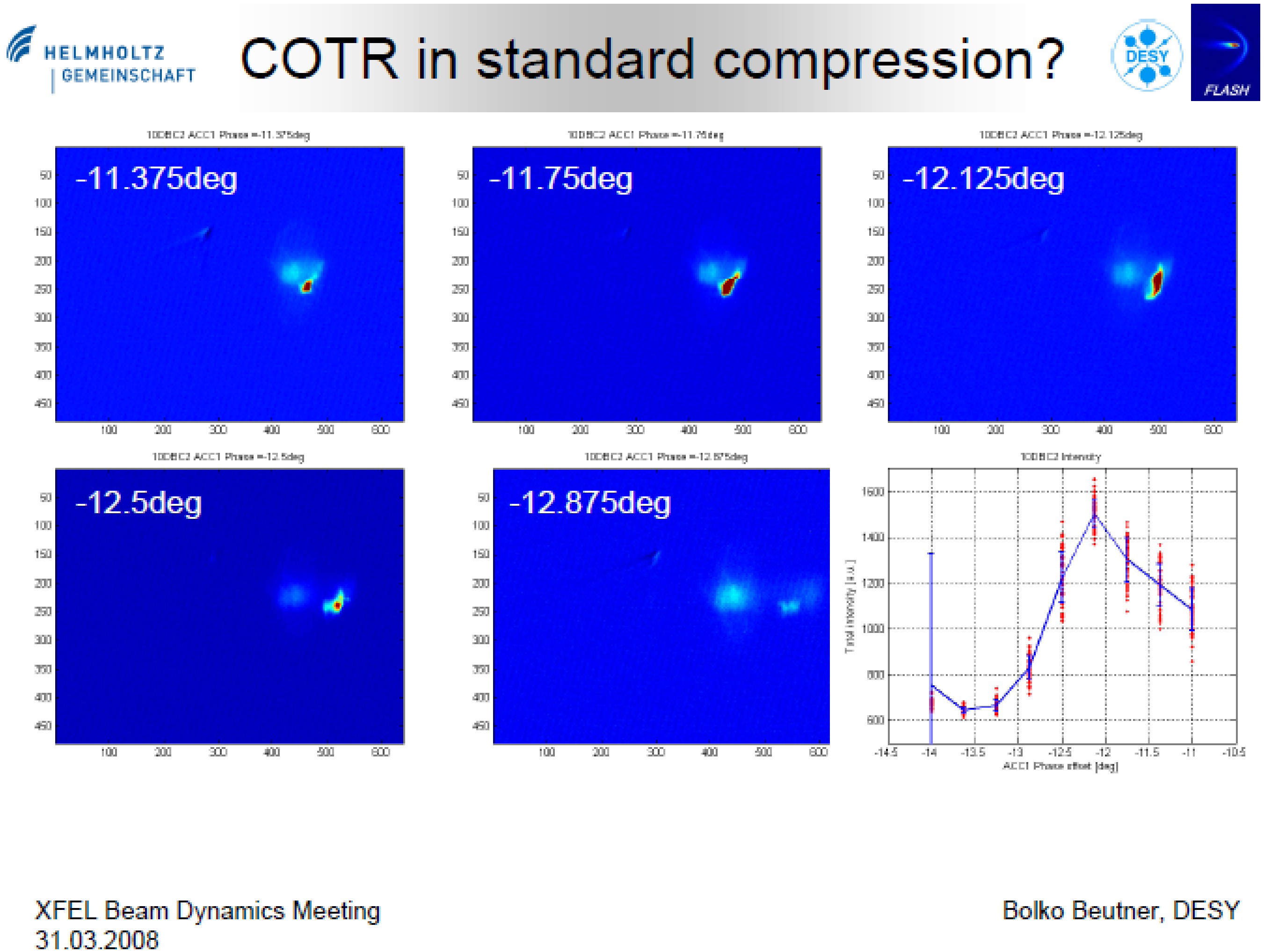
M. Huning et al., NIM A 475 (2001) p. 348



T. Shaftan and Z. Huang, Experimental characterization of a space charge induced modulation in high-brightness electron beam, PRST AB 7, 080702 (2004)

Coherent Optical Transition Radiation at FLASH (DESY)

B. Beutner, XFEL Beam Dynamics Meeting, 2008



Coherent Plasma Oscillation in a Drift Section

$$\boxed{\begin{aligned}\tilde{I}(L_d,\omega) &= \left[\tilde{I}(0,\omega)\cos\phi_p - i\tilde{V}(0,\omega)\left(\sin\phi_p / W_d\right)\right] e^{i\phi_b(L_d)} \\ \tilde{V}(L_d,\omega) &= \left[-i\tilde{I}(0,\omega) W_d \sin\phi_p + \tilde{V}(0,\omega)\cos\phi_p\right] e^{i\phi_b(L_d)}\end{aligned}}$$

$$\tilde{V}(z,\omega) = -\left(mc^2/e\right)\tilde{\gamma}(z,\omega)$$

(Chu's Relativistic Kinetic Voltage)

$$\phi_b = \frac{\omega}{v_0} L_d \qquad \phi_p = \theta_{pr} L_d \qquad \theta_{pr} = r_p \frac{\omega_p'}{v_0}$$

$$\omega_p' = \left(\frac{e^2 n_0}{m\varepsilon_0 \gamma_0^3}\right)^{1/2} \qquad W_d = r_p^2 \sqrt{\mu_0/\varepsilon_0} \Big/ k\theta_{prd} A_e$$

Quarter Period Plasma Oscillation in a Drift Section

$$\boxed{\underline{For \quad L_d = \pi / 2\theta_{prd}} :}$$

$$\underline{\underline{M}} = \begin{pmatrix} 0 & -i/W_d \\ -iW_d & 0 \end{pmatrix} e^{i\phi_b}$$

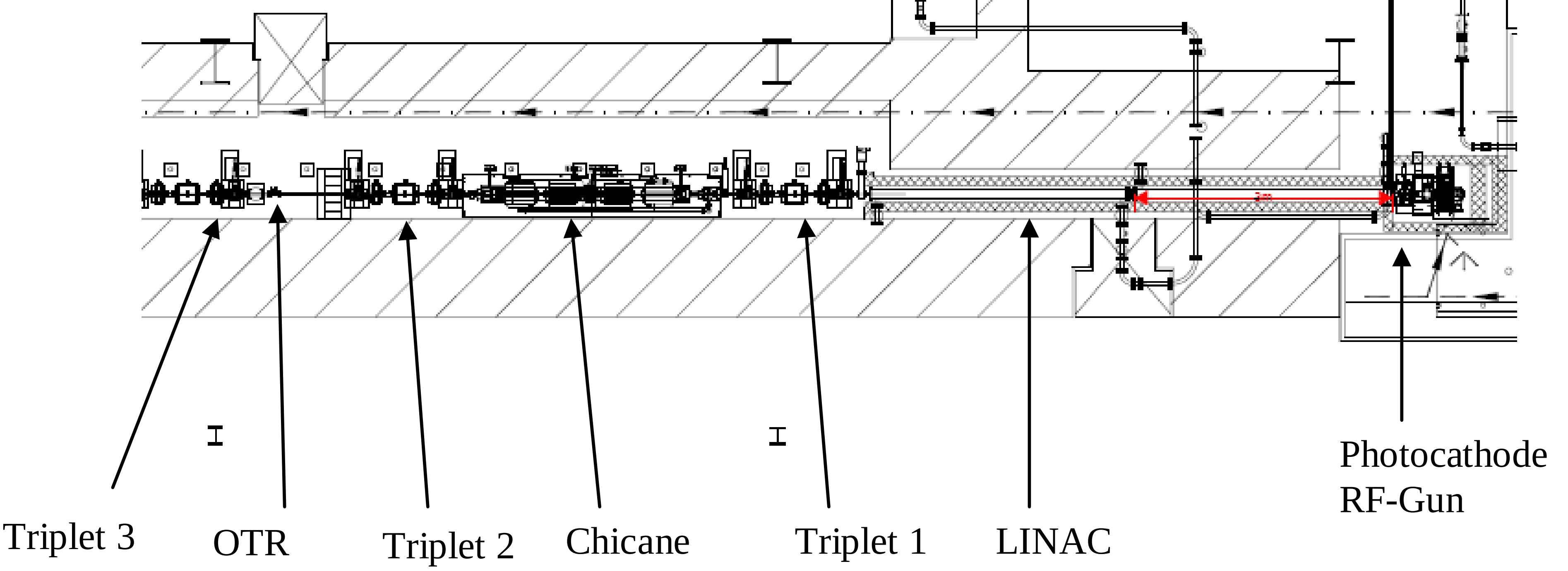
$$\boxed{\begin{aligned} \tilde{I}(L_d) &= -ie^{i\phi_b}\tilde{V}(0)/W_d \\ \tilde{V}(L_d) &= -ie^{i\phi_b}\tilde{I}(0)W_d \end{aligned}}$$

$$\underline{If \quad \tilde{V}(0) = 0,} \qquad then: \quad \tilde{I}(L_d) = 0$$

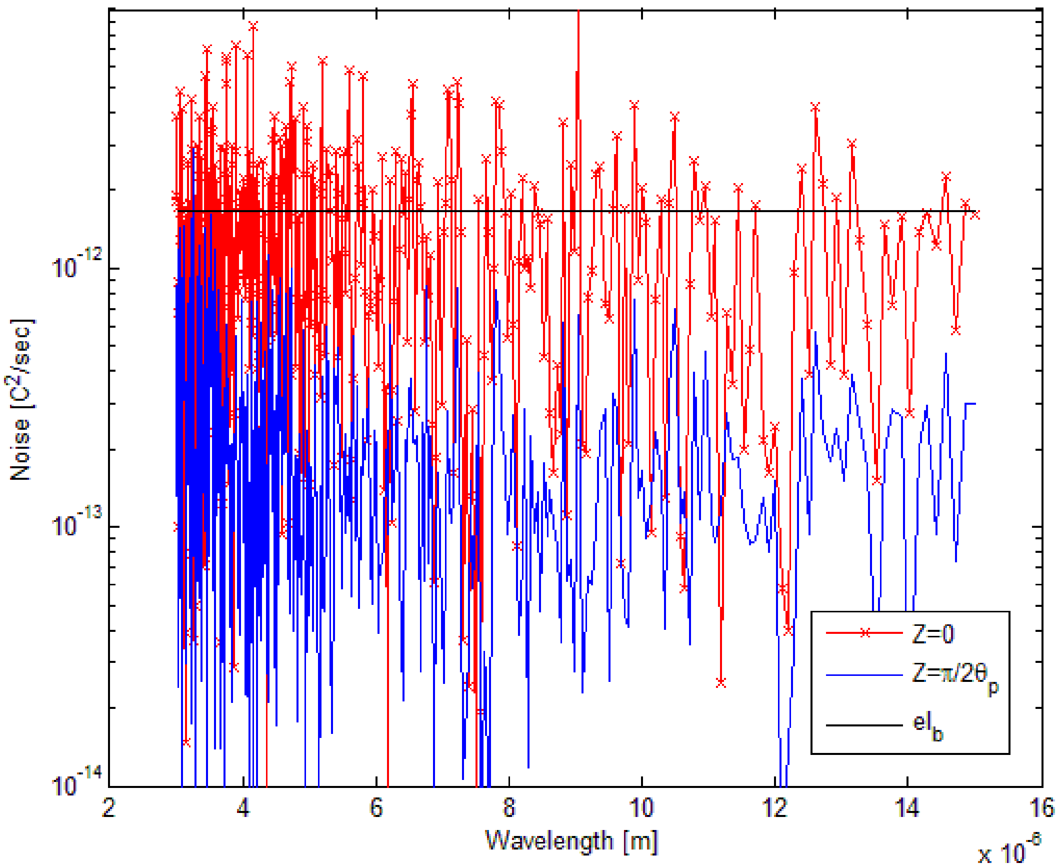
$$\tilde{V}(L_d) = -ie^{i\phi_b}W_d\tilde{i}(0)$$

ATF layout and parameters

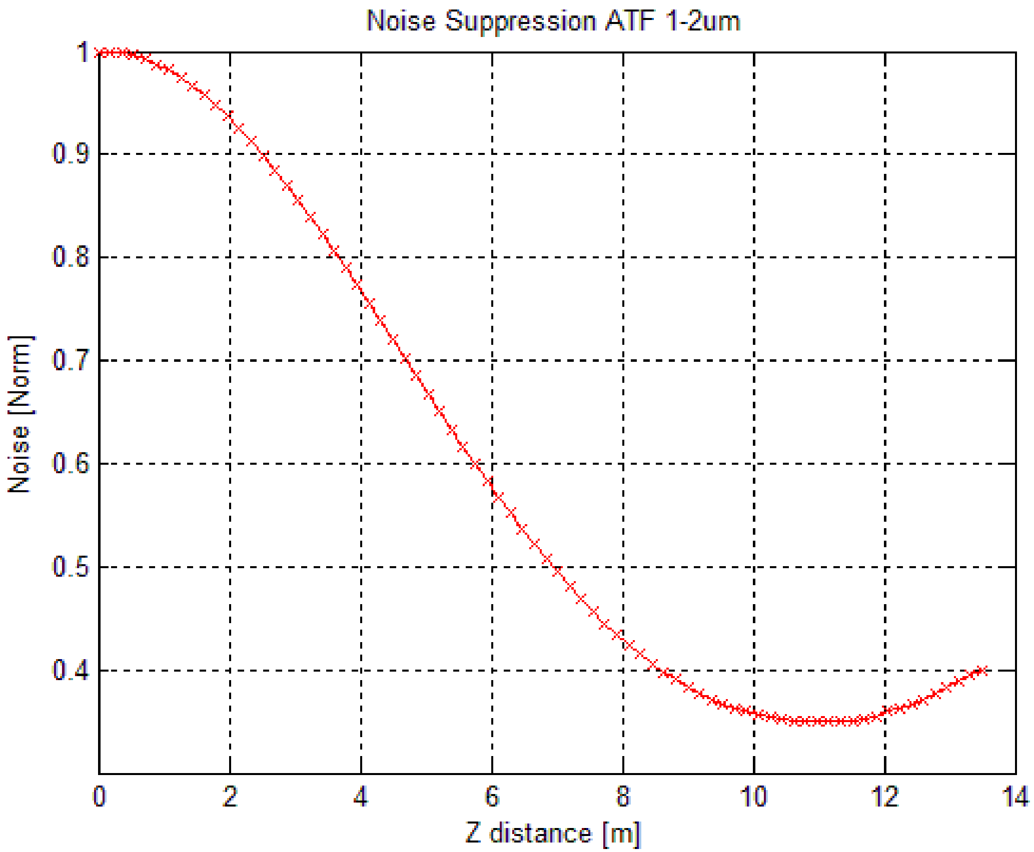
- Beam parameters:
  - E_0=75 MeV
  - I_0=100 A
  - ΔE < 5 keV
  - ε_n = 3 µm
  - **$L_{\pi/2}$=9.1m**



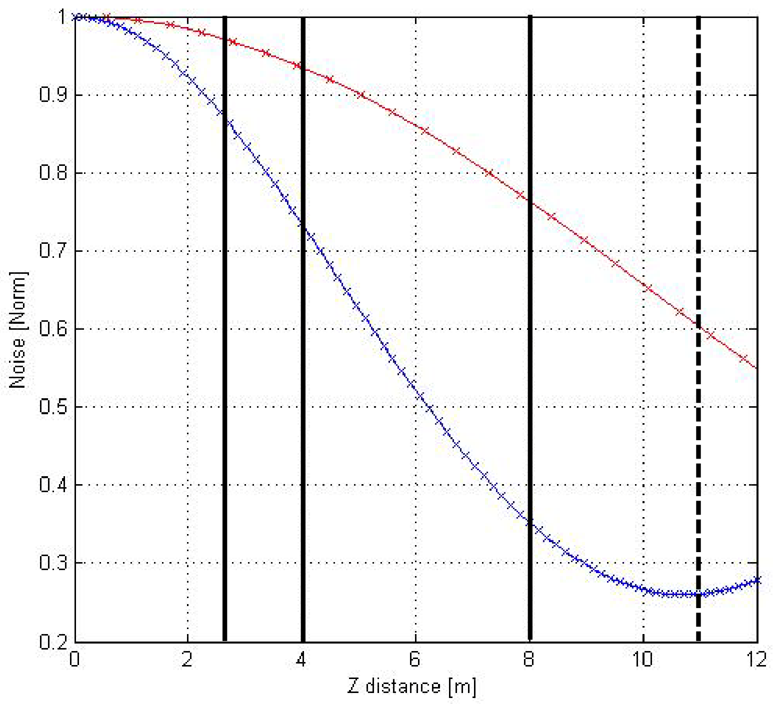
Spectral Noise Reduction
(ATF parameters, z=9.1m)



Noise vs Propagation Distance for ATF Parameters (σ = 300um)

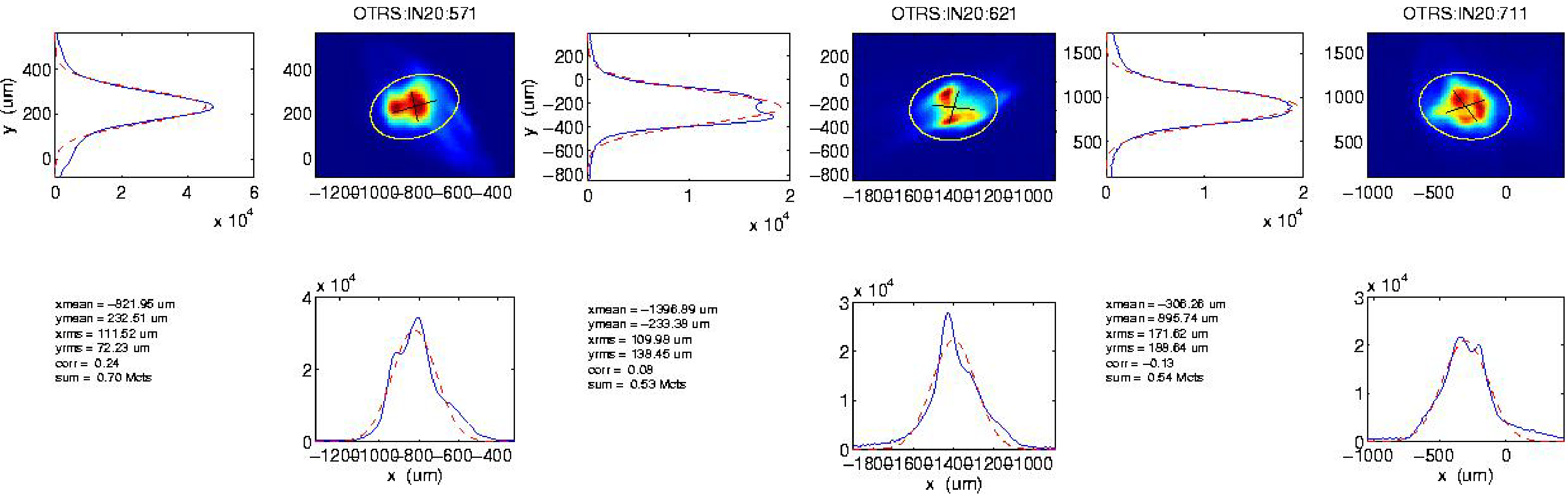


Noise suppession as a function of distance and Beam Width for Fixed Current (100A)



By measuring integrated OTR signals at different positions and different beam widths (blue – σ = 300[um], red - σ = 700[um]) it is possible to observe current noise suppression and compare to theoretical predictions.

Preliminary Experiment Performed in LCLS

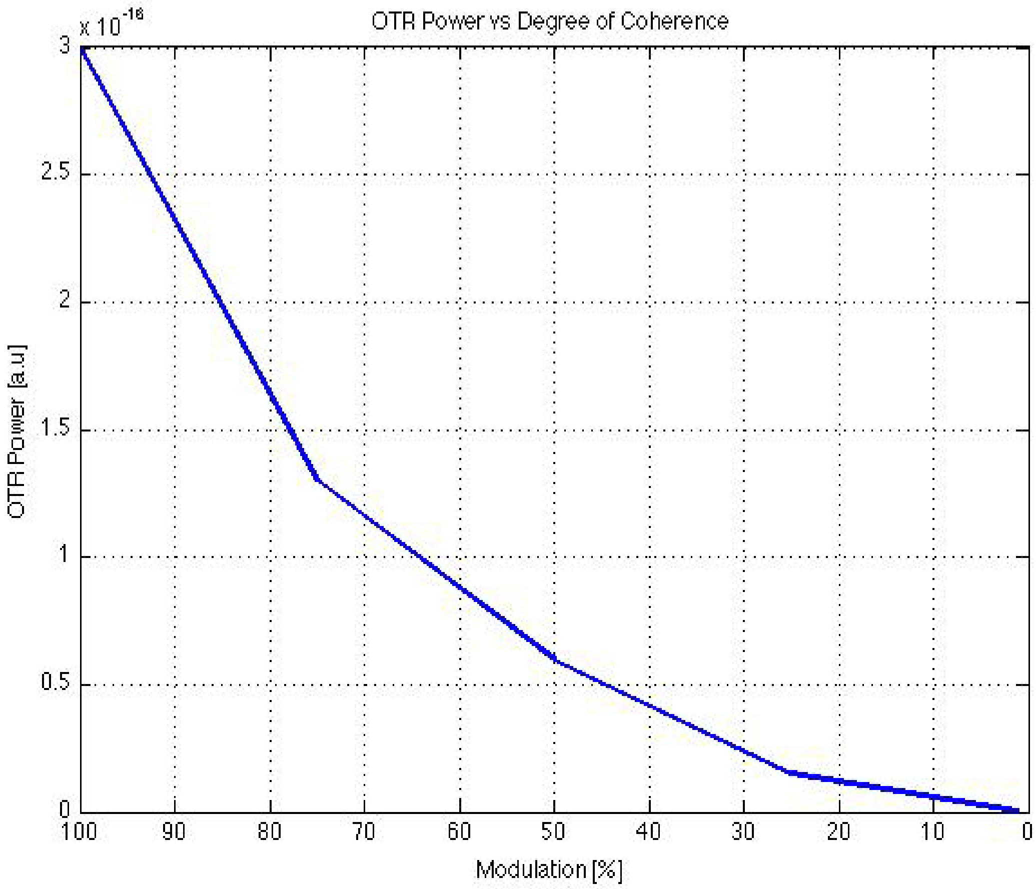


OTR 2 **OTR 3** **OTR 4**

Reduction in Amplitude (before the bend)

Theoretical Integrated OTR Power for Decreasing Current Modulation Coefficient

$$P(\omega_1 \langle \omega \langle \omega_2) = N^2 \int_{-\infty}^{\infty} \int_{\omega_1}^{\omega_2} \frac{dP_e(\theta_x, \theta_y, \omega)}{d\Omega d\omega} \left| M_b(\theta_x, \theta_y, \omega) \right|^2 d\theta_x d\theta_y d\omega$$



$$\frac{dP_e}{d\Omega d\omega} = \frac{e^2}{16\pi^3 c\varepsilon_0} \frac{\gamma^4(\theta_x^2 + \theta_y^2)}{[1 + \gamma^4(\theta_x^2 + \theta_y^2)]^2}$$

M_b is the longitudinal bunching factor

Work Plan:

A. Preparatory stage:

- Set and verify (measurements and simulations) the parameters of the beam: predict beam transport parameters by simulation and verify by measurement.
- Set quads parameters in normal operation. Use available diagnostics to measure OTR power along the beam line.
- Characterize e-beam parameters and find the parameter limits for operation (no compression).

B. Experimental Study Stage:

1. Operate LINAC1 (75MeV), chicane - off. Set quad triplet 1 to attain free uniform drift with beam waist=0.5mm. Beam diagnostics are OTR screens with NIR CCD (λ=1-1.8μ) that will replace the YAG screens located (z=0 – LINAC1 exit), z=1m, z=2.5m (Chicane screen), z=4m, z=8m. Optional: screen at z=12m (conditioned on assembly of transport line extension)
2. Measure the OTR integrated power on the different screen locations to determine the noise intensity evolution.: A. using CCD camera, B. (optional) using detector and wide angle focusing optics.
3. Operate LINAC1 (75MeV), chicane - off. Measurements of OTR power at z=8m for different settings of triplet quads 1 will provide the dependence of the current noise on the beam density and beam waist size.
4. Effect of current density will be measured by changing bunch current (charge) using neutral density filters placed at the laser pathway.
5. Turn chicane on. Study effect of dispersion.

SUMMARY OF PROPOSAL REVISIONS

- This proposal was submitted last year and the following revisions were made here in response to the committee recommendations.
- The analytical model of noise suppression [Gover, PRL, 2009] was confirmed by 3-D simulation [Nause, JAP, 2010].
- Simulations, specific to ATF parameters, were performed, and showed a detectable effect.
- Simulations show effect at λ=1-2μm, where we can use a standard high-sensitivity NIR camera (λ=1-1.8μm) [Previous plans to measure at λ=5-10μm required FIR optics].
- A. Nause acquired experience in OTR measurements in LCLS. Appreciable OTR signals were measured from an uncompressed bunch using a standard λ=.4-1.1μm camera.
- A revised two-stage work plan.

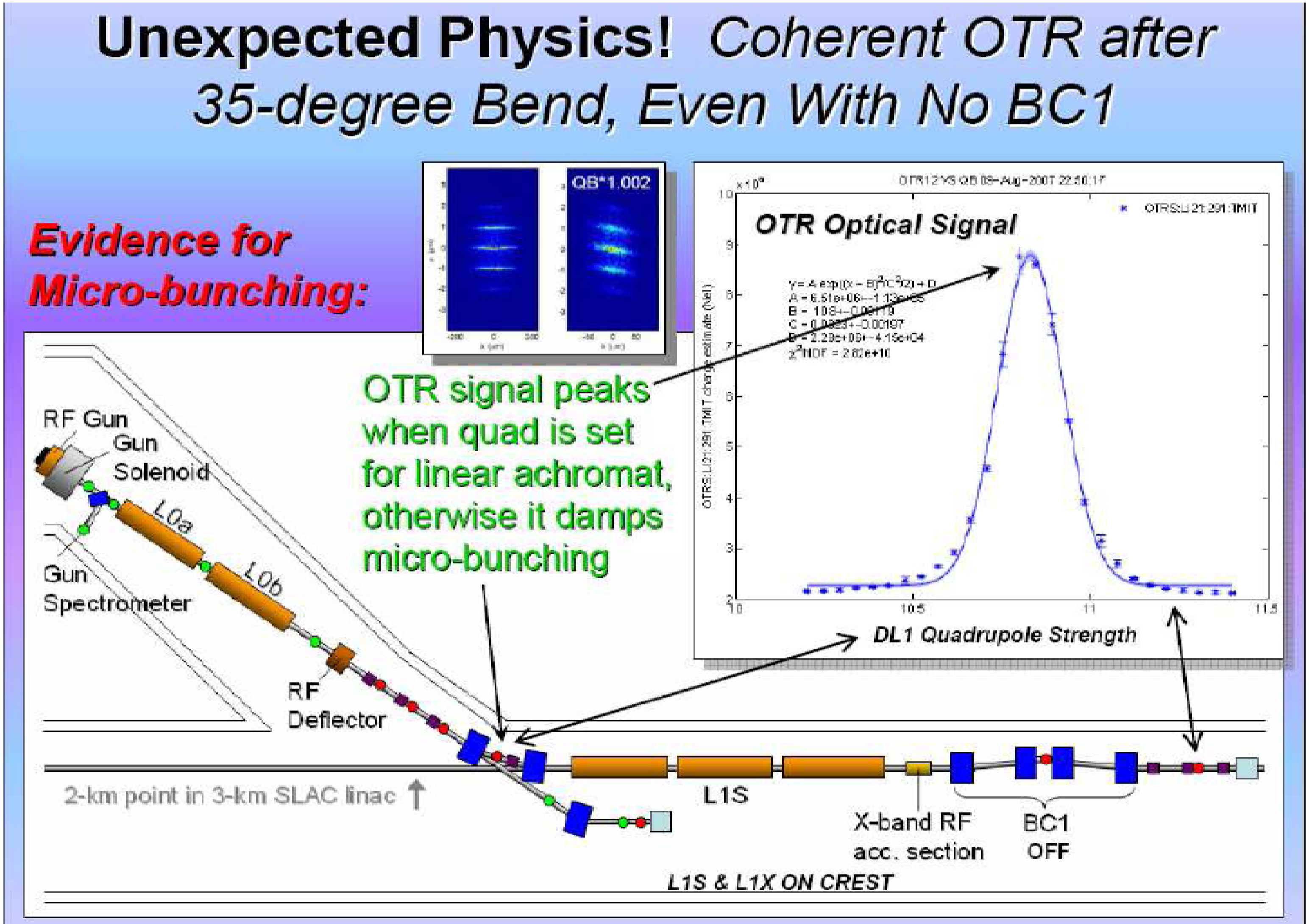
Conclusions

- Experimental evidence of strong collective effects in modern high-brightness machines
- Progress in understanding of physics behind these effects
- Search for cure against them
- Presented is new concept on manipulating electron beam phase space and suppressing microbunching
- Experiment at ATF will
  - Advance understanding of physics
  - Prove efficiency of new concept

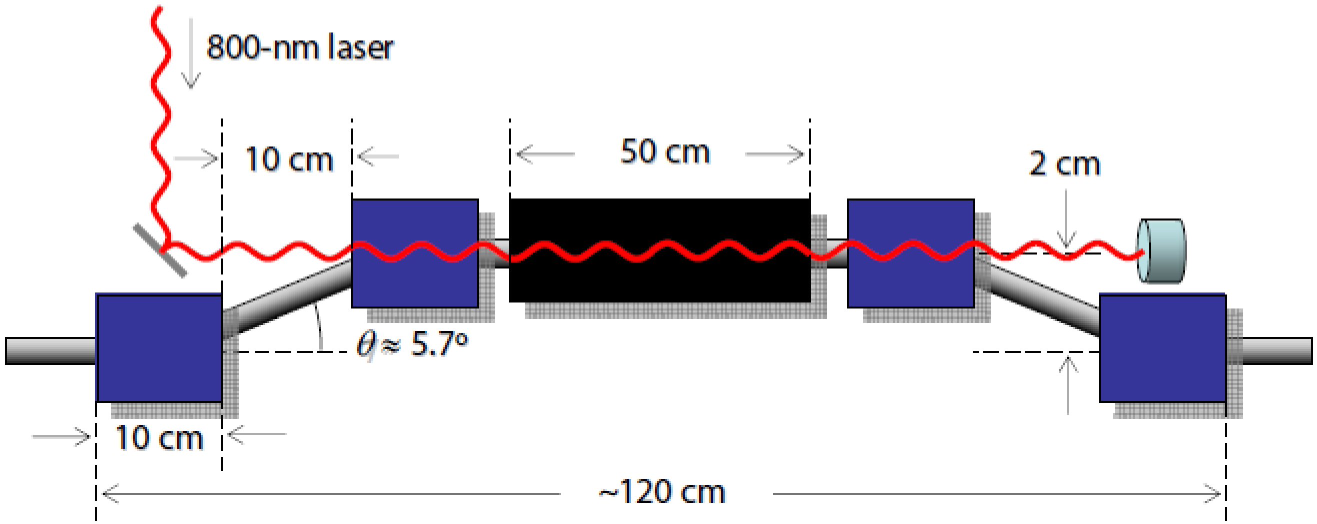
Coherent Optical Transition Radiation in LCLS/SLAC

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

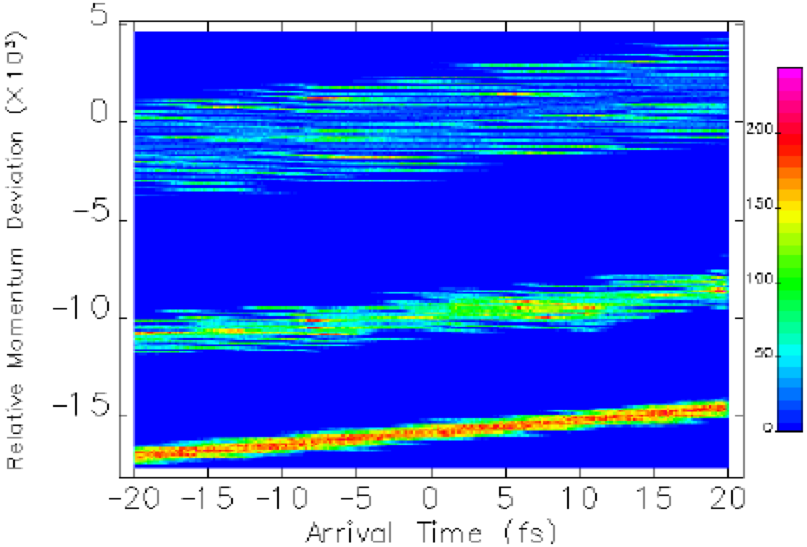
R. Akre et al, Phys. Rev. ST-AB, 11, 030703 (2008)



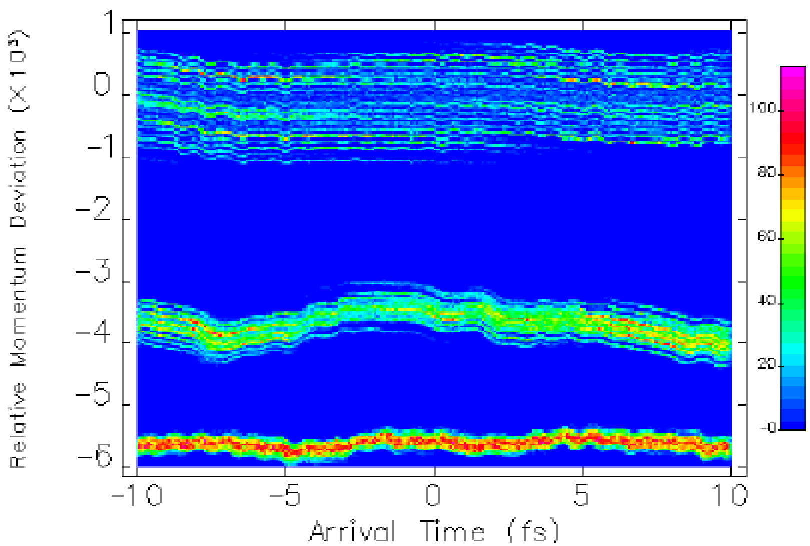
Laser-Heater at LCLS



Layout of the LCLS laser heater inside a magnetic chicane at 135 MeV



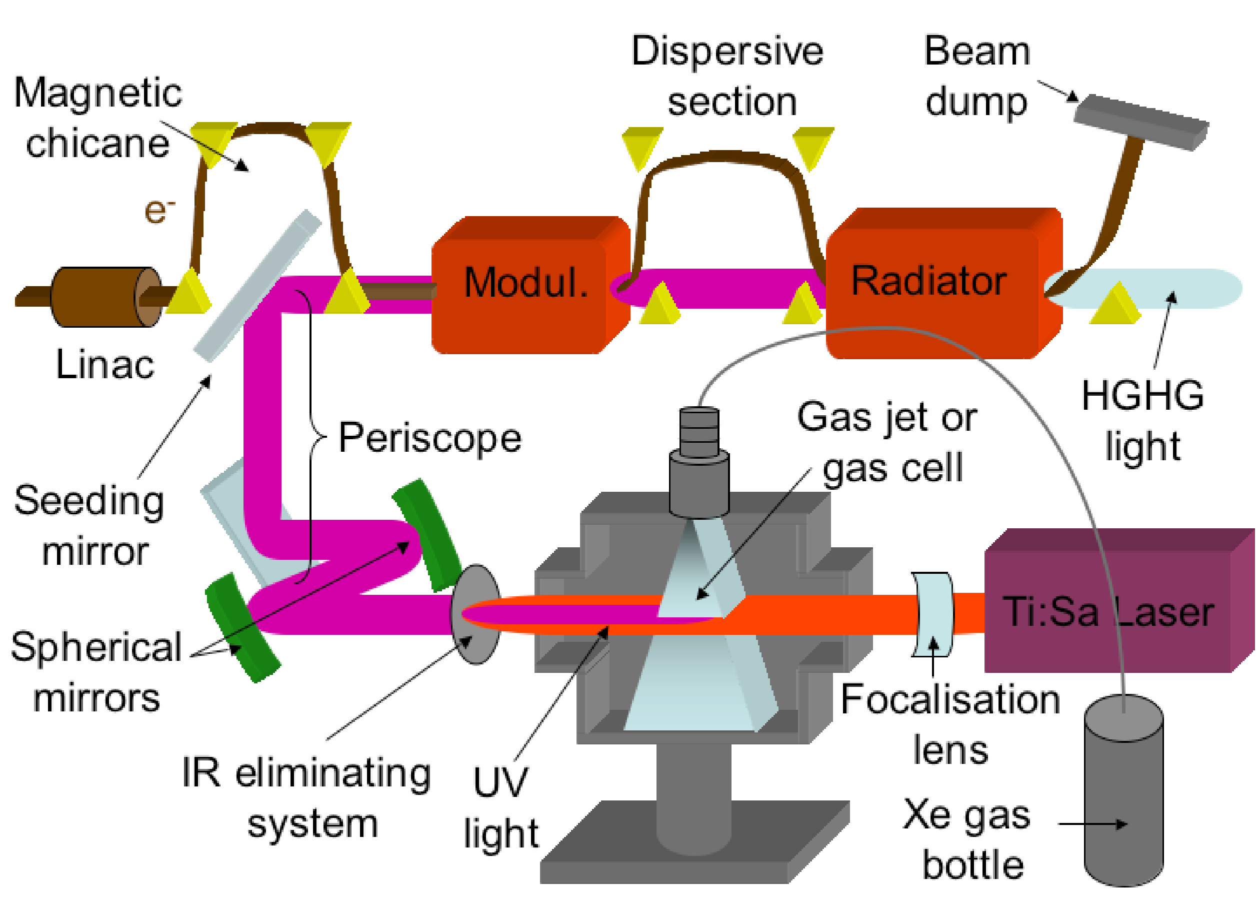
(a)End of BC2 at 4.5 GeV



(b)Undulator entrance at 14 GeV

Seeding the FEL of SCSS With the 13TH Laser Harmonic of a Ti: Sa Laser Produced in Xe Gas

G. Lambert, T. Shintake, SPring-8/RIKEN



Concept

Random Signal Spectral Domain

$$\breve{I}(\omega) = \int_{-T/2}^{T/2} I(t) e^{i\omega t} dt$$

$$\breve{v}_z(\omega) = \int_{-T/2}^{T/2} v_z(t) e^{i\omega t} dt$$

$$\breve{V}(\omega) = -\left(mc^2/e\right)\gamma_0^3 v_0 \breve{v}_z(\omega)$$

Current Noise Transformation in a Drift Section

If $\overline{\mathrm{Im}\left(\breve{I}(0)\breve{V}^*(0)\right)} = 0$:

$$\overline{\left|\breve{I}(z,\omega)\right|^2} = \overline{\left|\breve{I}(0,\omega)\right|^2} \cos^2\phi_p + \frac{1}{W_d^2}\left|\breve{V}(0)\right|^2 \sin^2\phi_p$$

$$\overline{\left|\breve{V}(z,\omega)\right|^2} = W_d^2 \overline{\left|\breve{I}(0,\omega)\right|^2} \sin^2\phi_p + \left|\breve{V}(0)\right|^2 \cos^2\phi_p$$

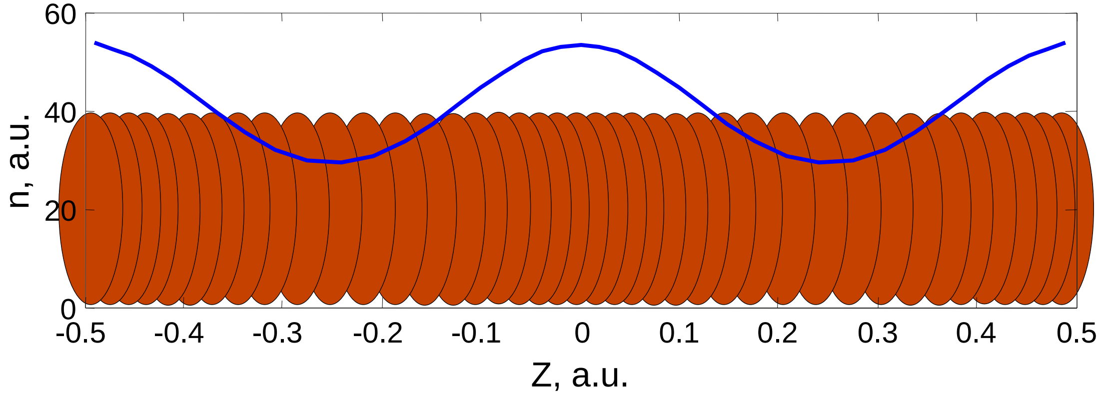
At $\phi_p = \theta_p L_d = \pi/2$:

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

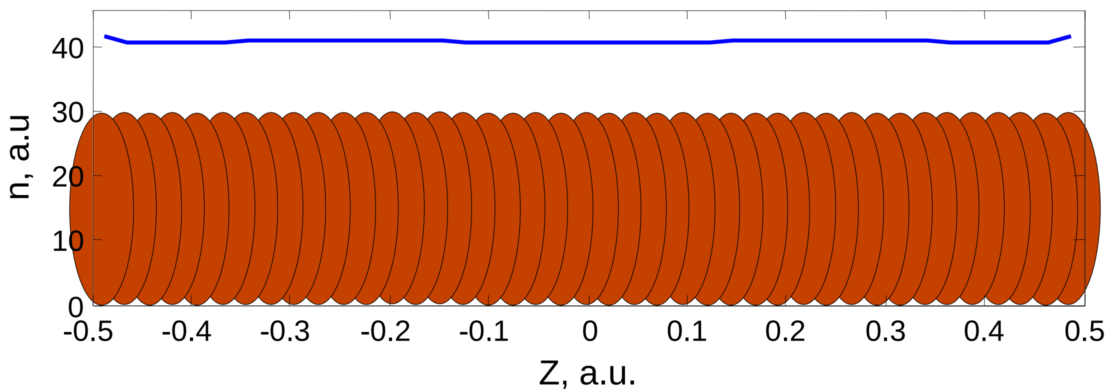
$$\overline{\left|\breve{V}(L_d,\omega)\right|^2} = \overline{\left|\breve{I}(0,\omega)\right|^2} / W_d^2$$

Dynamics of Beam Plasma Longitudinal Oscillation in a Drift Region (Moving Frame)

$t = 0$

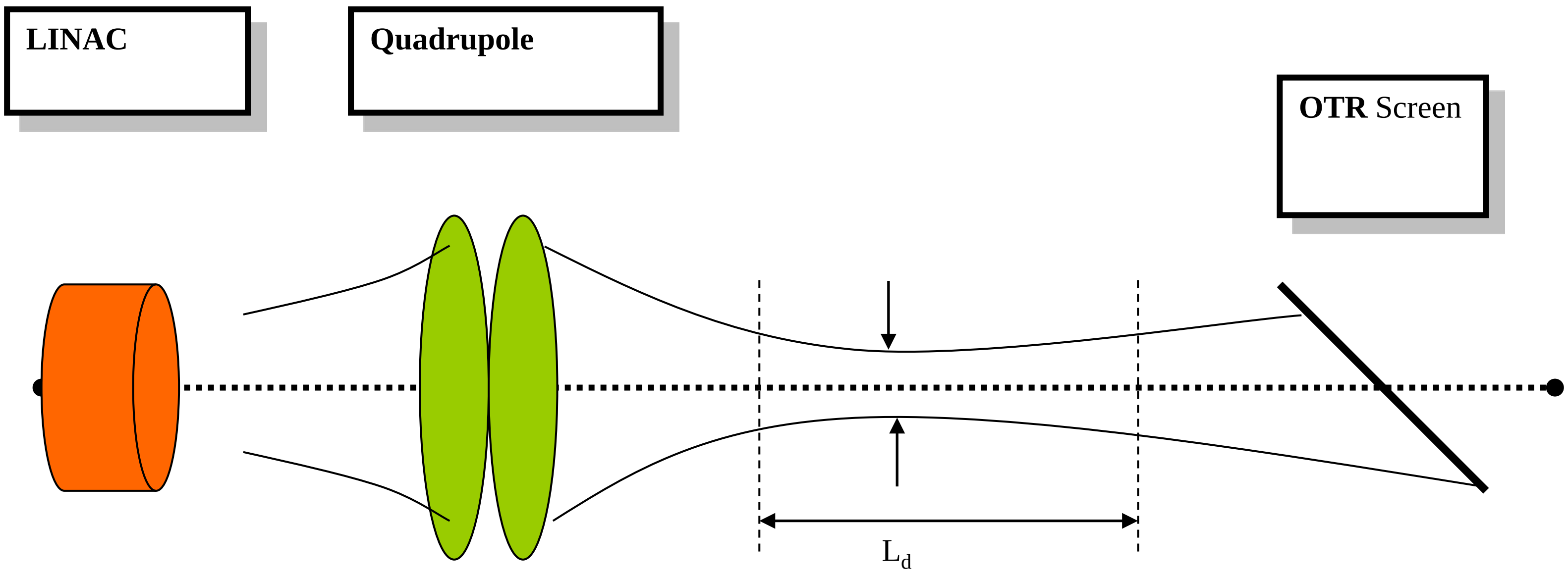


$t = \pi/2\omega_{pr}$

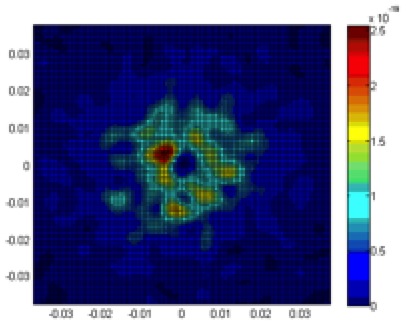


Experiment at ATF

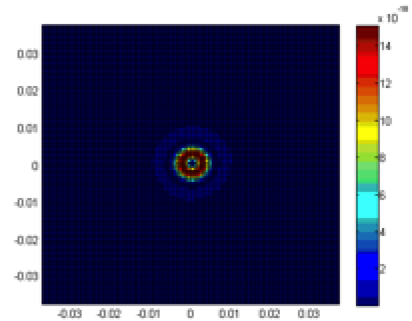
Collective Interaction Drift Section as the Waist of a Free Propagation Beam



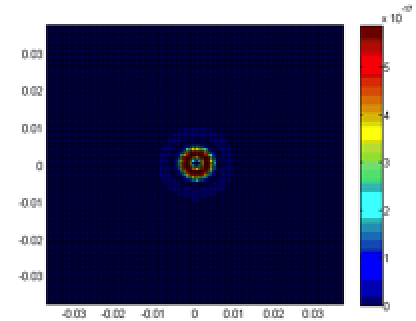
OTR Amplitude Growth for Increasing Portion of Coherent Modulation



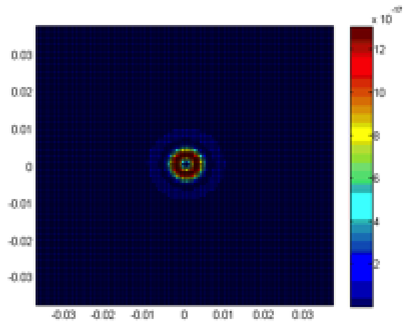
Shot-Noise
Peak = 2.5e-19



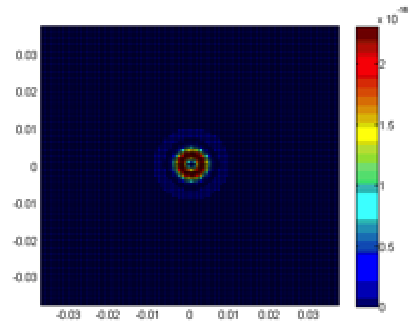
25% modulation
Peak = 15e-18



50% modulation
Peak = 6e-17

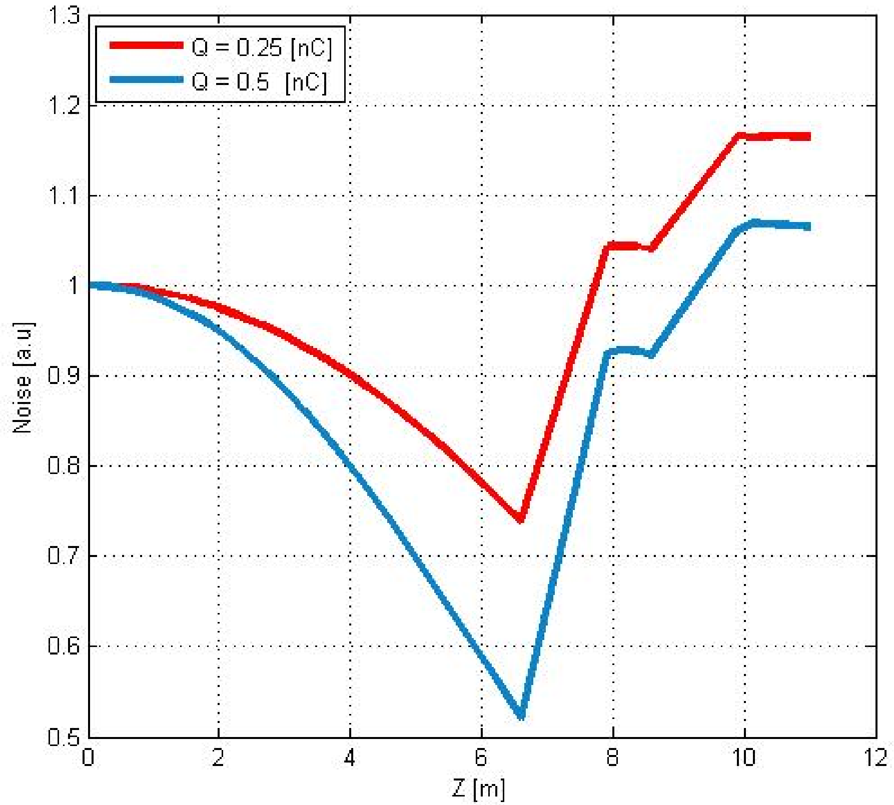


75% modulation
Peak = 13e-17



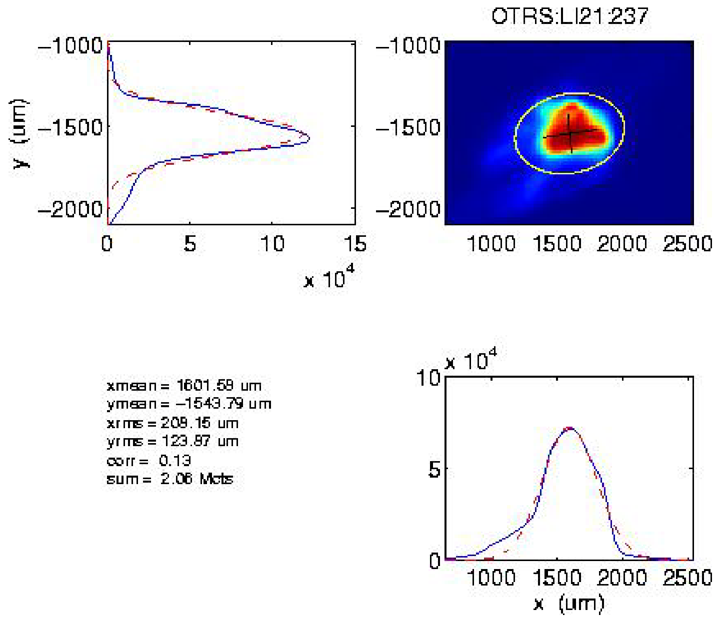
100% modulation
Peak = 3e-16

Preliminary Experiment Performed in the LCLS



Simulation results indicated reduction downstream the bend (Z = 7[m]) and increased noise after. The experiment was measuring the OTR intensities of screens along this trajectory.

Preliminary Experiment Performed in the LCLS



OTR 11

100% growth in OTR counts (after the bend)

Outlook

- Introduction
- Collective effects observed in modern FELs
- Concept of noise reduction in e-beam
- Proof-of-principle experiment at ATF
- Conclusions