Recent Progress in the High-Gain FEL Theory

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Introduction

• A fourth-generation light source: a high-gain x-ray FEL operated in SASE mode

• 3D theory in the exponential growth regime well developed (energy spread, emittance, diffraction, guiding)

• Tremendous progress in high-gain experiments
  wavelength down to < 100 nm
  saturation achieved

• Stimulate better understandings of high-gain theory, some aspects are discussed in this talk
(mostly based on collaborative work with K.-J. Kim)

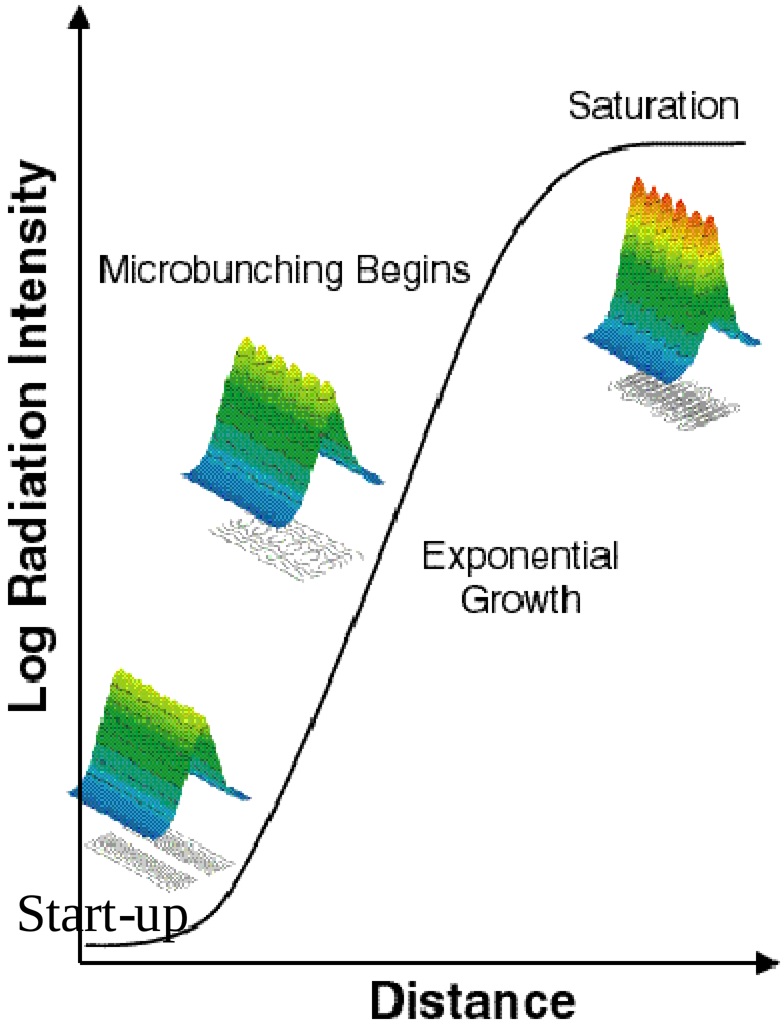
Theory: Overview

Start-up stage

External signal or spontaneous radiation interacts with the e-beam resonantly at undulator λ

Energy modulation ➔ density modulation (microbunching) ➔ coherent radiation at λ ➔ **exponential growth (L_G)**

At sufficiently high power, electrons fully microbunched and trapped in the ponderomotive field ➔ reach **saturation (P_{sat})**



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Start-up Process

- Spontaneous emission: many transverse modes
- FEL instability favors a particular (fundamental) mode

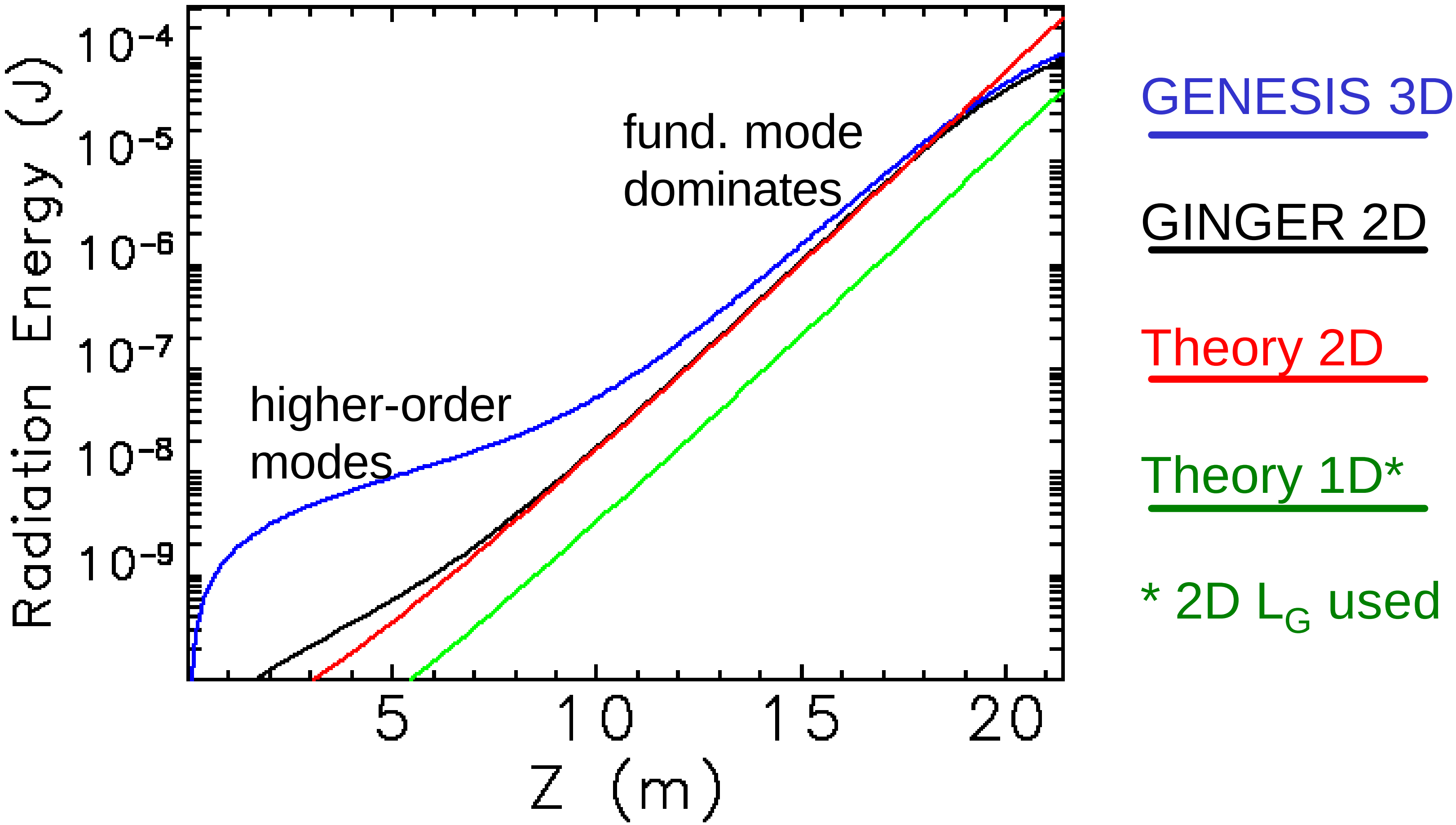
➔ proper modal decomposition for initial value problem

$$\frac{dP}{dw} = g_A \left[\left(\frac{dP}{dw}\right)_{\text{signal}} + \left(\frac{dP}{dw}\right)_{\text{noise}} \right] \exp\left(\frac{Z}{L_G} - \frac{(\Delta w)^2}{2 s_w^2} \right)$$

- Effective start-up noise (for SASE): power of the fundamental mode over the first two gain length L_G, can increase with energy spread and emittance through L_G

- 2D Solution determines the radiation energy level in exponential gain regime

Comparison with Time-dependent Codes



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Transverse and Temporal Properties: Review

- Diffraction + Gain ➔ transverse mode selection
  - ⇒ fundamental mode dominates (gain guiding)
  - ⇒ good transverse coherence

- SASE is a chaotic light temporally

  Coherence length = $(2\sigma_\omega)^{-1}$ ($\propto \sqrt{z}$) << bunch length

  SASE intensity fluctuation (Γ distribution)

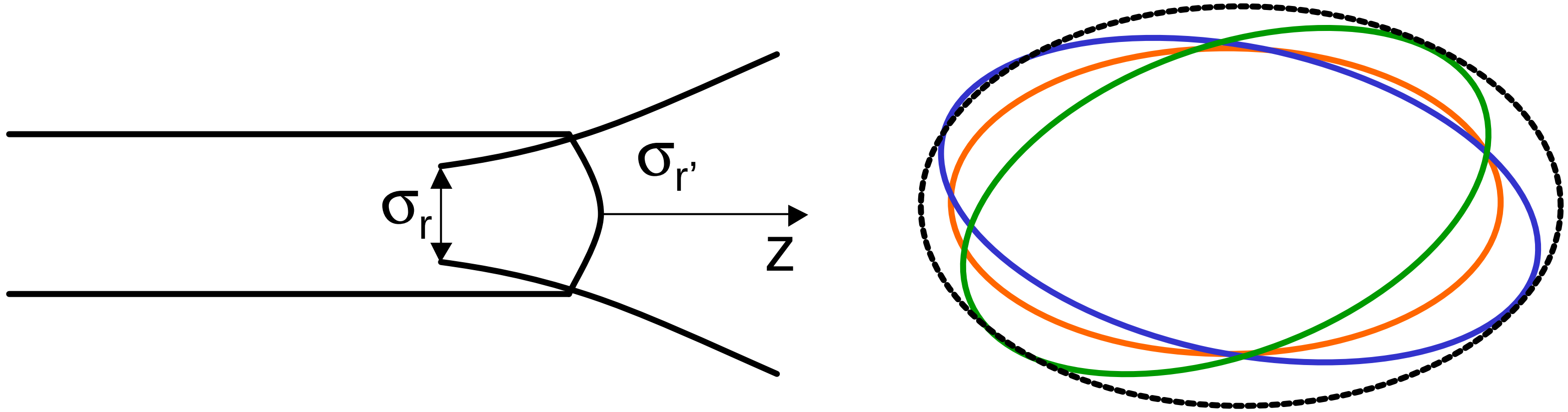
$$\frac{\Delta I}{I} = \frac{1}{\sqrt{M}}, \quad \text{where } M = \frac{\text{bunch length}}{\text{coherence length}}$$

Transverse and Temporal Properties: Interplay

Transverse and Temporal Properties: Interplay

- Transverse coherence somewhat affected by "large" SASE bandwidth (Saldin et al.)
- A different fundamental mode at each wavelength

- Smearing of radiation transverse phase space ellipses



Transverse coherence: LEUTL~ 90%, LCLS ~ 97%

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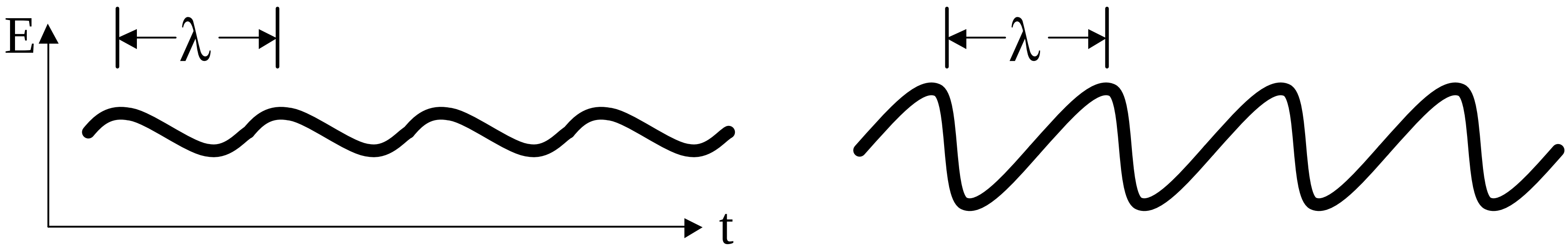
Nonlinear Harmonic Generation

- FEL instability creates energy and denstiy modulation at λ,
- Near saturation, strong bunching at fundamental produces rich harmonic components

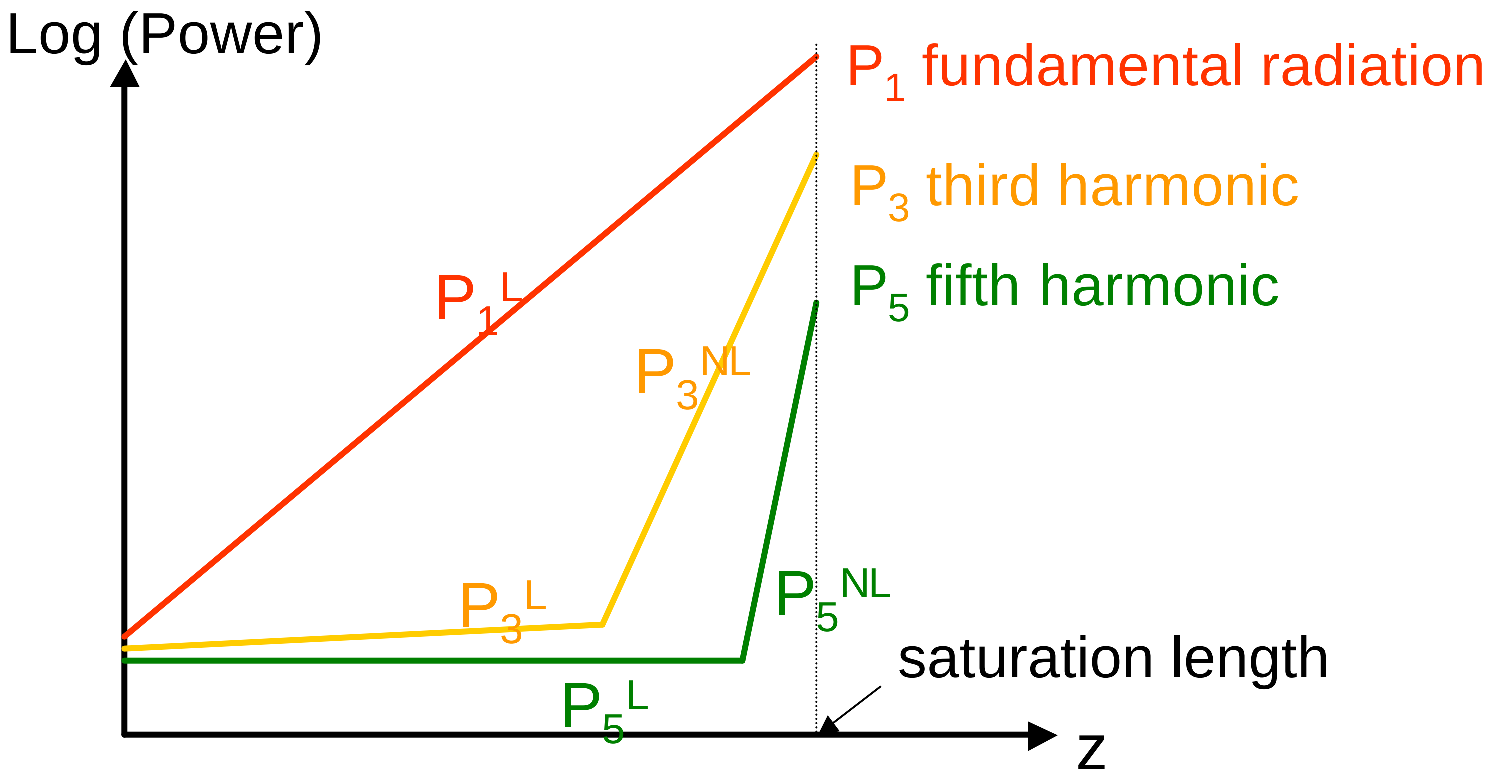
small signal, linear regime

near saturation, nonlinear regime



- Coherent harmonics determined by fundamental
  - ➔ gain length L_G/n
  - ➔ transverse coherence
  - ➔ temporal structures

Plenty of Power at (3X) Shorter Wavelength



• Theory predicts third harmonic reaches 1% of fundamental, verified by recent high-gain experients (HGHG and VISA)

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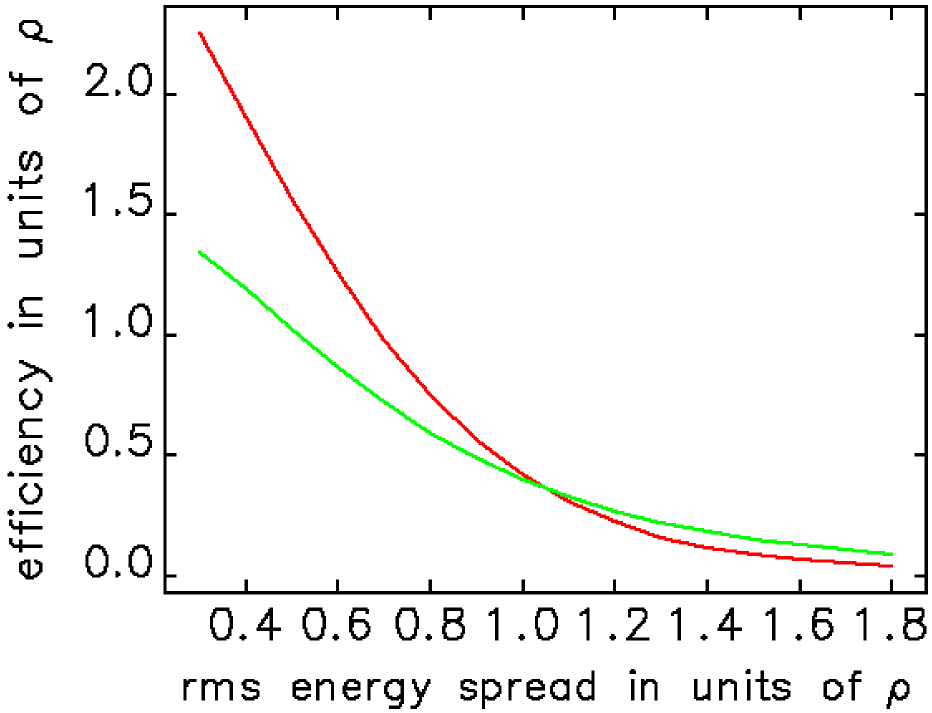
Saturation Mechanism

• Quasi-linear relaxation: strong radiation field modifies e-beam distribution ➔ increases energy spread ➔ stops the gain ➔ FEL saturation



- Quasi-linear solution
- Simulation fitting (Xie)

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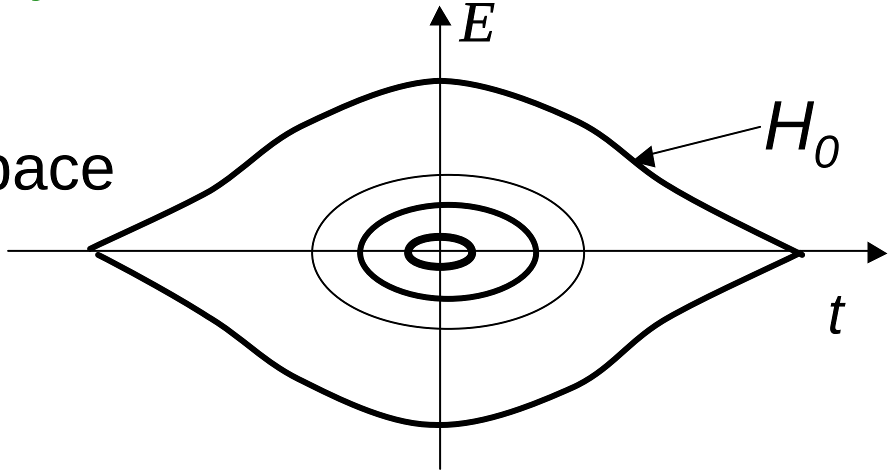
Saturation Behaviors

• XFELs operate in saturation for max. power/stability, seeding schemes go deep saturation to reduce fluctuation

• Electrons trapped by combined radiation+undulator fields

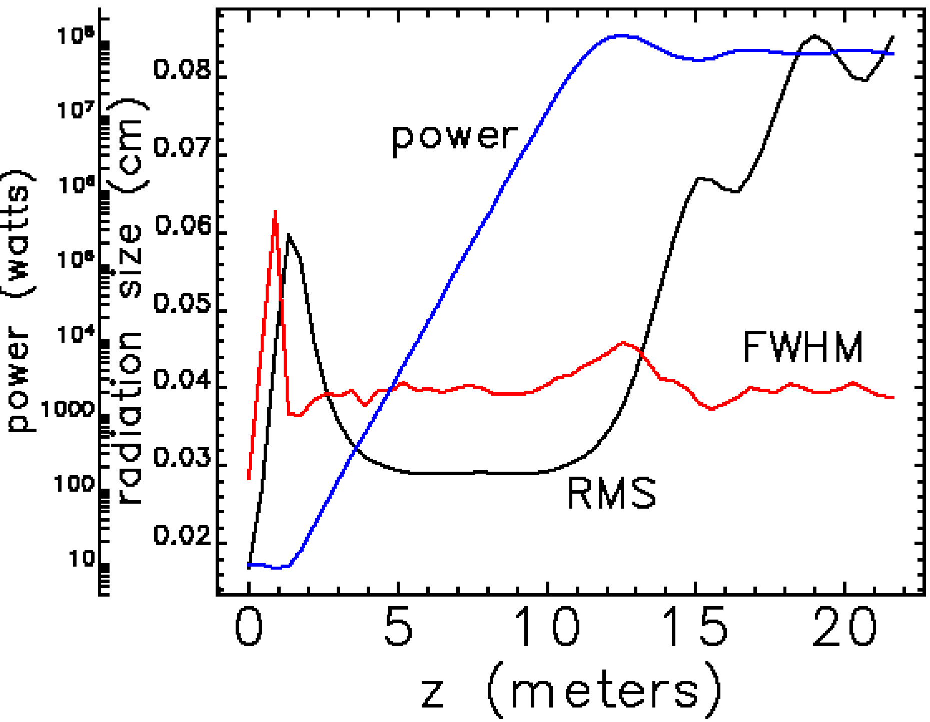
saturation phase space

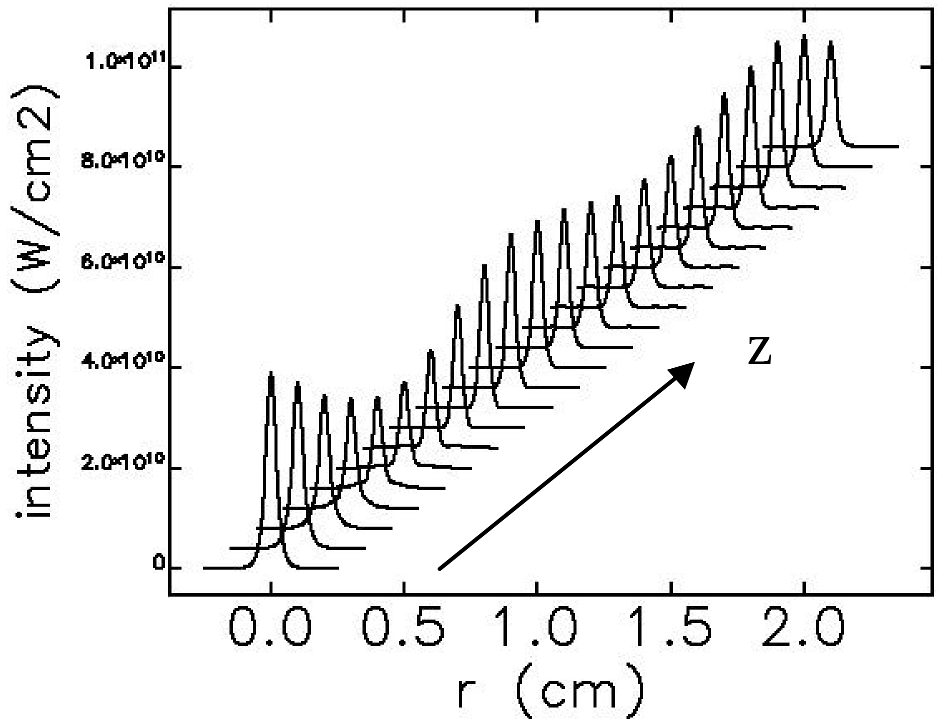
like an RF bucket



• Radiation power stays roughly constant, but phase advances due to the beam-radiation interaction
➔ an effective index of refraction (>1) (Scharleman et al.)

Refractive Guiding





- Guided mode that carries fixed power ➔ constant FWHM

  some excess power diffracts out ➔ increased rms size

  other excess power stays oscillatory

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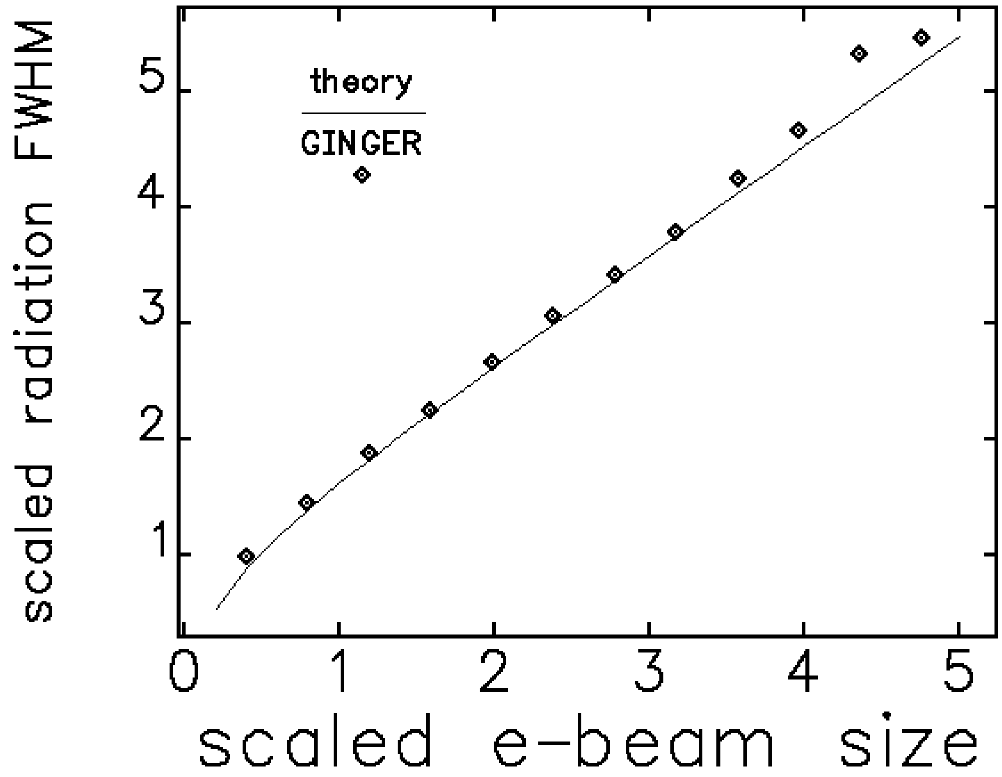
Guided Mode after Saturation



- Valid when emittance < $\lambda/4\pi$
- For XFELs, emittance > $\lambda/4\pi$, any guiding?

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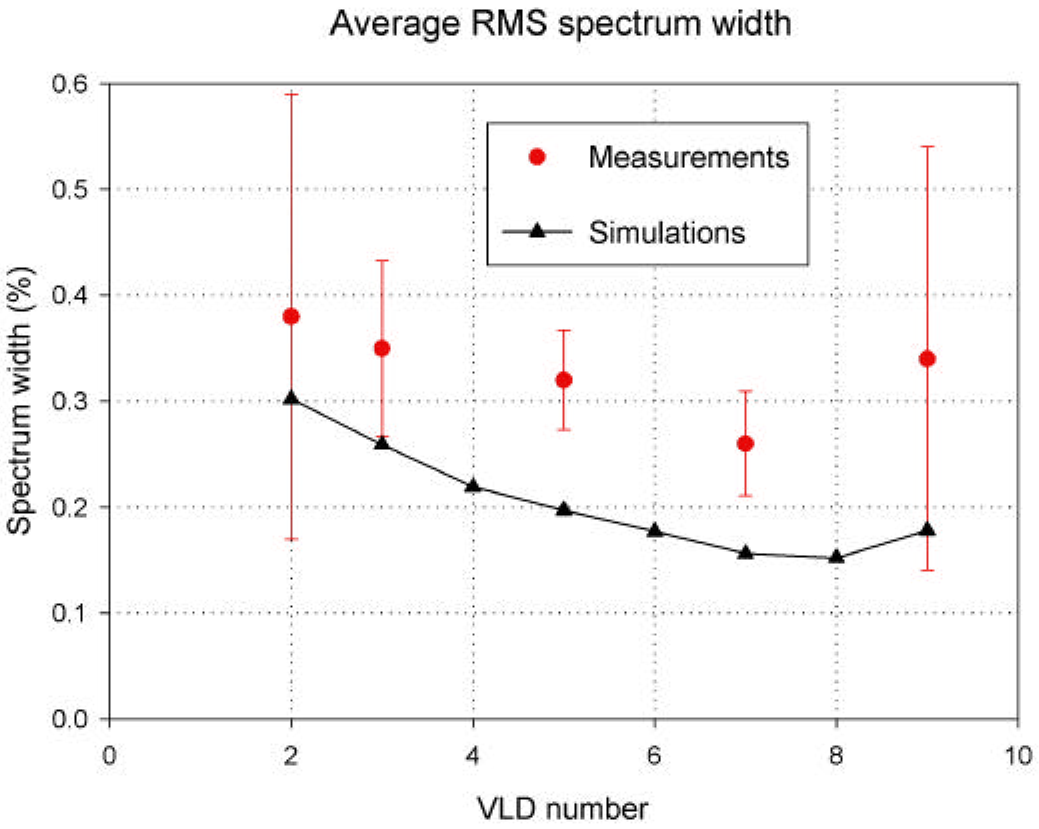
Sideband Instability

- Before saturation, SASE spectrum undergoes gain narrowing
- After saturation, spectrum redshifts and broaden because electron's synchrotron motion in the bucket generates sidebands

- LEUTL shows such a behavior (Sajaev et al.)



Conclusion

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• The excitement of XFELs leads to progress in all areas of high-gain FEL research (including theory)

• Evolution of FEL fundamental and harmonic radiation can be completely determined for simple e-beam distributions from start-up to near saturation

• Partial understanding of saturation behavior, more needed in combination with numerical simulations

• Quantum effects (Schroeder et al.) are negligible in XFELs except for quantum fluctuation due to spontaneous radiation (Saldin et al.)

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