Expected Properies of Coherent LCLS FEL Emission

BERKELEY LAB

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Talk Outline

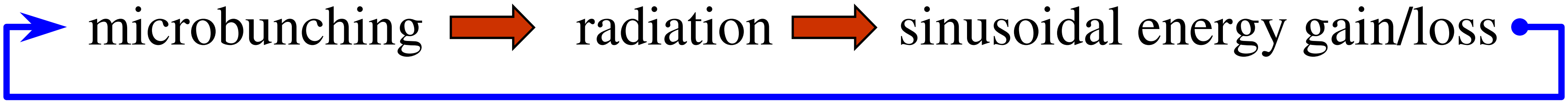
- Basic "steady-state" FEL amplifier physics
  - instability mechanism, gain curve and "FEL parameter" ρ, sensitivity to e-beam parameters
- Basic "time-dependent" (polychromatic) amplifier physics
  - "fast" time-variations arising from shot noise initiation
  - "slow" time variations arising from e-beam temporal variations (*i.e.* current, energy-spread, emittance)
  - realistic start-to-end e-beam input to undulator and expected FEL output properties
  - growth of longitudinal and transverse coherence with z
- Diagnostic separation of coherent (FEL) and incoherent (spontaneous emission) microbunching components

FEL Instability

- Resonance: radiation advances (relative to e-beam) one x-ray wavelength per undulator wavelength:

$$\lambda_s = \lambda_u \times \frac{(1+K^2/2)}{2\gamma^2}$$

- FEL instability arises from microbunching and synchrotron-like rotation of e- in radiation+undulator ponderomotive wells



microbunching → radiation → sinusoidal energy gain/loss

- Requirement for high gain: high current, low $\delta\gamma$ and ε

Microbunching, radiation grow exponentially with *z*

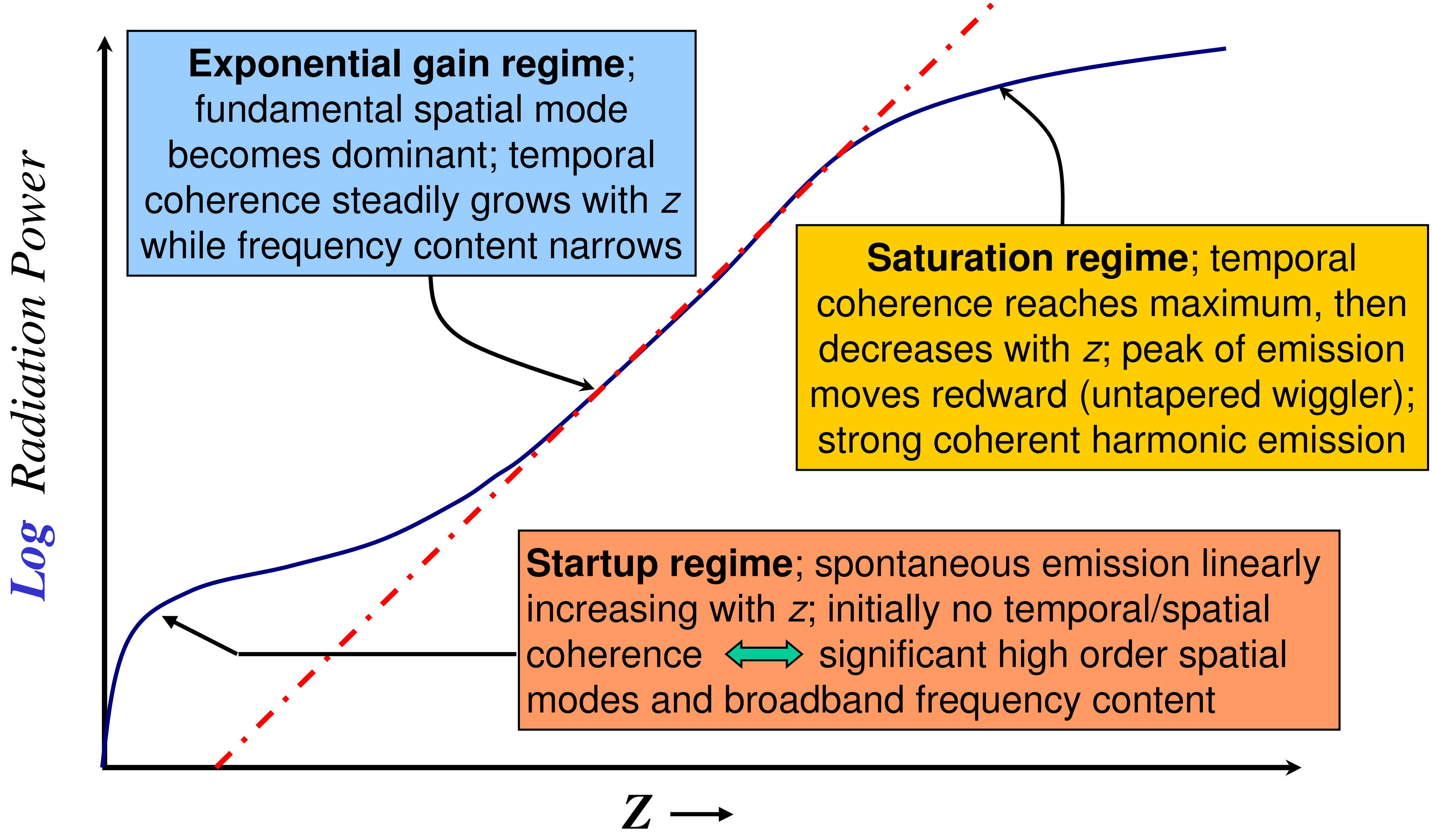
- For sufficiently high currents and long undulators, instability grows exponentially with $L_{gain} \approx \lambda_u / 4\pi\sqrt{3}\,\rho$

- FEL (Pierce) parameter ρ sets many FEL characteristics:

$$\rho_{1D}^3 \equiv \frac{\omega_p^2 K^2}{32 c^2 \gamma^3 k_u^2} \propto \frac{I_{\mathbf{B}}}{\varepsilon\beta} \quad \text{and} \quad \rho_{3D} \sim \rho_{1D} / 1.5 \quad \text{for LCLS}$$

  - Saturation length $L_{SAT} \sim \lambda_u / \rho \sim 18\ L_{GAIN}$
  - Saturated power $P_{SAT} \sim \rho\ P_{beam}$
  - Normalized RMS bandwidth $\Delta\omega/\omega_0 \sim \rho\ (L_{SAT} /\ z)^{1/2}$
- For LCLS, $\rho \sim$ 4E-4, $L_{GAIN} \sim$ 4-5m, $L_{SAT} \sim$ 70-100 m, $P_{SAT} \sim$ 25 GW

SASE FEL "Topography"



Exponential gain regime; fundamental spatial mode becomes dominant; temporal coherence steadily grows with *z* while frequency content narrows

Saturation regime; temporal coherence reaches maximum, then decreases with *z*; peak of emission moves redward (untapered wiggler); strong coherent harmonic emission

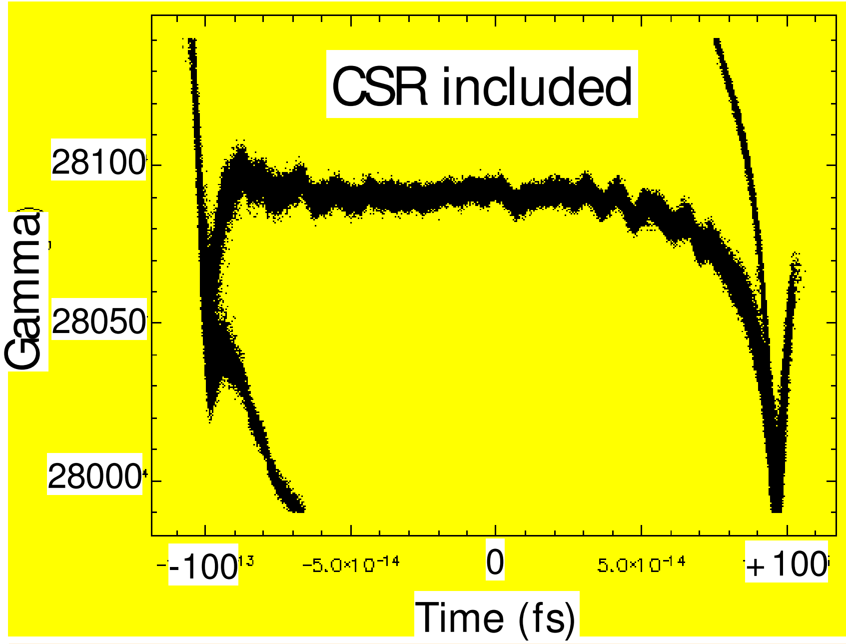
Startup regime; spontaneous emission linearly increasing with *z*; initially no temporal/spatial coherence ⟺ significant high order spatial modes and broadband frequency content

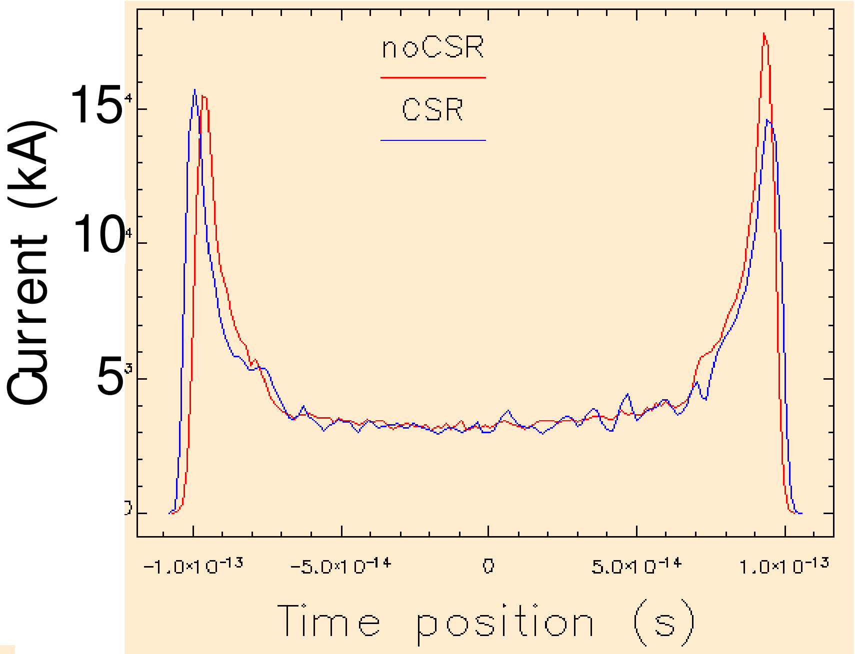
Temporal Variation Topology

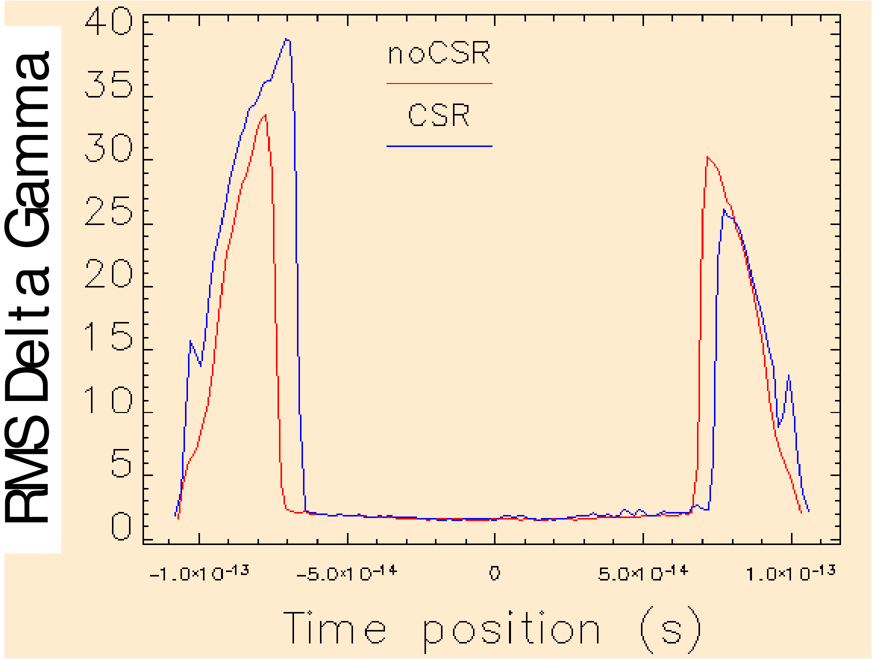
Property	Fast	Slow
Source	Microbunching from e-beam shot noise	"Slow" e-beam variations (I_B, γ, $\delta\gamma$, ε, $<x>$, $<y>$, $<x'>$, $<y'>$); CSR & wake effects
Effect on Output Power	"Spiky" output; low long. coherence (sub-fs)	Slow (multi-fs) variation in P_{sat}, z_{sat} , central λ
Effect on Output Power	Relatively broadband, "spiky" output	Possible slow chirp in central λ
Shot-to-Shot Repeatability	None locally (spike position, phase completely random); <P> ~ constant	Possible high repeatability (depends on injector, accelerator, & compressor)

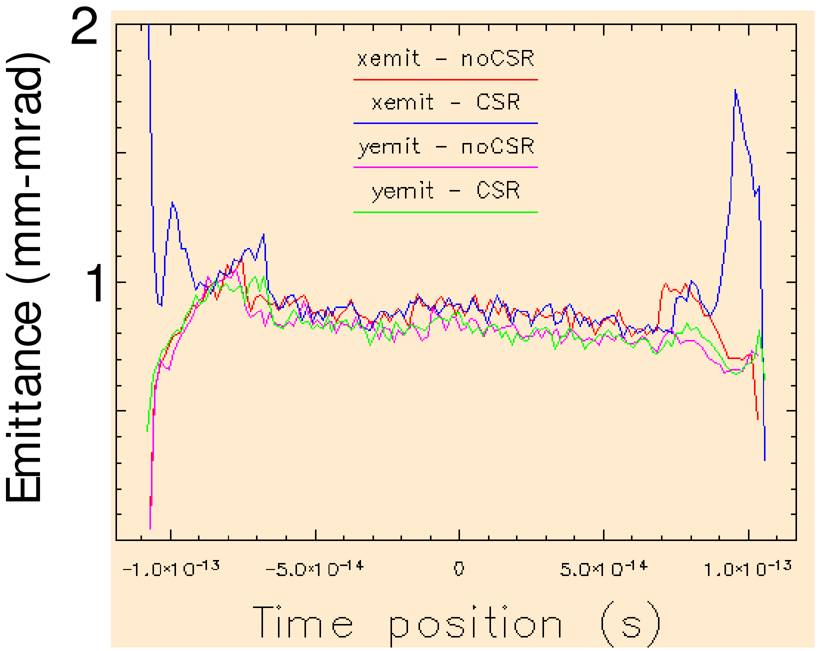
1-nC LCLS: E-beam at undulator entrance

ELEGANT results from P. Emma; envelope parameters from modified Elegant2genesis

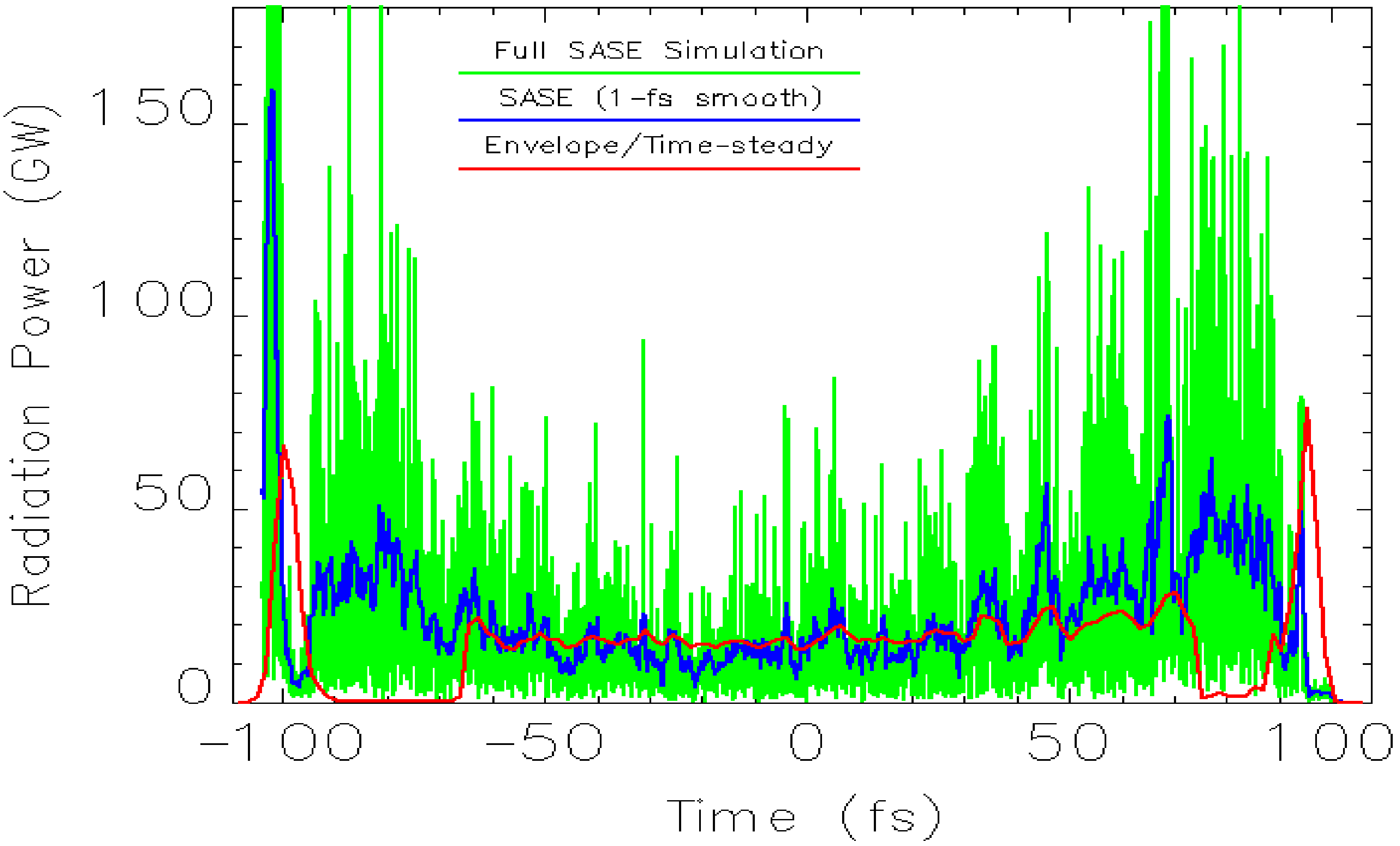






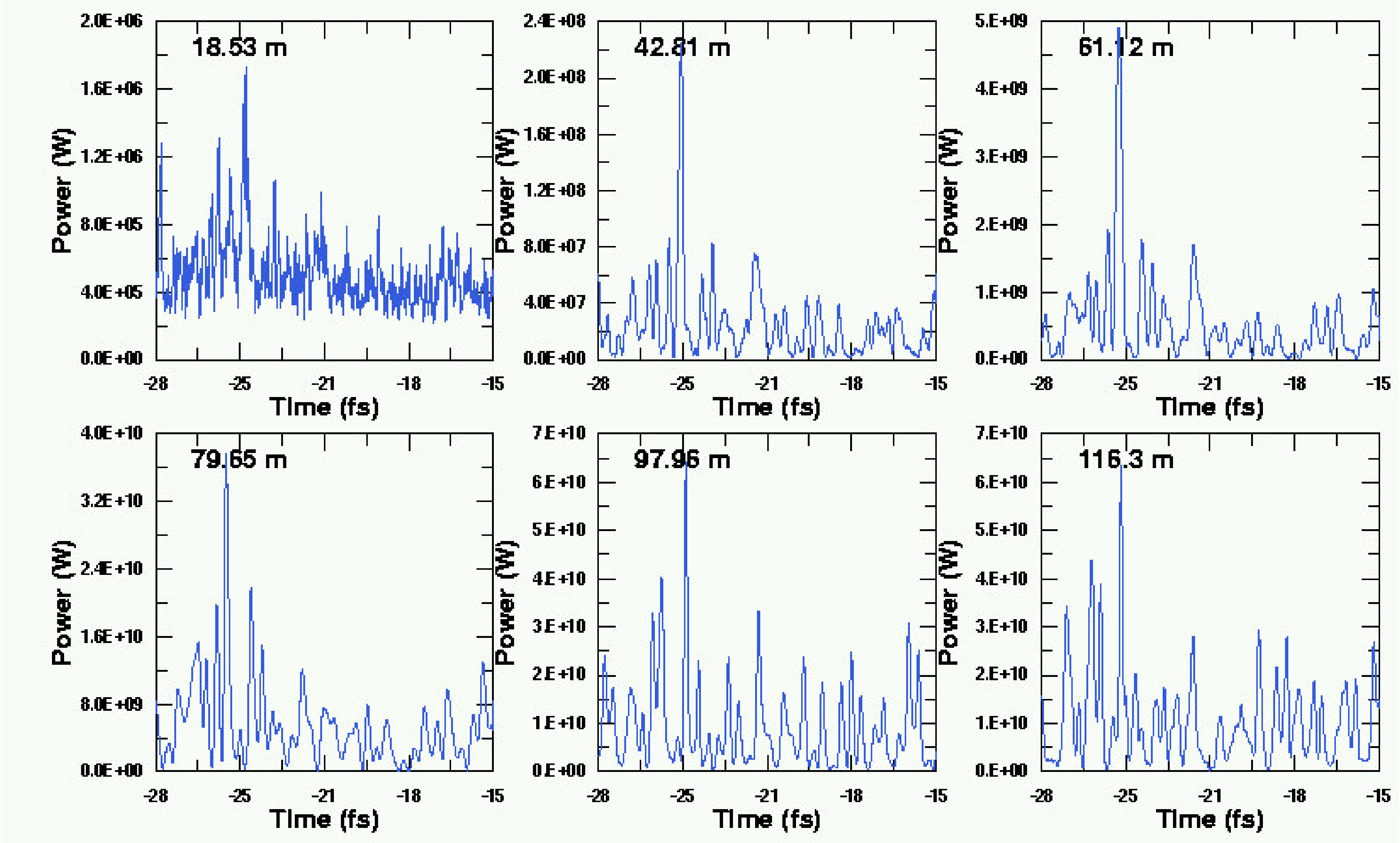


Predicted Output Power versus Time



2003 S2E parameters; GINGER simulation of full LCLS pulse with 12-as resolution; SASE results at output (120 m); time-steady result for max power

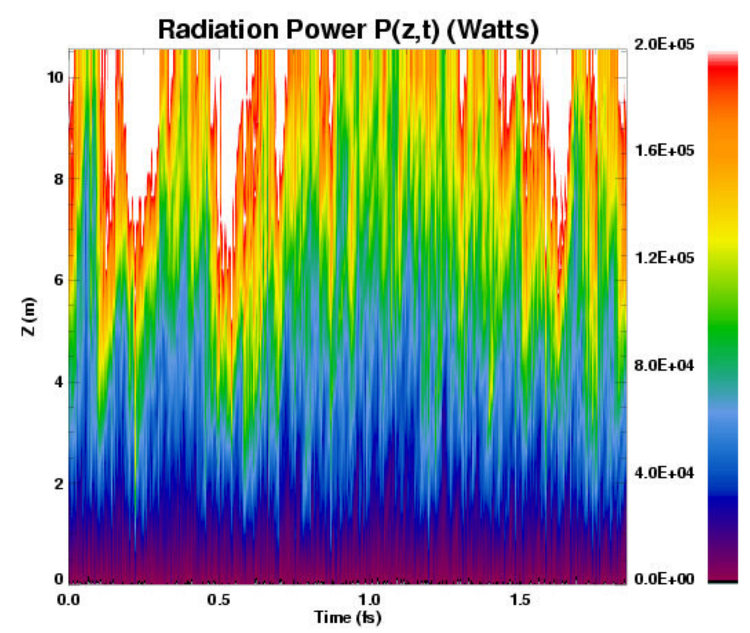
“Local” P(t) Snapshots – “fast” time variation

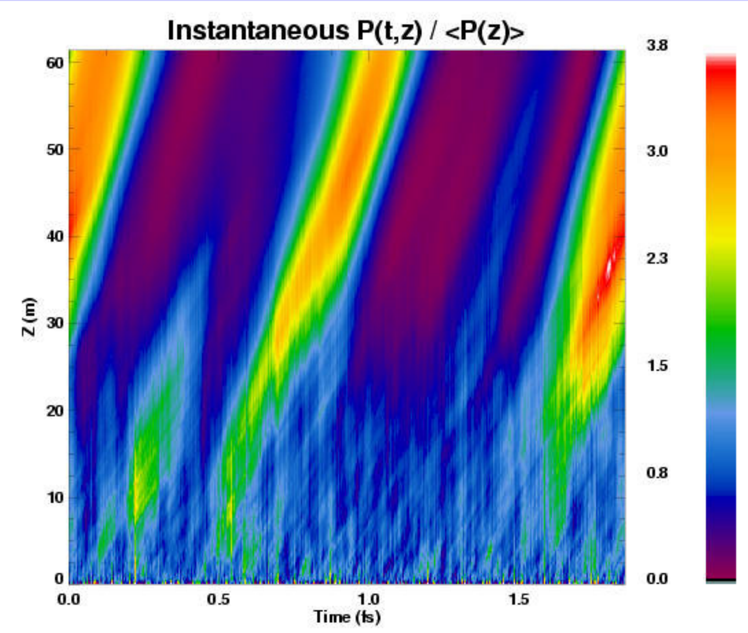


GINGER "standard" LCLS example of noise -> organized start-up -> exponential gain

Total power shows development into spikes by z~10 m

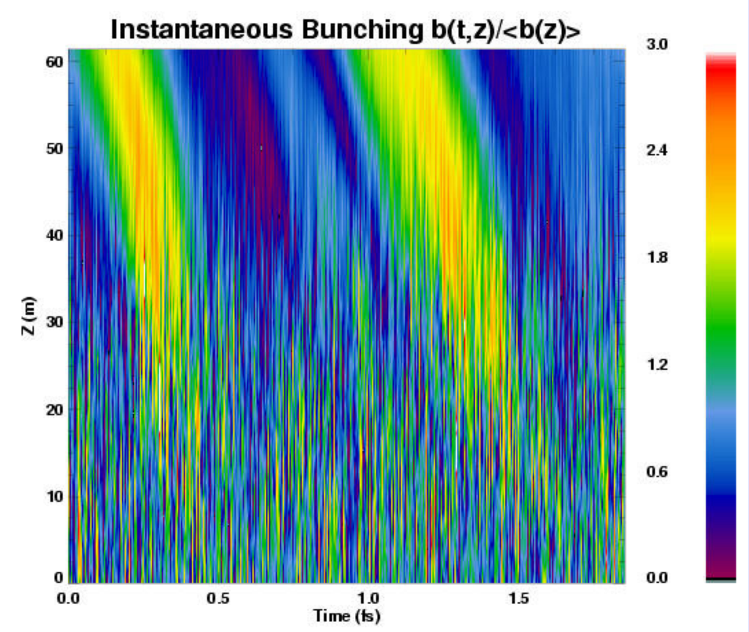
Normalized power shows self-similar spike propagation $[c - v_G] \sim 2/3\ v_{slip}$

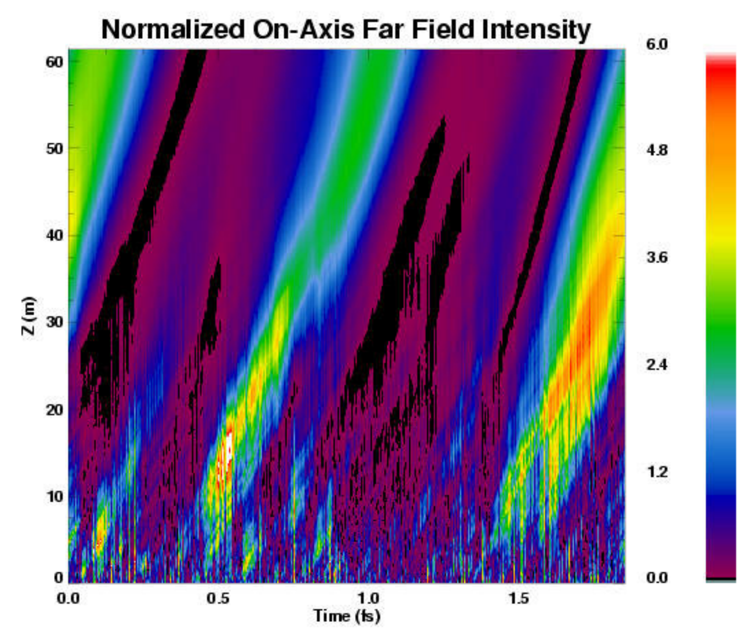




On-axis far field radiation sub-*c* spike propagation evident earlier in z

Norm. bunching shows self-similar spike propagation at $v_G > \langle v_z \rangle$





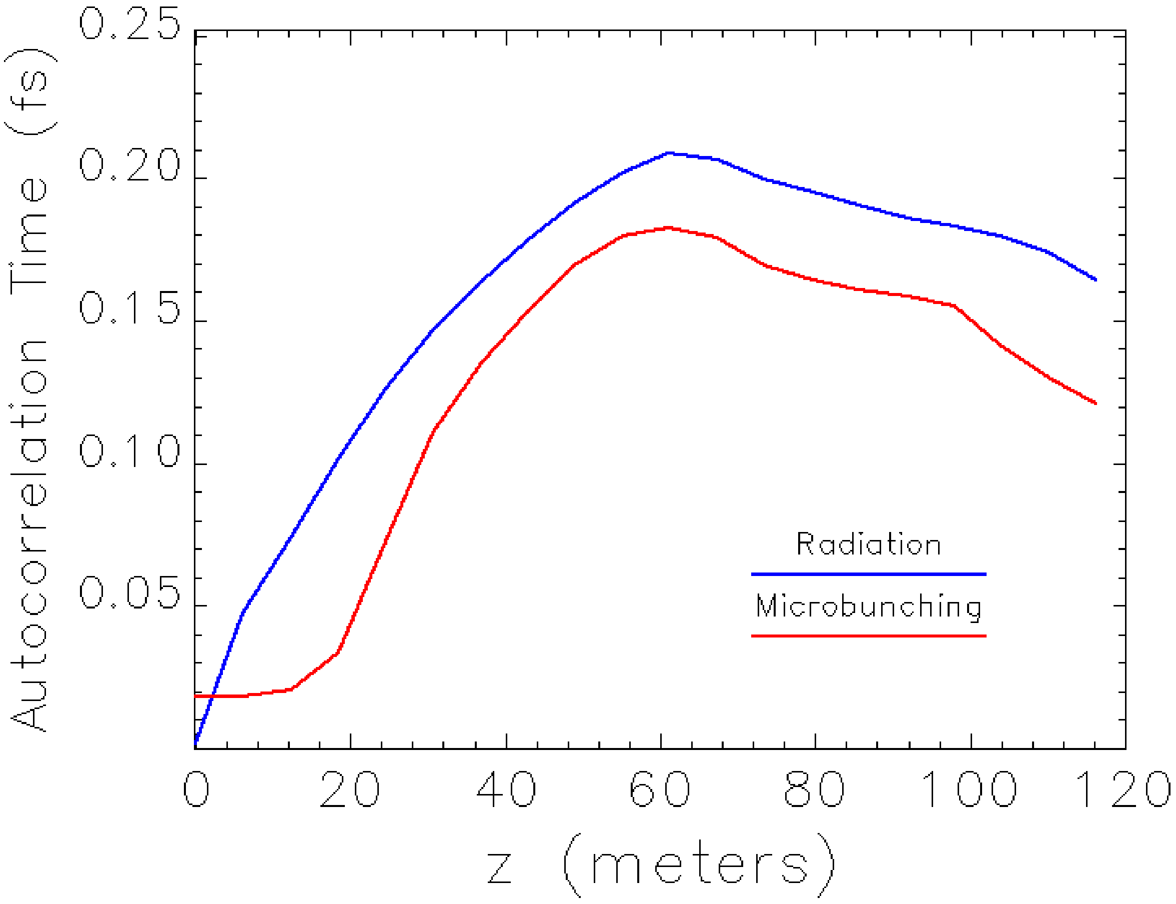
Development of Longitudinal Coherence

- In exponential gain regime, τ_c steadily increases as $\sqrt{z}$
  - For SASE, $\tau_c \sim 0$ at $z=0$
  - Due to slippage and gain narrowing, τ_c increases (some individual temporal spikes exponentially grow and widen in time)
- Maximum τ_c reached 1-2 gain lengths before initial SASE power saturation
  - Beyond saturation, τ_c decreases (and $\Delta\omega/\omega_0$ increases) due to radiation emission to redward portion of spectrum (λ shift due to particle energy loss and sideband-like spectral chirp across intense radiation spikes)
- Nonlinear harmonic emission can be strong near saturation --- possibly useful diagnostic

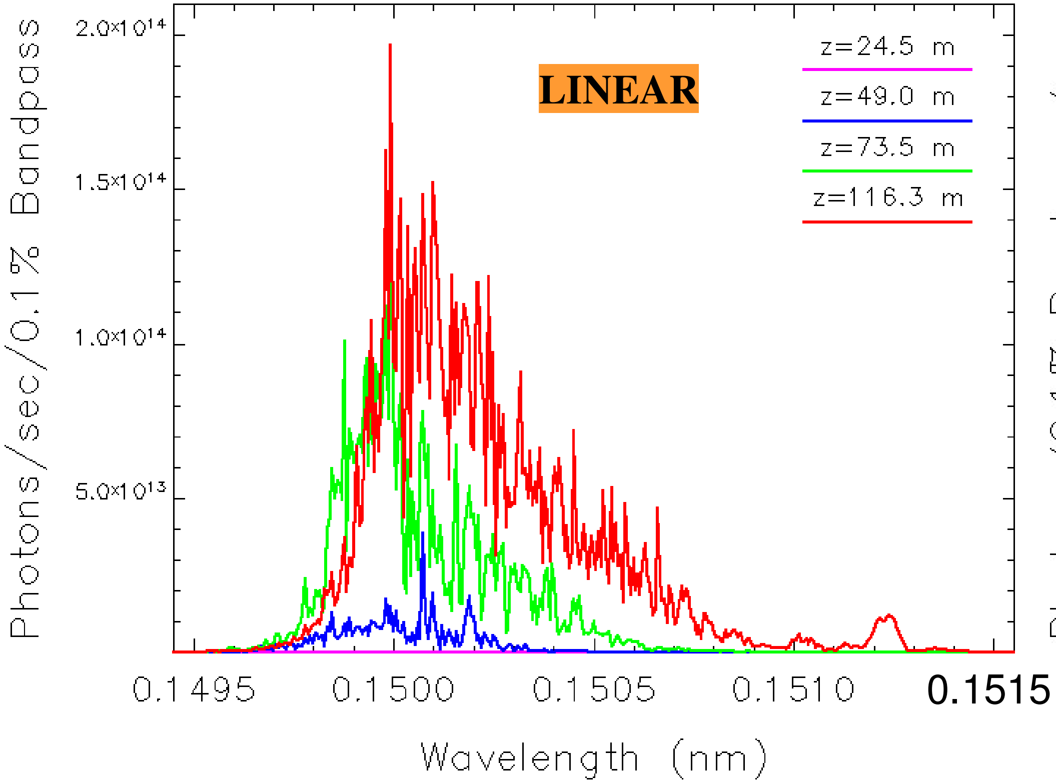
Growth of Longitudinal Coherence

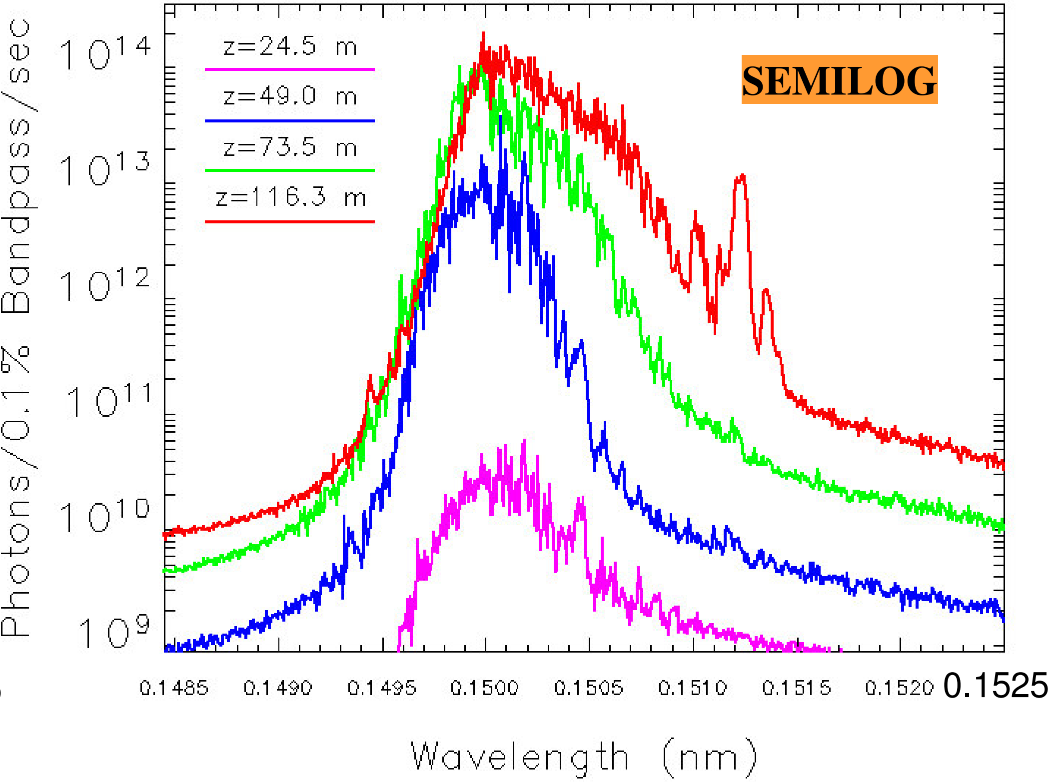
"Start-to-End" LCLS

- 2003 undulator layout
- Emma Parmela-ELEGANT macroparticle input to GINGER FEL code
- 12 as slice resolution
- Coherence time τ_c defined by $A(\tau_c)/A(0) = 0.5$
- Radiation τ_c determined from on-axis far field
- Microbunching τ_c determined using full radial averaging of particle phase



Radiation Spectrum Development





2003 S2E LCLS parameters; full 200-fs pulse;
presumed 120 Hz rep rate; GINGER simulation

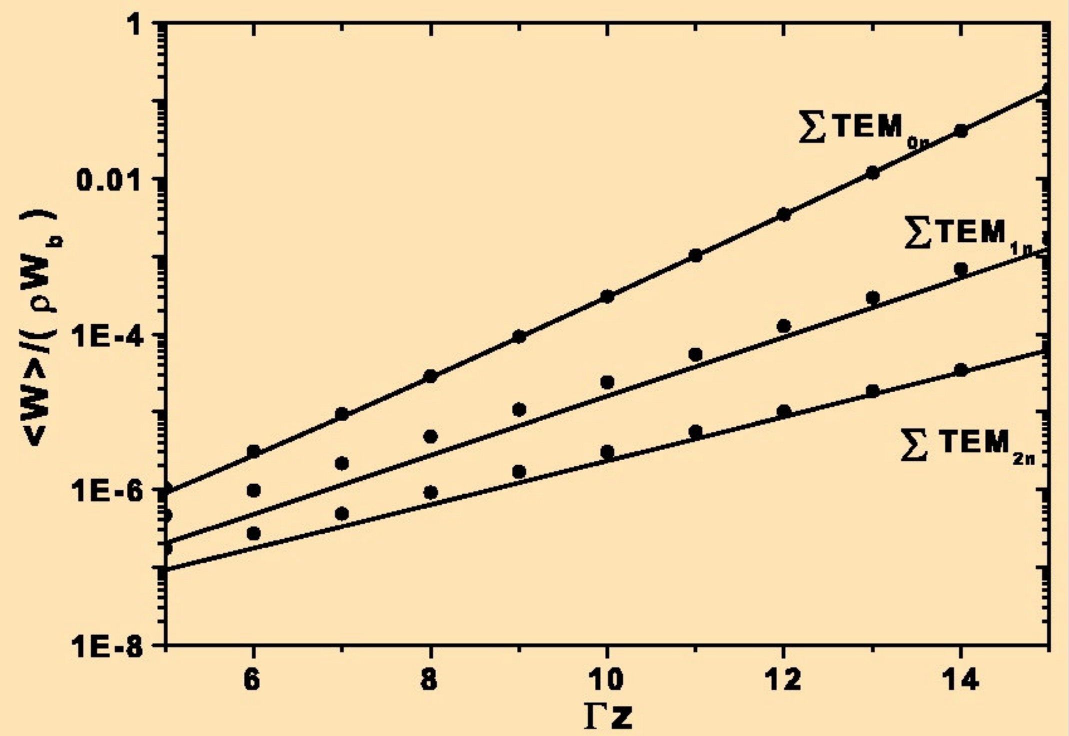
Development of Transverse Coherence

- Lowest order, axisymmetric mode strongly favored
  - less affected by diffractive losses
  - less affected by particle betatron motion (*i.e.* diffusion)
  - less affected by slippage-induced temporal averaging
  - ➢ significantly higher overall growth rate
- Expectation is LCLS will have nearly-full transverse coherence by $z/L_{SAT} \sim 0.8$
- Far-field profile generally extremely smooth
  - less contamination by spontaneous emission
  - Fundamental mode quickly dominates on-axis emission

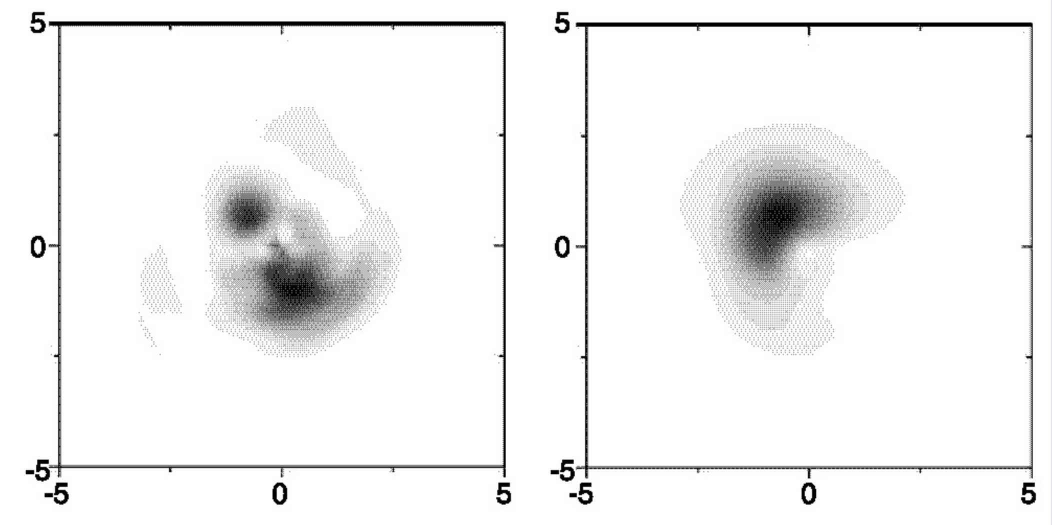
Linear FAST simulation, analytic results show contribution of high order modes

Results from Saldin *et al.*, *Opt. Comm.* 186 (2000), 1895.

- no energy spread or emittance, $L_G/Z_R=1$, 7×10^7 e- / λ_S
- 3D linearized code FAST



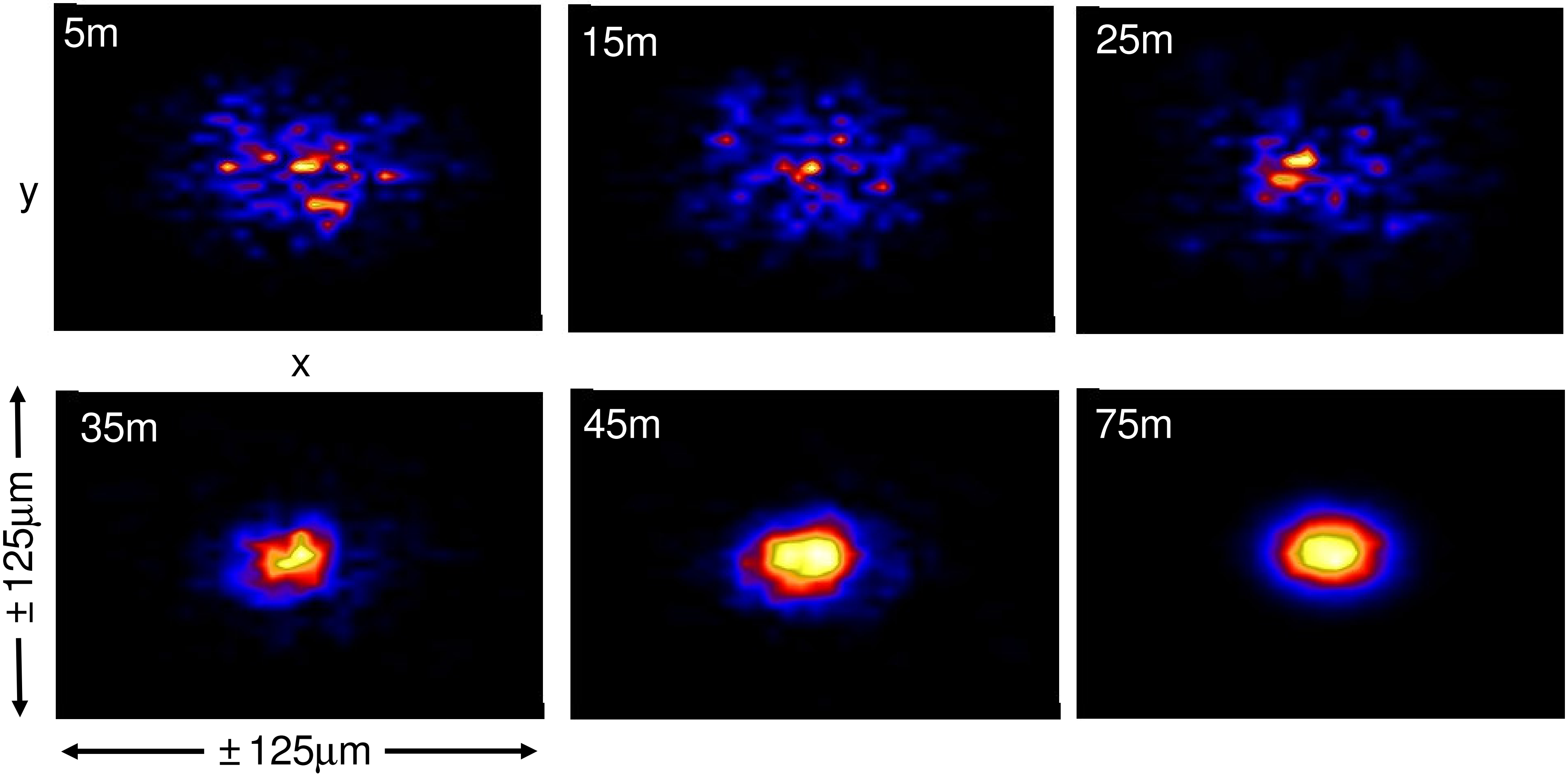
Radiation power vs *z* in gain lengths for 3 lowest azimuthal modes (each again summed over lowest 3 radial modes); lines=*theory*; dots=*simulation*



Transverse radiation profiles across 1 temporal radiation slice at $z/L_G=5$ and 10

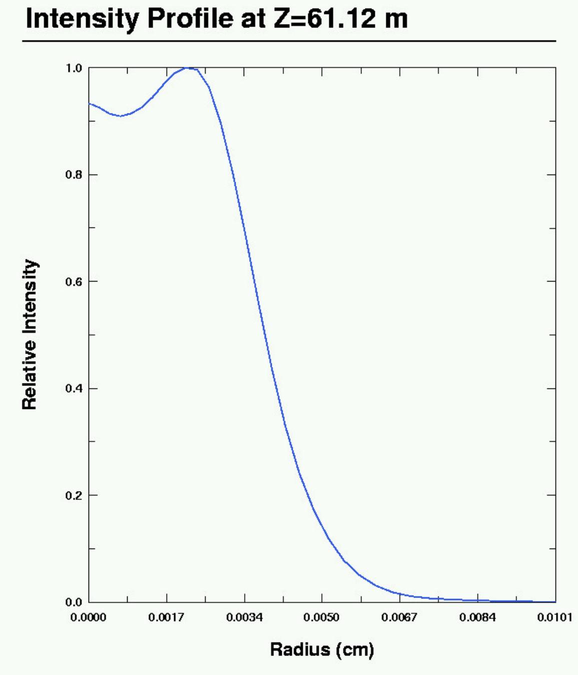
Courtesy M. Yurkov

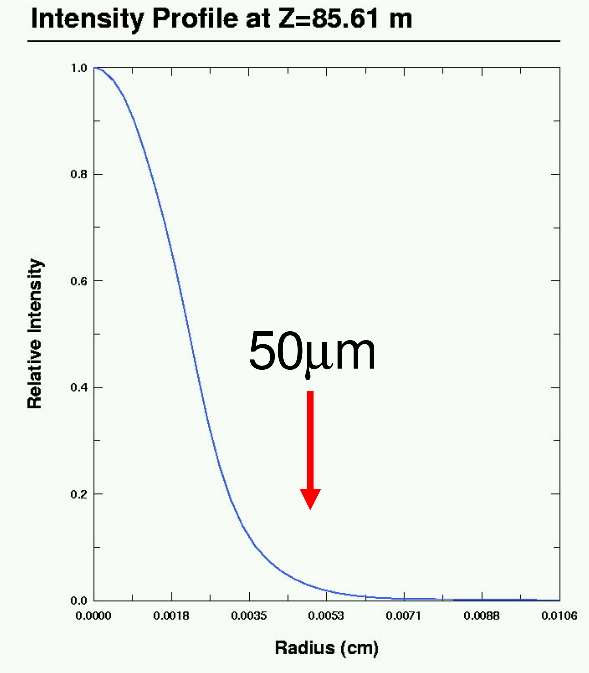
Near-Field Radiation Intensity vs. Z

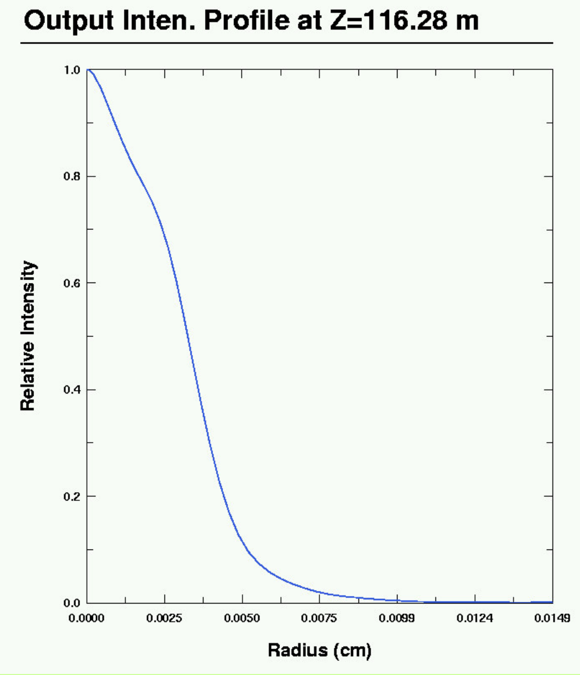


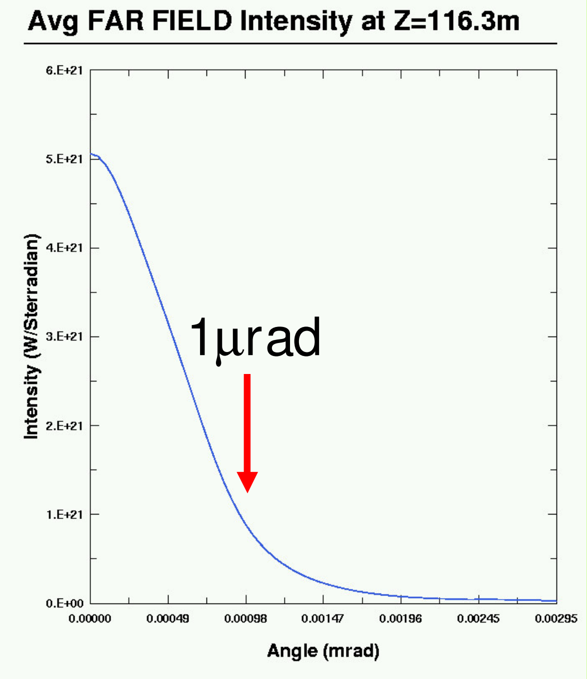
GENESIS LCLS SASE run / 2004 lattice & beam parameters / courtesy S. Reiche

Axisymmetric Intensity Profiles


Intensity Profile at Z=61.12 m

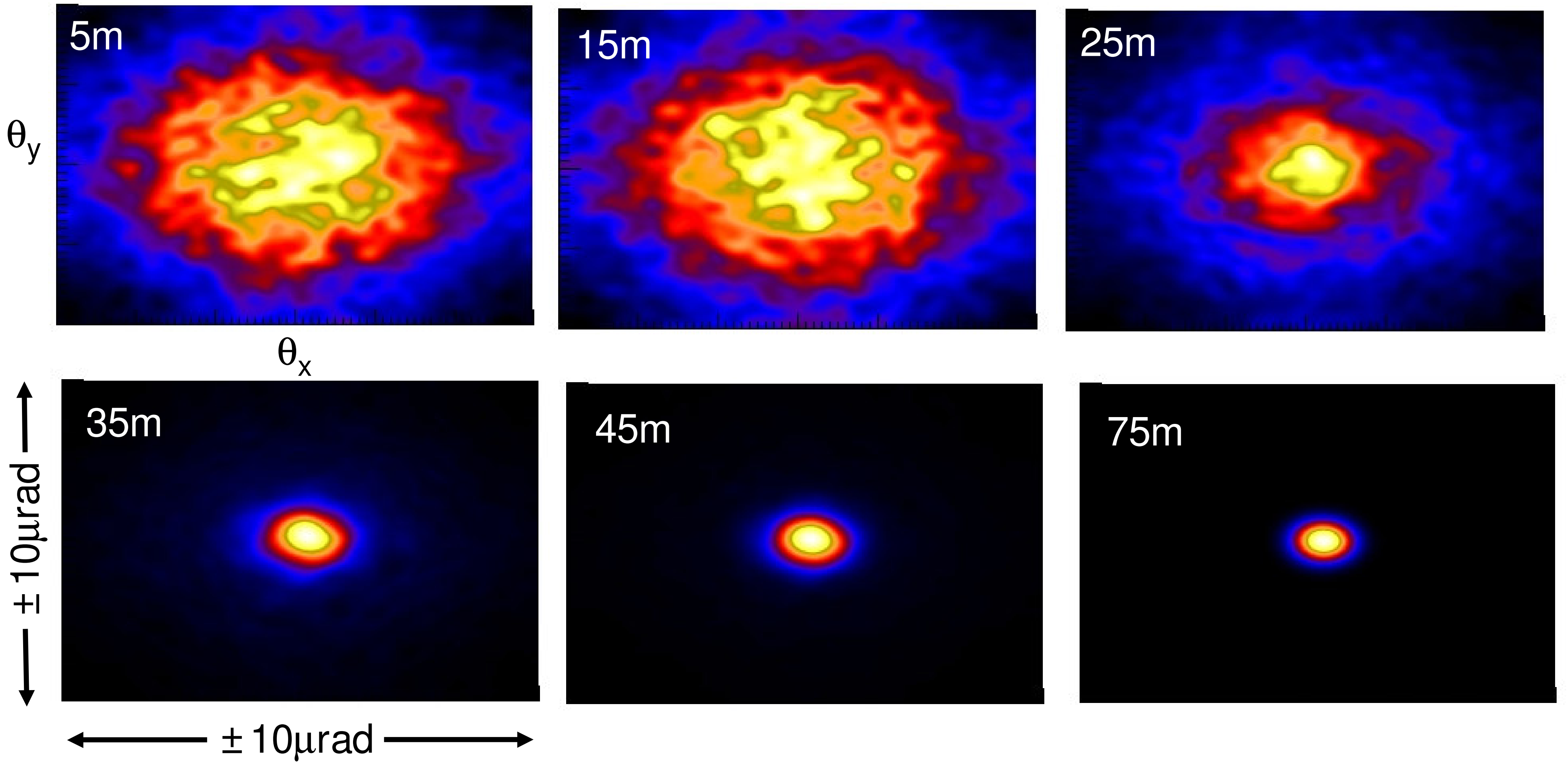

Intensity Profile at Z=85.61 m


Output Inten. Profile at Z=116.28 m


Avg FAR FIELD Intensity at Z=116.3m

GINGER LCLS S2E run;
Temporal interval = (-27,-15) fs
Saturation @z~90 m
Most radiation contained within r=50µm
Far-field mode size ~1µrad

Projected Far-Field Intensity vs. Z

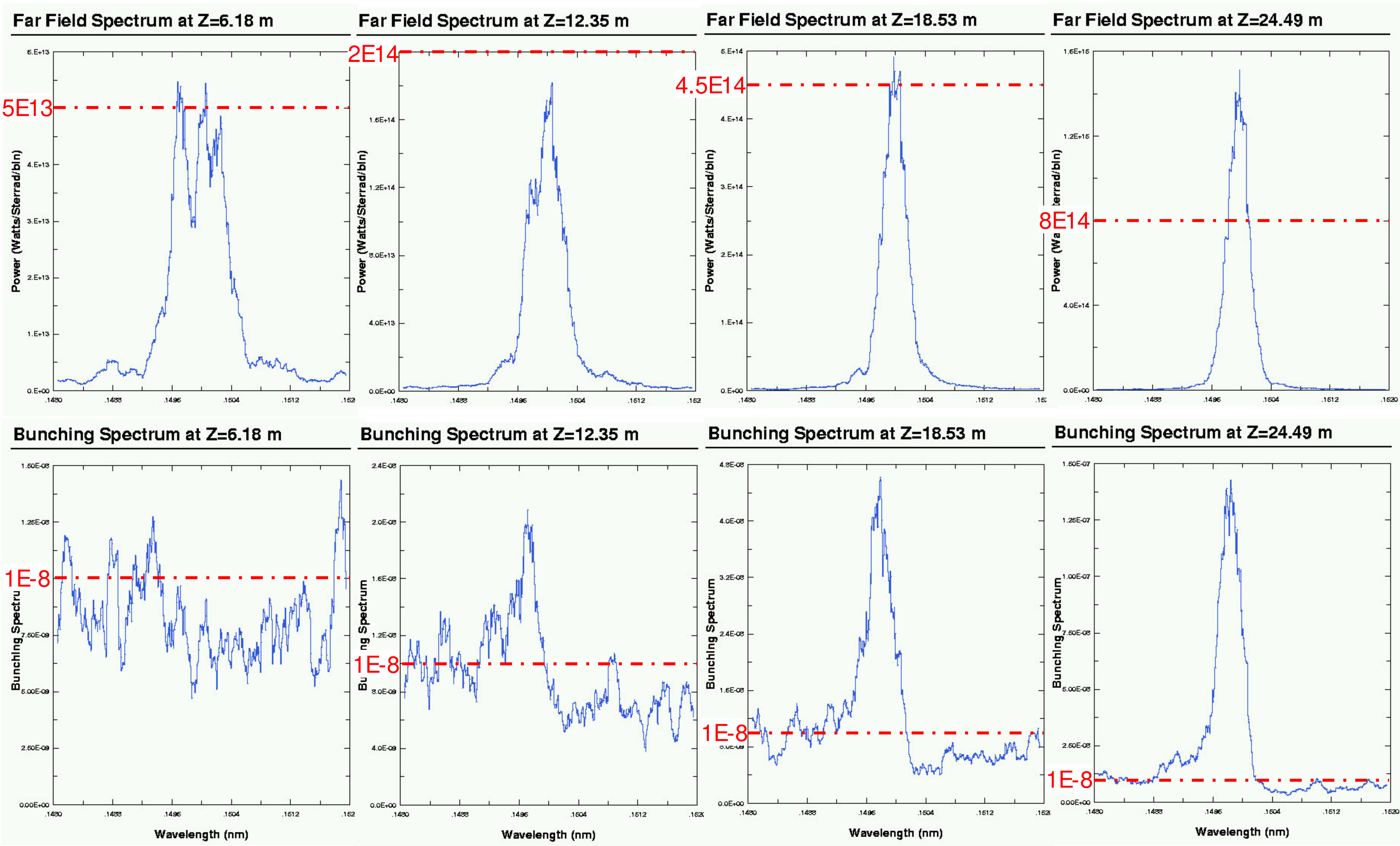


GENESIS LCLS SASE run / 2004 lattice & beam parameters / courtesy S. Reiche

CXTR from microbunching may provide useful early-z diagnostic

- Until z ≥ 25 m (~5 gain lengths), spontaneous emission (SE) typically is stronger than coherent FEL emission (esp. in near-field)
- Unlike SE, incoherent microbunching constant with *z* **=>** coherent FEL microbunching becomes obvious much more rapidly in *z* than does FEL radiation
- Spectrally-resolved coherent x-ray transition radiation (CXTR) from coherent microbunching dominates incoherent component after ~3-4 gain lengths
- A. Lumpkin (ANL) has analyzed expected CXTR, proposes to exploit off-axis emission properties to separate it spectrally from intense SE background (which off-axis is red-shifted) (see his contribution to *LCLS-TN-04-2*)

Far-Field and Microbunching Spectra vs. Z



Far Field Spectrum at Z=6.18 m

Far Field Spectrum at Z=12.35 m

Far Field Spectrum at Z=18.53 m

Far Field Spectrum at Z=24.49 m

Bunching Spectrum at Z=6.18 m

Bunching Spectrum at Z=12.35 m

Bunching Spectrum at Z=18.53 m

Bunching Spectrum at Z=24.49 m

Summary

- SASE growth with *z* is exponential
  - relative contrast to spontaneous emission increases with z
  - Growth rate, P_{SAT} , z_{SAT} , and central λ can vary along pulse
- Inverse spectral bandwidth, longitudinal and transverse coherence all increase with *z*
  - Far field radiation tends to be far “cleaner” in terms of relative contrast to spontaneous emission
  - Averaged over the full 200+ fs, the LCLS pulse will have good shot-to-shot repeatability but any 1-fs portion will have large shot-to-shot variation (see next two talks!)
- A spectrally-resolved microbunching diagnostic may be very useful in measuring coherent FEL emission at early *z*