Current-Enhanced Self-Amplified Spontaneous Emission

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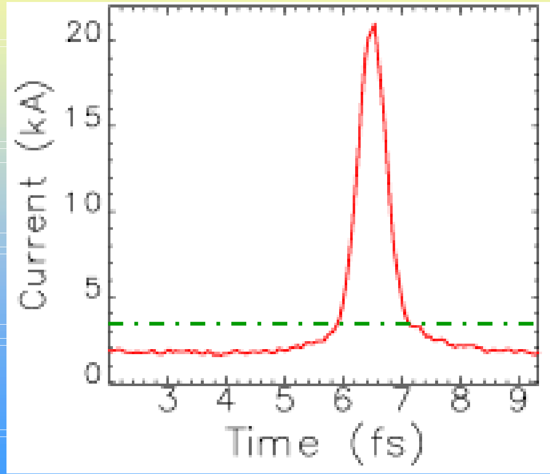
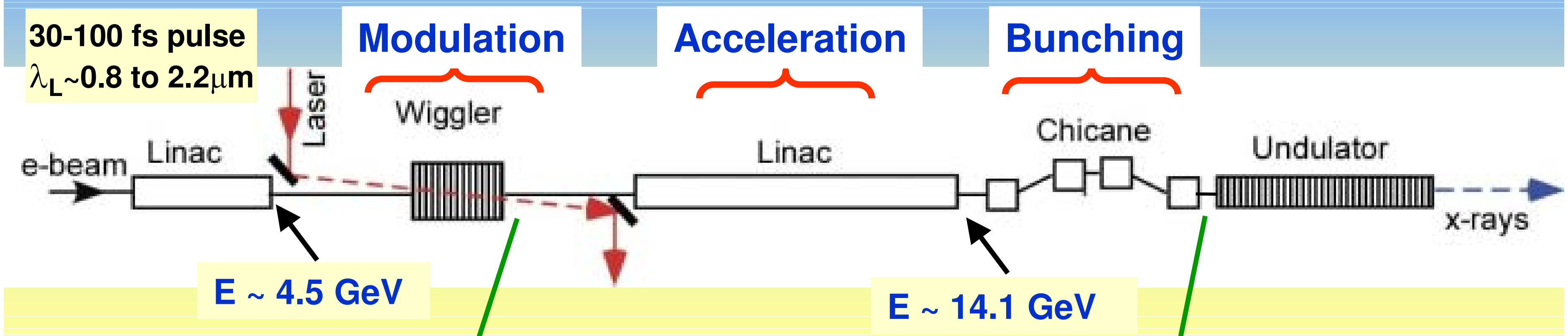
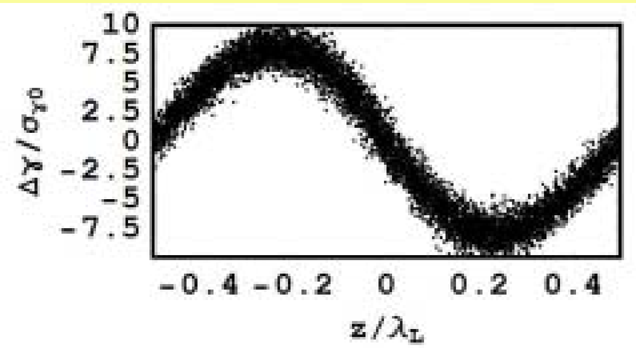


- **Benefits:** Exponential gain length reduction for XUV & X-ray FEL's, absolute temporal synchronization, control of radiation pulse envelope
- **Technique:** Exploit $\sigma_\gamma/\gamma < \rho$ to increase peak I, ρ, σ_γ; produce strong current enhancement into sub-fs, periodic spikes ($\langle I_B \rangle$ unchanged)
- **How:** Use optical laser + short wiggler at moderate γ to modulate $\gamma(t)$, followed by dispersive element at large γ to produce I(t)
- **Concerns:** Degradation from unwanted collective effects in accelerator and undulator

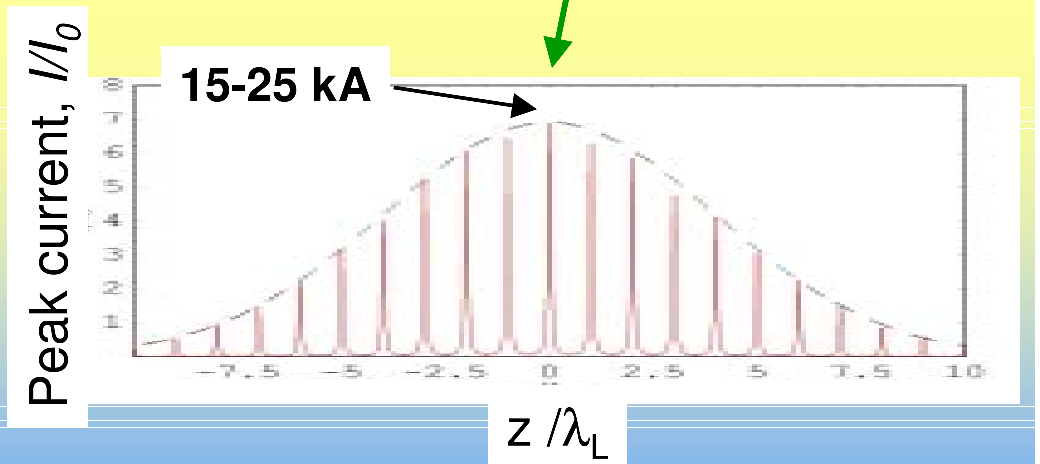
Stanford Linear Accelerator Center
Stanford Synchrotron Radiation Laboratory

ESASE: "nuts and bolts"





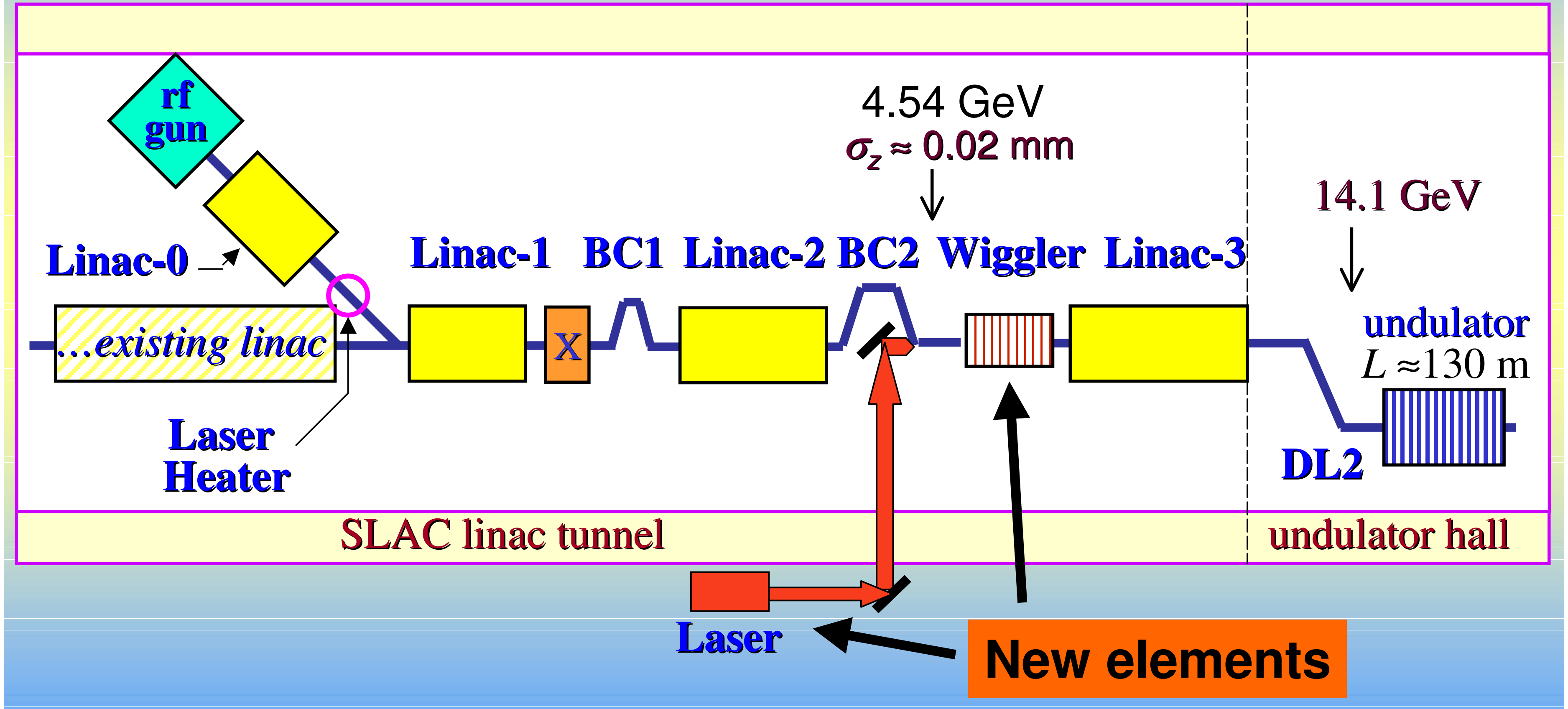
One optical cycle



- Laser peak power ~ 10 GW ("easy")
- Short wiggler, ~ 10 periods

Electron beam after dispersive bunching

A schematic of the LCLS with ESASE

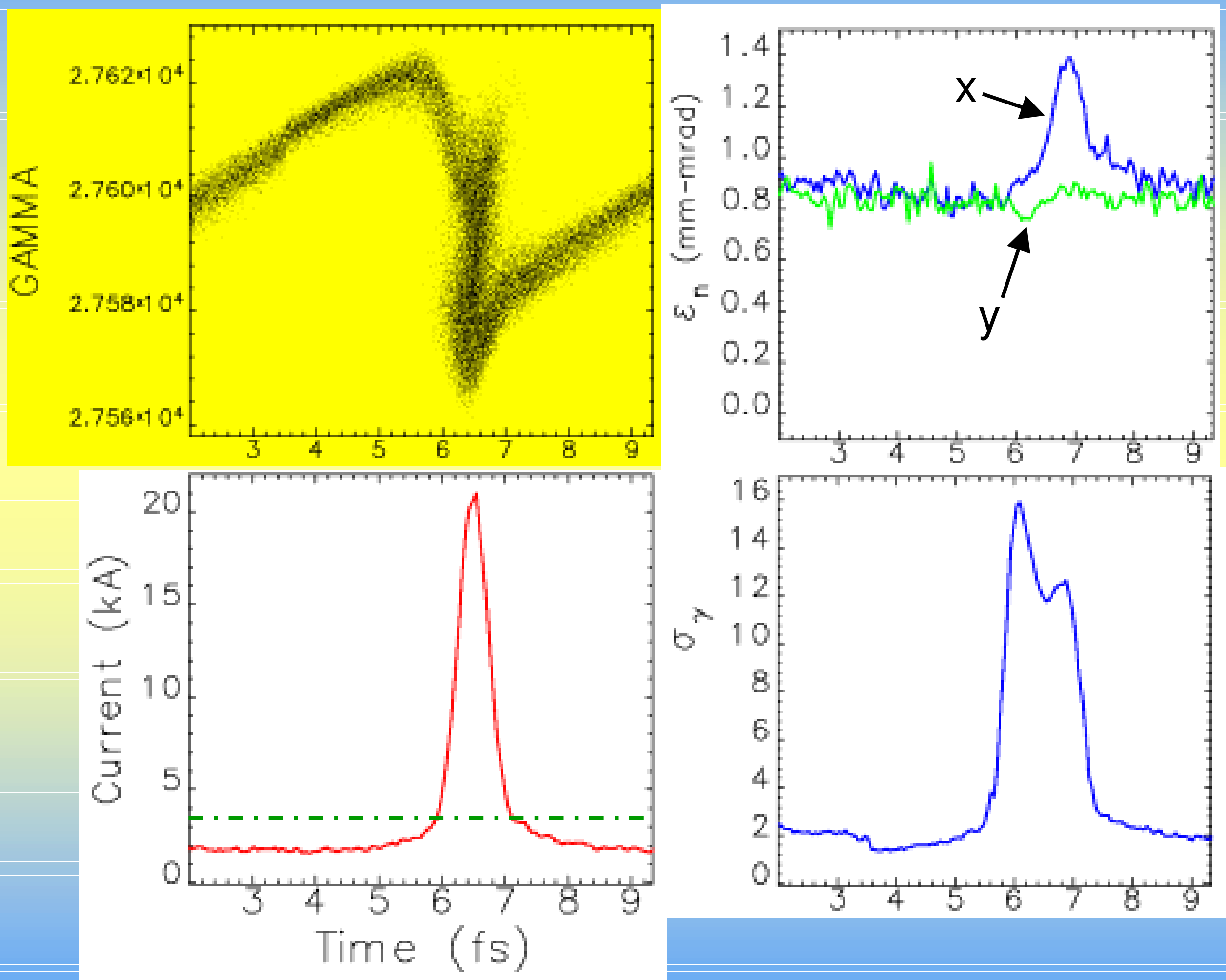


Longitudinal properties of a single spike

Electron beam phase space after chromatic dispersion section (*ELEGANT* results)

$B = \Delta\gamma/\sigma_{\gamma 0} = 5$

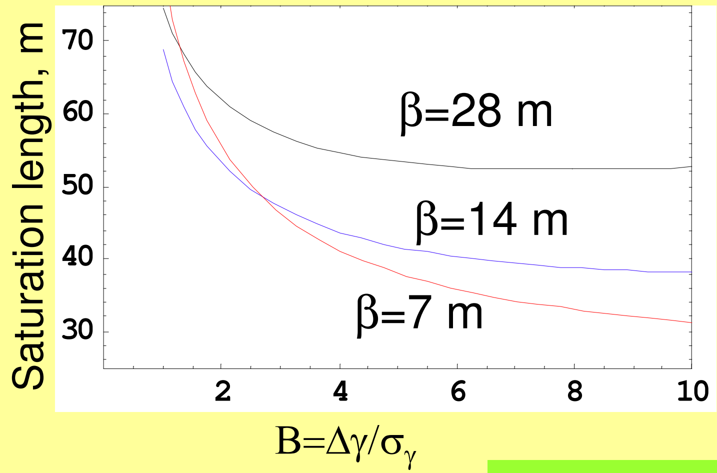
$\lambda_L = 2.2\mu m$



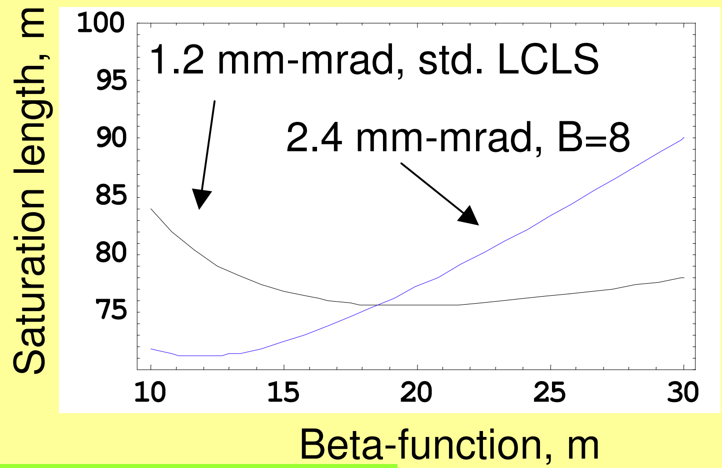
Effective width $\Delta z_0 \cong \lambda_L / 2B$ should be > slippage ~ $\lambda_r N_u$ ~ $1.2\ \lambda_r/\rho$ at $z=L_{sat}$

Potential improvements from ESASE technique

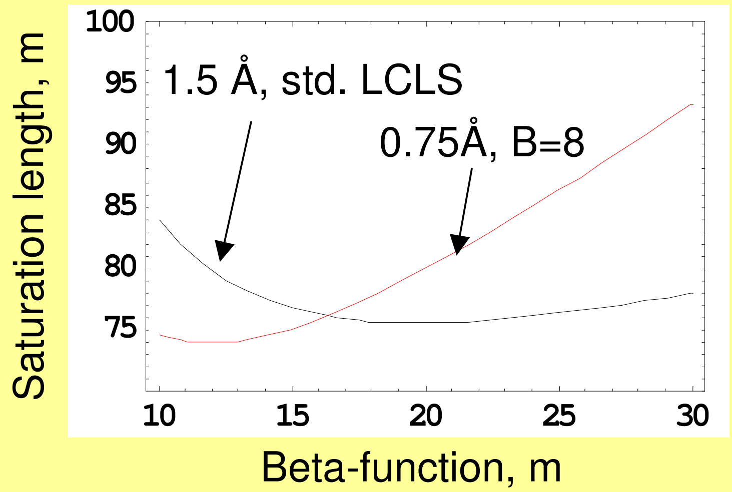
Shorter gain/saturation length



Allows larger emittances



Access to shorter wavelengths



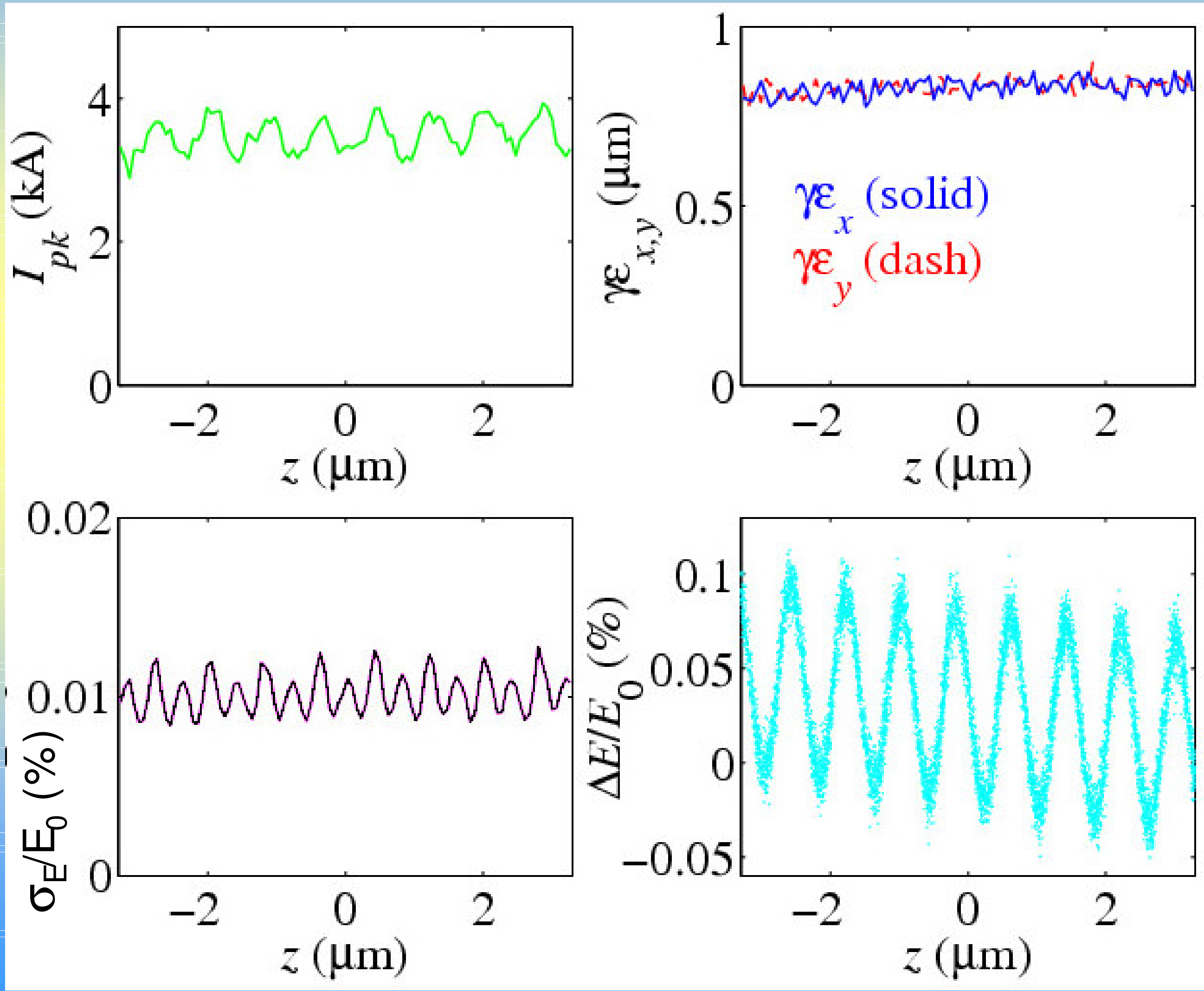
Analytic results using M. Xie fitting formula

No slippage or other temporal variation effects

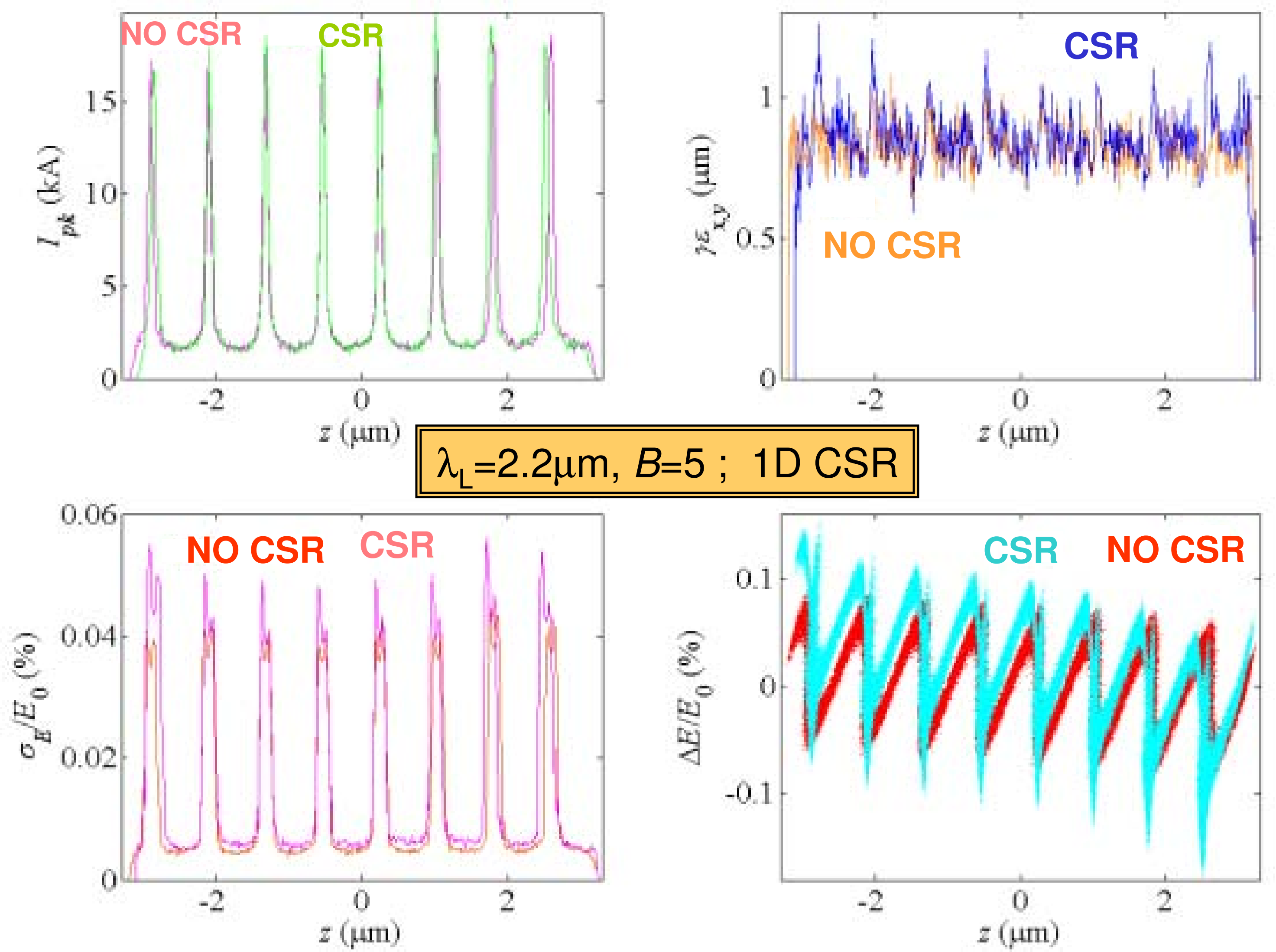
(This is probably as good as it can get!)

"Start-to-End" simulations: Beam properties at linac exit (14.4 GeV) --- *ELEGANT*

- Macroparticles imported from Parmela simulation
- Linac simulation:
  - λ_L=2.2μm, *B*=5 for laser modulator
  - includes energy spread induced by laser heater
  - includes wakes & CSR effects
  - does not include space charge effects
- Results show some current modulation, increase in σ_E
  - emittance appears unchanged (0.8 mm-mrad)



Post-dispersion, at undulator entrance



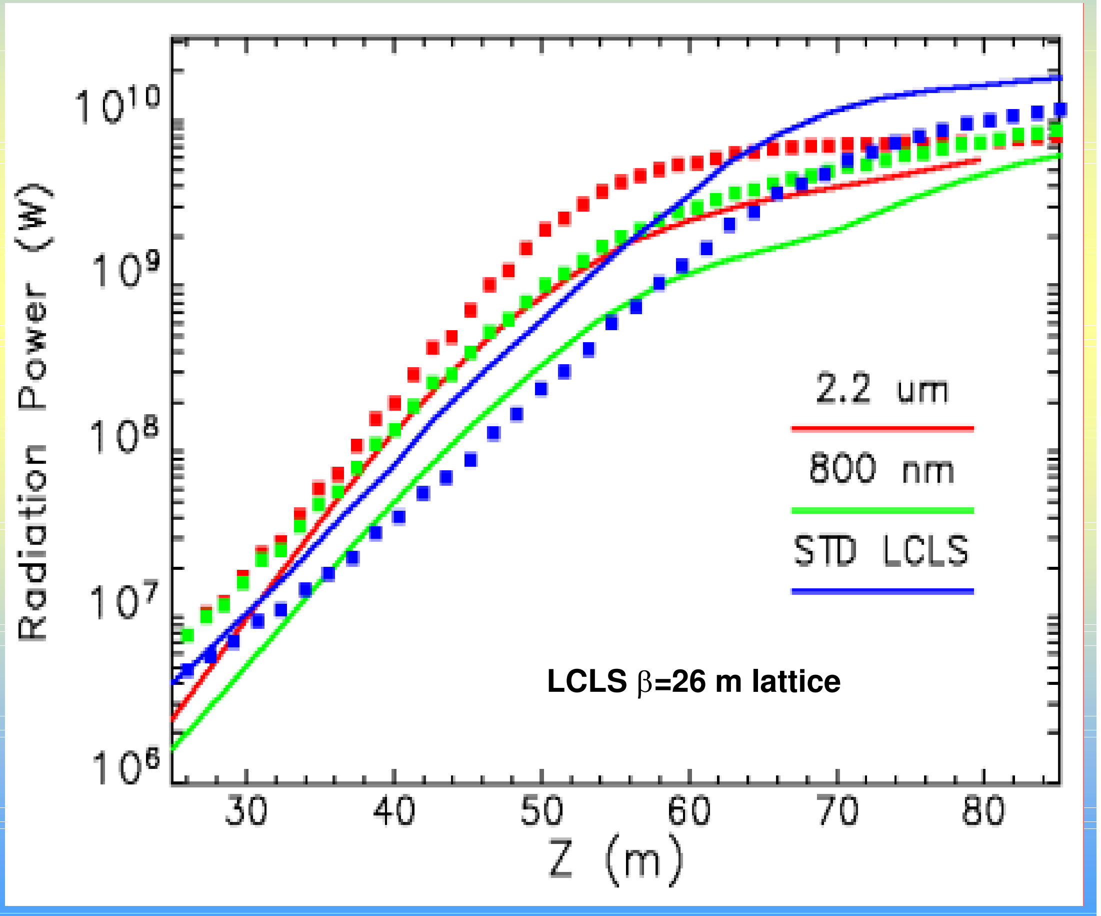
λ_L=2.2μm, *B*=5 ; 1D CSR

CSR effects look non-trivial but <u>manageable</u> (suppression likely due to large R51)

FEL simulation results for <β> = 26 m (achievable using present hardware)

"Start-to-End" simulations

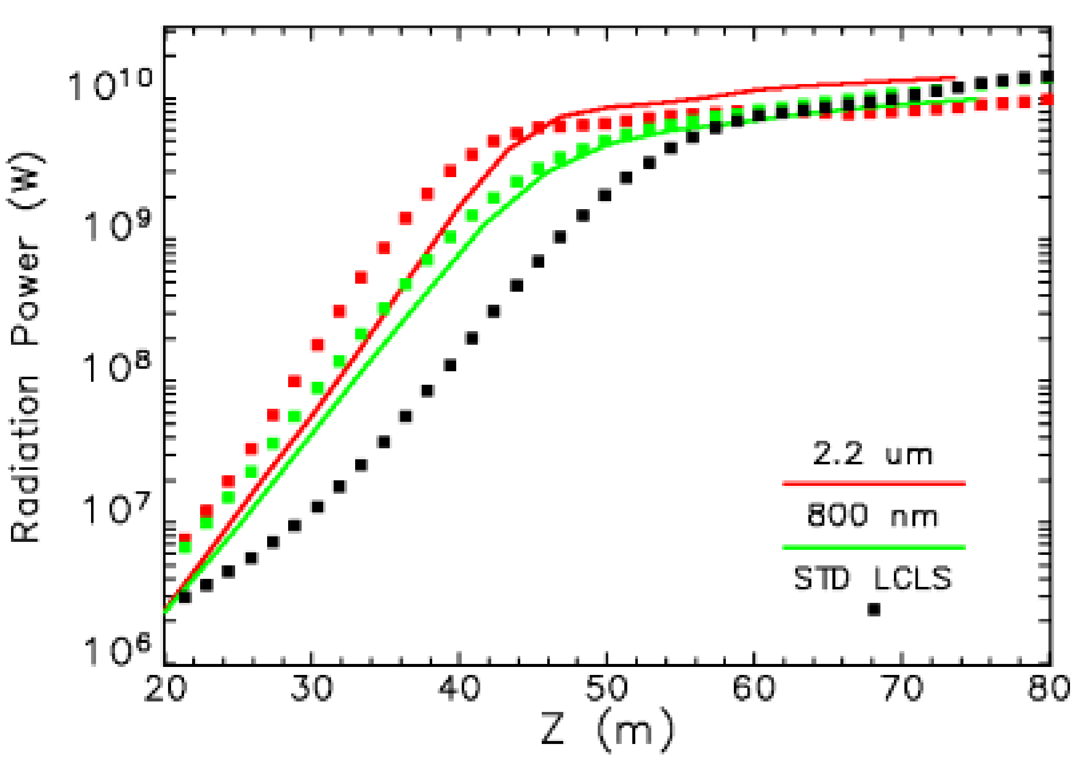
- *PARMELA* -> *ELEGANT* -> *GINGER* (lines) / *GENESIS* (boxes)
  - –Full 6D phase space reconstruction/sampling
- P_L~10 GW, Δγ -> ±14, *B*=5
- Standard case (0.8 mm-mrad) tracked through same accelerator configuration sans laser modulation
- ESASE cases saturate ~10 m earlier but at 2X <P> reduction
  - – <10X power contrast at all z
- <β> not optimal for ESASE



FEL simulation results for <β> = 12m
(requires LCLS hardware modification)

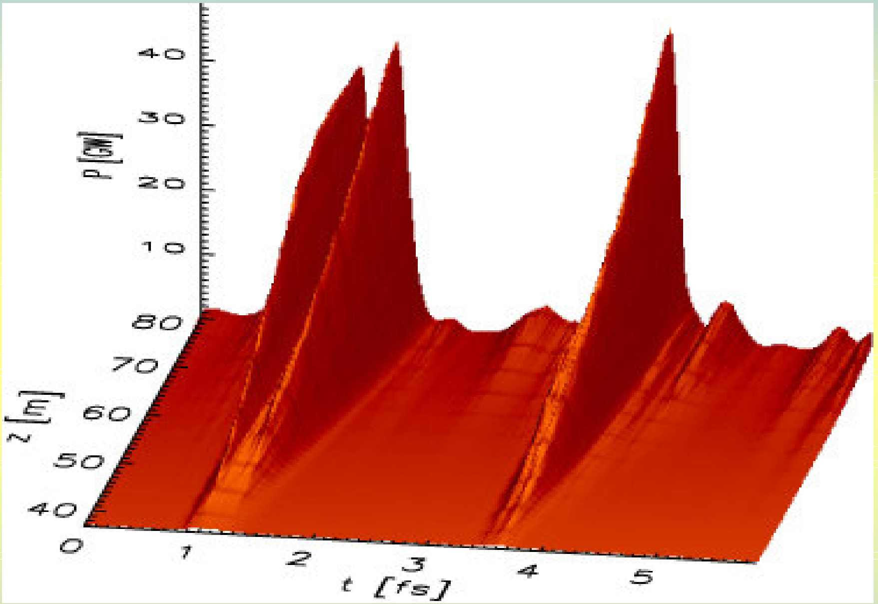
"Start-to-End" simulations

- 3-m FODO lattice period
  - drifts+quads occupy 2 * 0.24 m
  - not compatible with current LCLS lattice design
- Standard case performs well at this β due to low emittance (0.8 mm-mrad)
- ESASE cases saturate by 50 m
  - ~8-20X power contrast
  - sufficient to dominate SASE radiation from unmodulated portion of e-beam pulse

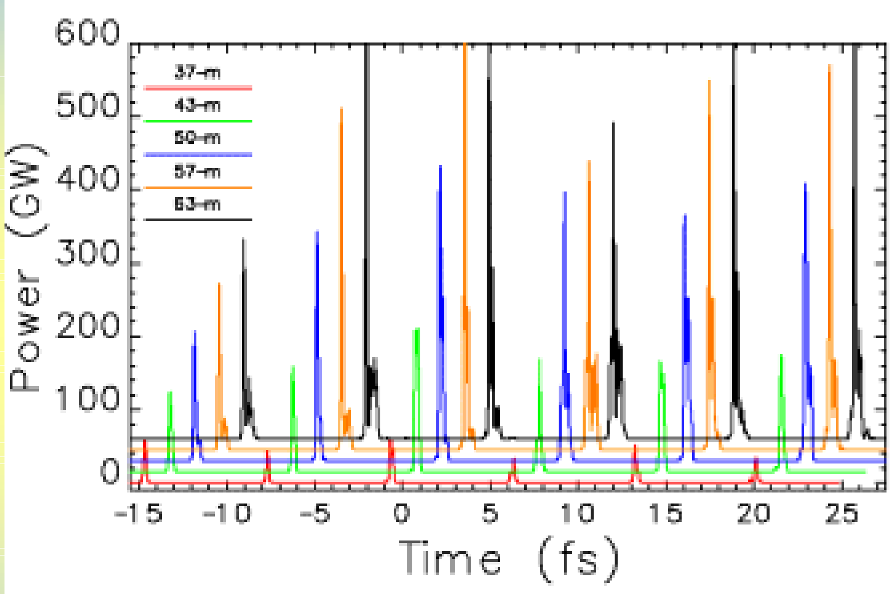


X-ray radiation from individual ESASE spikes

<β>=26 m, λ_L=800 nm; *GENESIS*



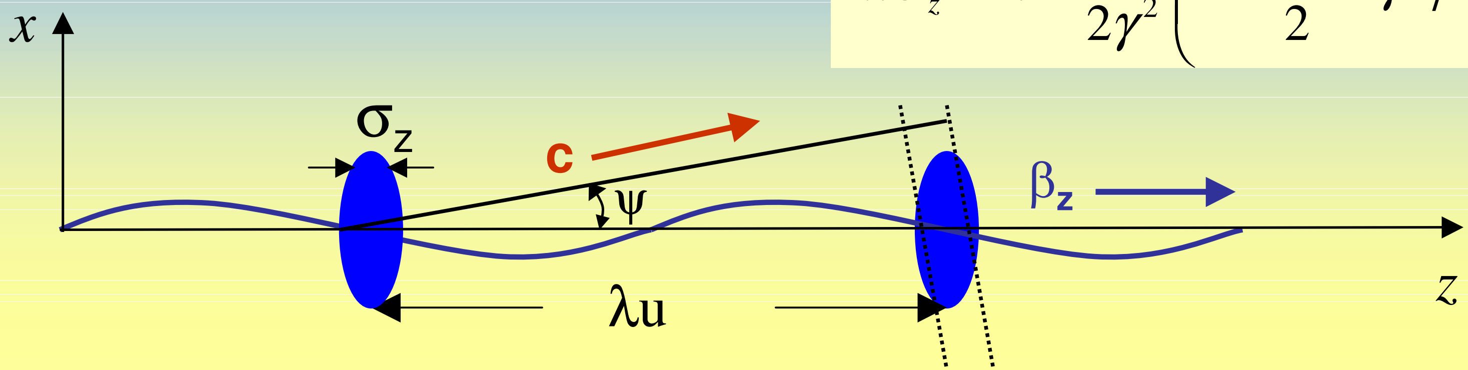
<β>=12 m, λ_L=2.2 μm; *GINGER*



- Each radiation spike is nearly temporally coherent and transform-limited
- Carrier phase for x-ray wave is *random* from spike to spike
- Pulse durations < 200 attoseconds may be possible with 800-nm laser

Coherent off-axis radiation in the undulator

$$2\pi\sigma_z \sim \lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\psi^2\right) \approx \frac{\lambda_u}{2}\psi^2$$



- Radiation field for $\lambda \sim 2\pi\sigma_z$ in the undulator is resonant at angle ψ with beam velocity

- 1D "wake" (E. Saldin *et al.*, *NIM A* **417**, 158 [1998])

For I_{peak} = 23 kA, and σ_z = 30 nm, we find induced σ_γ/γ = 0.15% at L_u ~ 30 m (1D!!!)

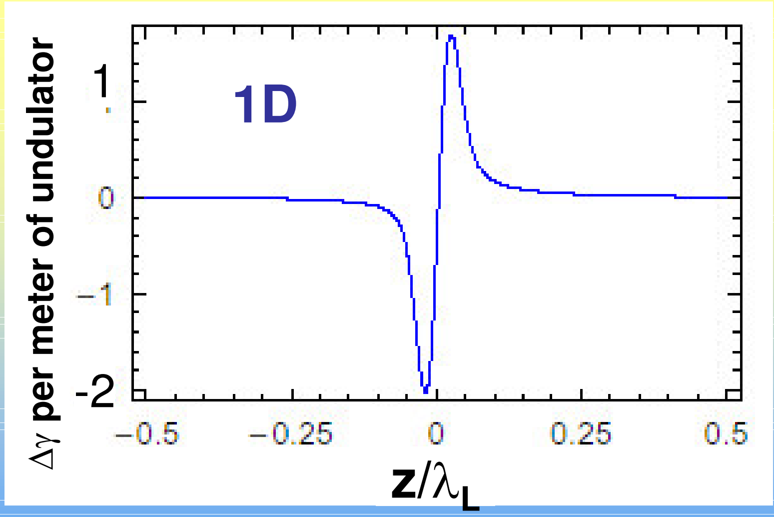
Suppression of off-axis CUR due to non-zero transverse beam size

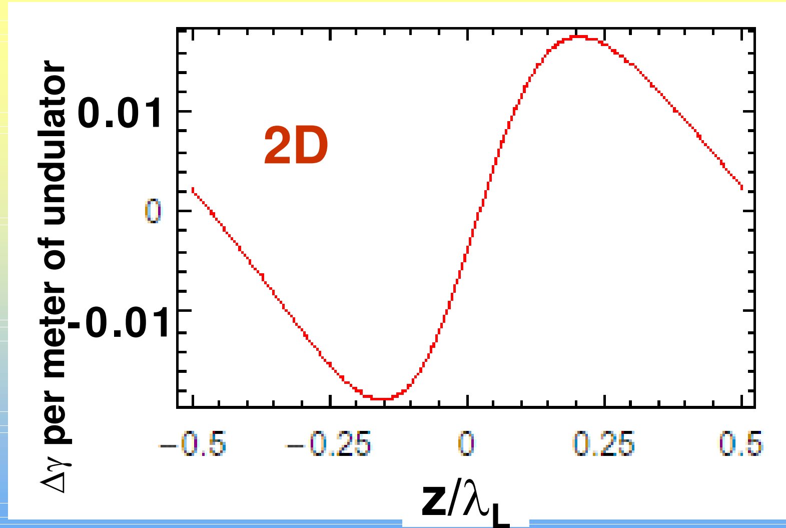
Coherent radiation: $P(\sigma_x) = N^2 \int dk \frac{dP_1}{dk} f(k)$

Bunch form factor : $f(k) = e^{-(k\psi\sigma_x)^2 - k^2\sigma_z^2}$

angle $\psi \ll 1$
$\psi^2 = 4\pi / k\lambda_u$

Energy loss distribution along the current spike

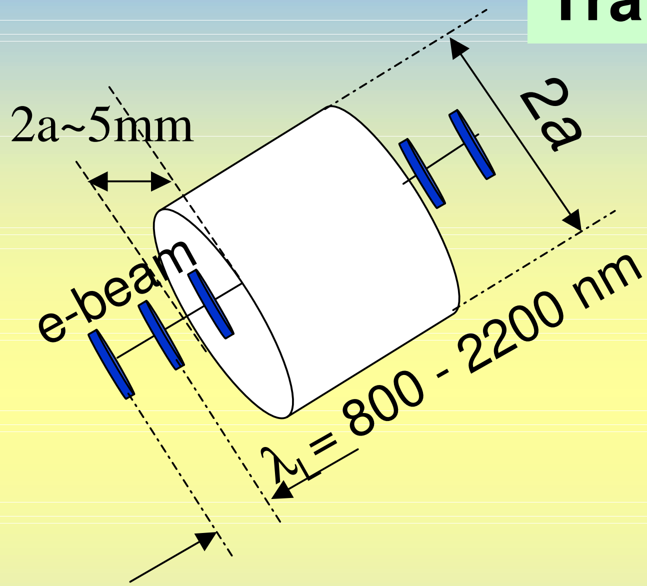


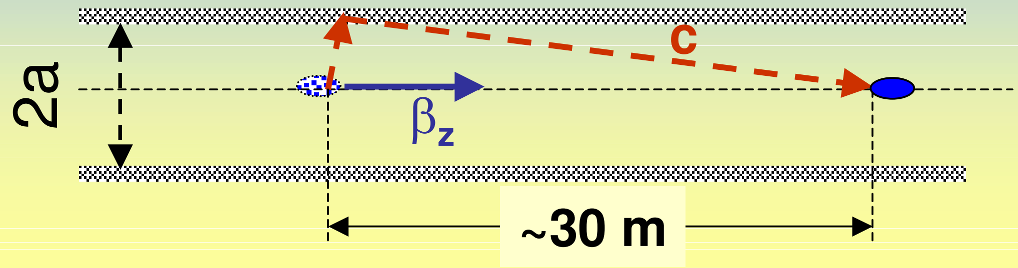


➡ **A consideration for choice of focusing strength!**

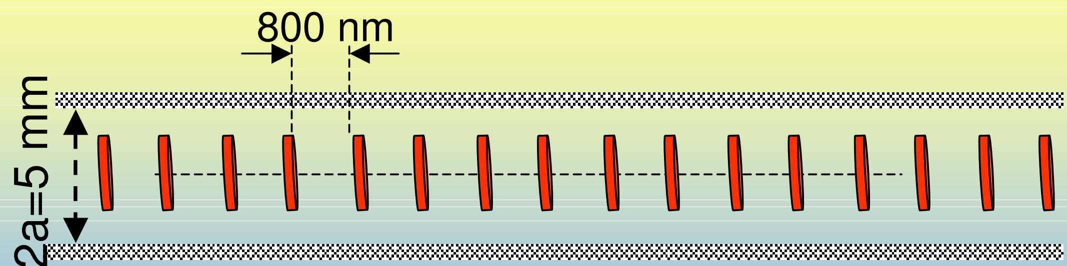
Resistive wall wake field

Transient wake field effect





Single bunch catch-up distance ~ $a^2/2\sigma_{spike}$



Steady state wake

For λ_L=800 nm and *B=5*, peak transverse fields at wall are only ~1.3X greater than unmodulated case

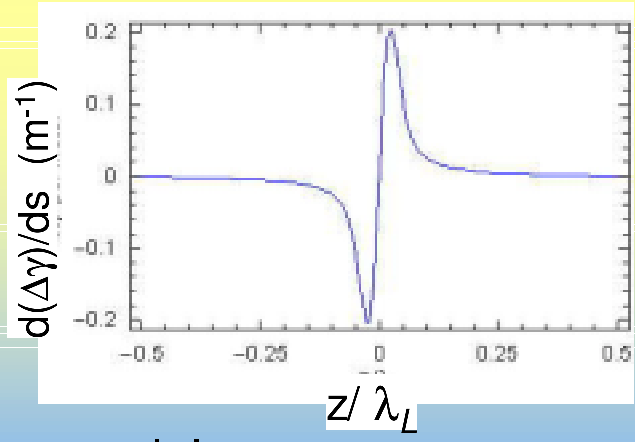
Expected induced $\delta E/E_0 < 2 \times 10^{-4}$ at z=50 m

Longitudinal Space Charge Effects

- With $k_n = nk_L$, $k_n\sigma_x/\gamma << 1$ (pencil beam limit), and $k_n a/\gamma >> 1$ (free space limit), space charge impedance is

$$Z(k_n) \approx i\frac{Z_0}{4\pi}\frac{k_n}{\gamma^2}\left(1 + 2\ln\frac{\gamma}{k(\sigma_x + \sigma_y)}\right)$$

- For <I>=3.4kA, B=5, λ_L=2.2μm, σ_x=33μm, $d(\Delta\gamma)/ds$ ~ 0.05 m^{-1}
  - Increases to 0.2 m^{-1} for B=8, λ_L=0.8μm



- Possibly problematic for 200-m drift between DL2 and undulator entrance
  – Current bunching can be delayed to just before undulator
- Energy spread induced by space charge in undulator < spike σ_γ

Summary of Possible ESASE Benefits

1) Shorter gain length, earlier saturation, very high peak power, and good contrast (for $\langle\beta\rangle \leq 12$ m) in pulse output energy

2) Control of x-ray pulse duration via laser pulse shaping
=> possibility for solitary ~100 attosecond x-ray pulse

3) Each spike is nearly temporally coherent, with a bandwidth ~ transform-limited;
but random carrier phase from spike to spike

4) Absolute synchronization between modulating laser pulse and output x-ray pulse => pump-probe expts.

5) Possibility for
=> relaxed emittance requirement
=> shorter x-ray wavelengths

Further optimization of ESASE for LCLS is likely (low Q?)

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- M. Borland for support and improvements to *ELEGANT*
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