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Theory and Simulation of CSR Microbunching in Bunch Compressors

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Introduction

• X-ray FELs require very bright e-beams:
low-emittance (~1 μm), high peak current (~ a few kA)

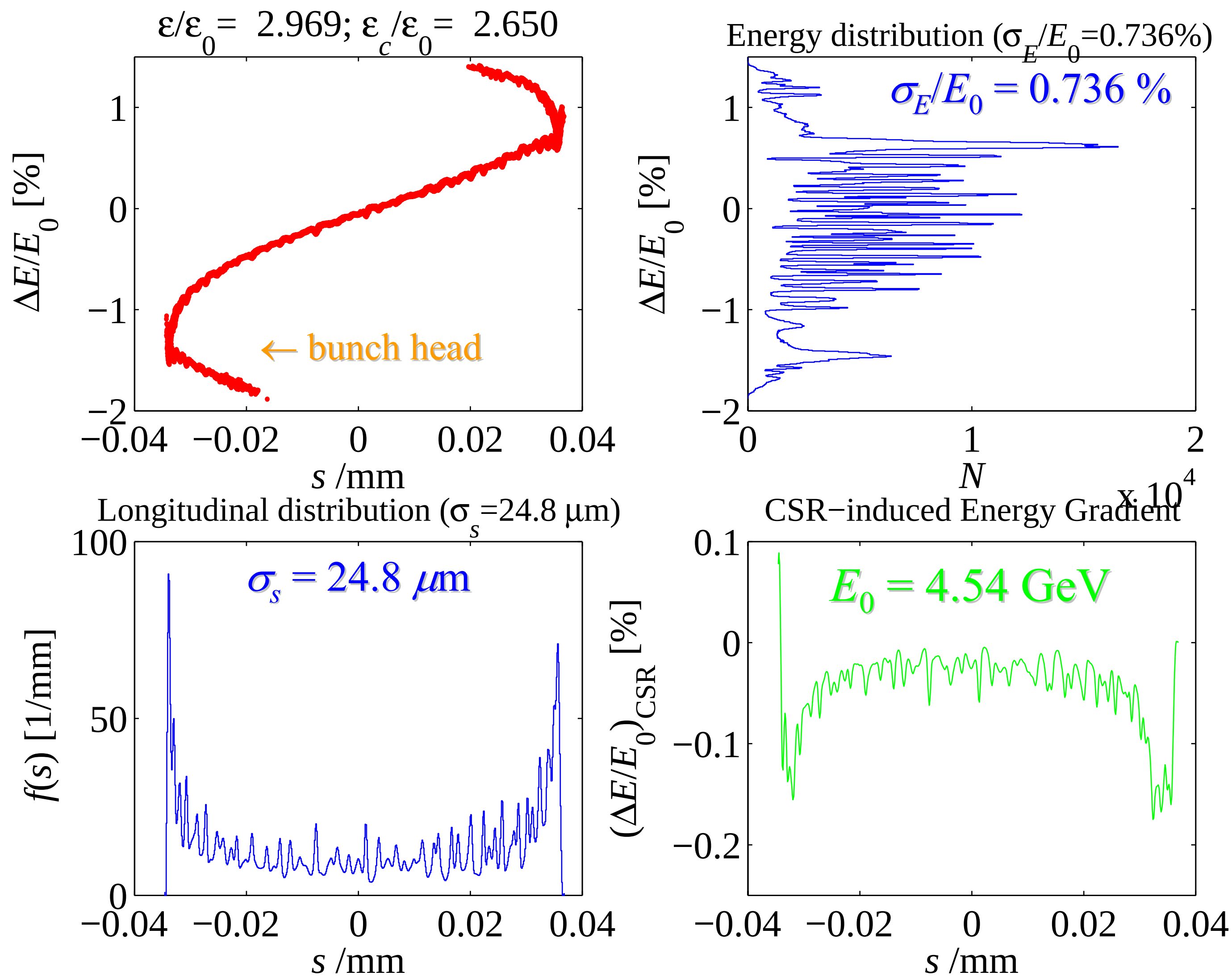
• PC-RF guns: low-emittance, low current (~100 A)

• Bunch length compression (4 ps→100 fs,100 A→4 kA), must not degrade the emittance

• CSR effects in compressor chicanes very challenging!

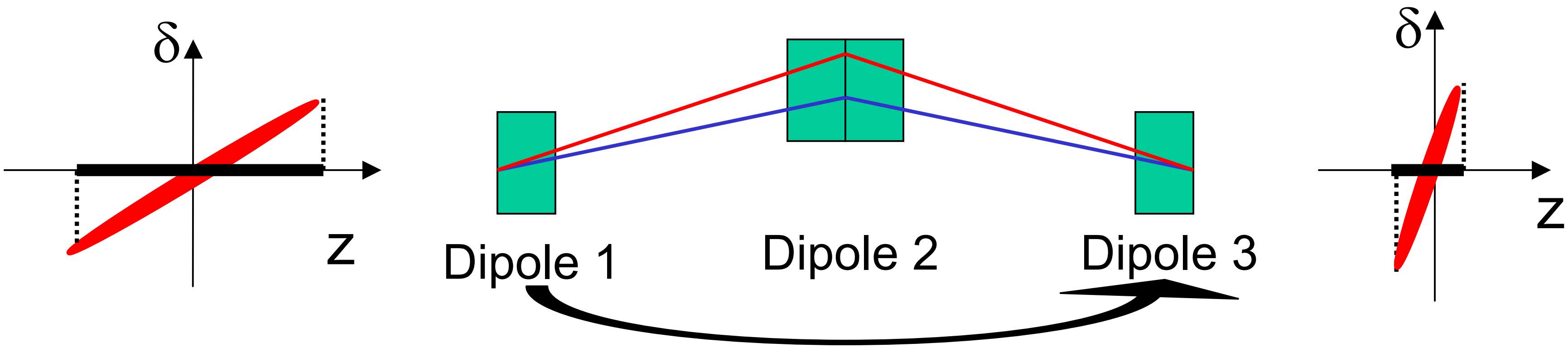
• Recently, a CSR microbunching instability is found by start-to-end LCLS simulations (Borland), could potentially corrupt the sliced emittance and energy spread

LCLS Distribution After BC2 Chicane



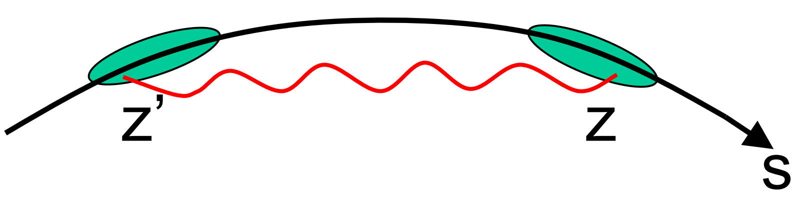
Compressor and CSR

chirped beam ⇨ path length difference ⇨ compressed beam



$\Delta z = R_{56}\ \Delta\delta$

- Radiation from bunch tail catch up the head, increase energy spread and emittance



- CSR "wake" W(z-z') or impedance Z(k) ($k = 2\pi/\lambda$) (Derbenev et al., Murphy et al.)

CSR Microbunching

- CSR emitted from sub-bunch structures for wavelengths $\lambda << \sigma_z$ interacts back to the bunch, leading to a microbunching instability

(similar to microwave instability in a ring)

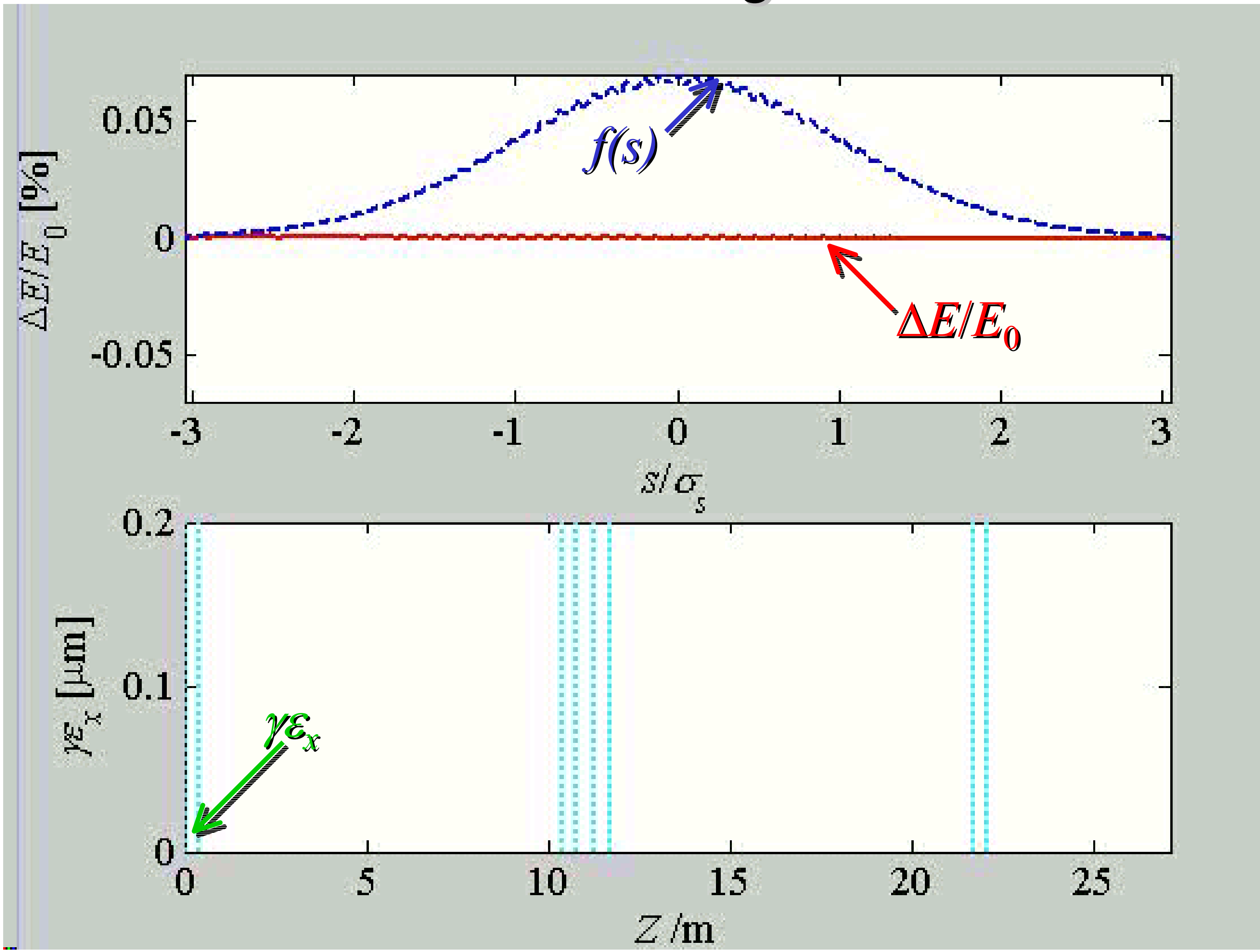
density modulation at λ

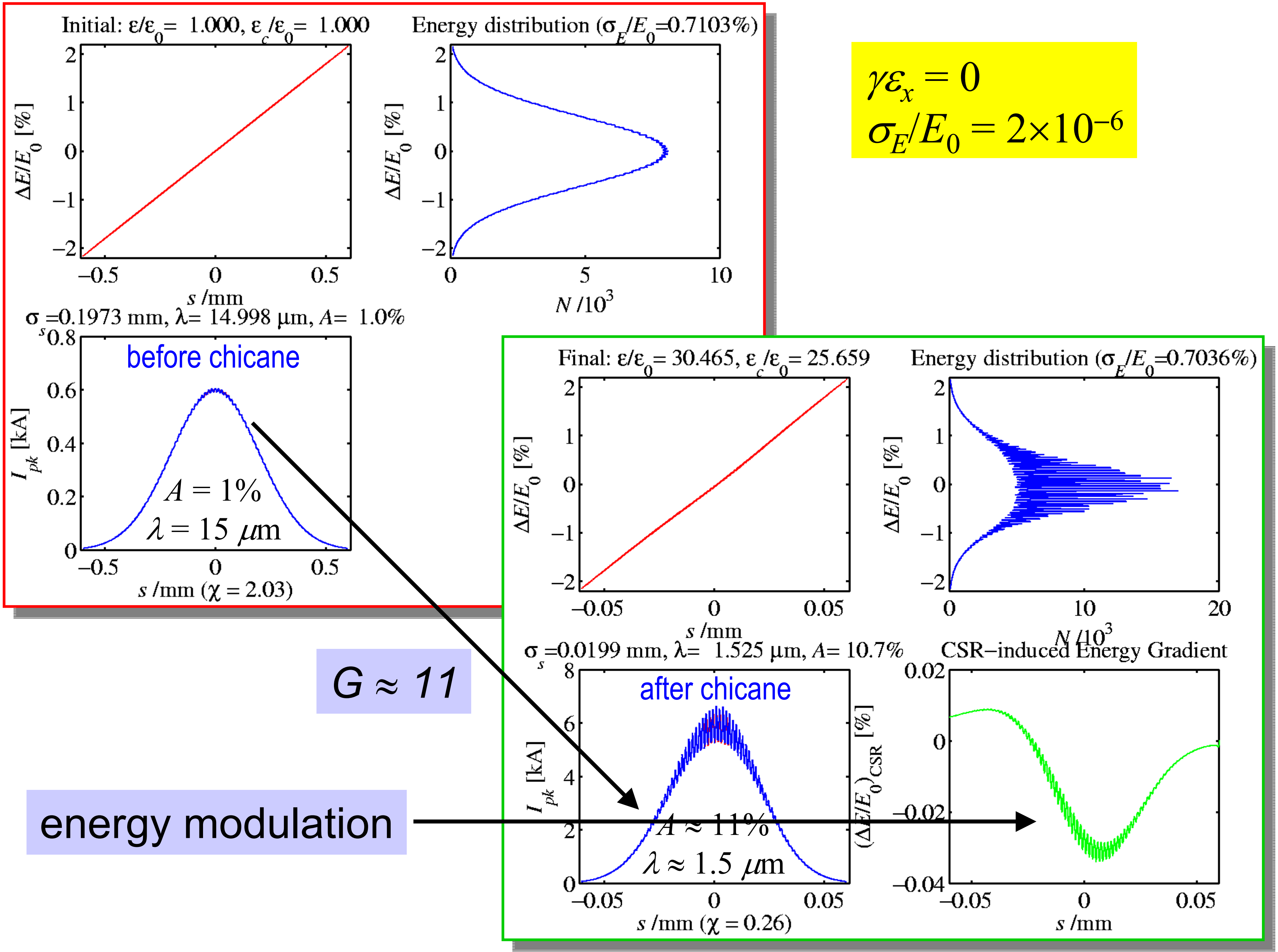
R56 CSR impedance

energy modulation at λ

- This process can be initiated by either density or energy modulation

CSR Microbunching Simulation





Initial: ε/ε0= 1.000, εc/ε0= 1.000
Energy distribution (σE/E0=0.7103%)
ΔE/E0 [%]
s /mm
N /10^3
σs=0.1973 mm, λ= 14.998 μm, A= 1.0%
before chicane
Ipk [kA]
A = 1%
λ = 15 μm
s /mm (χ = 2.03)
γεx = 0
σE/E0 = 2×10^−6
Final: ε/ε0= 30.465, εc/ε0= 25.659
Energy distribution (σE/E0=0.7036%)
σs=0.0199 mm, λ= 1.525 μm, A= 10.7%
CSR−induced Energy Gradient
after chicane
A ≈ 11%
λ ≈ 1.5 μm
s /mm (χ = 0.26)
(ΔE/E0)CSR [%]
G ≈ 11
energy modulation

Theory

- Define a bunching parameter b at modulation wavelength $\lambda = 2\pi/k$ (fourier decomposes the current)

- Linear evolution of b(k;s) can be described by an integral equation (Heifets et al.; Huang&Kim)

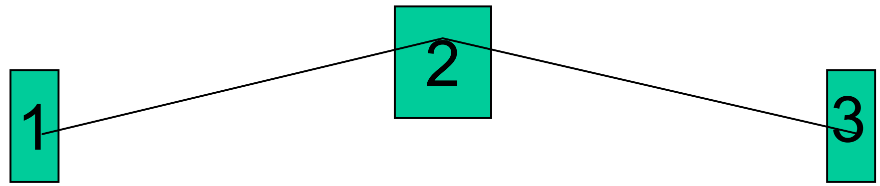
$$b(k(s);s) = b_0(k(s);s) + \int_0^s d\tau K(\tau,s) b(k(\tau);\tau)$$

$$\text{kernel } K(\tau,s) = ik(s)R_{56}(\tau \to s)\frac{I(\tau)}{\gamma I_A}Z(k(\tau)) \times \underbrace{\exp(\ldots\varepsilon,\sigma_\delta\ldots)}_{\text{Landau damping}}$$

- For arbitrary initial condition (density and/or energy modulation), this determines the final microbunching

Staged Amplification

- Typical chicane



dipole separation ΔL >> dipole length L_b

$$R_{56}(\tau \to s) \sim \begin{cases} \dfrac{L_b^3}{\rho^2} & \text{within the same dipole} \\ \dfrac{\Delta L\, L_b^2}{\rho^2} & \text{from one dipole to another} \end{cases}$$

- Ignore the induced bunching from energy modulation in the same dipole (Saldin et al.)
- Consider staged amplification from dipole to dipole by setting $K(s',s)=O(L_b/\Delta L)=0$ if $s-s' < \Delta L$

Iterative Solution

- Integral equation can be solved by two iterations

$$b(k;s) = b_0(k;s) + \overbrace{\underbrace{\int_0^s ds' K(s',s) b_0(k';s')}_{\text{one-stage amplification}}}^{I_f(1\to 3) + I_f(2\to 3)}$$

dominant in low-gain

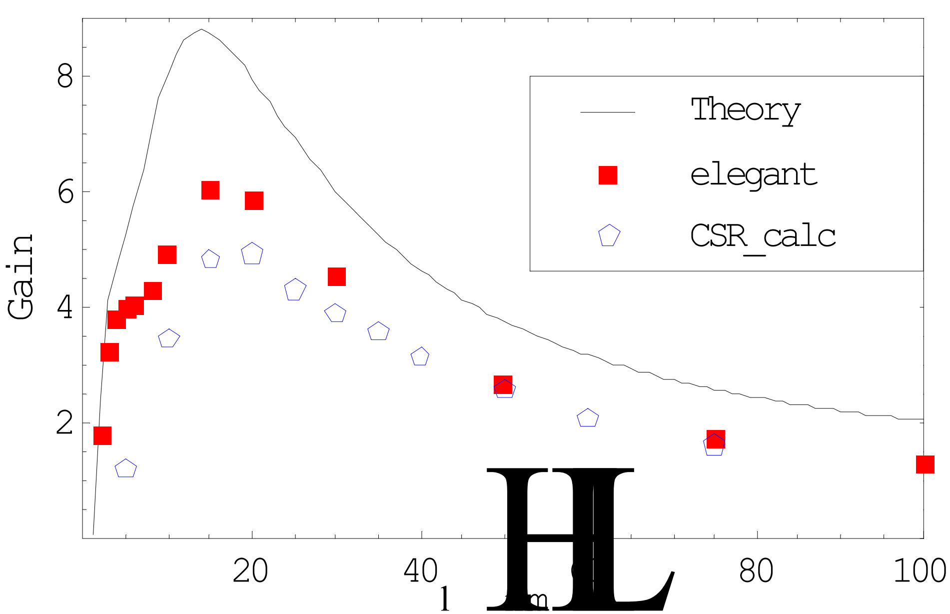
$$+ \overbrace{\underbrace{\int_0^s ds' K(s',s) \int_0^{s'} ds'' K(s'',s') b_0(k'';s'')}_{\text{two-stage amplification}}}^{I_f^2(1\to 2\to 3)}$$

dominant in high-gain

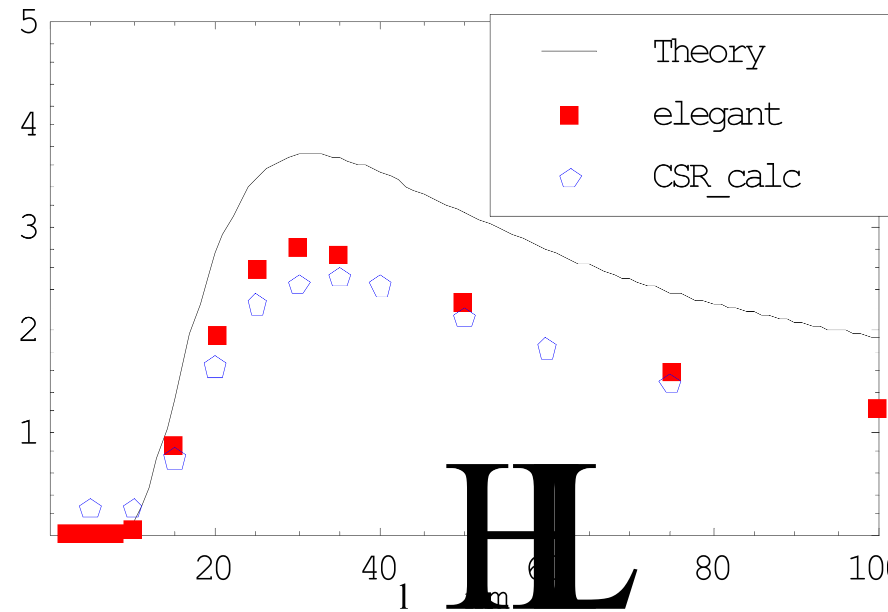
- Calculate gain=$|b_{final}/b_{initial}|$ as a function of λ, and compare with simulation results

Berlin CSR Benchmark Chicane

- Elegant and CSR_calc (matlab based) codes used
- a few million particles are loaded with 6D quiet start
- CSR algorithm based on analytical wake models

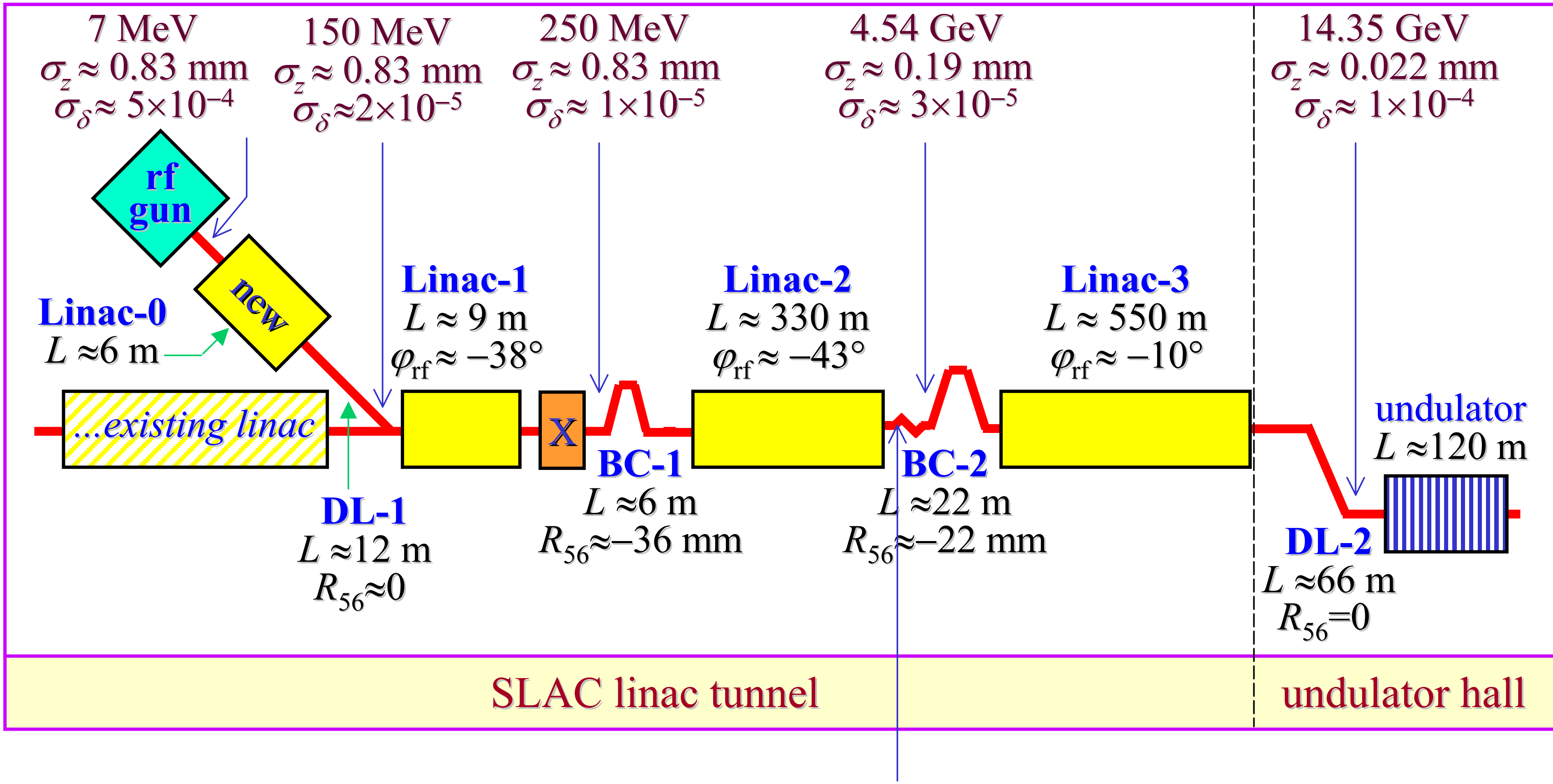


σ_δ=2×10^{-6}, $\gamma\varepsilon_x$=1 μm



σ_δ=2×10^{-5}, $\gamma\varepsilon_x$ =1 μm

LCLS Acceleration and Compression Systems

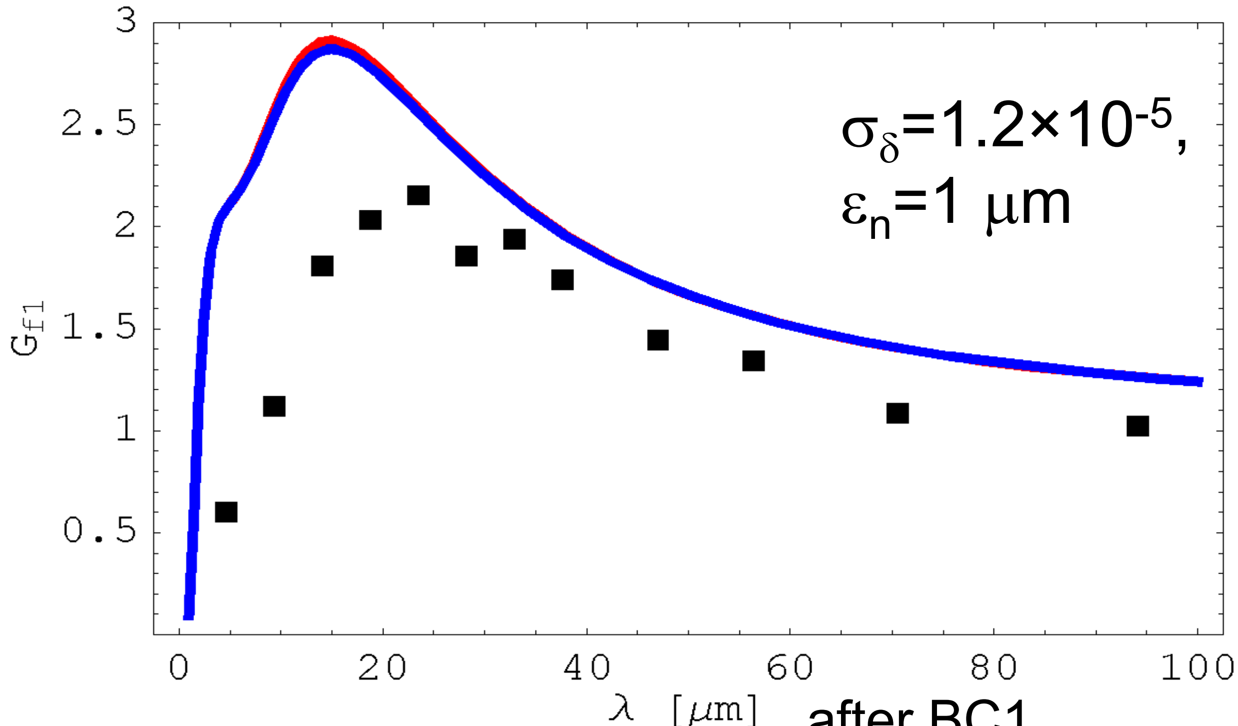


To damp the instability, a SC wiggler can be placed right before BC2

To increase the incoherent energy spread (still small for FEL instab.)

BC1

- BC1 gain in density modulation is low (so is BC2)



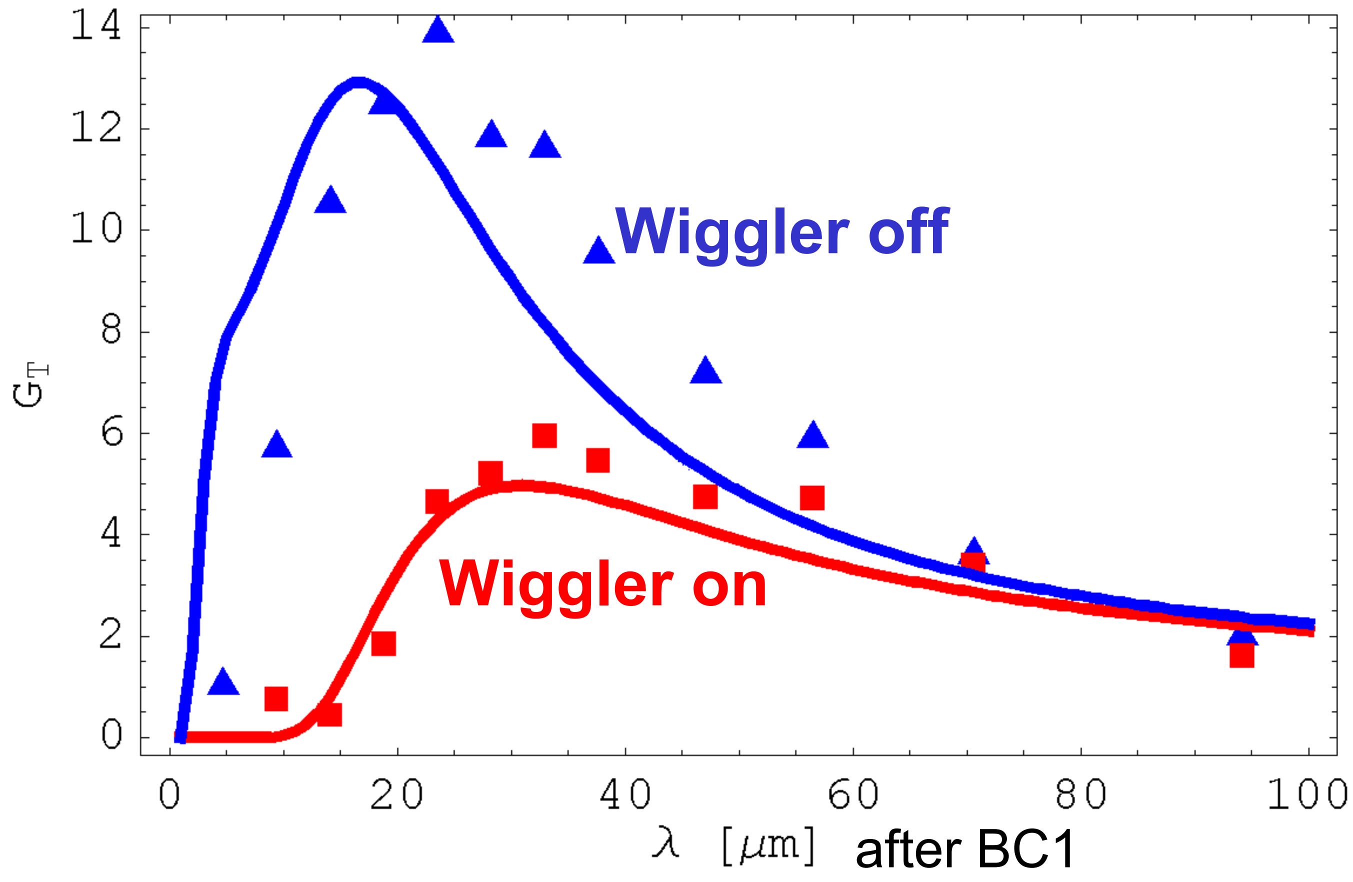
after BC1

- CSR also induced energy modulation in BC1

$$\Delta p(s) \approx -\int_0^s ds \frac{I(s')}{\gamma I_A} Z(s') b(s') \exp(\ldots \varepsilon, \sigma_\delta \ldots)$$

BC1+BC2

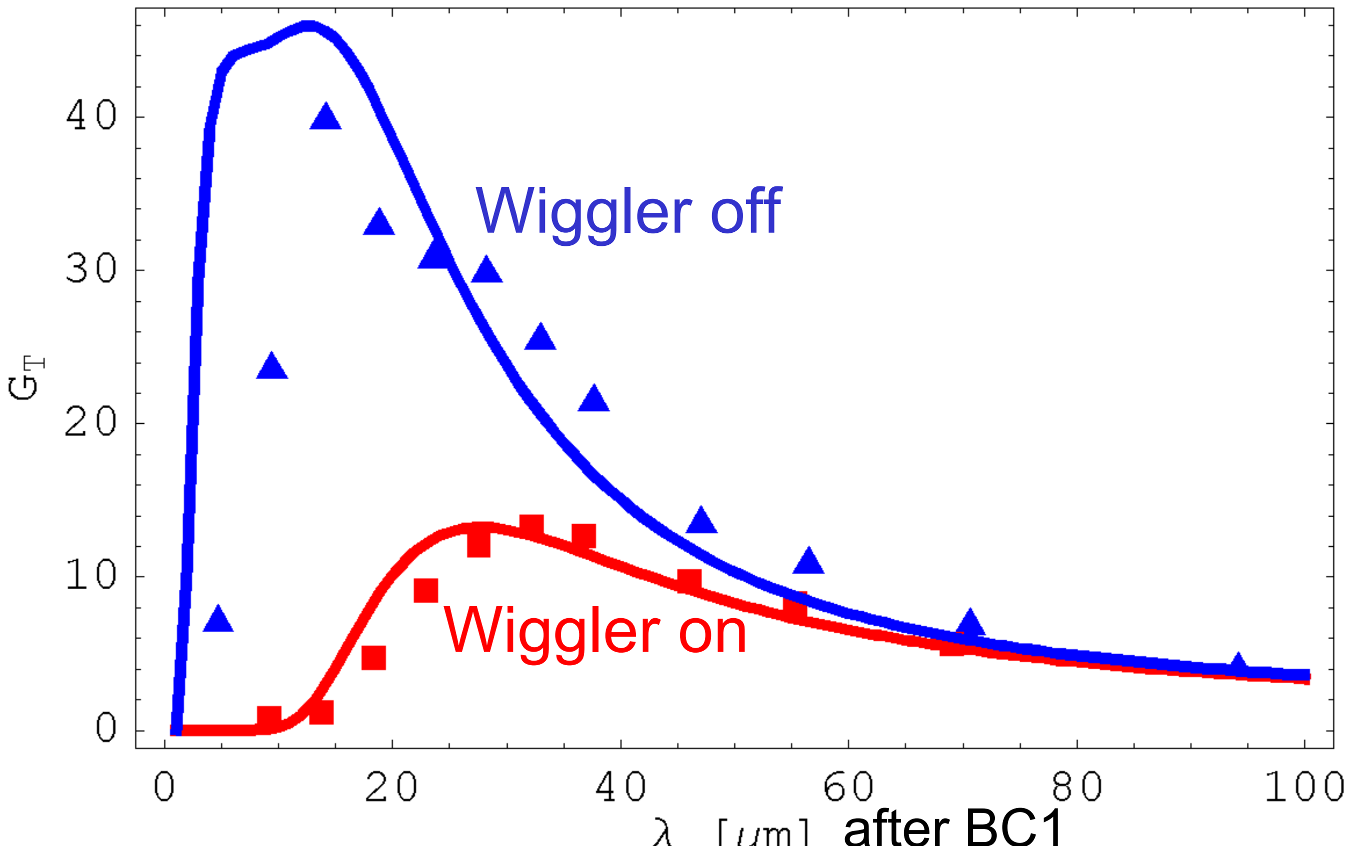
• BC2 not only amplifies density modulation gained in BC1, but turns BC1 energy modulation into gain in density modulation
➔Total gain of BC1+BC2 > BC1 gain X BC2 gain



Full LCLS Gain

• LCLS has four bend systems: BC1, BC2, and two beam transport dog legs (DL1, DL2)

• DLs have very small R56 ➔ ignore induced density modulation but keep track of induced energy modulation



Comments on Initial Conditions

• From shot noise

$$b_{\text{eff}} \sim \frac{1}{\sqrt{N_{\text{coh. length}}}} \sim (10^{-4} \rightarrow 10^{-5})$$

with a gain less than 100, this should be a small effect

• From sharp bunch structure

(due to laser ripple in PC RF guns?)

$$b \approx \frac{N_{\text{spike}}}{N_{\text{total}}}$$

• Other sources of energy modulation (geometric wake…)

(simulations show more gain (2X) for full lattice and wake

• Watch out for numerical noise in simulations!

Summary

• CSR microbunching instability is governed by an integral equation which is solved iteratively for chicanes

• Initialized by density and/or energy modulation, cascading through multiple chicanes and bends

• Two similar but independent CSR codes shows reasonable agreement with each other and with theory

• Full LCLS gain is significant but not detrimental for shot noise start-up

• The damping wiggler reduces the microbunching gain and the sensitivity to the initial bunch distribution