Microbunching Instability in FEL Linear Accelerators

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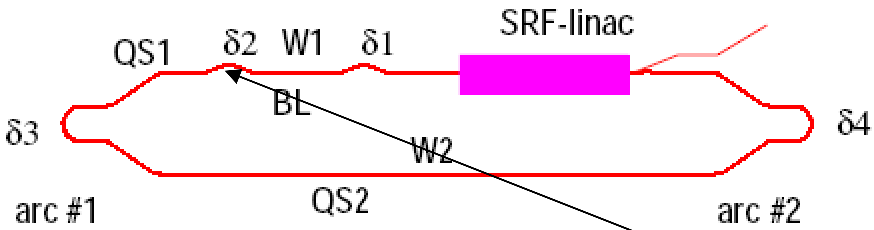
Jefferson Lab's
CENTER for ADVANCED STUDIES of ACCELERATORS

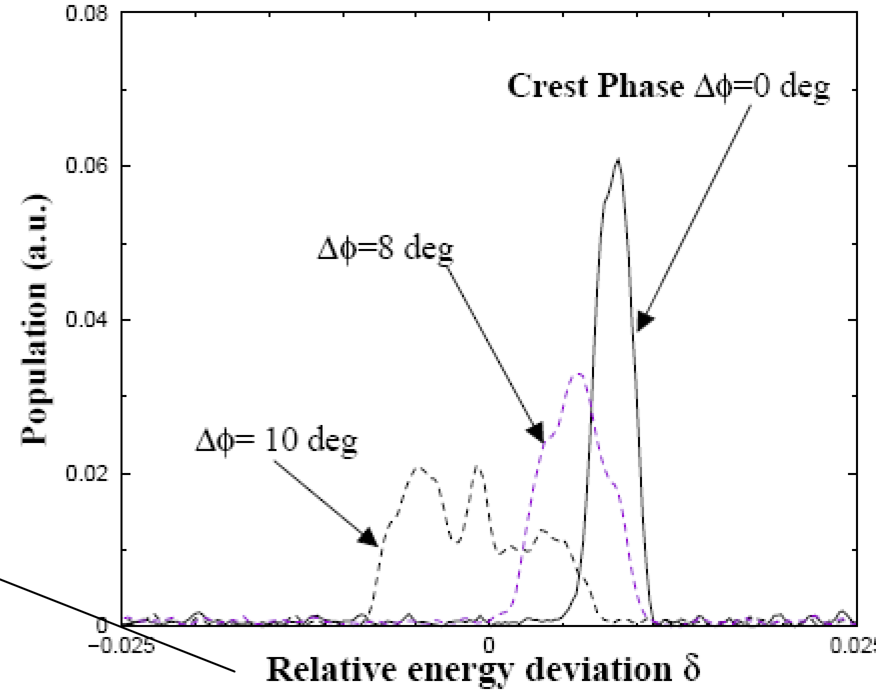
Outline

- Introduction
- Microbunching instability driven by CSR and LSC
- LCLS analysis and cures
- DUV-FEL beam modulation studies
- Conclusions

Microbunch structures observed after compression

- JLab *(Piot et al., EPAC 2000)*





- Similar longitudinal structures at TTF and DUV-FEL

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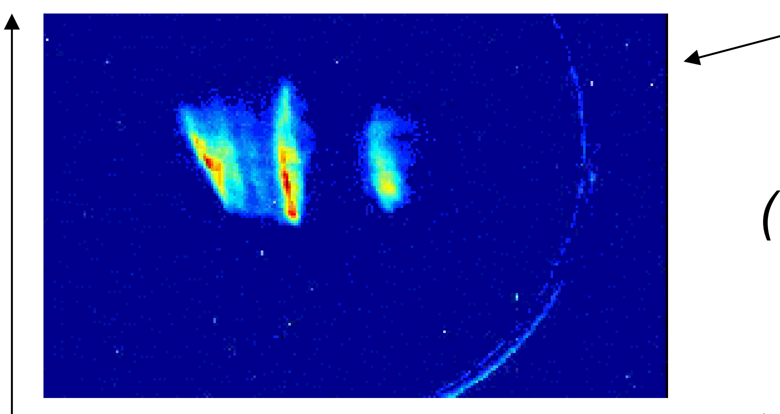
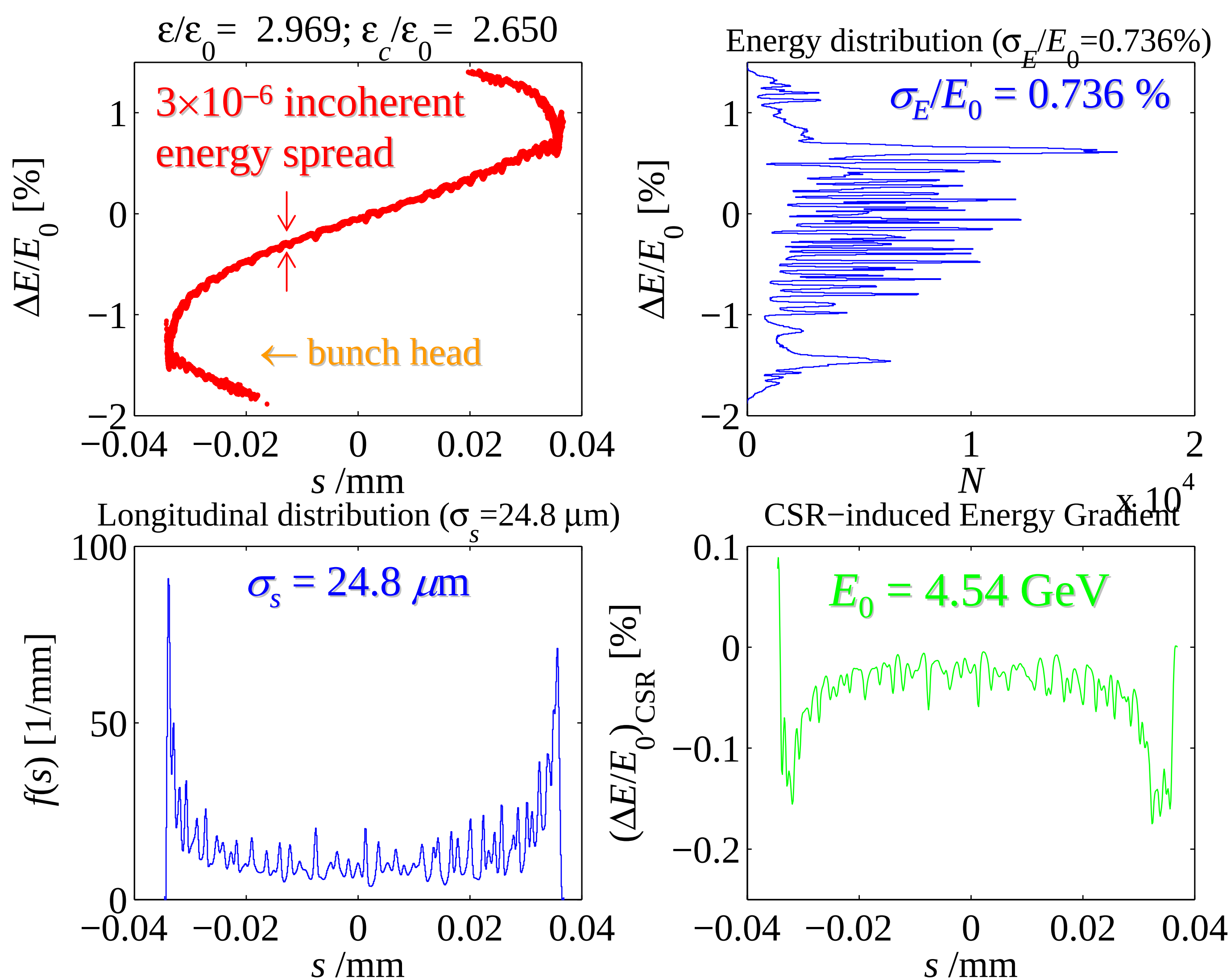


(Graves et al. PAC 2001)

x (energy and time)

LCLS Distribution After BC2 Chicane



M. Borland et al, PAC 2001, ELEGANT tracking

Introduction

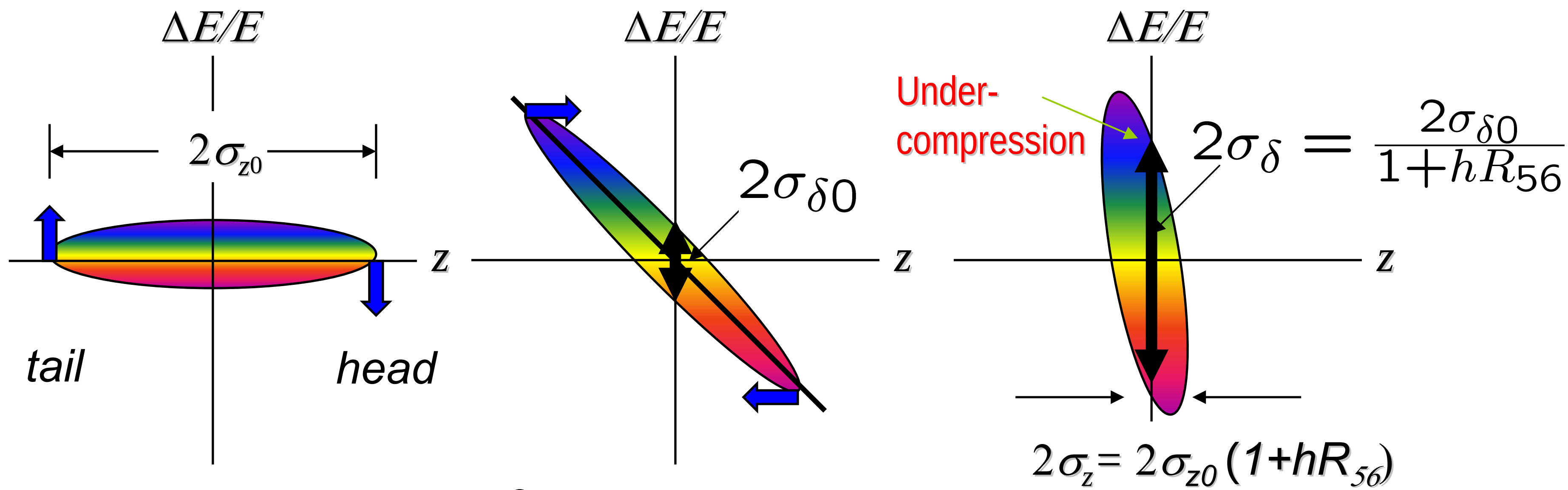
- FEL interaction in the undulator requires very bright electron beams (high current, small emittance and energy spread)

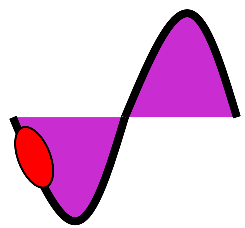
- Such a bright beam interacting with self-fields in the accelerator may be subject to undesirable instabilities

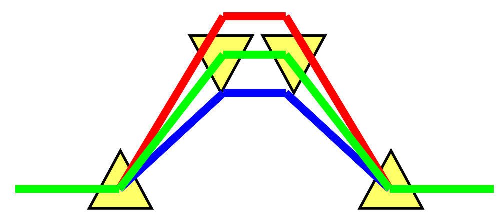
- Bunch compressors designed to increase the peak current can give rise to a microbunching instability that may degrade the beam quality significantly

- This talk discusses physics of this instability, how to suppress it for short-wavelength FELs, and some experimental evidence relevant to the instabitily

Bunch compression







$V = V_0 \sin(\omega z)$

$\Delta z = R_{56}\, \Delta E/E$

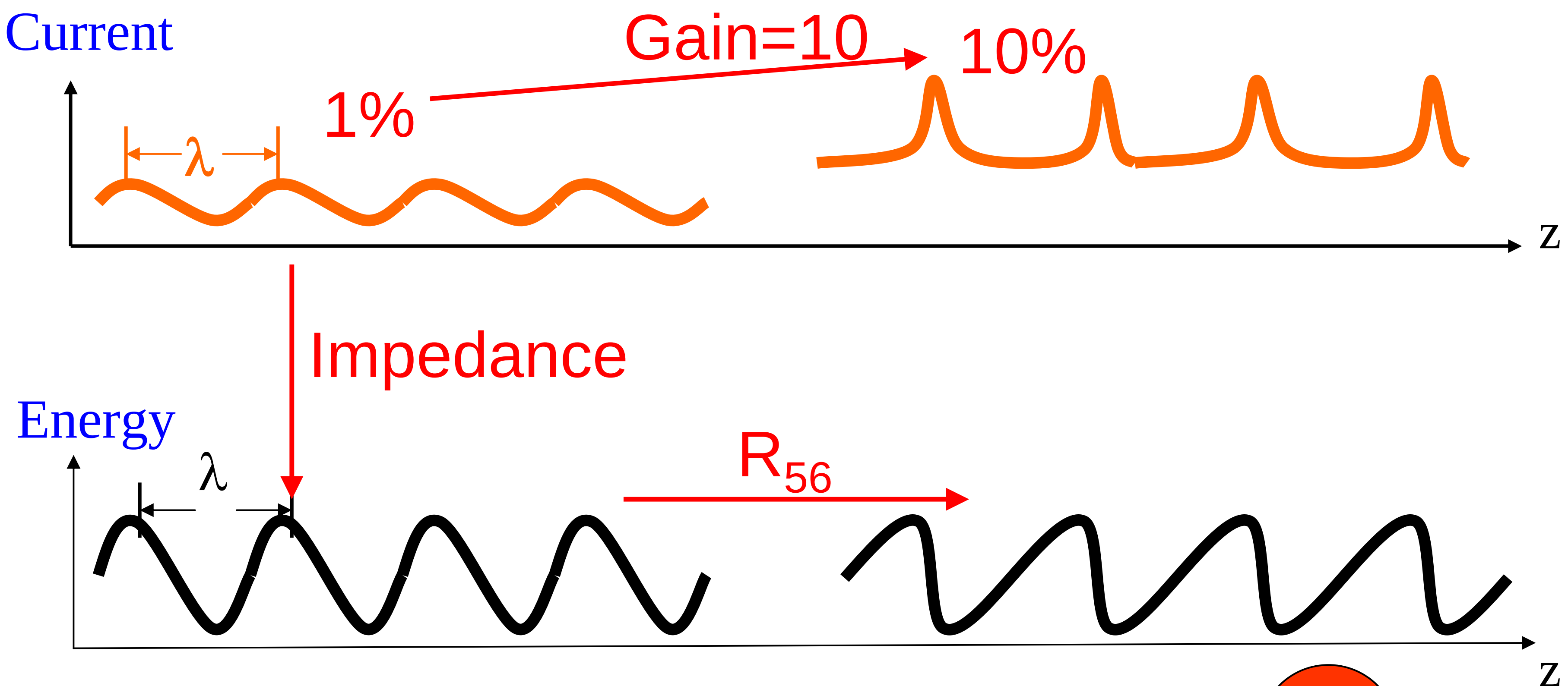
RF Accelerating Voltage

Path Length-Energy Dependent Beamline

linear "chirp" $h = \dfrac{\Delta E/E}{\Delta z} < 0$

Instability mechanism

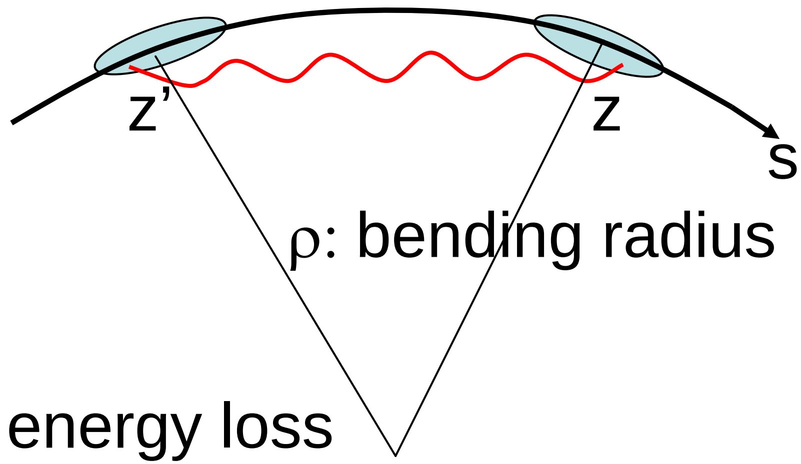
• Initial density modulation induces energy modulation through longitudinal impedance Z(k), converted to more density modulation by a compressor (*Saldin, Schneidmiller, Yurkov, NIMA, 2002*)



➔ growth of slice energy spread (and emittance)

CSR wake and impedance

- Powerful radiation generated for $\lambda \sim$ bunch length or bunch micro-structure lengths



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

- Steady-state, line-charge CSR energy loss

$$\frac{d(\Delta E)}{ds} = -\frac{e}{4\pi}\int_{-\infty}^{z} \underbrace{\frac{2Z_0}{3\rho^{2/3}(z-z')^{1/3}}} \frac{dI}{dz'}dz'$$

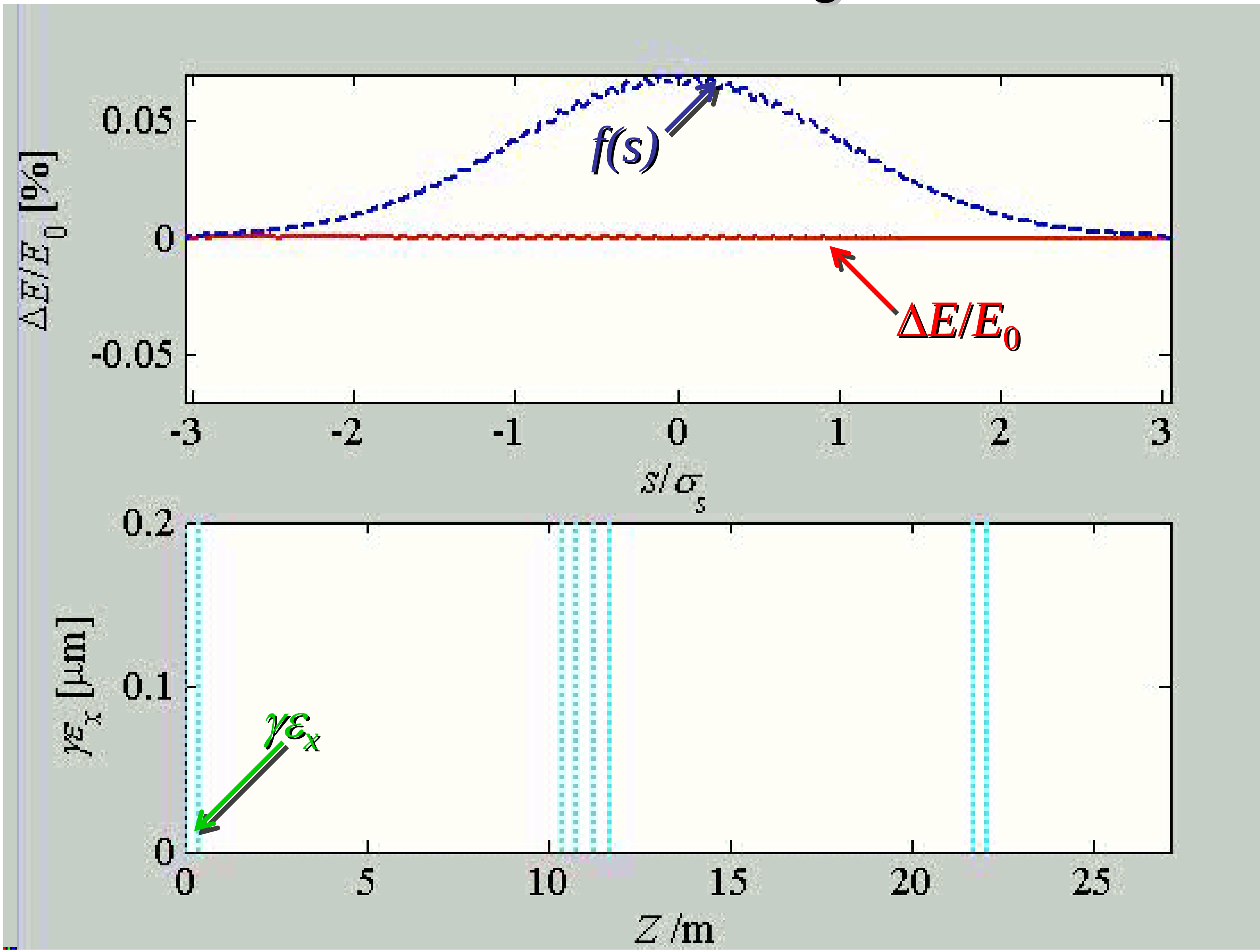
CSR "wake", stronger at smaller scale

- Longitudinal CSR impedance Z(k) ($k = 2\pi/\lambda$)

$$Z_{CSR} = -iA\frac{cZ_0}{4\pi}\frac{k^{1/3}}{\rho^{2/3}}$$

Derbenev et al., 1995
Murphy et al., PAC 1995

CSR Microbunching Movie

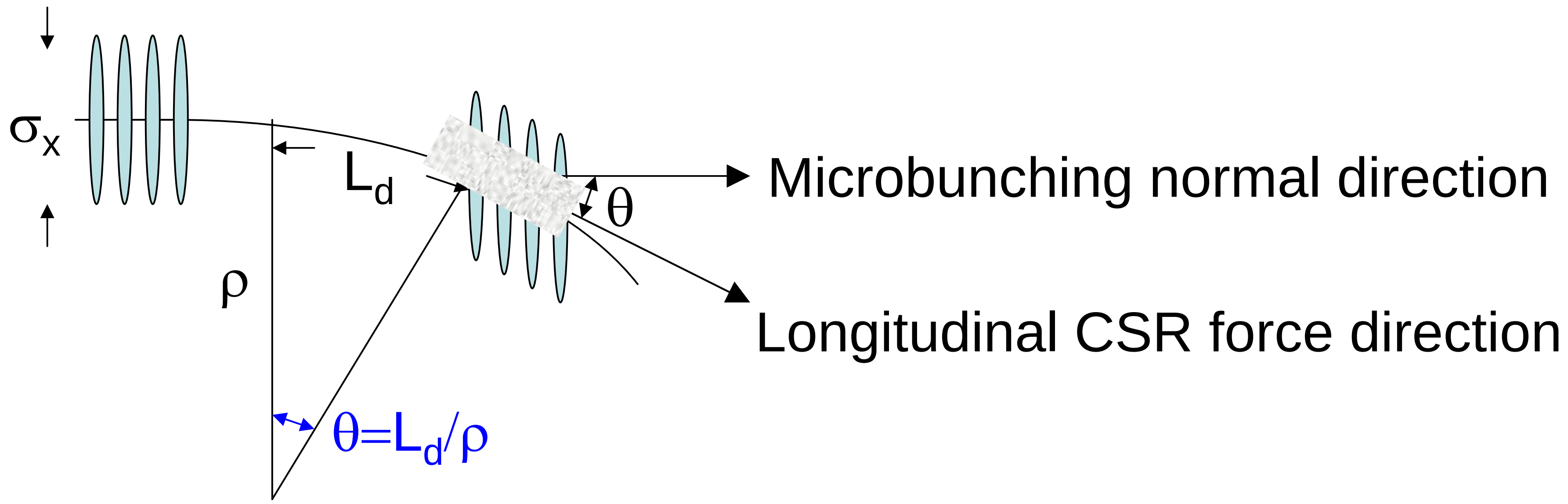


courtesy P. Emma

Emittance damping to CSR microbunching

Emittance damping to CSR microbunching

- Consider a microbunched beam moving in a dipole



- Characterize density modulation by a bunching factor

$$b(k) = \frac{1}{Nec} I(k) = \frac{1}{Nec} \int_{-\infty}^{\infty} I(z) e^{-ikz} dz$$

- Smearing of microbunching when projected to longitudinal z direction in the bend

$$\frac{L_d}{\rho} \sigma_x = \frac{L_d}{\rho} \sqrt{\epsilon_x \beta} \sim \lambda / 2\pi$$

Integral equation and approx. solution

- Linear evolution of b(k;s) governed by an integral equation

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

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

- Iterative solution for a 3-dipole chicane

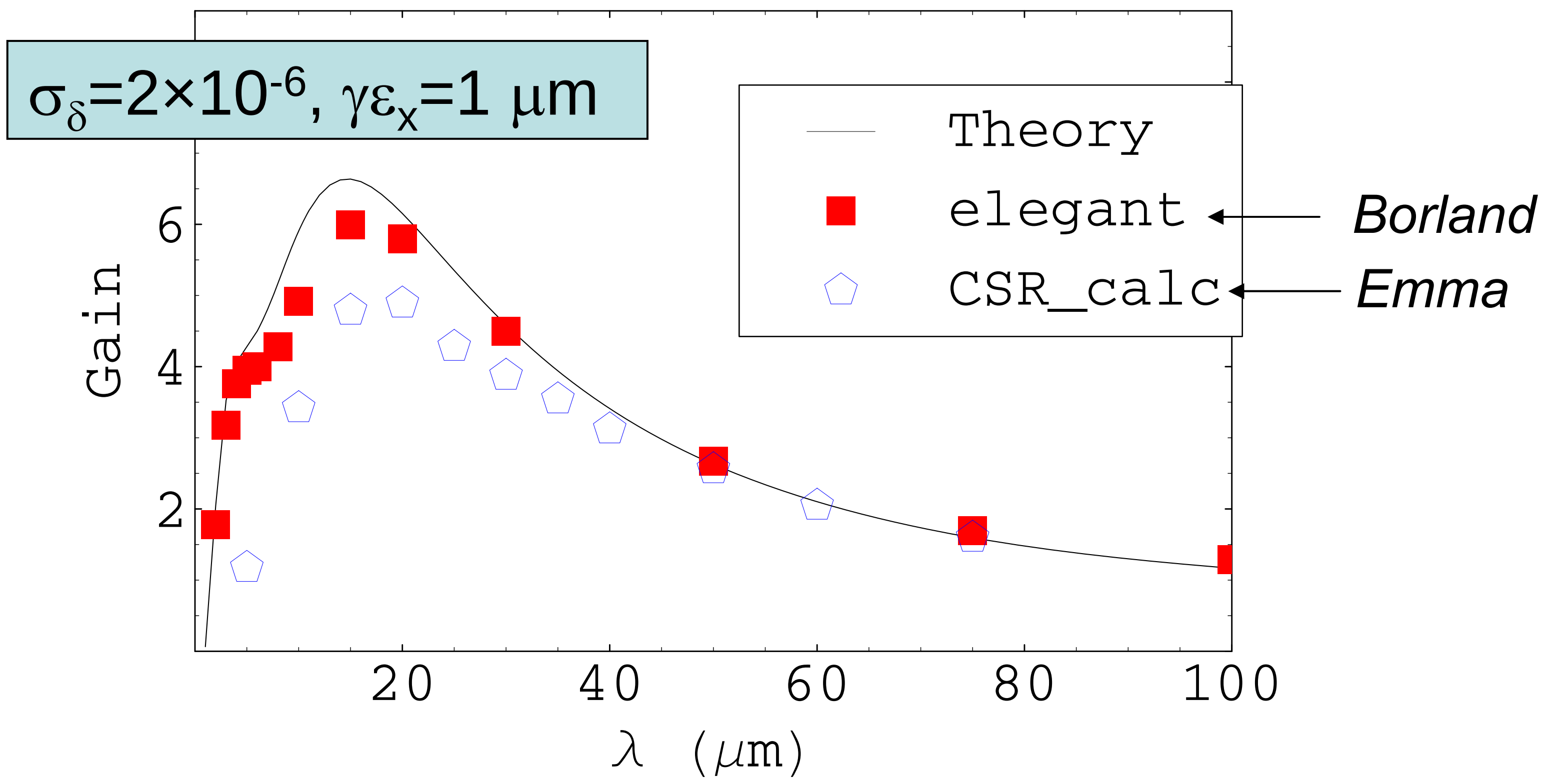
$$b(k;s) = b_0(k;s) + \underbrace{\underbrace{\int_0^s ds' K(s',s) b_0(k';s')}_{\text{one-stage amplification}}}_{I_f(1\to 3) + I_f(2\to 3)}$$

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

- *Heifets, Stupakov, Krinsky PRST, 2002;*
- *Huang, Kim, PRST, 2002*

Numerical example: Berlin Benchmark

- 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



- More about CSR, see http://www.desy.de/csr/

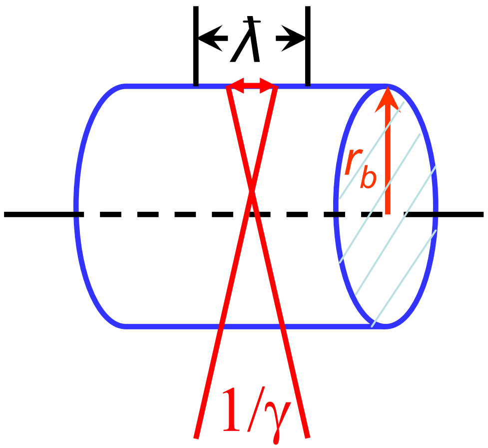
LSC Impedance

- Free-space longitudinal space charge impedance

$$Z(k) = \frac{4i}{kr_b^2}\left[1 - \frac{kr_b}{\gamma}K_1\left(\frac{kr_b}{\gamma}\right)\right]$$

$$= \frac{4i}{kr_b^2} \text{ if } \frac{kr_b}{\gamma} \gg 1$$

$$= \frac{ik}{\gamma^2}\left(1 + 2\ln\frac{\gamma}{r_b k}\right) \text{ if } \frac{kr_b}{\gamma} \ll 1$$



- At low energy in the injector region, space charge oscillation dynamics (typically requires careful SC simulations)

- At higher linac energy, beam density modulation freezes and energy modulation accumulates due to LSC, can dominate microbunching gain at very high frequencies *(Saldin, Schneidmiller, Yurkov, NIMA, 2004)*

- CSR impedance much stronger than LSC, but LSC instability is not subject to emittance damping (chicane is achromat)

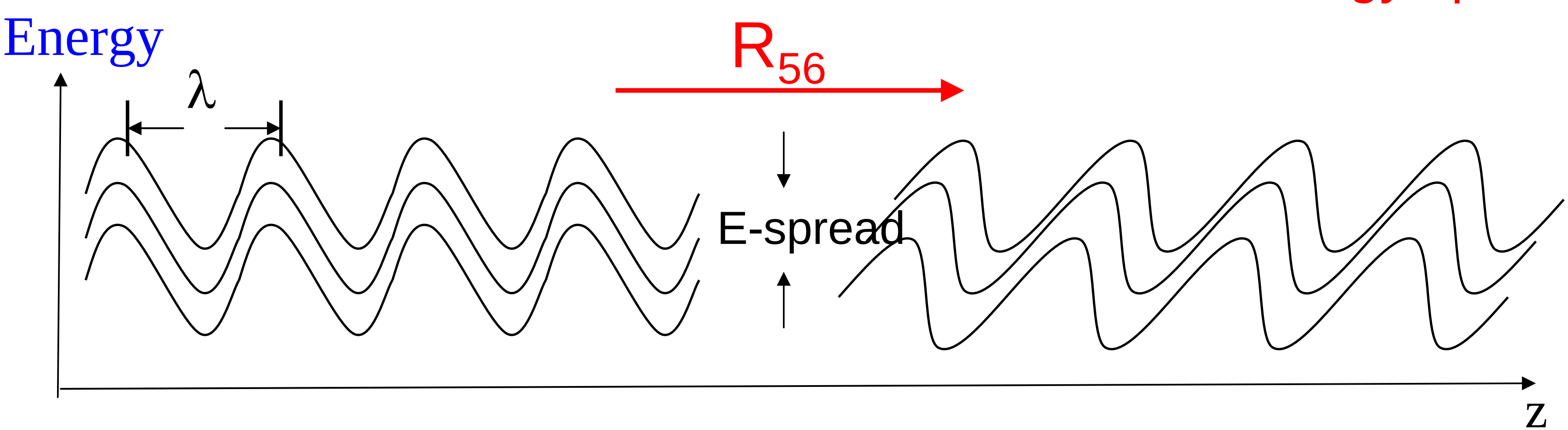
LSC instability gain and Landau damping

- Gain due to upstream impedances (LSC, linac wake)

$$G \equiv \left|\frac{b_f}{b_0}\right| = \frac{I_0}{\gamma I_A}\left|k_f R_{56}\int_0^L ds Z(k_0;s)\right| \exp\left(-\frac{1}{2}k_f^2 R_{56}^2 \sigma_\delta^2\right)$$

local energy spread

- No emittance damping!

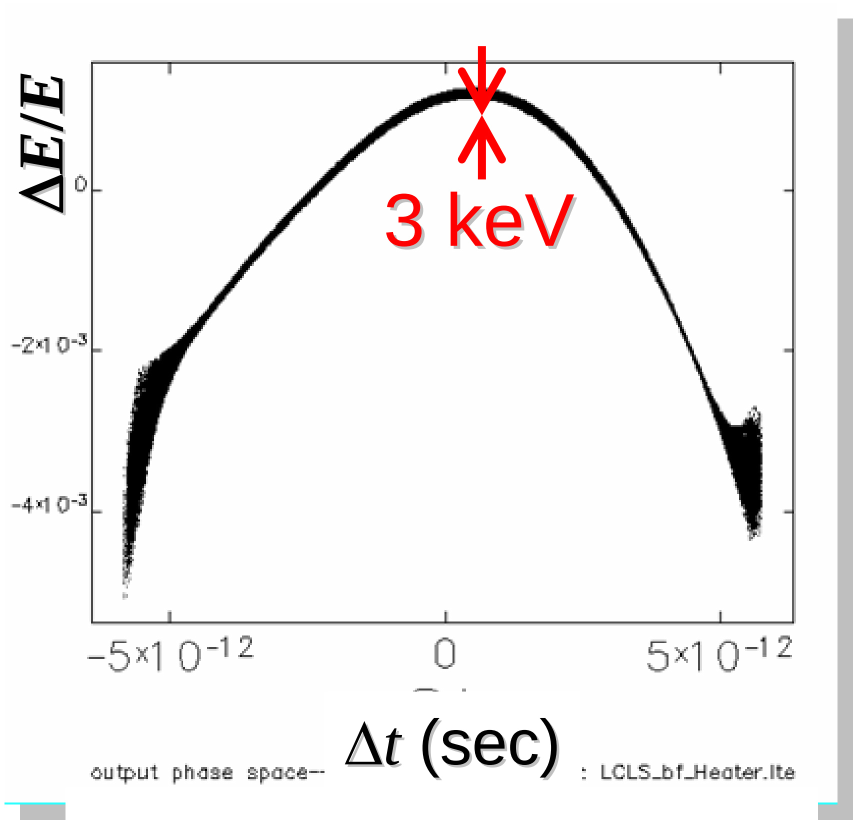


- All beams have finite incoherent (uncorrelated) energy spread, smearing of microbunching occurs if

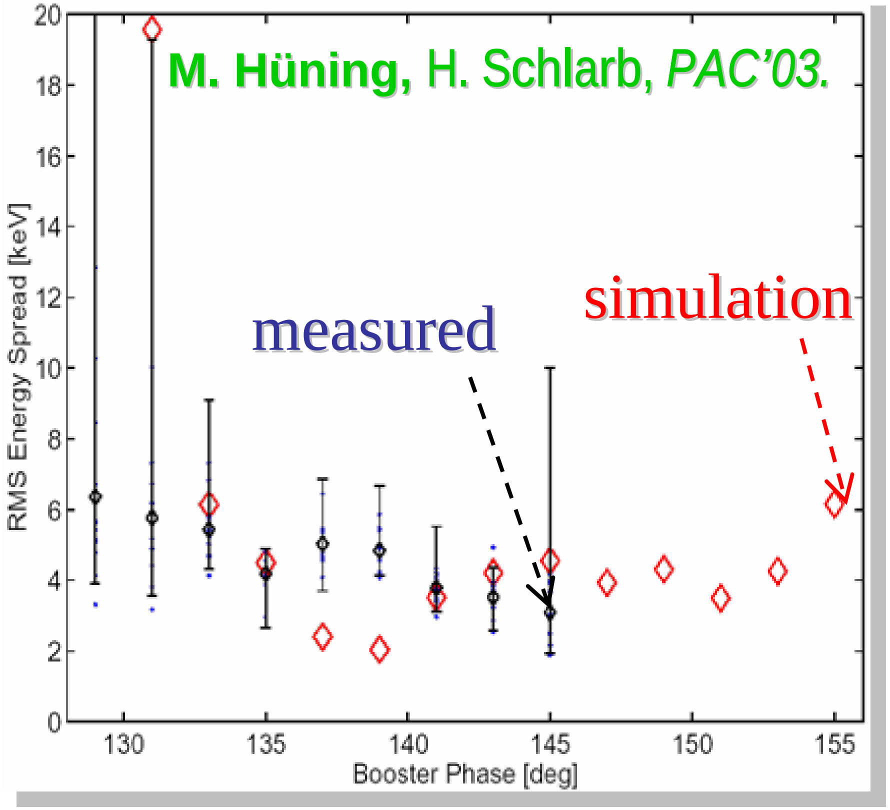
$$R_{56}\left(\frac{\Delta E}{E}\right)_{inc} \sim \lambda/(2\pi)$$

Uncorrelated energy spread of PC RF gun

Parmela at 1 nC



TTF measurement at 4 nC



• "Intrinsic" energy spread mostly generated from r-dependent LSC force in the gun (*Huang et al., PAC 2005*)

• 3 keV (rms), accelerated to 14 GeV, & compressed $\times 32$

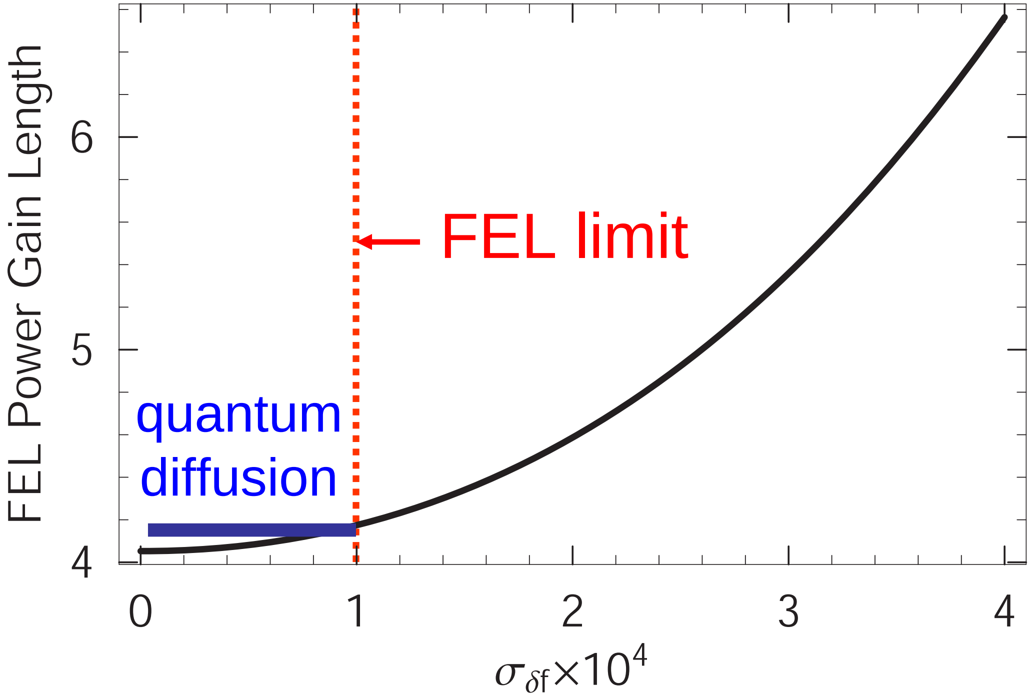
$\Rightarrow$ $3\times10^{-6}\times32/14 < 1\times10^{-5}$ relative energy spread

Heating within FEL tolerance

Heating within FEL tolerance

- LCLS FEL parameter $\rho \sim 5\times10^{-4}$, not sensitive to energy spread until $\sigma_\delta \sim 1\times10^{-4}$

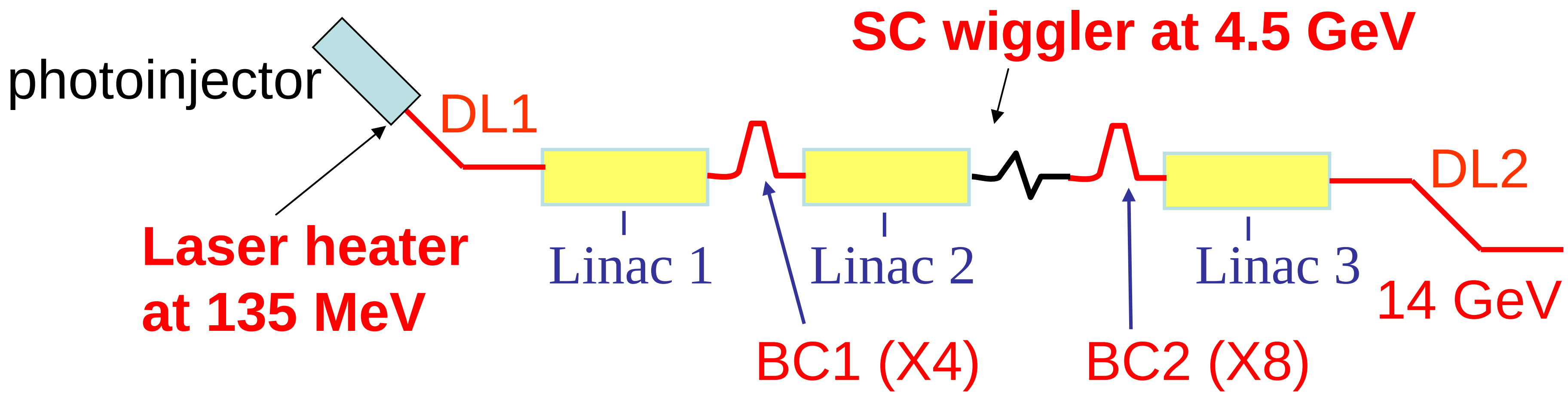
M. Xie's fitting formula
$\gamma\varepsilon = 1.2\ \mu m$
$I_p = 3.4$ kA
$\beta = 20$ m



- 10^{-5} "intrinsic" energy spread too small and cannot be used in LCLS undulator due to QE (no effect on FEL gain when $<10^{-4}$)

➔can increase σ_δ by a factor of 10 without FEL degradation in order to suppress microbunching instability

LCLS accelerator systems



- Two bunch compressors to control jitters and wakefield effect
- Impedance sources: LSC, CSR, and linac wakefields
- Two Landau damping options (to increase E-spread 10X)

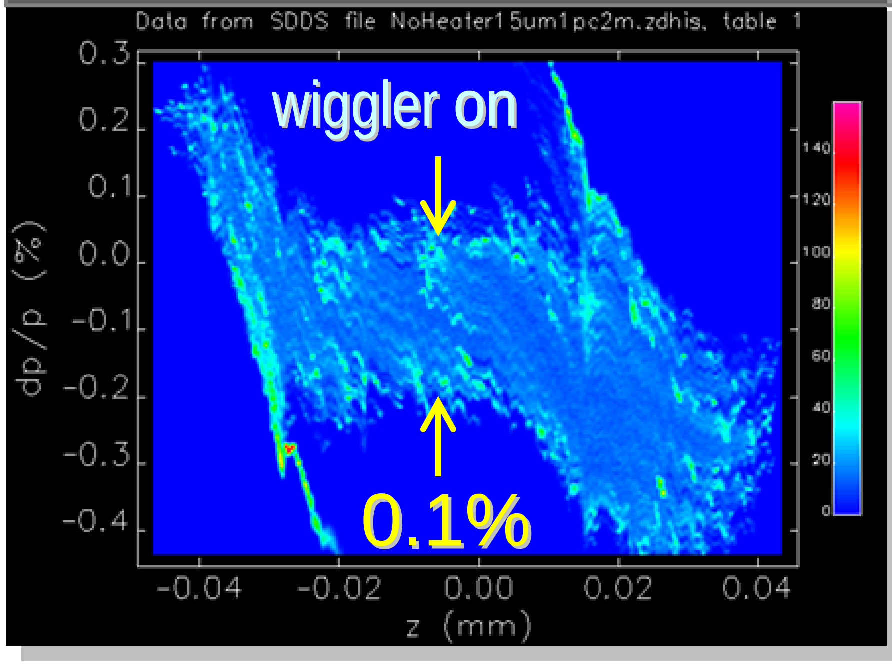
  a SC wiggler before BC2 to suppress CSR microbunching

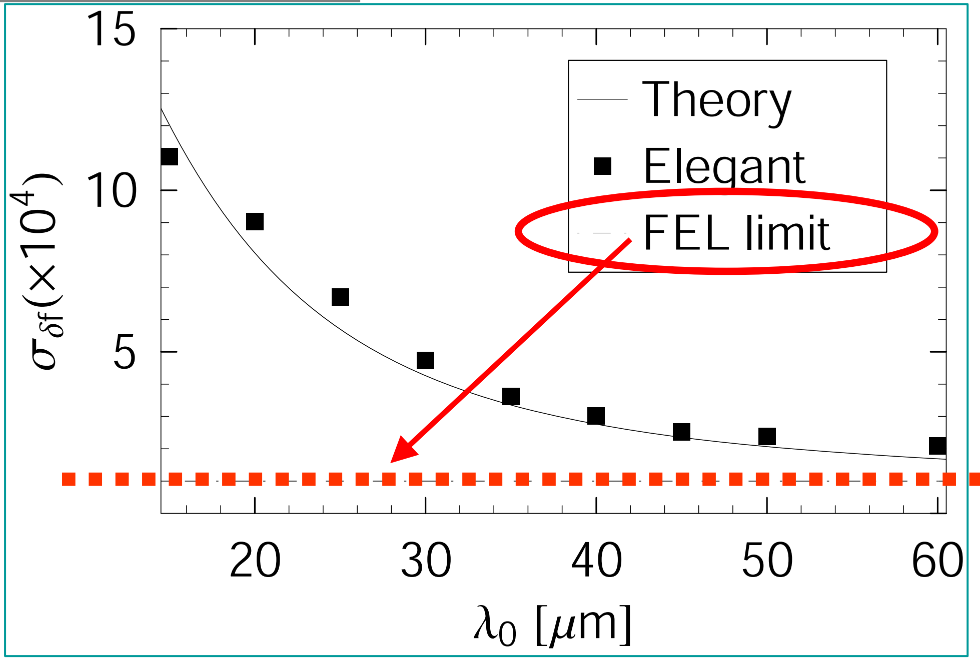
  or a laser heater for LSC instability (suggested by Saldin et al.)

Growth of slice energy spread

- High BC1 gain ➔ significant energy modulation in Linac-2 ➔ temporally smearing in BC2 to become effective slice energy spread (➔ SC wiggler too late)

Final long. phase space at 14 GeV for initial 15-μm 1% modulation at 135 MeV



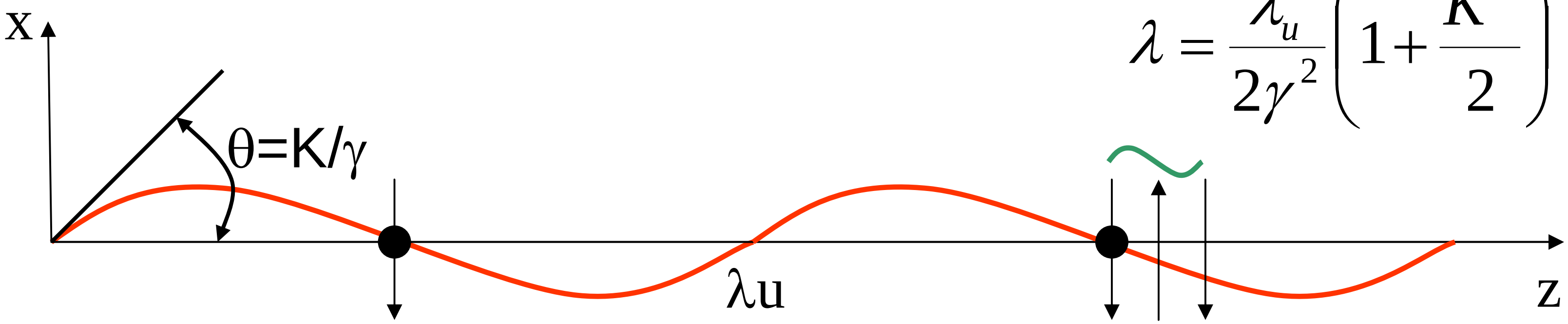


Need ~0.1% initial density modulation at injector end or suppress BC1 gain effectively

Beam-radiation interaction in an undulator

- Undulator radiation

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$



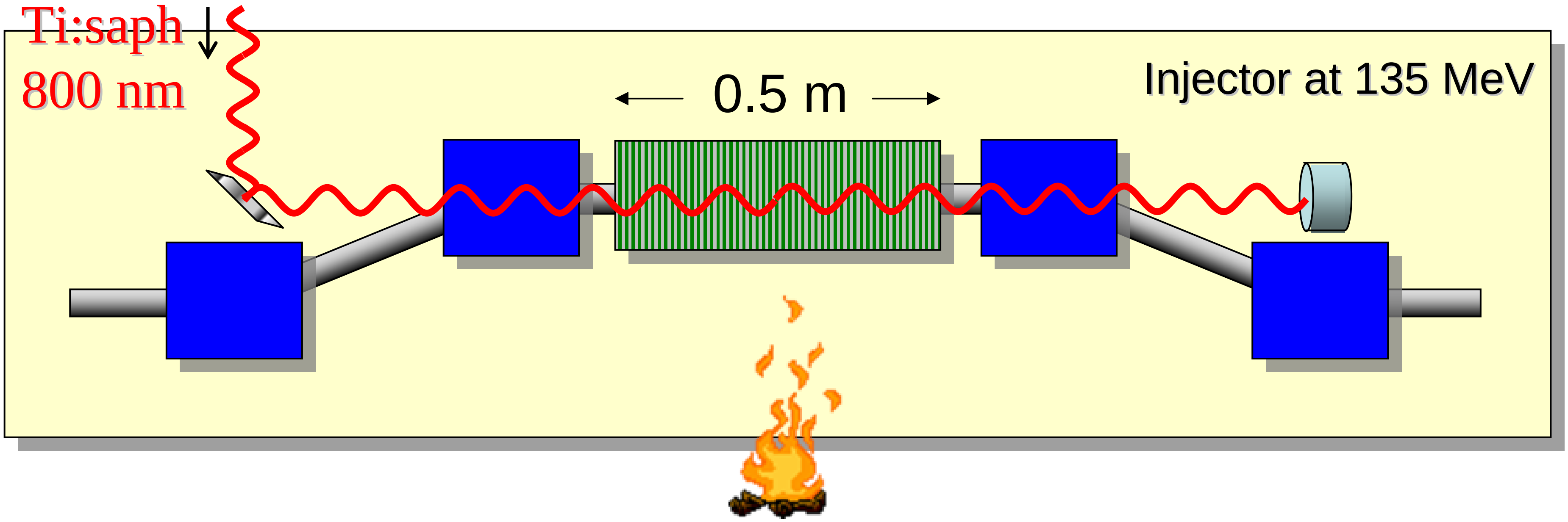
- FEL interaction: energy exchange between e- and field ($\boldsymbol{v}\bullet\boldsymbol{E}=v_x E_x$) can be sustained due to the resonant condition

- Some e- loss energy, others gain ➔ energy modulation with a relative amplitude

$$\delta_L(r) = \sqrt{\frac{P_L}{P_0}}\frac{K L_u}{\gamma_0^2 \sigma_r}[\mathrm{JJ}]\exp\left(-\frac{r^2}{4\sigma_r^2}\right)$$

laser peak power — 8.7 GW — laser rms spot size

LCLS laser heater design

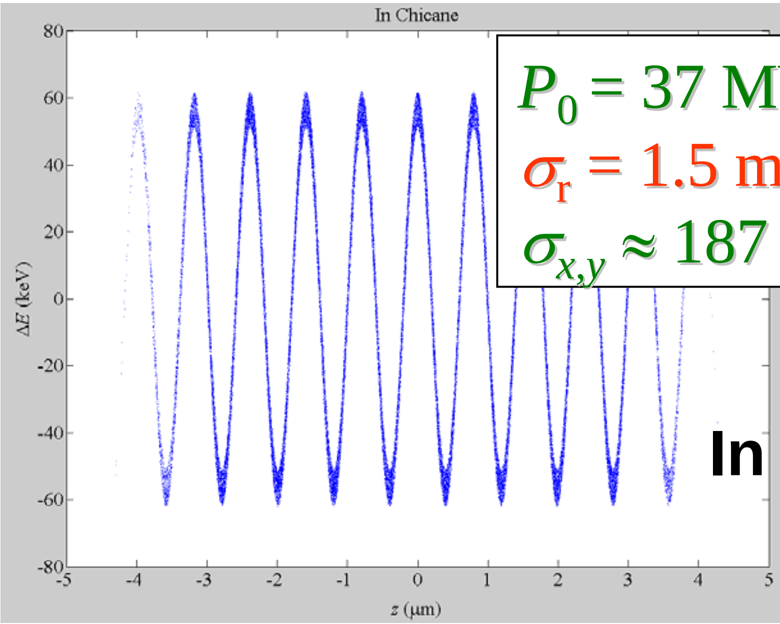


• Laser-electron interaction in an undulator induces rapid energy modulation (at 800 nm), to be used as effective energy spread before BC1 (3 keV➔ 40 keV rms)

•Inside a weak chicane for easy laser access, time-coordinate smearing (Emittance growth is negligible)

Huang et al., PRST-AB 7, 2004

Large laser spot size

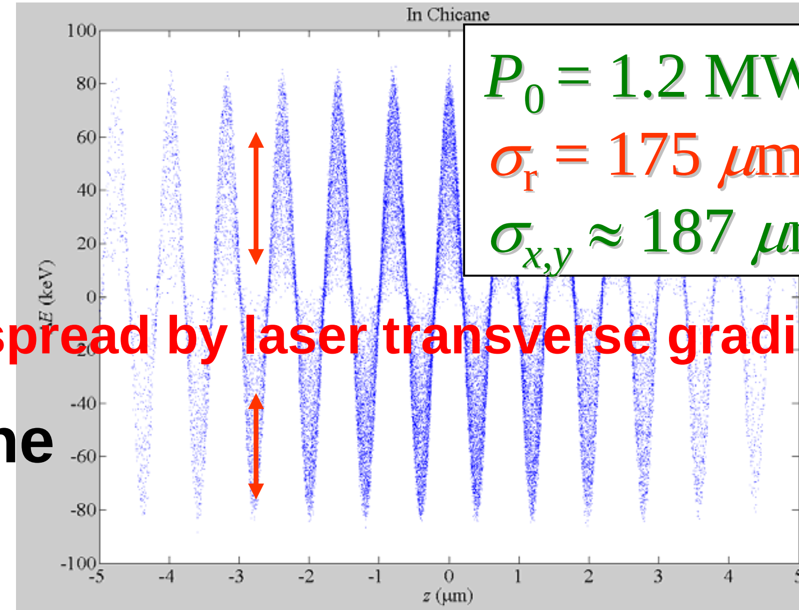


$P_0 = 37$ MW

$\sigma_r = 1.5$ mm >>

$\sigma_{x,y} \approx 187\ \mu$m

Matched laser spot size



$P_0 = 1.2$ MW

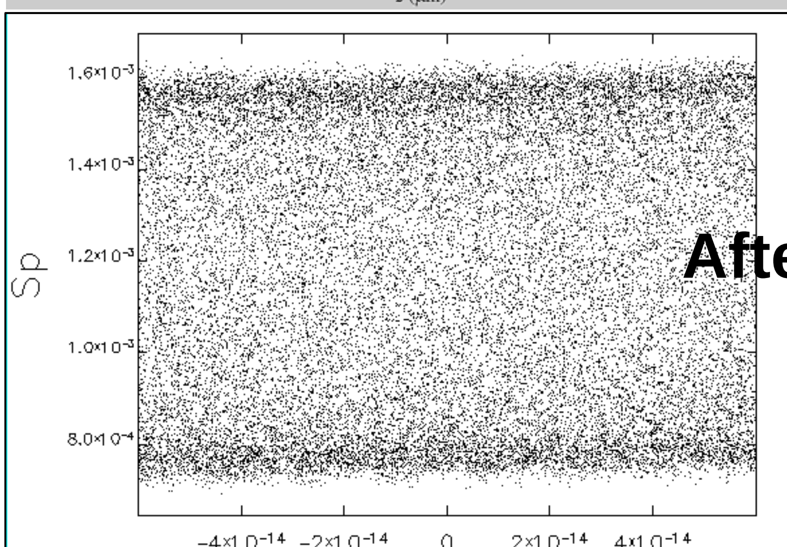
$\sigma_r = 175\ \mu$m

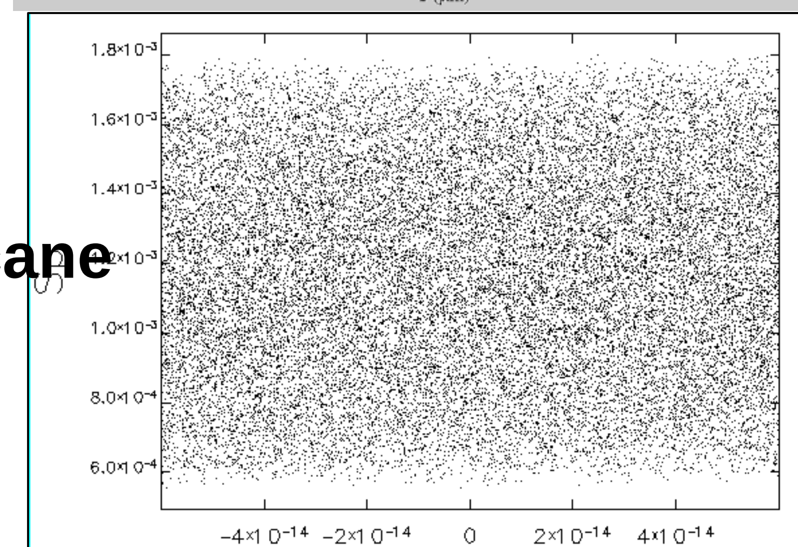
$\sigma_{x,y} \approx 187\ \mu$m

spread by laser transverse gradient

In Chicane

After Chicane





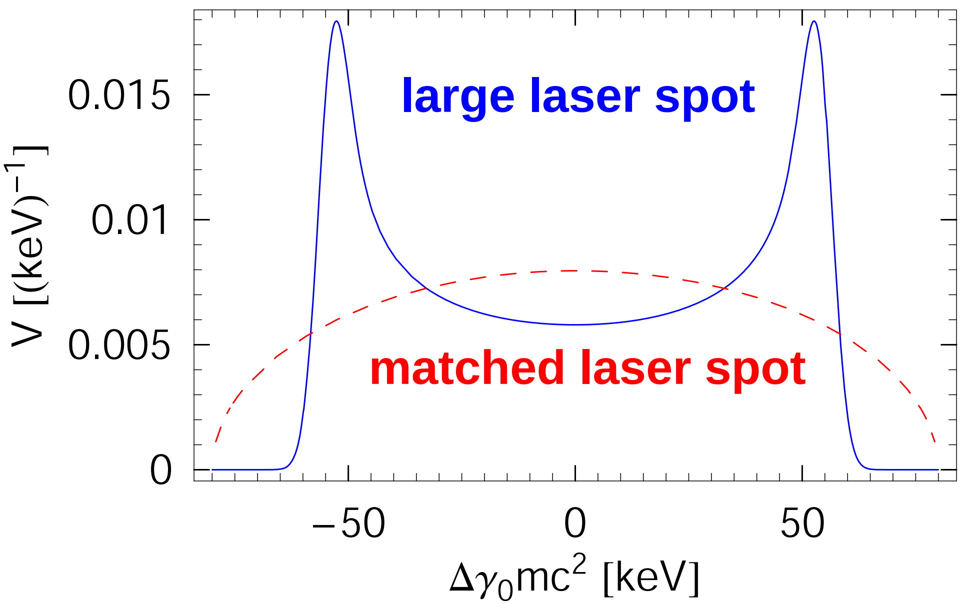
Non-uniform heating

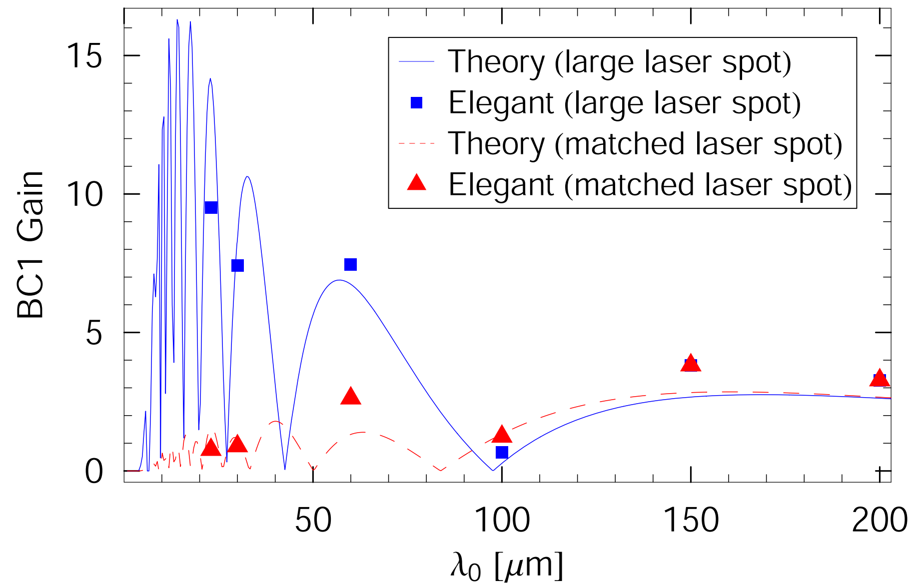
more uniform heating

Gain suppression depends on laser spot size

Gain suppression depends on laser spot size

- Large laser spot generates “double-horn” energy distributioin, ineffective at suppressing short wavelength microbunching
- Laser spot matched to e-beam size creates better heating





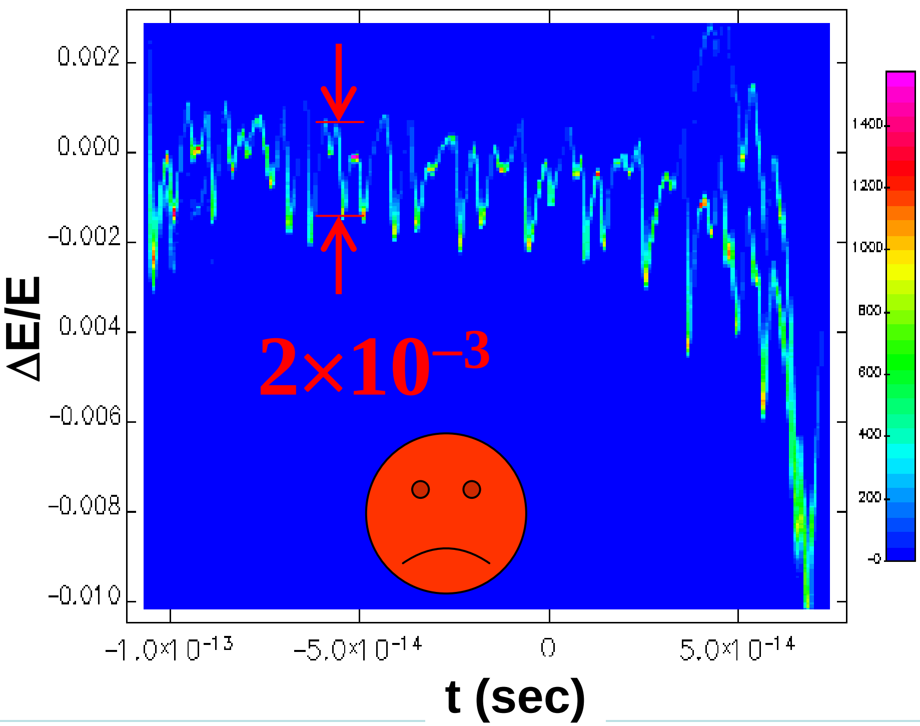
$$\frac{G_L}{G_0} = J_0(k_f R_{56}\delta_L) \sim (k_f R_{56}\delta_L)^{-1/2} \text{ when } \sigma_r \gg \sigma_x$$

$$\frac{G_L}{G_0} = 2\frac{J_1(k_f R_{56}\delta_L)}{k_f R_{56}\delta_L} \sim (k_f R_{56}\delta_L)^{-3/2} \text{ when } \sigma_r = \sigma_x$$

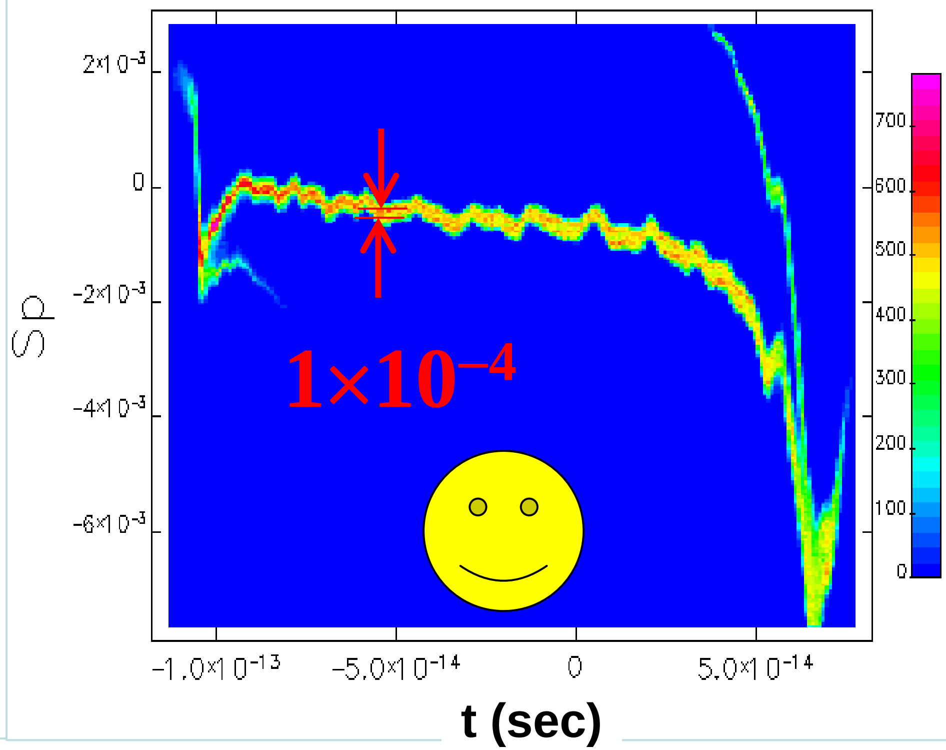
Start-to-end simulation

• Injector space charge dynamics modeled by ASTRA, Linac by ELEGANT with LSC/CSR/machine impedances

Example: final long. phase space at 14 GeV for initial 8% uv laser intensity modulation at λ=150 μm



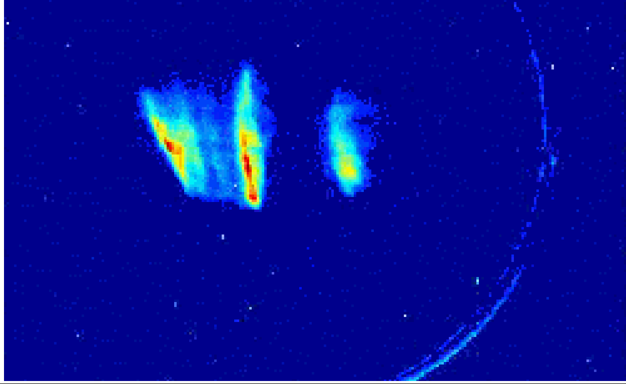
No Laser-Heater

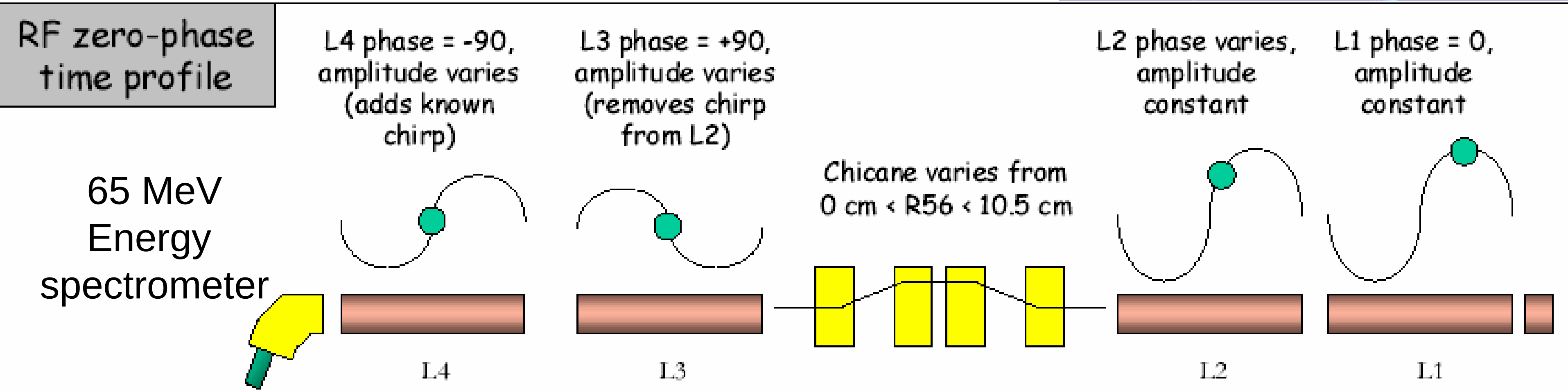


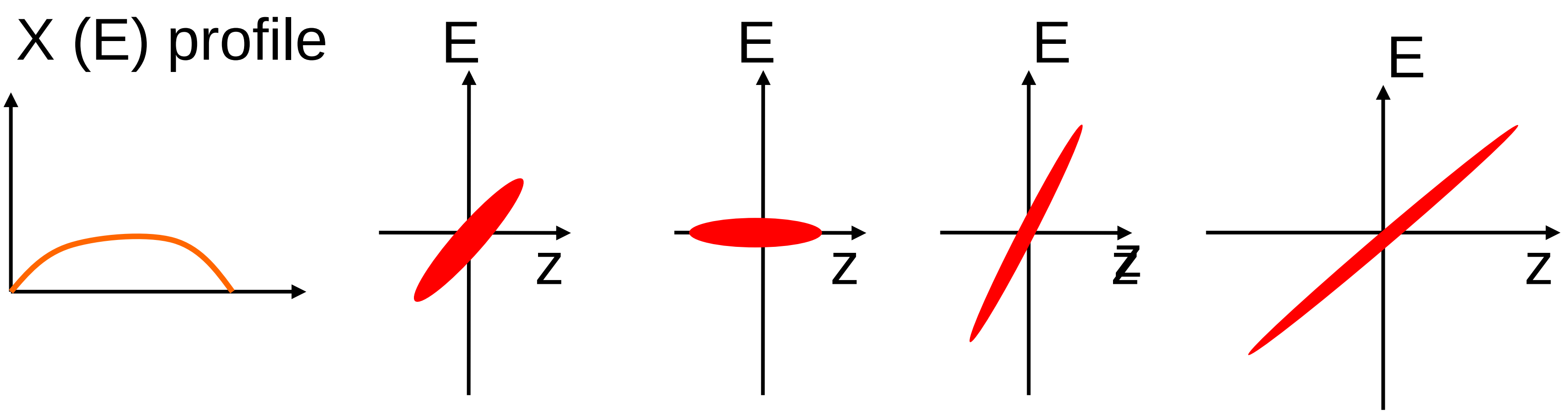
Matched Laser-Heater

SDL zero-phasing experiment

(Graves et al. PAC01)



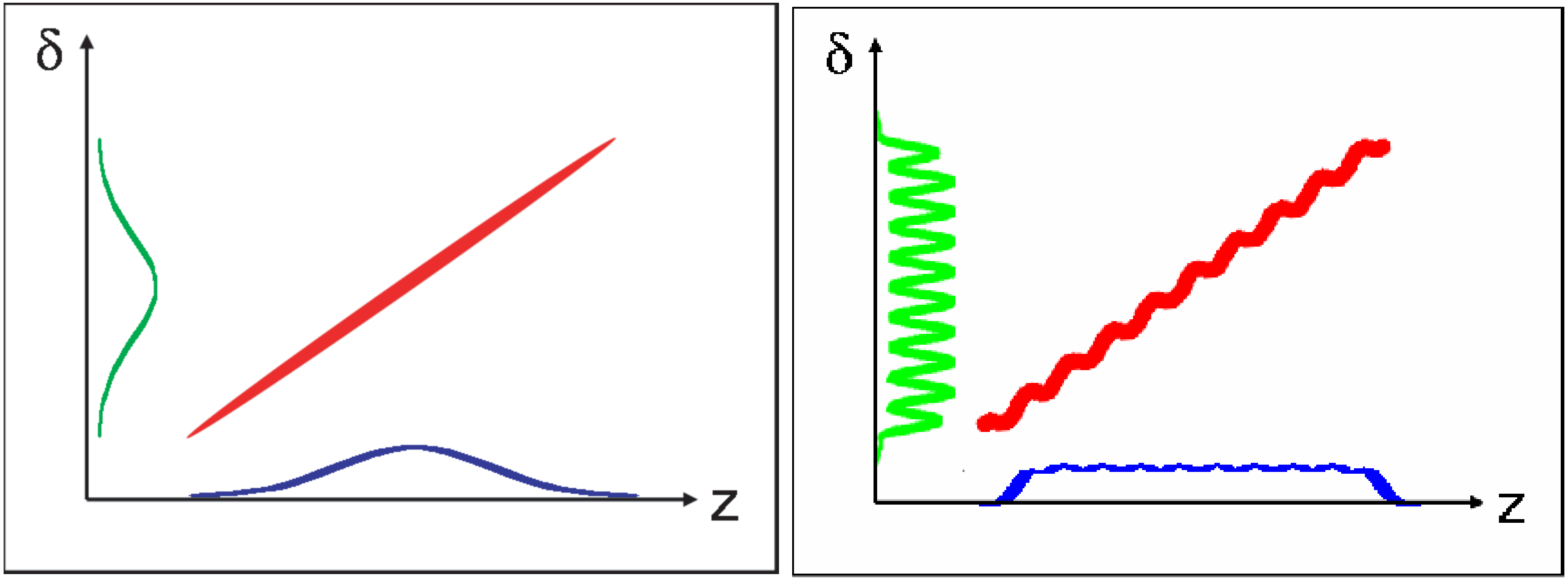




Zero phasing sensitive to energy modulation

Zero phasing sensitive to energy modulation

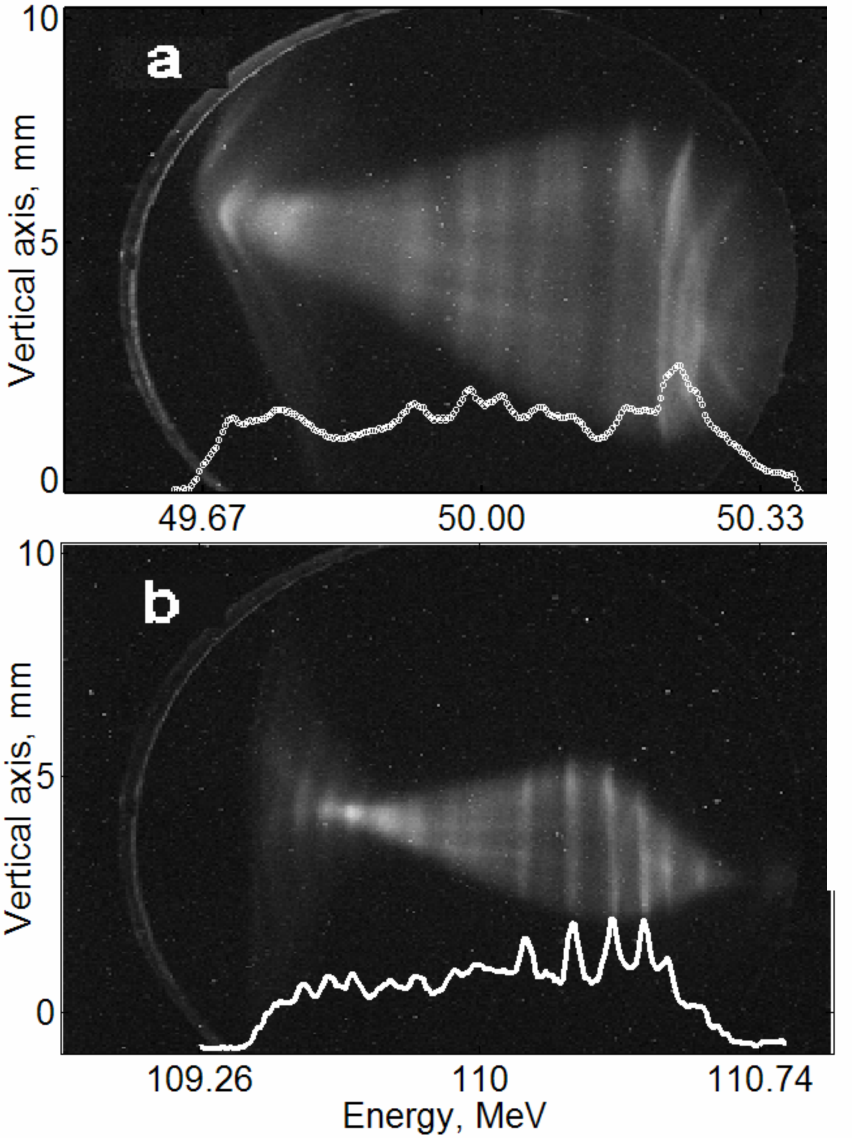
• rf zero phasing energy spectrum is very sensitive to beam energy modulation

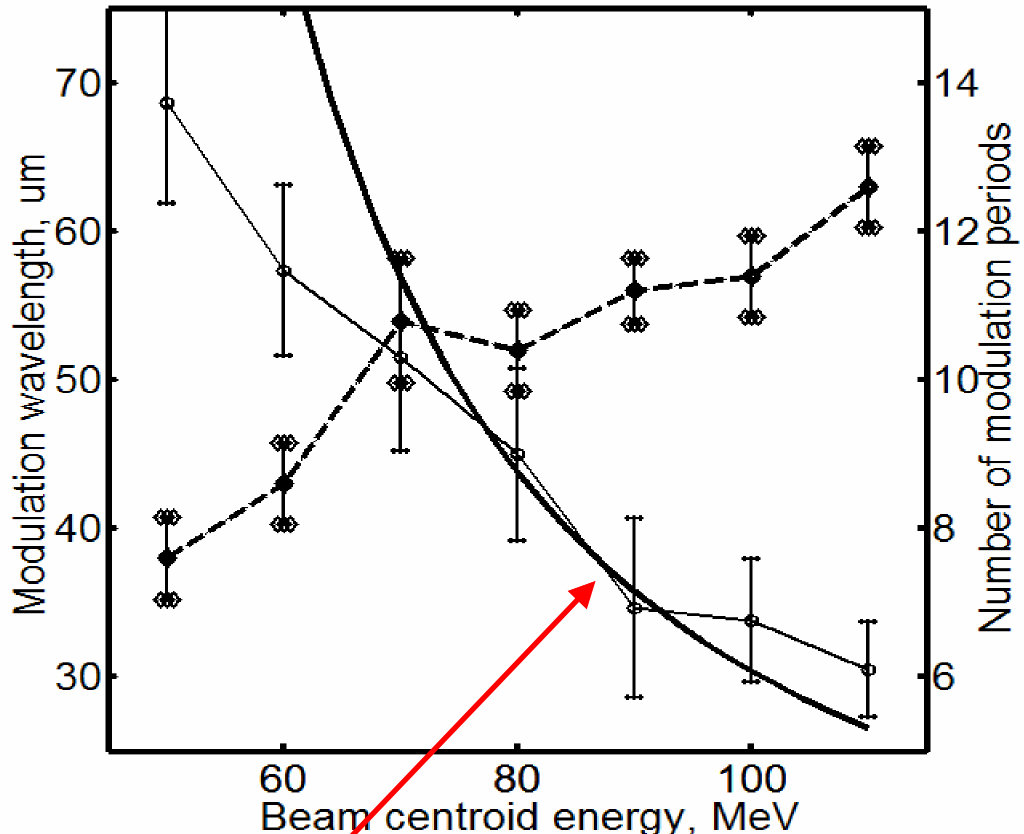


• Small energy modulation gets projected to large horizontal density modulation (enhanced by λ_{rf}/λ_m ~ 1000)

• Measurement can be used to reveal energy modulations

Modulation wavelength



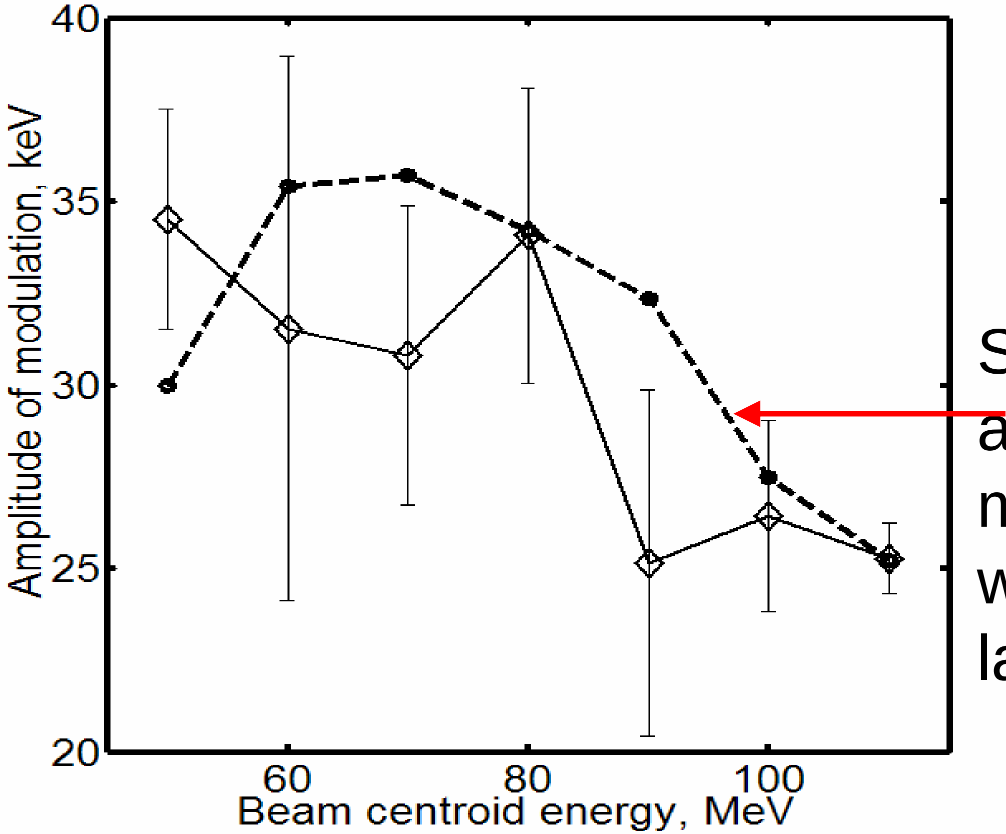


Wavelengths correspond to calculated maximum energy modulation due to space charge dynamics

Shaftan, Huang, PRST, 2004

Energy modulation amplitude

• Zero-phasing modulation can be used to extract energy modulation amplitude
➔ (25 – 35 keV at 200 A or $2X10^{-4}$ at 177 MeV)



Simulated energy modulation assuming 4% initial density modulation after chicane, which is comparable to drive laser modulation amplitude

• Such energy modulations can be converted to large density modulations if a downstream bunch compressor is used, and may hurt a short-wavelength FEL

Summary

- Microbunching instability driven by LSC, CSR and other machine impedances is a serious concern for short-wavelength FELs

- Strong LSC-induced energy modulation (and maybe density modulation) is characterized in DUV-FEL

- Beams from PC RF gun are too "cold" in energy spread, "heating" within FEL tolerance (~10X) to control the instability

- A laser heater with a laser spot matched to the transverse e-beam size is most effective in suppressing microbunching and is designed for LCLS

- It also gives flexible and desirable control of slice energy spread to manipulate FEL signal

Thanks for your attention!

Thank Lia and Alex for the invitation!