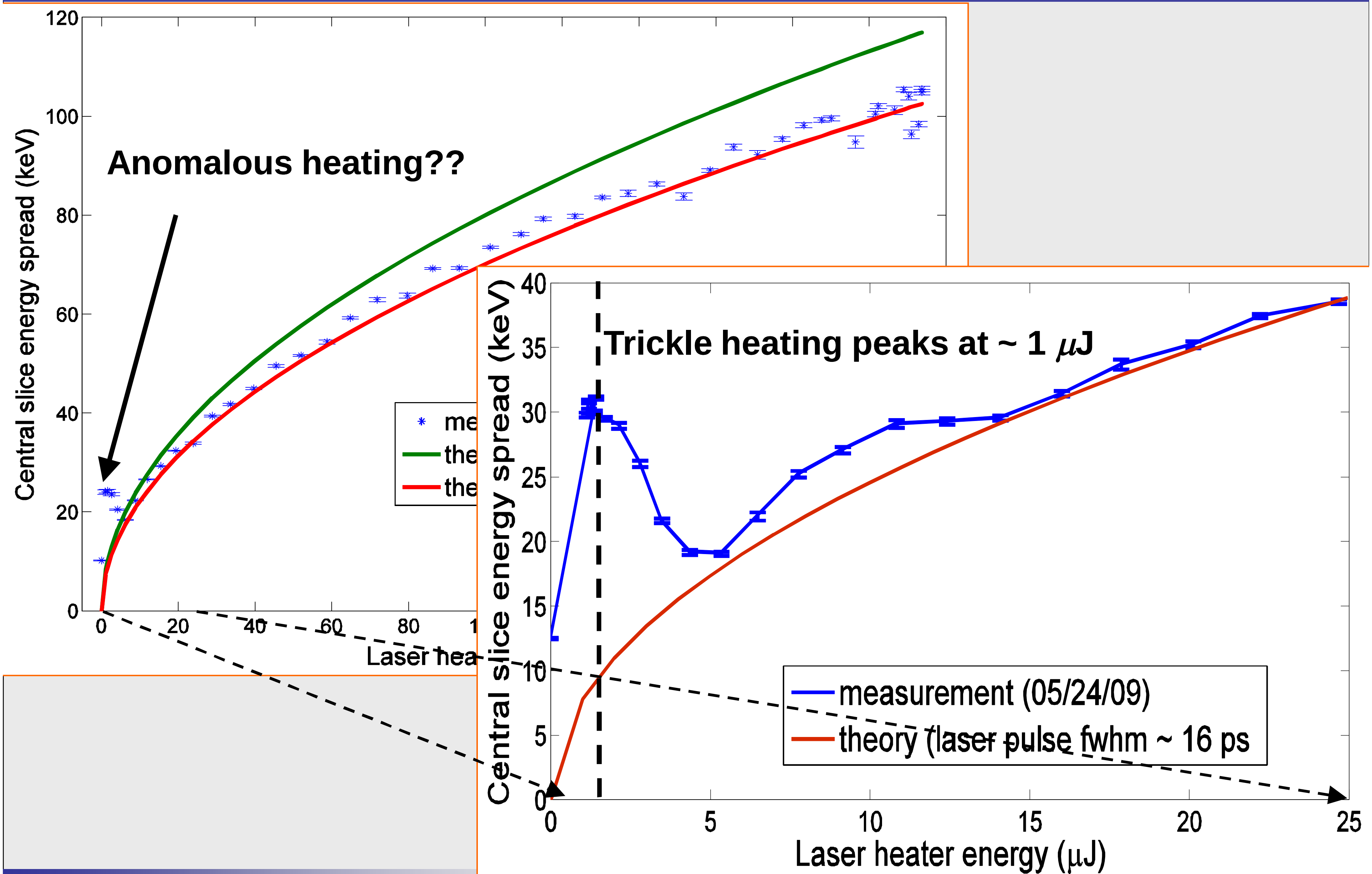
# LCLS trickle heating studies


*Z. Huang for the LCLS commissioning team*

# Introduction

- Anomalous heating at low laser energy level was observed almost right after the heater was turned on
- We didn't understand it for a long time (tried to blame CSR in the spectrometer dipole but calculations show a very small CSR effect)
- Simulations illustrate complicated 4D (x, x', $\delta$, z) phase space evolution after LH chicane
- A 3D Longitudinal space charge (LSC) theory was developed to explain the observed effect

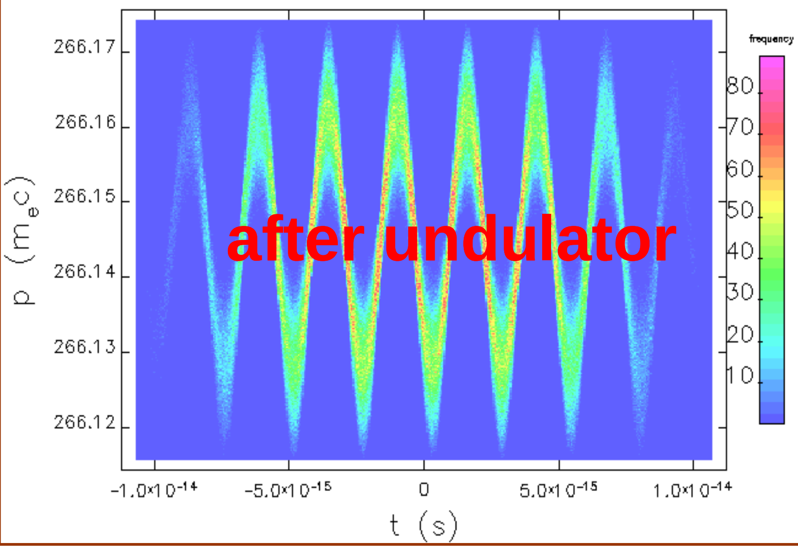
# “Trickle” Heating



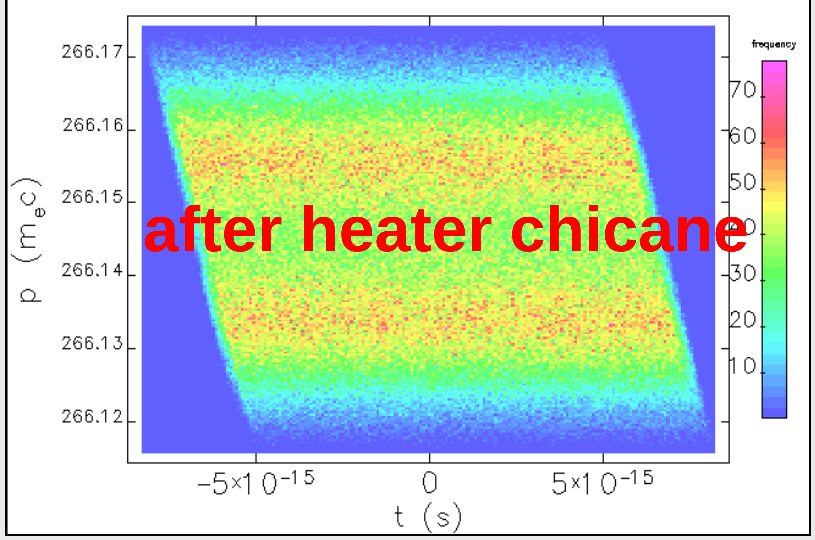
# Laser Modulation Hidden in 4D Phase Space

- Laser heater at 0.5 $\mu$J (Elegant simulation by Y. Ding)

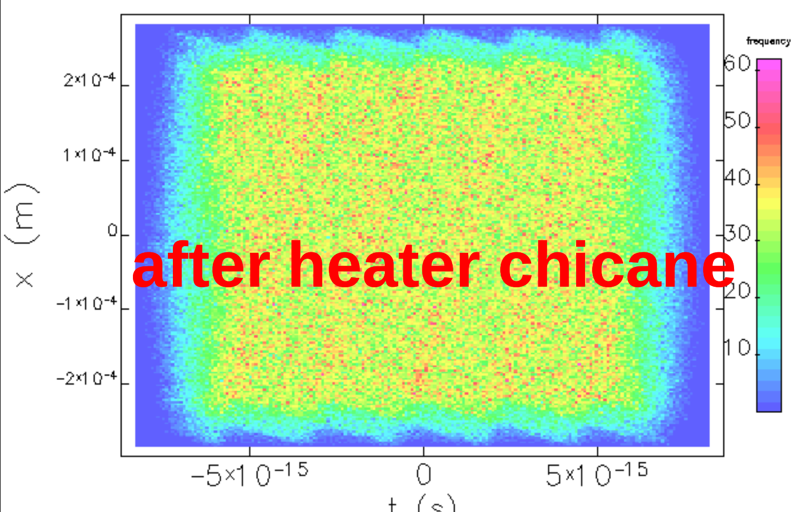
**Longitudinal phase space**



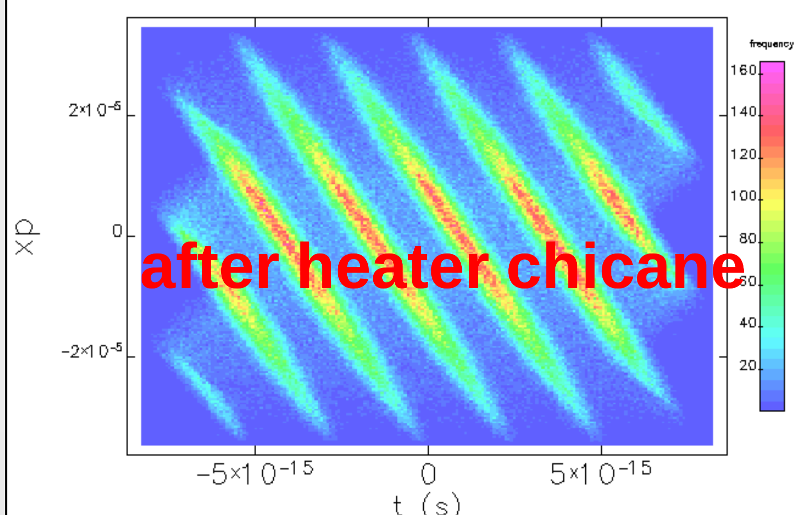

**Longitudinal phase space**



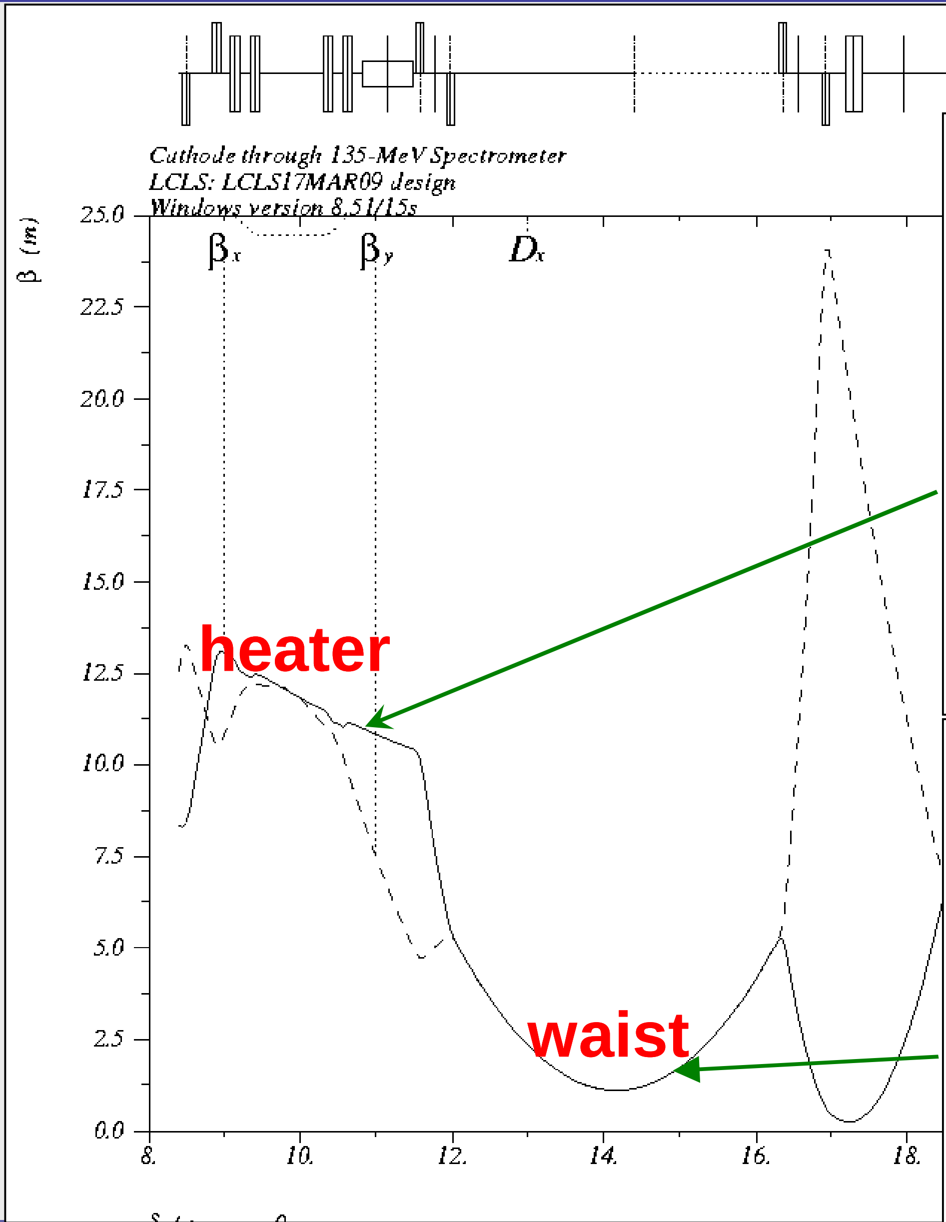

**x-t correlation**

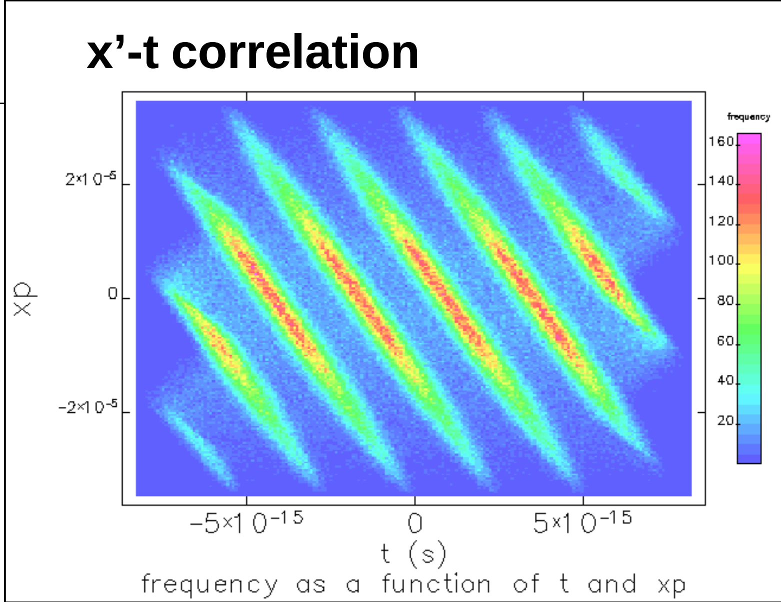


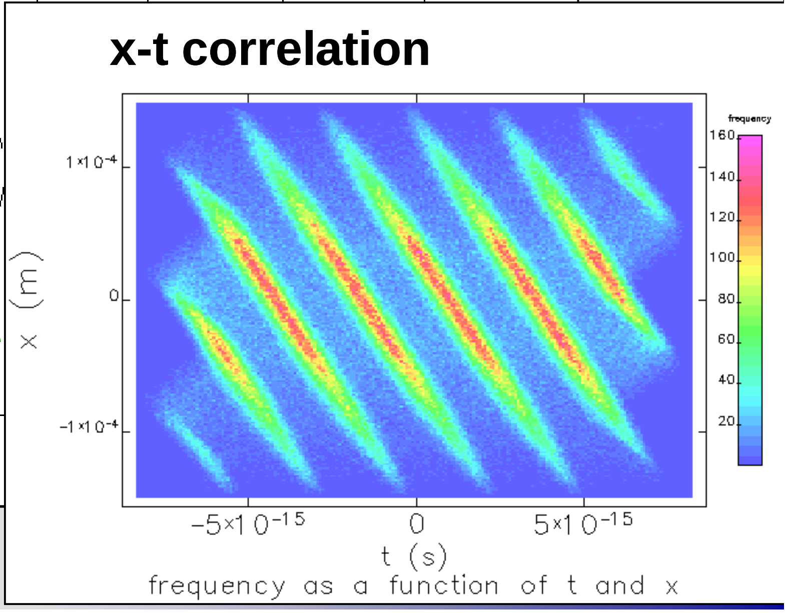

**x'-t correlation (R52 of half chicane)**



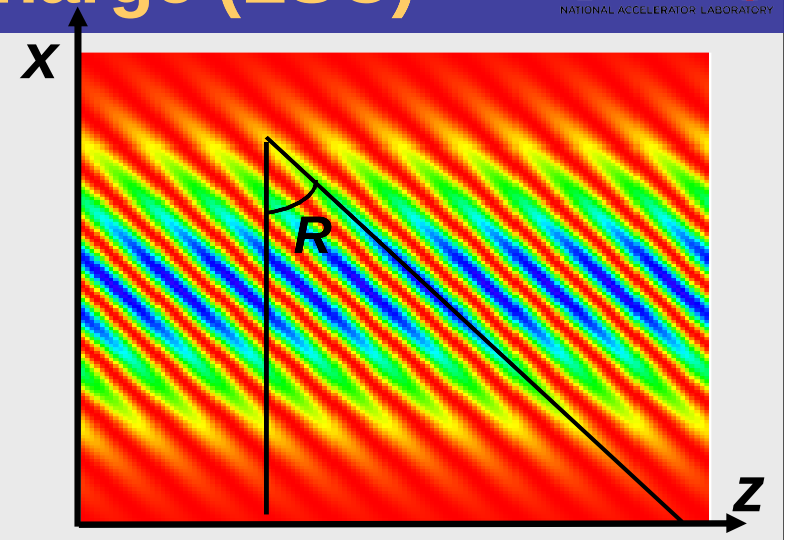
# Modulation Recovered in Real Space



# Longitudinal Space Charge (LSC)




- Consider a beam as shown

tilt angle $R = \Delta z/\Delta x$,

*R is related to transfer matrix*

- When $\sigma_x R > \lambda\!\!\!^{-}$ , longitudinal density modulation is suppressed strongly
- In a 1D approach (as used in *Elegant*), longitudinal modulation multiply by 1D LSC impedance to compute energy modulation

$$E_k^{1D} = a_0 \frac{-ei}{2\pi\epsilon_0 k_L \sigma_x^2} \exp\left(-\frac{k_L^2 R^2 \sigma_x^2}{2}\right)$$

- Beam clearly modulated for tilted microbunching in 3D density

# LSC for a beam with tilted $\mu$bunching

- Longitudinal space charge field

$$E_z(x,y,z) = \frac{e}{4\pi\epsilon_0}\int dx_1 dy_1 dz_1 \frac{\rho(x_1,y_1,z_1)\gamma(z-z_1)}{[(x-x_1)^2+(y-y_1)^2+\gamma^2(z-z_1)^2]^{3/2}}$$

$$\rho(x,y,z) = \frac{2a_0}{2\pi\sigma_x^2}\cos[k_L(z-Rx)]\exp\left(-\frac{x^2+y^2}{2\sigma_x^2}\right)$$

- Fourier transforming on-axis $E_z(x=y=0)$, we have

$$E_k = a_0\frac{-eik_L}{2\pi\epsilon_0\gamma^2}\int\frac{rdr}{2\pi\sigma_x^2}\int_0^{2\pi}d\phi\exp\left(-\frac{r^2}{2\sigma_x^2}\right)e^{-ik_L Rr\sin\phi}K_0\left(\frac{kr}{\gamma}\right)$$

- Introduce scaled parameters $\xi = k_L r/\gamma$ and $\xi_\sigma = k_L\sigma_x/\gamma$

$$E_k = a_0\frac{-eik_L}{2\pi\epsilon_0\gamma^2}\int\frac{\xi d\xi}{\xi_\sigma^2}\exp\left(-\frac{\xi^2}{2\xi_\sigma^2}\right)J_0(\gamma R\xi)K_0(\xi)$$

# 3D Limit

- When beam size $\sigma_x$ is much larger than $\gamma\lambda\!\!\!^{-}$, LSC field is

$$E_k = a_0 \frac{-ei}{2\pi\epsilon_0 k_L \sigma_x^2} \frac{1}{1+\gamma^2 R^2}$$

- LSC depends weakly on $\gamma R$ when $R<1/\gamma$
  ➔Tilted microbunching does not suppress LSC exponentially.
- A similar result for LSC induced microbunching is derived in this regime to study COTR (D. Ratner, A. Chao, Z. Huang, FEL08)
- 1D approach underestimates LSC by a large factor

$$\frac{E_k}{E_k^{1D}} = \frac{e^{k^2 R^2 \sigma_x^2/2}}{1+\gamma^2 R^2}$$

Take $\lambda_L$=758 nm, $\gamma$=264, $\sigma_x$=60μm, $\gamma R$ ~2, 1D underestimates LSC by a factor ~250!

- Now take into account beam optics downstream of heater

# LH chicane optics

- At the end of LH chicane, longitudinal position *z*

$$z = z_0 + R_{56}\left[\delta_0 + \delta_m \sin(k_L z_0)\right] + R_{52}x'_0$$

initial energy spread   laser-induced E-modulation   x'-z correlation

- Relative *z* position doesn't change after chicane, but x & x' do

$$x = R_{11}x_0 + R_{12}x'_0\,,$$
$$x' = R_{21}x_0 + R_{22}x'_0\,.$$

- After some phase advance, x'-z → x-z.
- If beam size is small there, strong LSC field is generated to energy-modulate the beam

- Sensitive to current, emittance, and focusing optics

# Integrate LSC over beamline



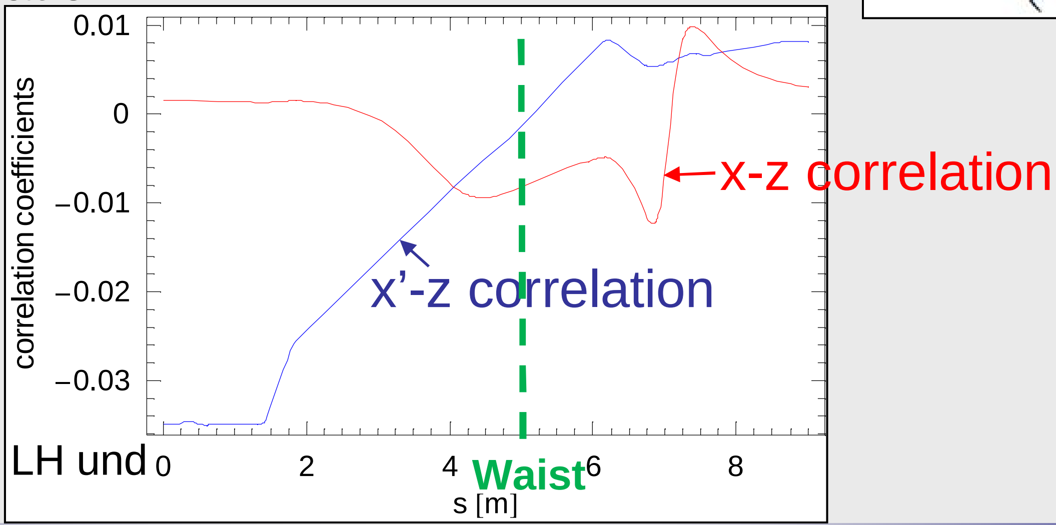
- Assume $k\sigma_x/\gamma$ >>1 (mostly OK) and equal x/y beam sizes
- Integrating LSC effect from LH to BXS with proper optics

$$\delta_{LSC} = \int ds \frac{eE_z(k_0)}{\gamma mc^2} = \frac{2i}{k_0\gamma}\frac{I_0}{I_A} J_1(k_0 R_{56}\delta_L) \exp\left(-\frac{k_0^2 R_{56}^2 \sigma_{\delta 0}^2}{2}\right) \times \int ds \exp\left(-\frac{k_0^2 \eta_c^2 R_{11}^2 \varepsilon}{2\beta}\right) \frac{1}{\sigma_x^2(1+\gamma^2 R^2)}$$

Longitudinal bunching factor w/o transverse correlation

dispersion in LH chicane

$$R = \eta\left(R_{21} + \frac{\alpha}{\beta} R_{11}\right)$$

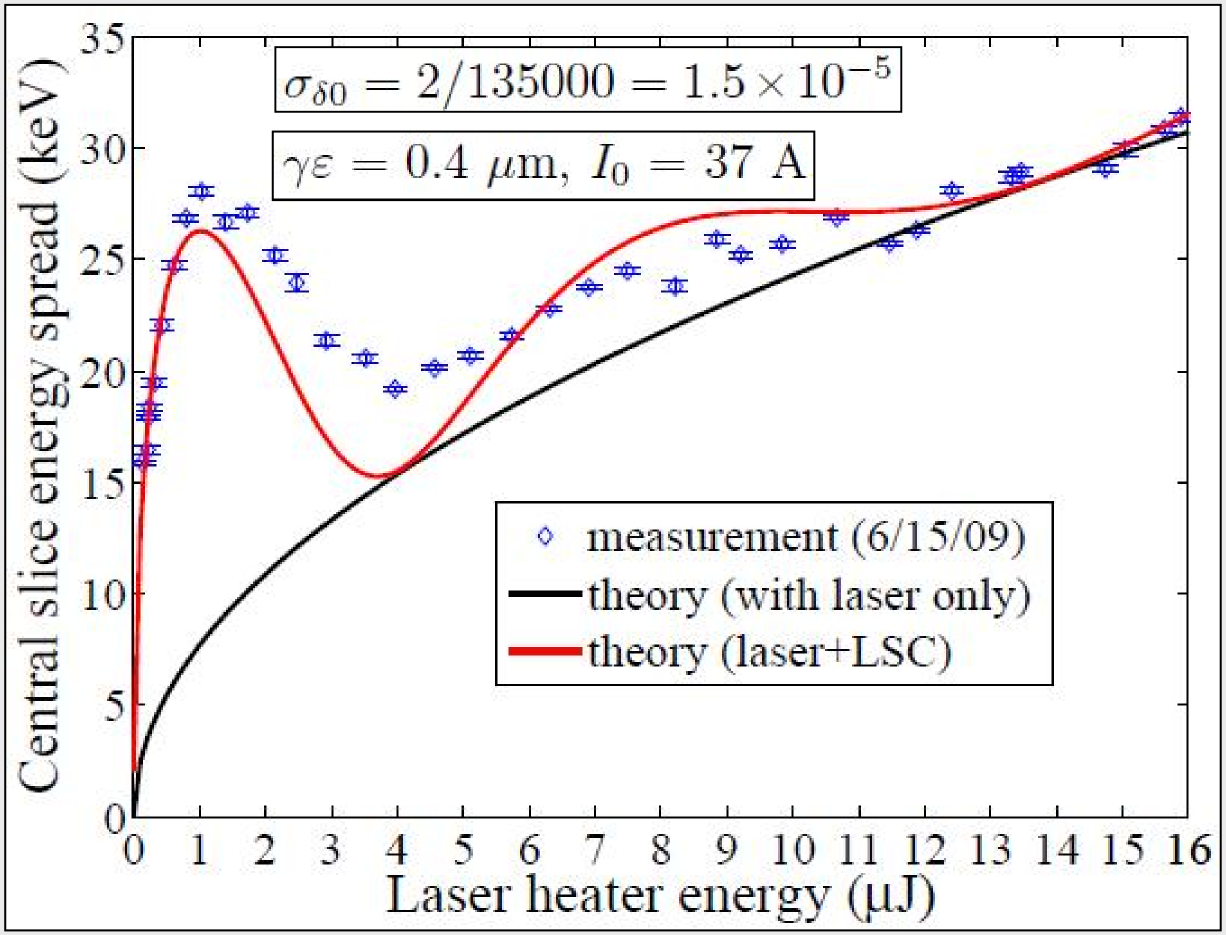


# Comparison with measurements



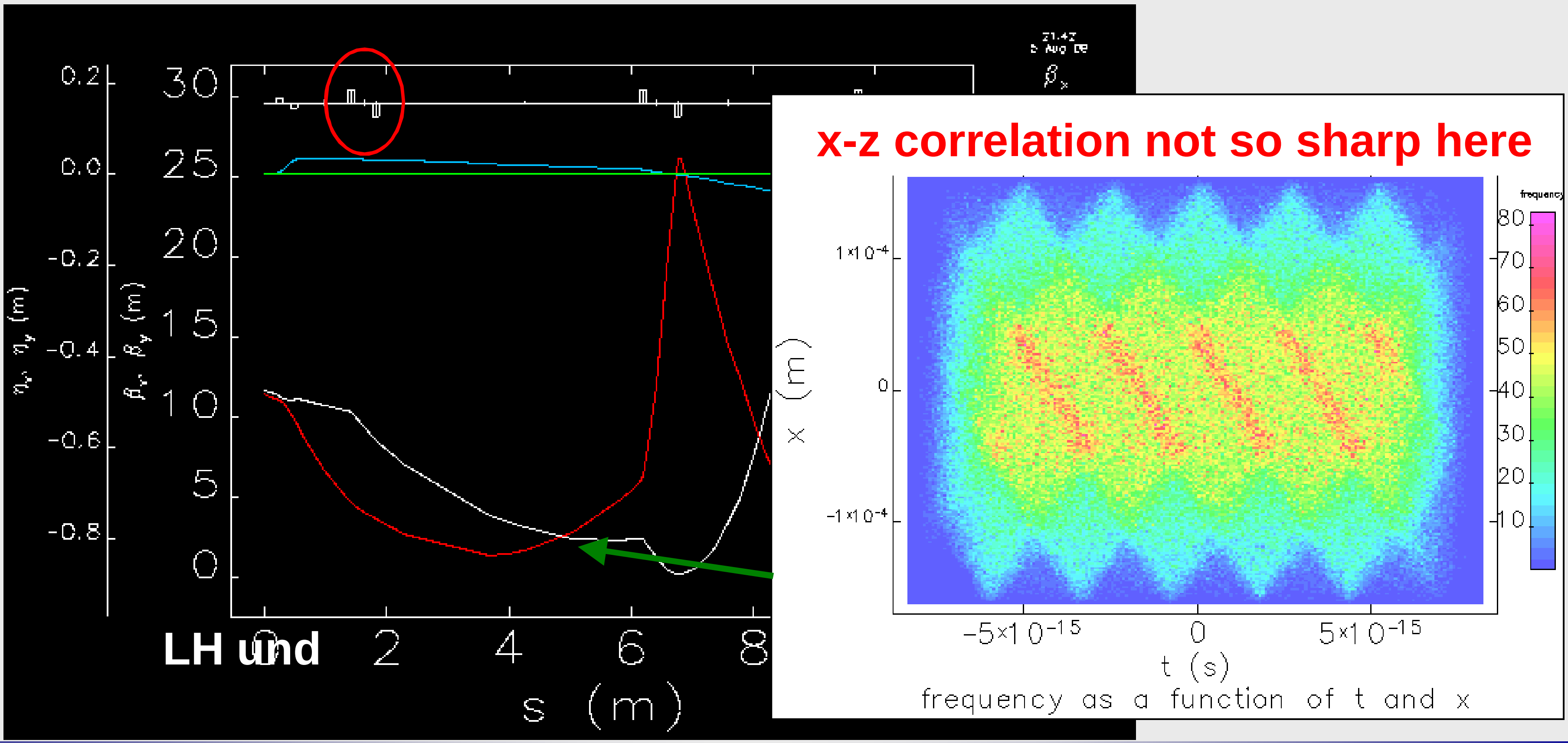
- Add LSC-induced E-spread to laser-induced E-spread

$$\sigma_{\delta_f} = \sqrt{\sigma_{\delta 0}^2 + \left(\frac{\sigma_{\Delta E}}{\gamma_0 mc^2}\right)^2 + 2|\delta_{LSC}|^2}$$



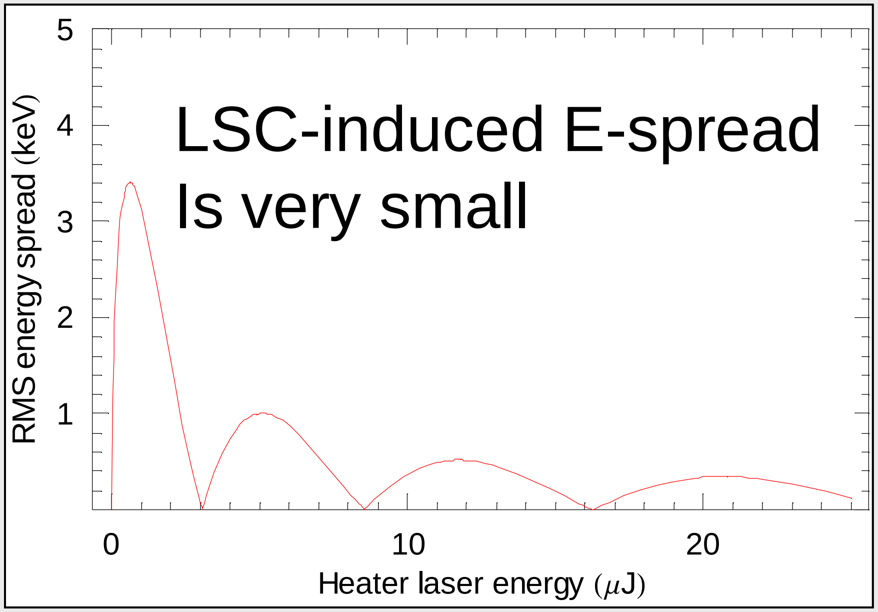
# To trickle or not to trickle

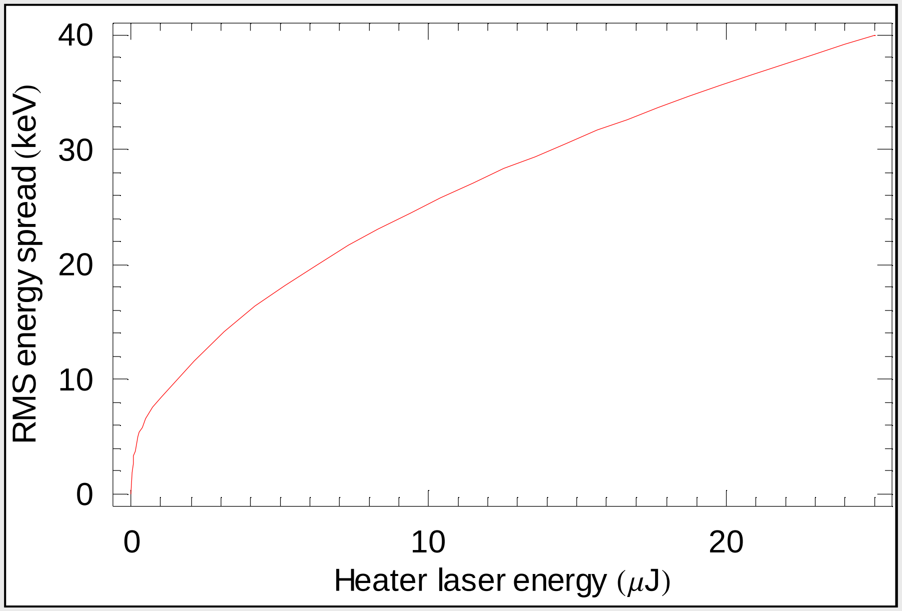
- In a few shifts we didn't observe trickle heating (suspect that transverse optics was changed by the matching program)
- Change only 2 quads after LH, with some optics mismatch downstream of LH chicane



# No trickle heating by tweaking optics

- In this setup, suppression of microbunching due to Gaussian angular spread is more effective



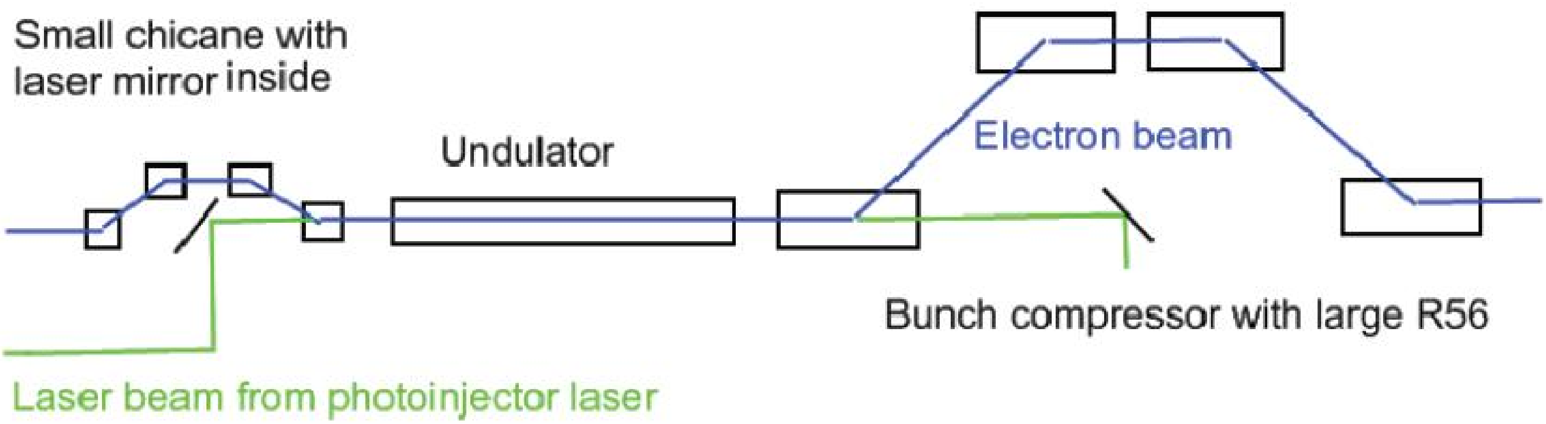




- LSC effect is too small with this optics to have trickle heating

- May be a viable way for the LCLS to get rid of trickle heating

# Laser heater for FLASH?






No dispersion in the undulator: no tilt of energy-chirped beam

Does this scheme avoid trickle heating? Safe smearing through BC2 - but what happens inside?

In the first dipole of BC2:

$$R_{51} = \theta \qquad R_{52} = \frac{R\theta^2}{2} \qquad R_{56} = \frac{R\theta^3}{6}$$

***Courtesy E. Schneidmiller***

# Laser heater for FLASH? (cont'd)



In the first dipole of BC2: coherent density modulations may appear due to $R_{56}$. For laser induced energy modulations about 10 keV the required $R_{56}$ (for strong density modulations) is on the order of 1 mm. For R = 1.6 m this corresponds to the bending angle 0.15 (middle of the dipole). At this position $R_{51}$= 0.15, $R_{52}$= 2 cm. For emittance 1 mm mrad and beta about 10 m:

$$\sigma_x R_{51} \approx 30 \mu m \qquad \sigma_{x'} R_{52} \approx 0.4 \mu m$$

to be compared with $\lambda/(2\pi) \approx 0.08 \mu m$ for green light.

The tilt parameter $(\gamma\theta)^2 = (\gamma R_{51})^2 \approx 10^3$ for "tilted LSC" (not applicable in bends

CSR is strongly suppressed due to transverse size $\sigma_x$ >> $(\lambda/2\pi)^{2/3} R^{1/3}$

and large tilt $\theta$ >> $(\lambda/2\pi R)^{1/3}$

$R_{51}$ and $R_{52}$ quickly increase along the compressor and smear modulations through the whole compressor, except very end – but there we have strong (and irreversible!) smearing due to $R_{56}$ = 20 cm.

No self-heating is expected - to be checked with codes like CSRtrack

# Summary

- Anomalous "trickle" heating is explained by a 3D LSC model.
- Trickle heating does not affect LCLS operation but may have implications to other laser heater designs as well as laser-manipulations of high-brightness beams.
- Low charge (20pC) experience: heater off seems to be best (or just as good).
- Simulations suggest a small amount of heating (~5 keV) optimizes low-charge performance (near full compression).
- We may have to get rid of trickle heating in order to control the slice energy spread at this small level!