Measurements of the LCLS Laser Heater and its impact on the X-ray FEL Performance

Z. Huang for the LCLS commissioning team

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Outline

- *Why a Laser heater?*
- *LCLS setup and measurements*
- *Effects on FEL performance*
- *Anomalous heating effects*

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Introduction

- Beams from photoinjectors have extremely small initial slice energy spread (2-3 keV).
- Such a "cold'' beam can undergo a *microbunching instability** in linacs and compressors that may ruin beam quality.
- "Heating" slice energy spread within the FEL tolerance can suppress the instability and make the beam more stable.
- Many FEL designs call for a laser heater in the injector.
- First of its kind was installed and commissioned at LCLS

* *Borland et al., NIMA (2002);*
Saldin, Schneidmiller, Yurkov, NIMA (2002);
Heifets, Stupakov, Krinsky, PRST-AB (2002);
Huang, Kim, PRST-AB (2002).

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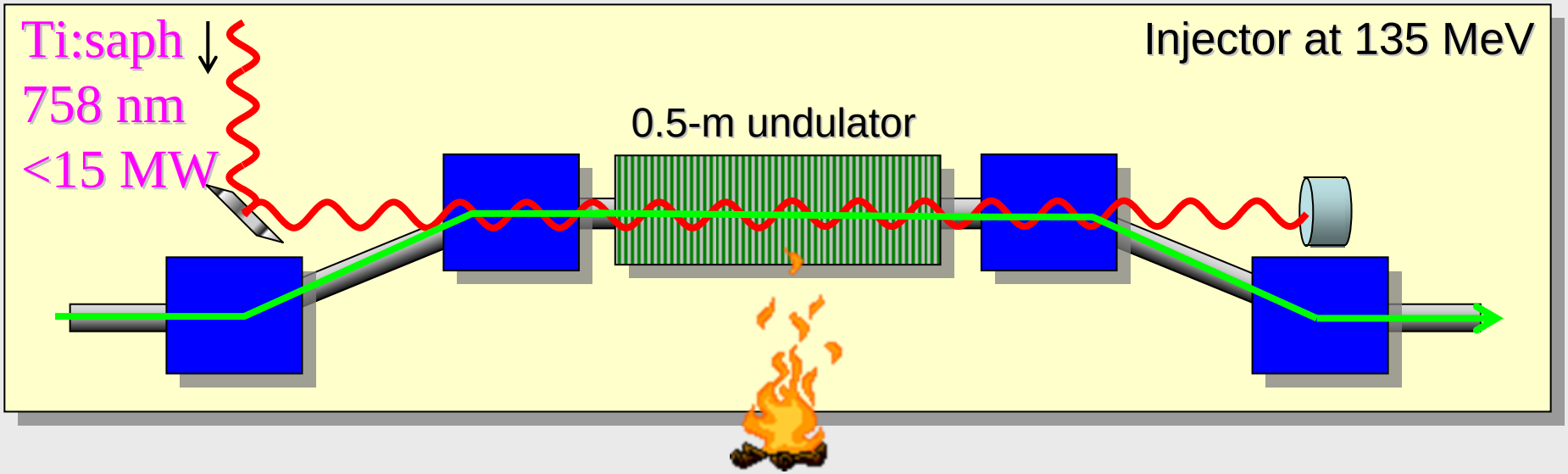
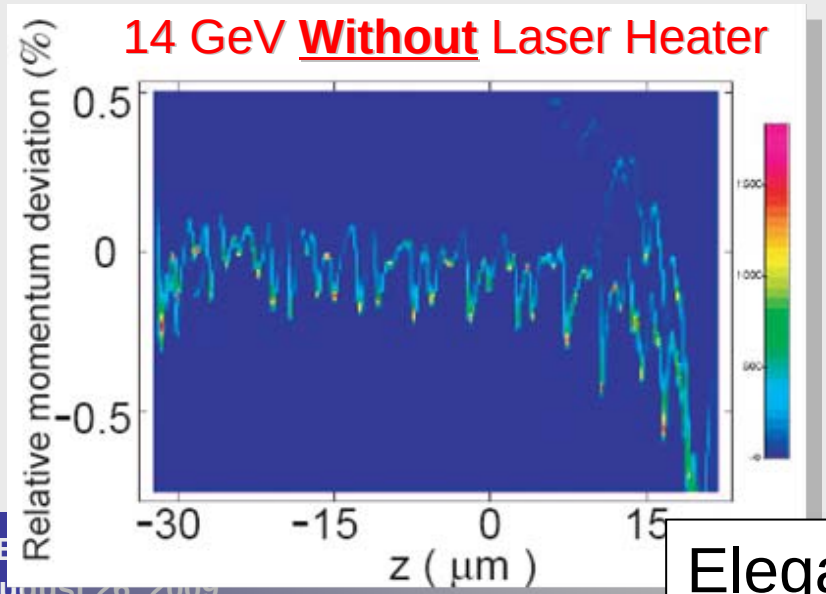
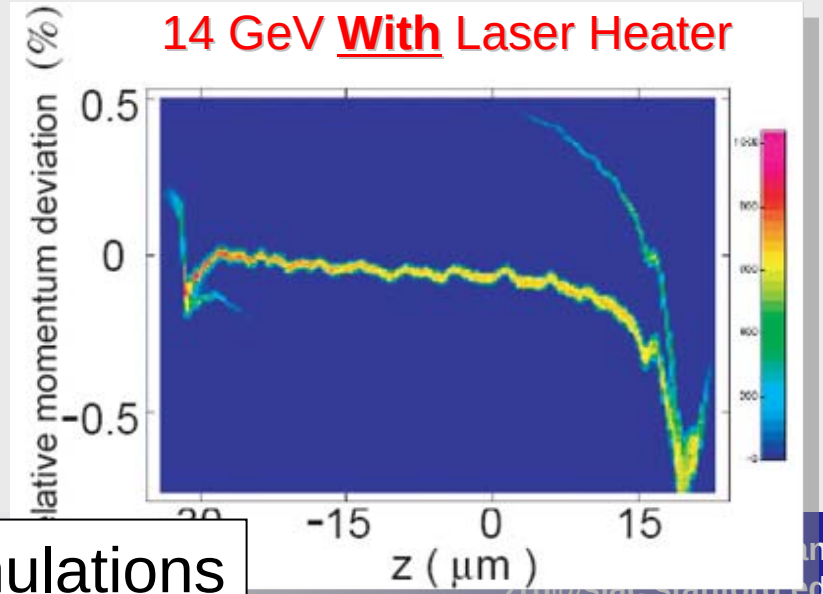
μ-Bunching Landau Damped by Laser Heater



'Laser heater' suggested by Saldin et al., NIMA, 2004; independently by J. Galayda

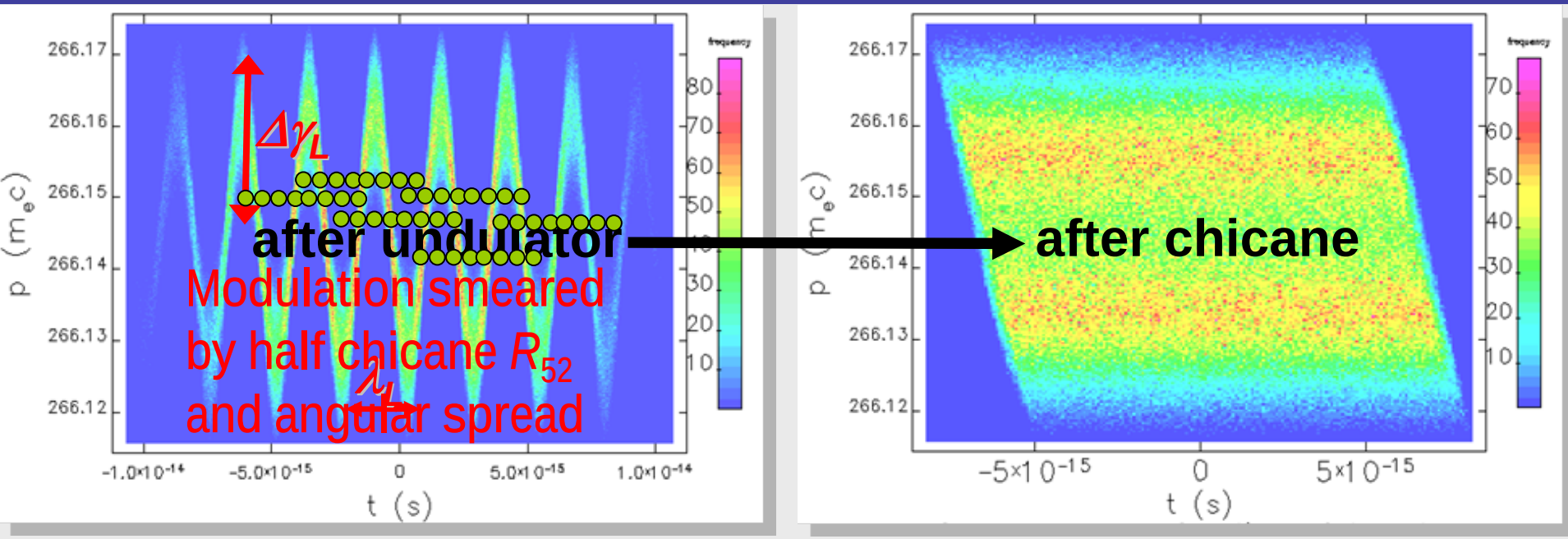
LCLS design study: Z. Huang et al., PRST 2004 (chicane suggested by T. Smith)





Elegant simulations

How does a laser heater work?



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

laser peak power

laser rms spot size

- The last half chicane time-smears the energy modulation leaving an effective "thermal" energy spread increase

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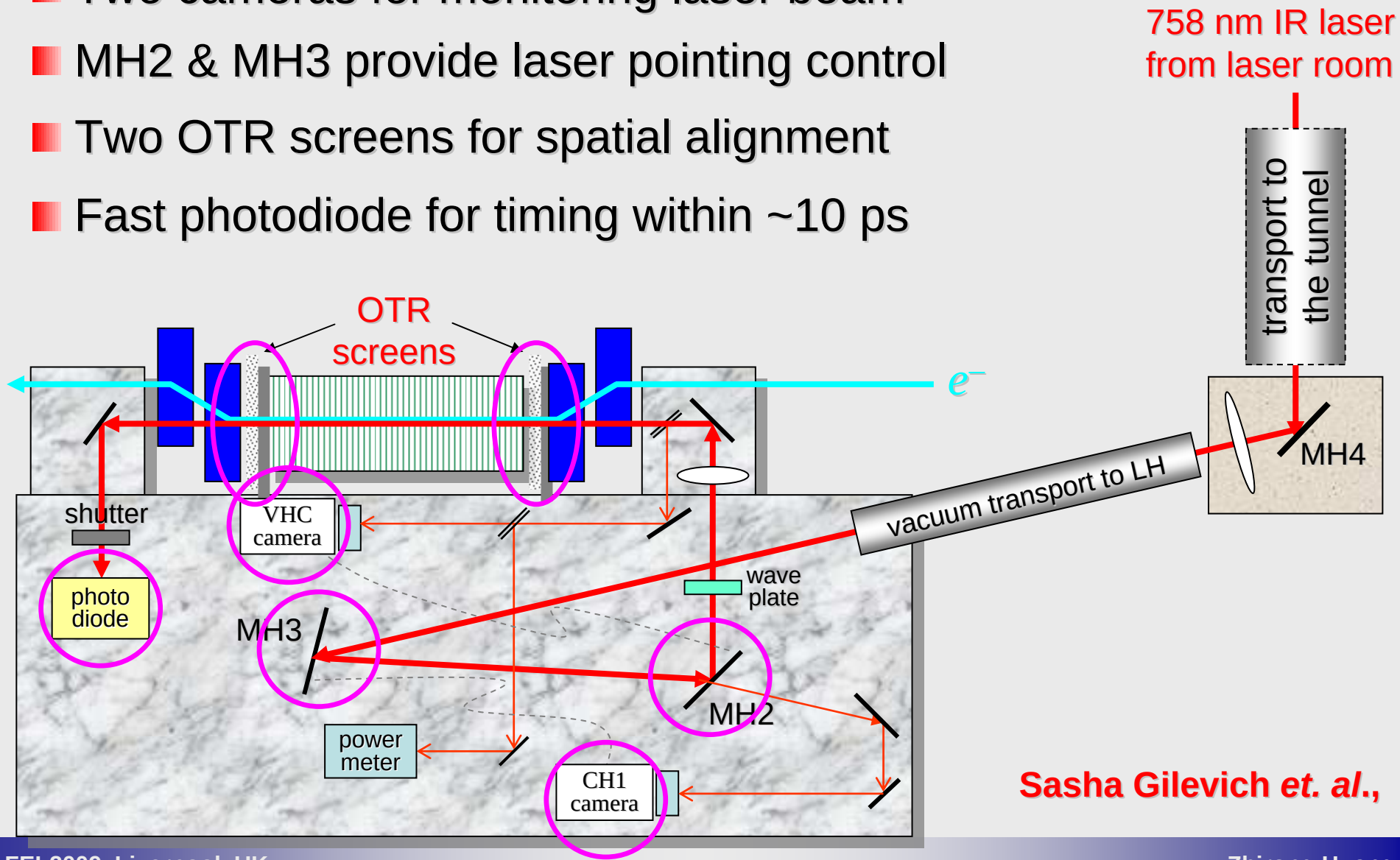
Layout of the Laser Heater Optics

- Two cameras for monitoring laser beam
- MH2 & MH3 provide laser pointing control
- Two OTR screens for spatial alignment
- Fast photodiode for timing within ~10 ps



Sasha Gilevich *et. al.*,

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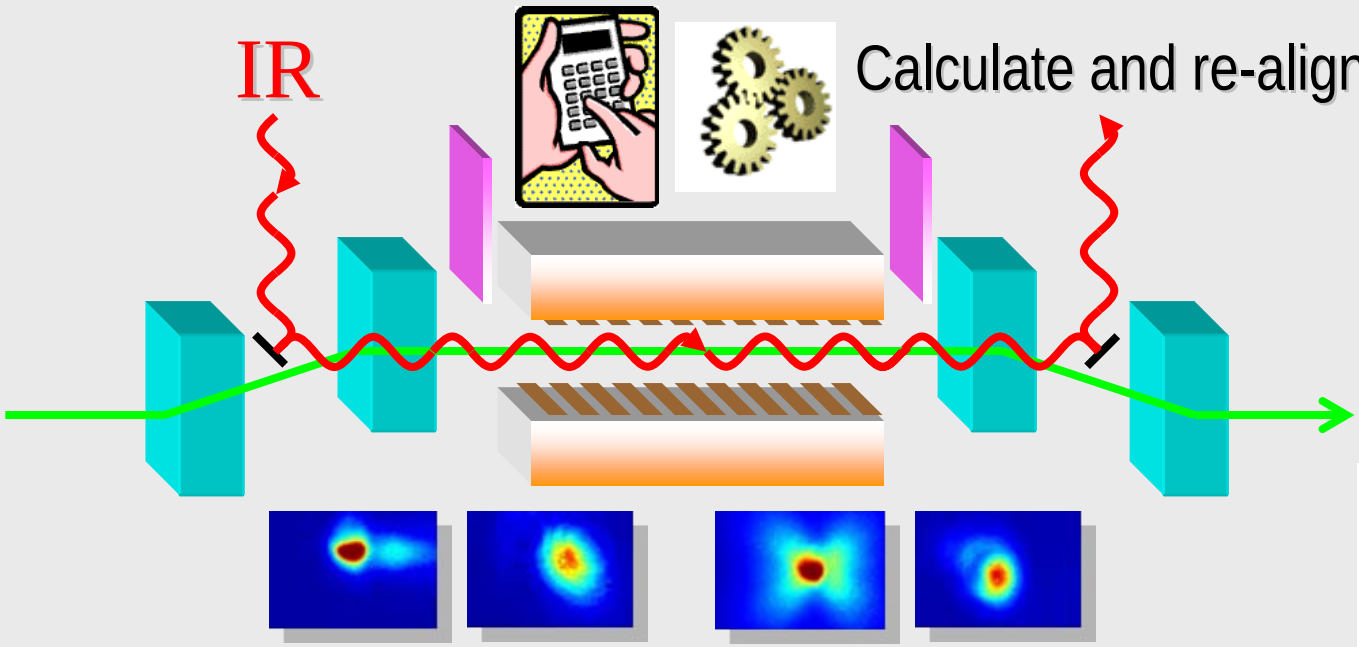
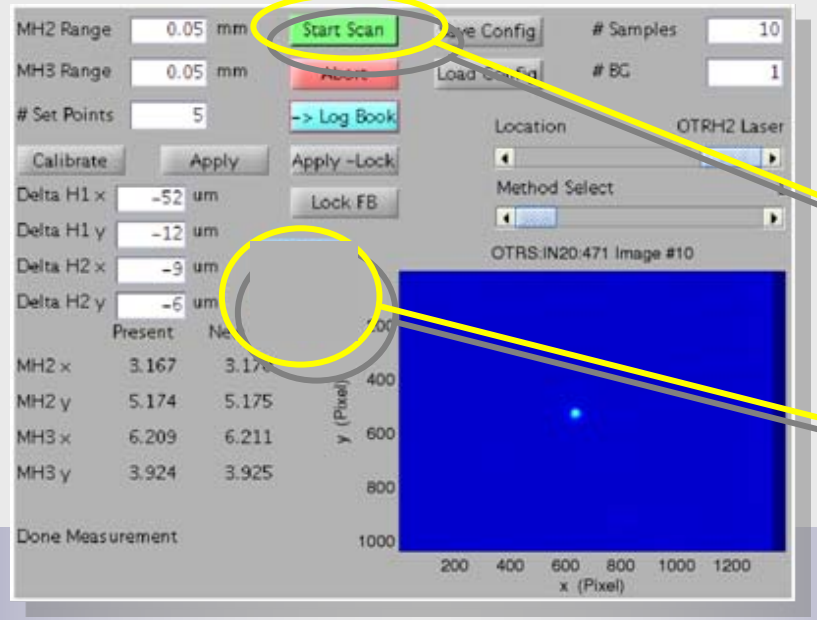
Laser Heater Spatial Alignment



Slide from
P. Emma



One button click
(~1 minute)

After three iterations
Dave approves it!

H. Loos

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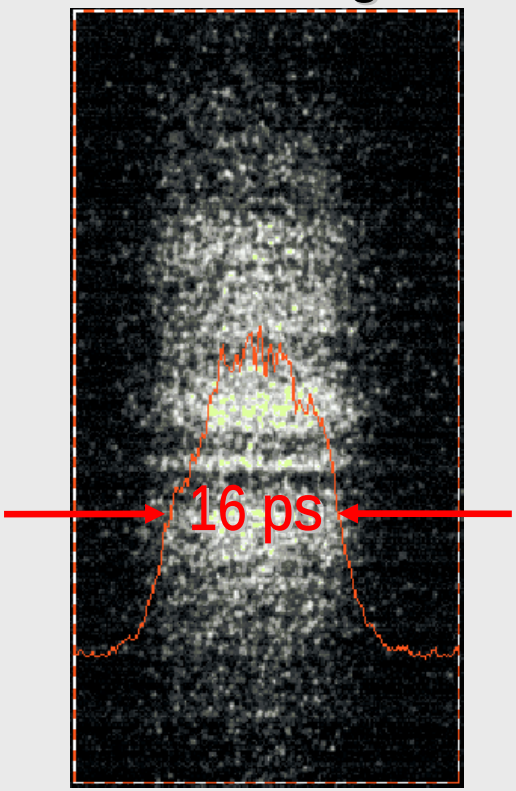
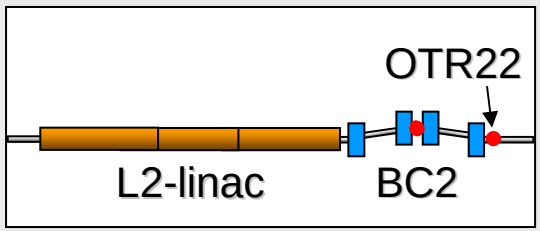
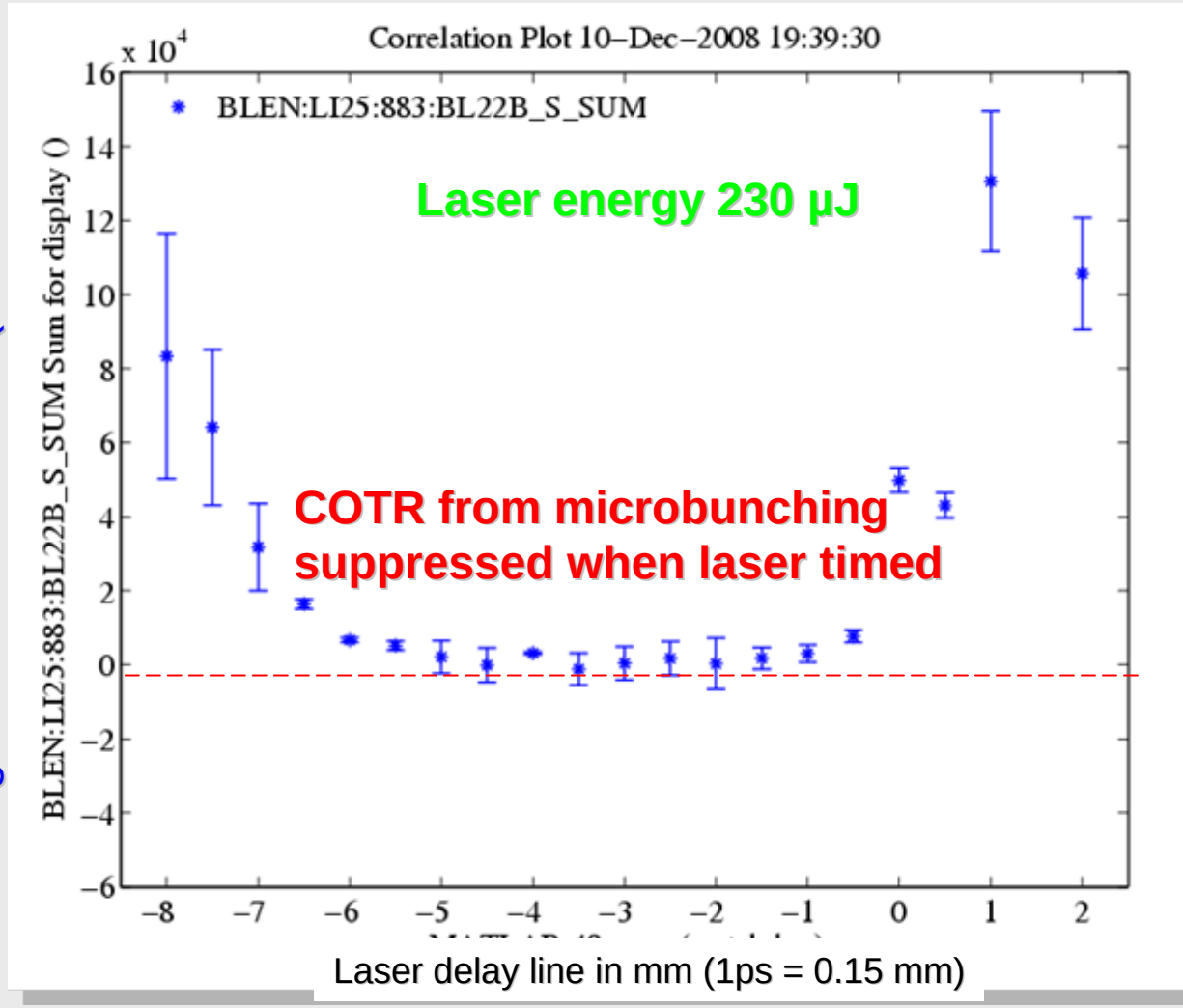
Laser Heater Temporal Overlap

- Laser pulse 10-20 ps, electron bunch 5-7 ps
- Laser timing done by minimizing the **COTR** signal after BC2





COTR signal after BC2 bends (OTR22 inserted)



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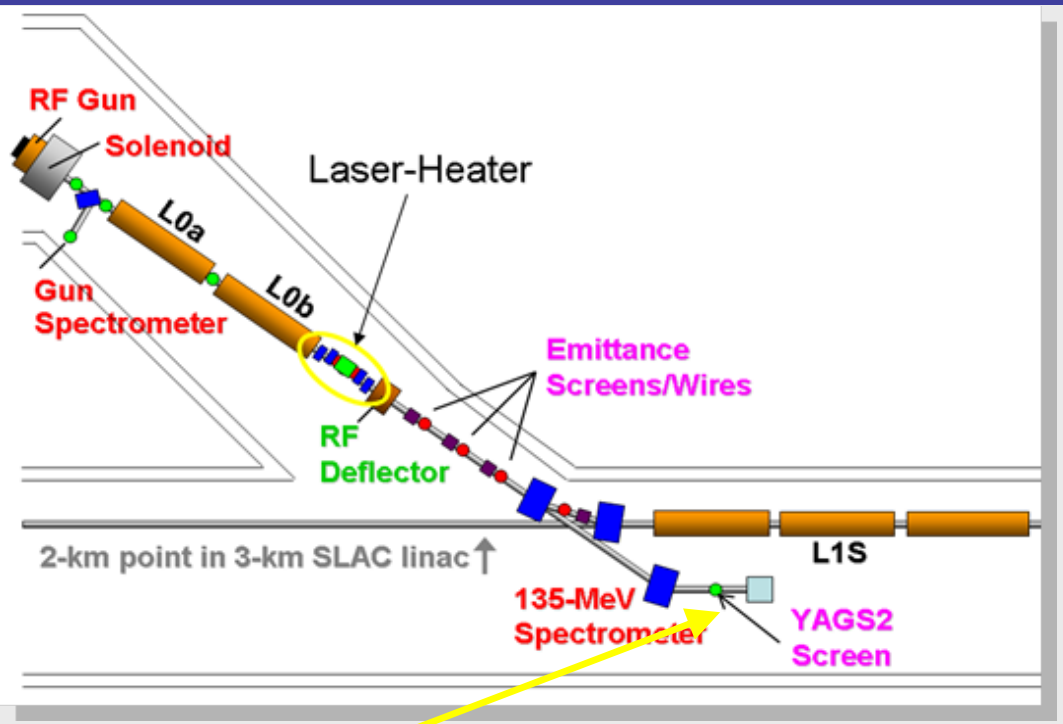
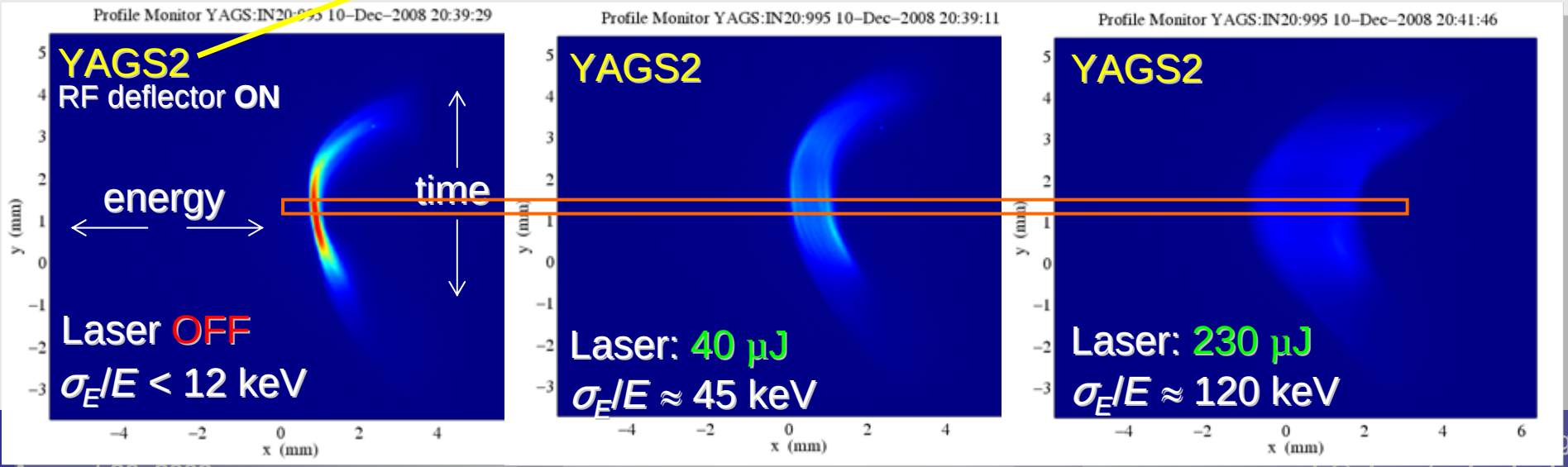
Heating Measurements





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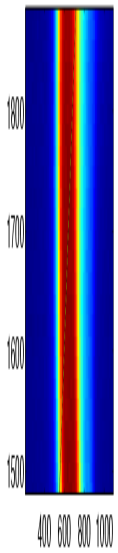
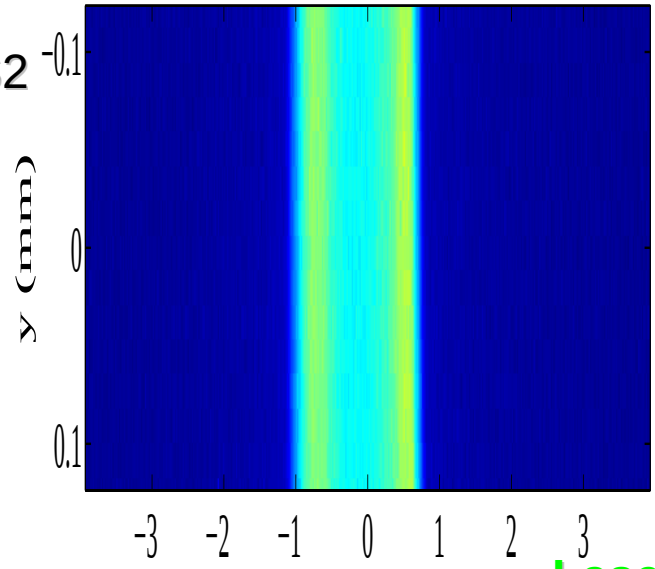
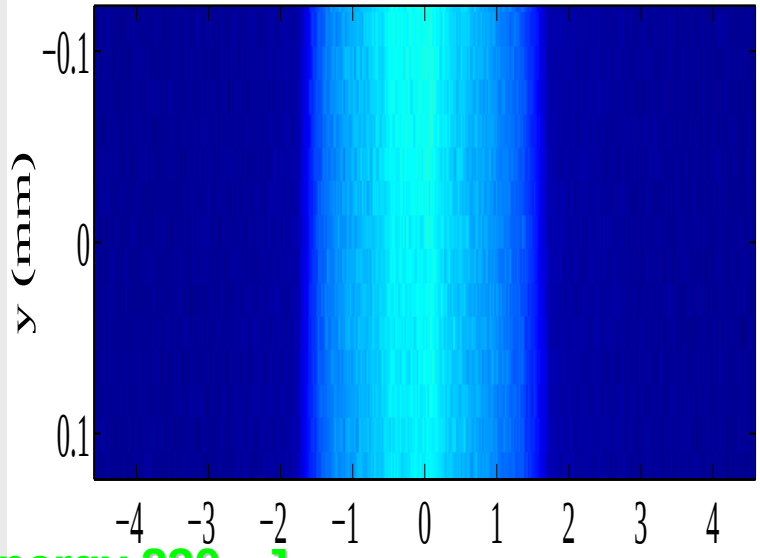
Slice Energy Spread

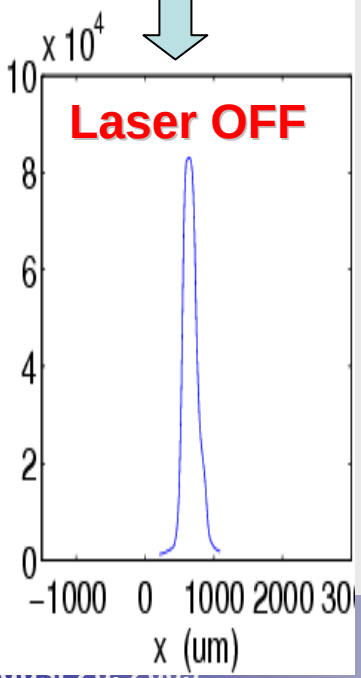


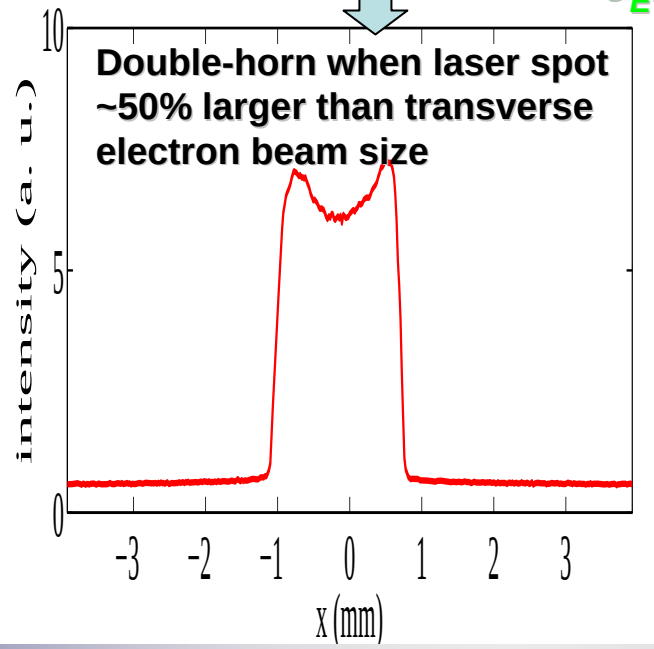


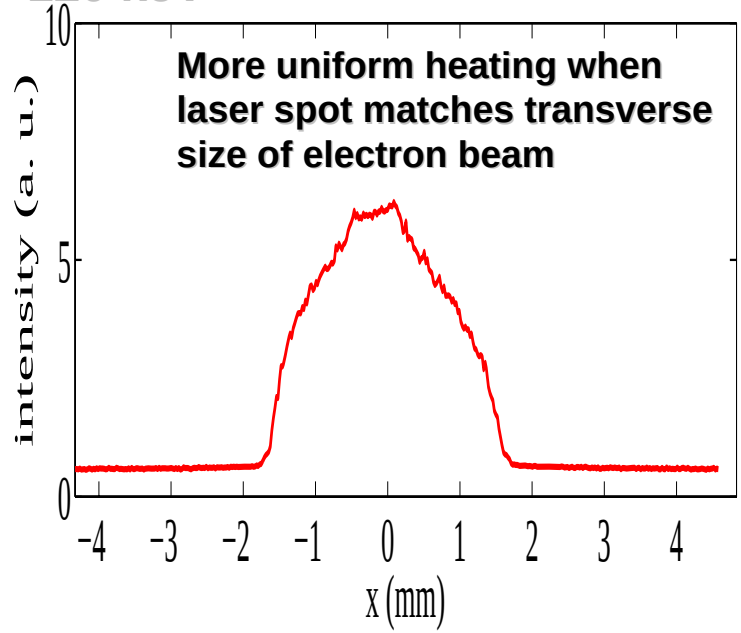


Laser energy 230 μJ

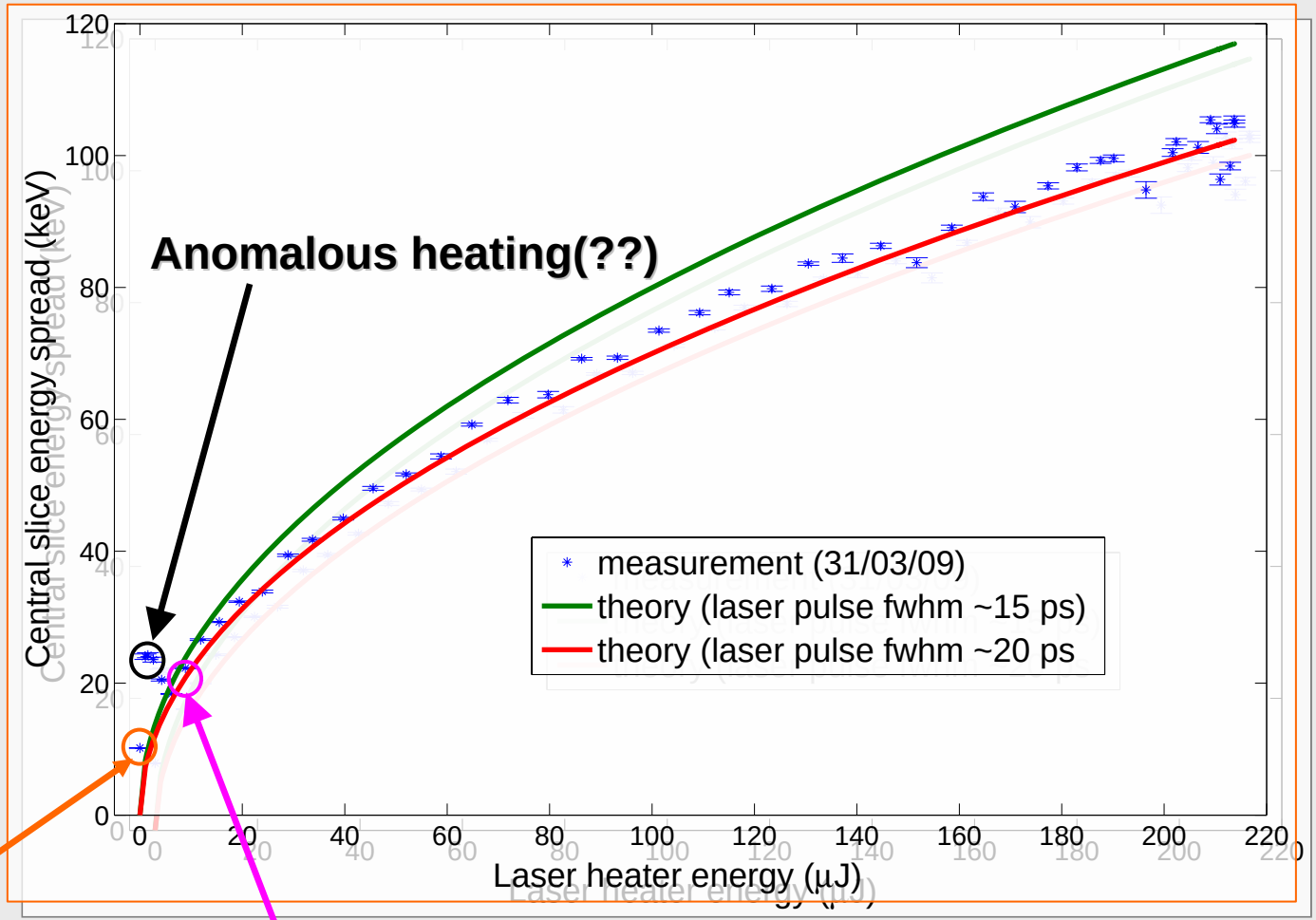
$\sigma_E/E \approx 120$ keV







Slice-E Spread vs. Laser Energy



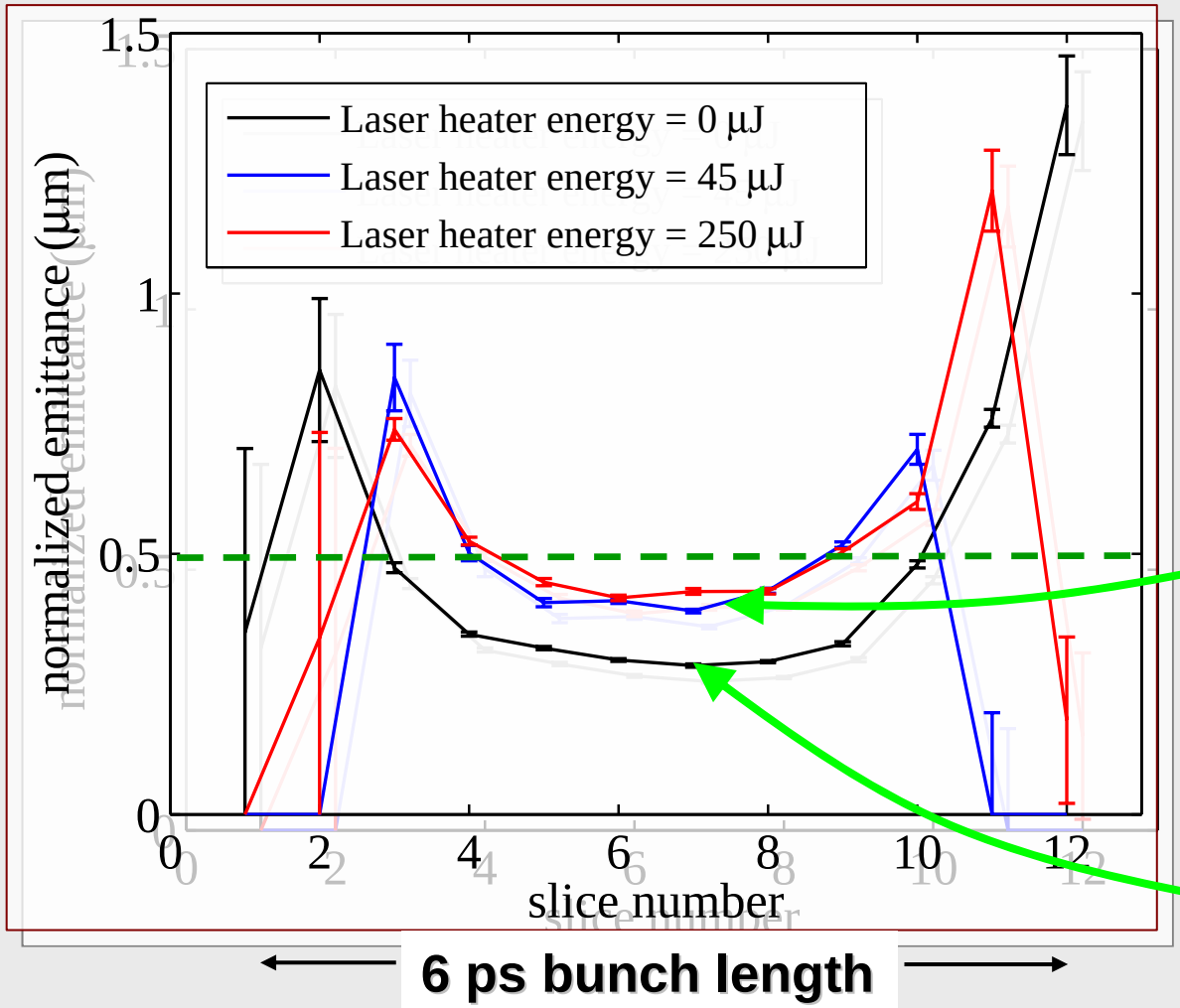
No heating < 10 keV
(limited by resolution)

Operating point (~7 uJ)
20 keV × compression ratio 75/14GeV = 1.1×10^{-4}

No Emittance Growth from Heating

- Laser-induced E-spread in chicane does not introduce emittance growth (< 2%)

$$\frac{\Delta\epsilon_x}{\epsilon_x} \approx \frac{1}{2}\left(\frac{\sigma_{\gamma_L}\eta}{\gamma_0\sigma_x}\right)^2$$



6 ps bunch length

Heater from 45 μJ to 250 μJ, no change in slice emittance

Heater off, COTR after LH chicane biases emittance results

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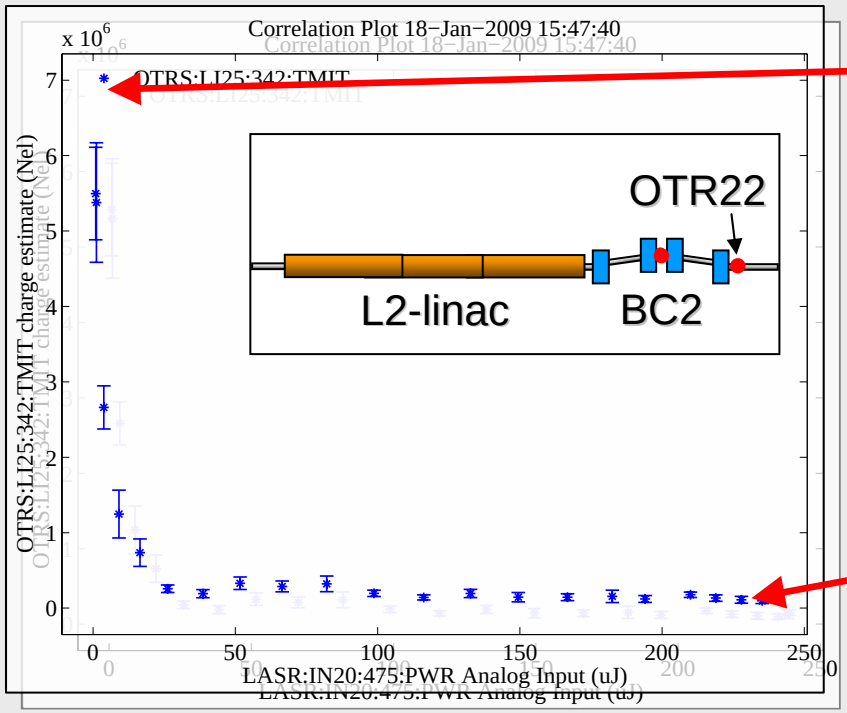
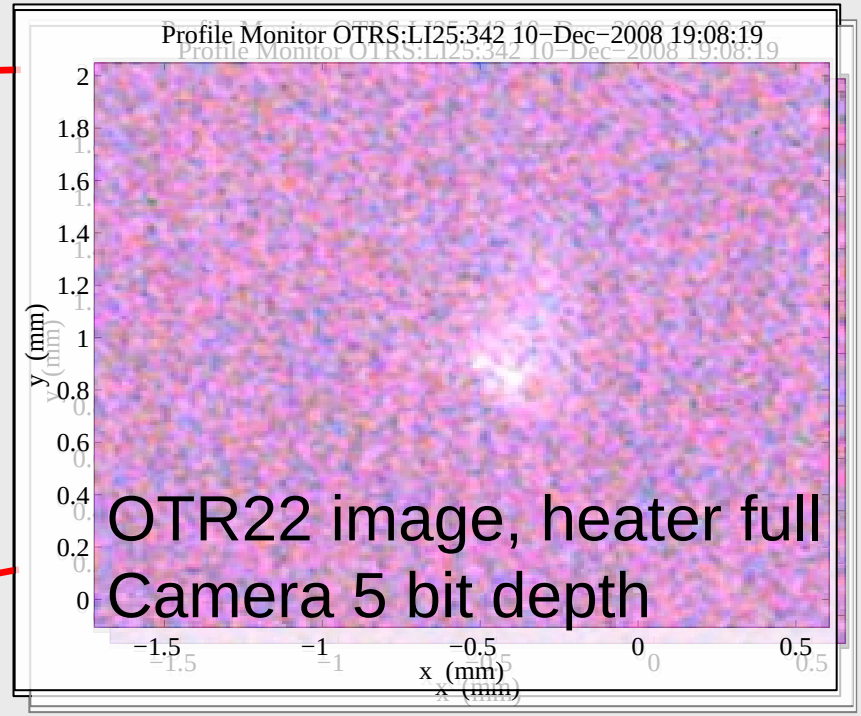
Effects on COTR

- Unwanted microbunching leads to many COTR problems in LCLS
- Laser heater suppresses COTR but not to incoherent level





- laser-heated energy profile non-Gaussian
- small part of beam escapes heating
- Microbunching restart from shot noise after a long linac and some R_{56}

- Alternative diagnostics (wires) used for beam profiles after compressors

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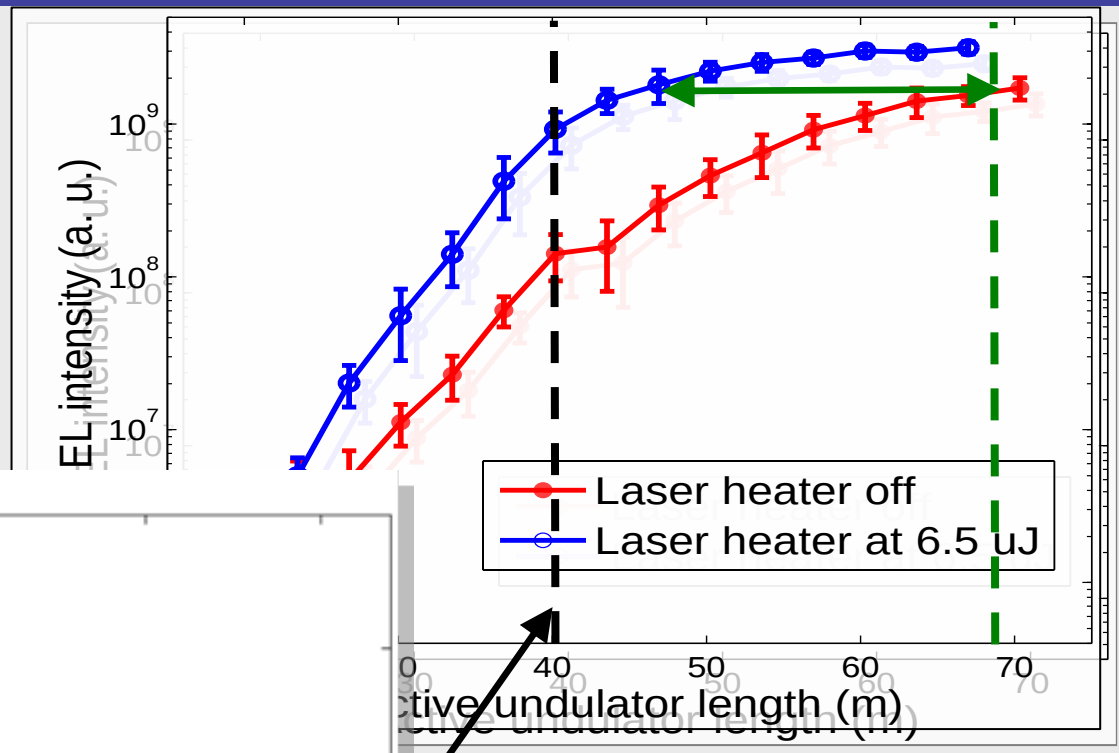
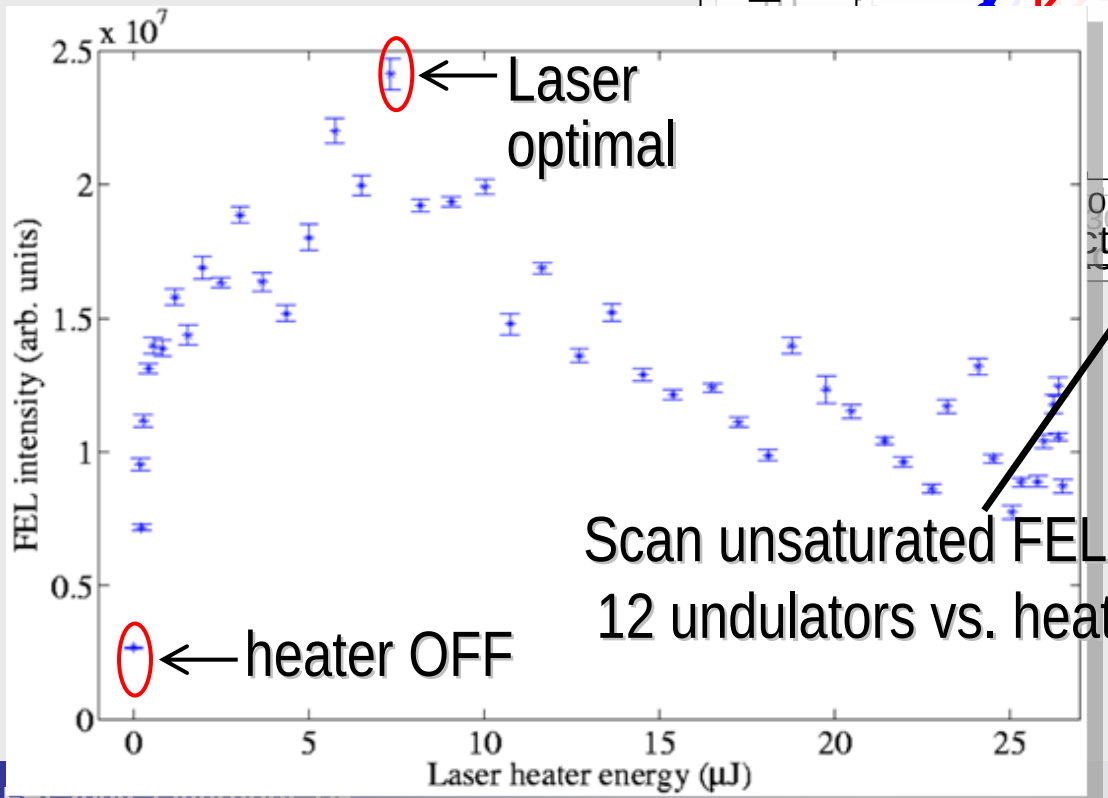
Laser Heater Improves FEL Power

250 pC, 3 kA, 1.5 Å FEL





Scan unsaturated FEL w/ 12 undulators vs. heater

- FEL saturation length 20 m shorter w/ heater
- FEL saturation power improves 2X w/ heater

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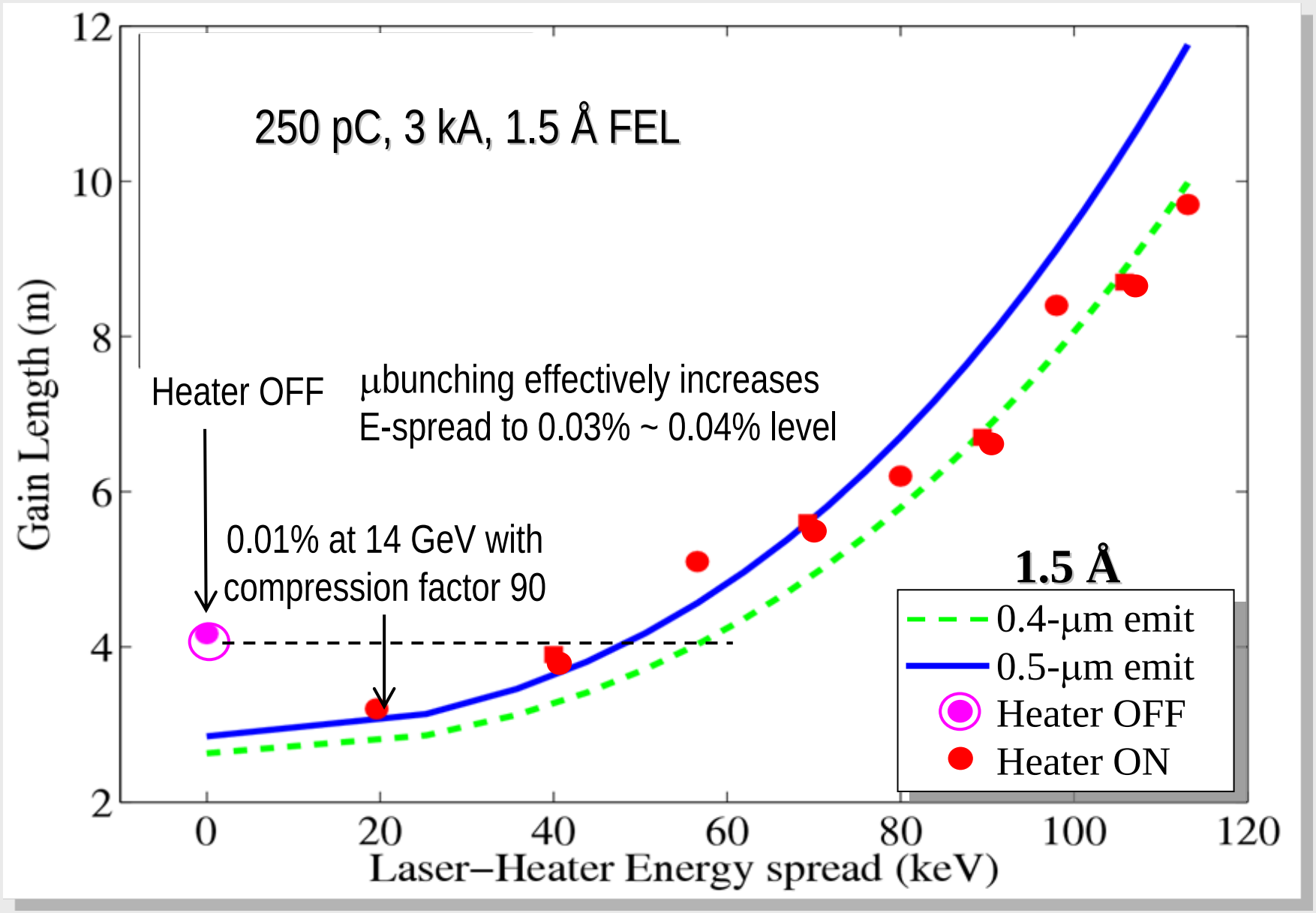
FEL Gain Length vs. Laser Heater



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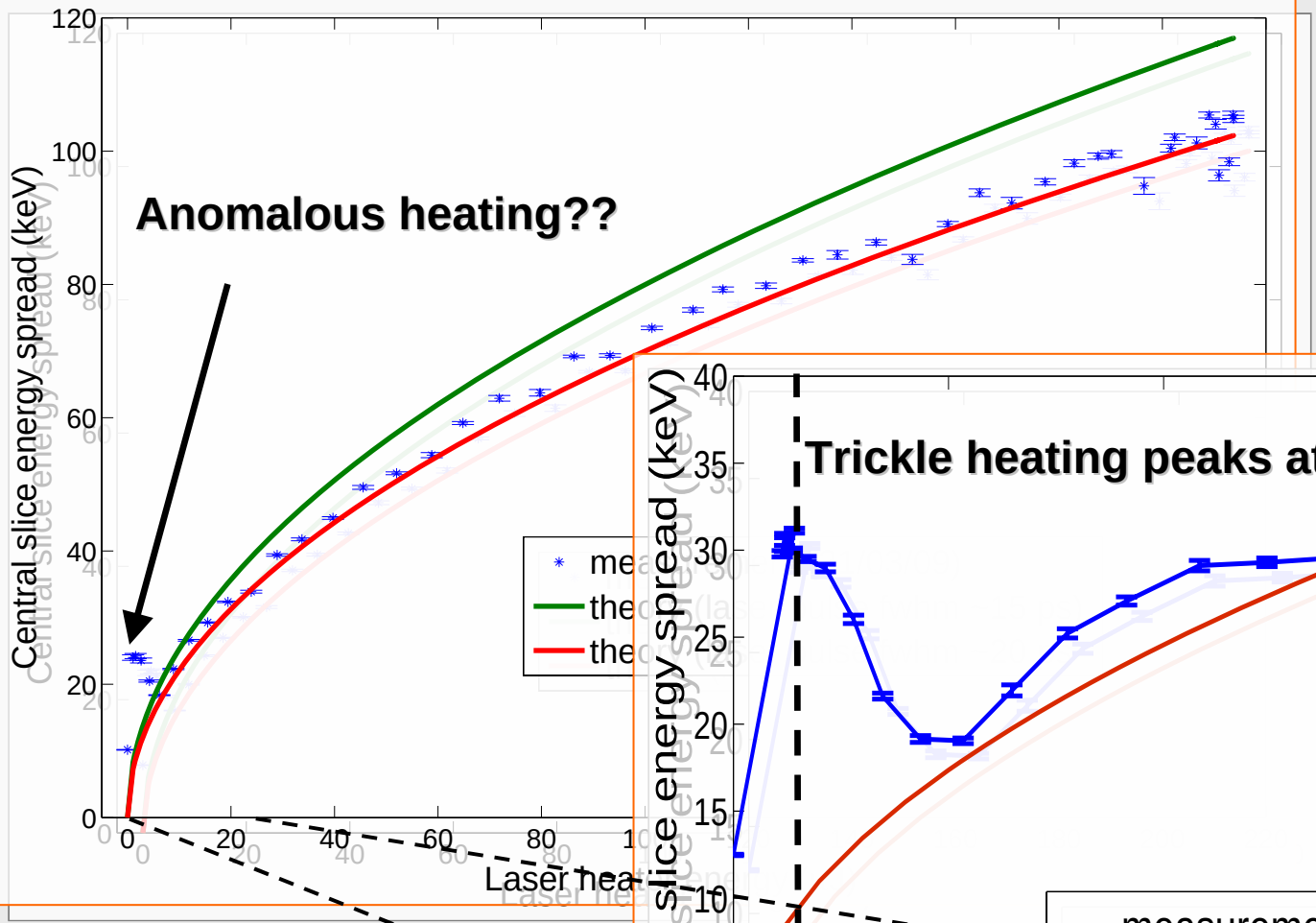
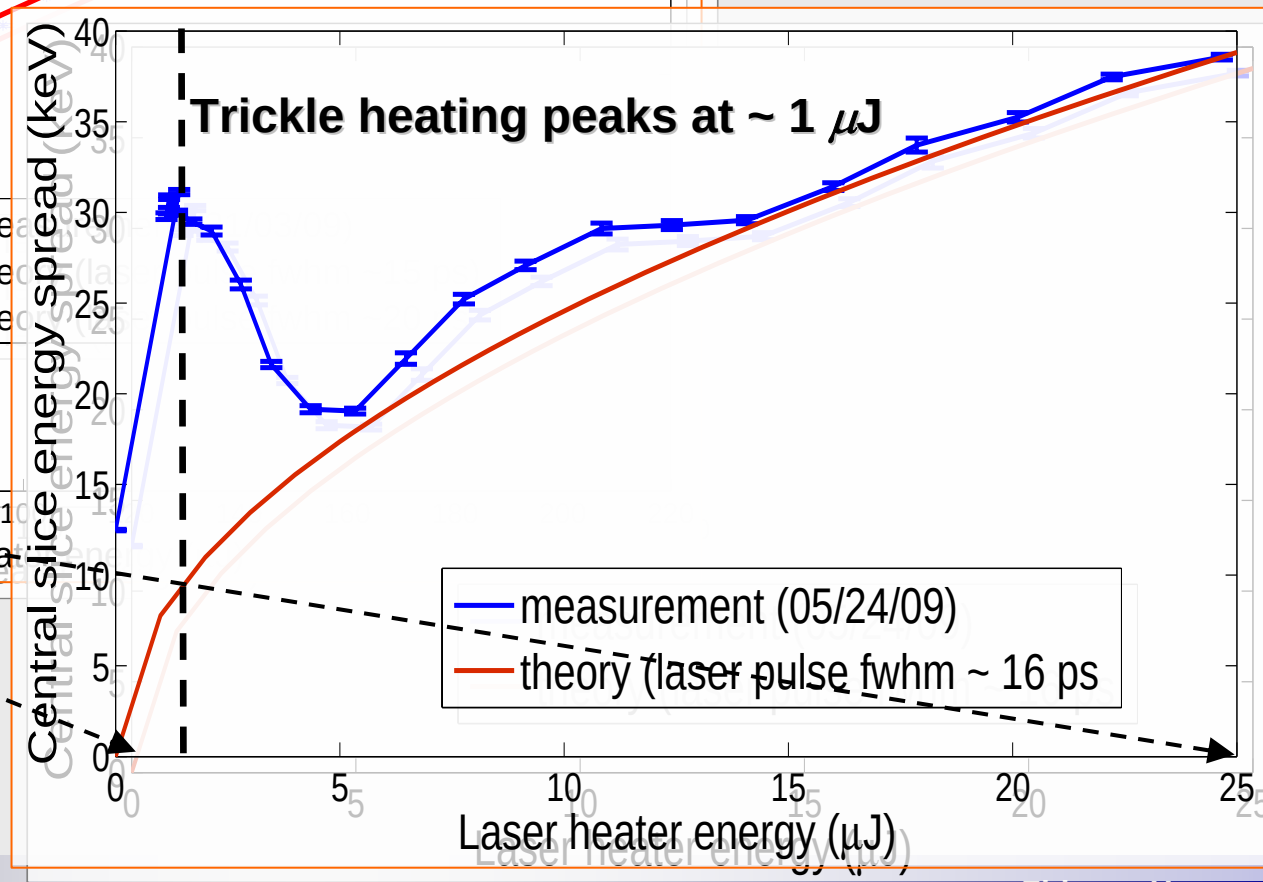
"Trickle" Heating





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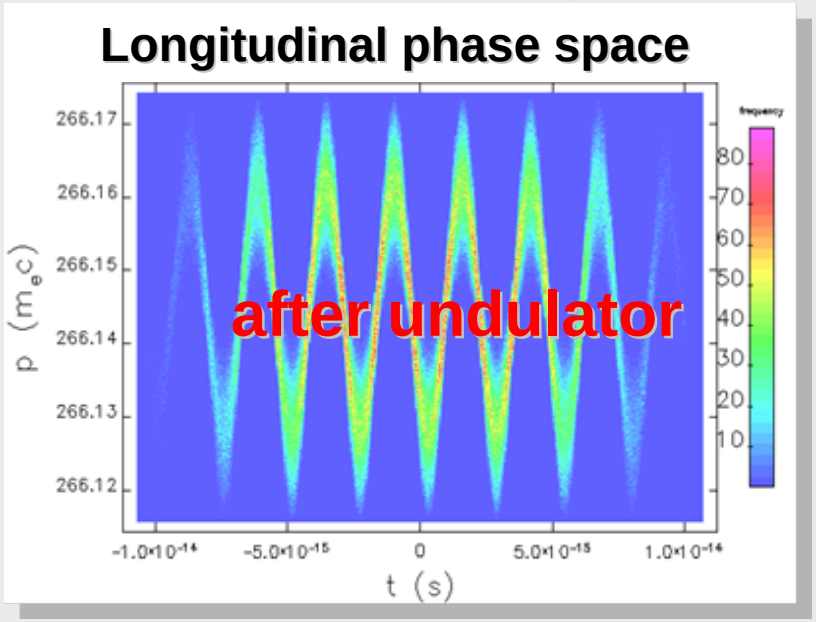
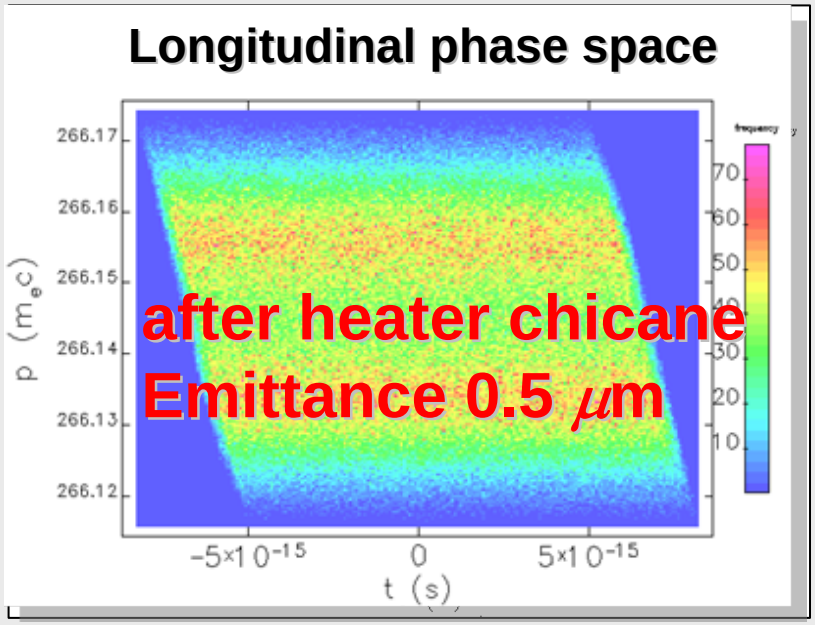
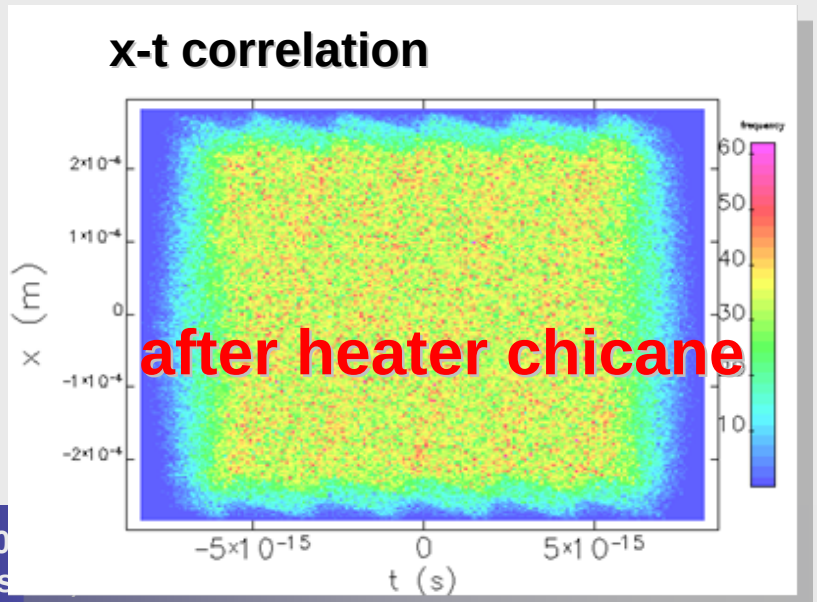
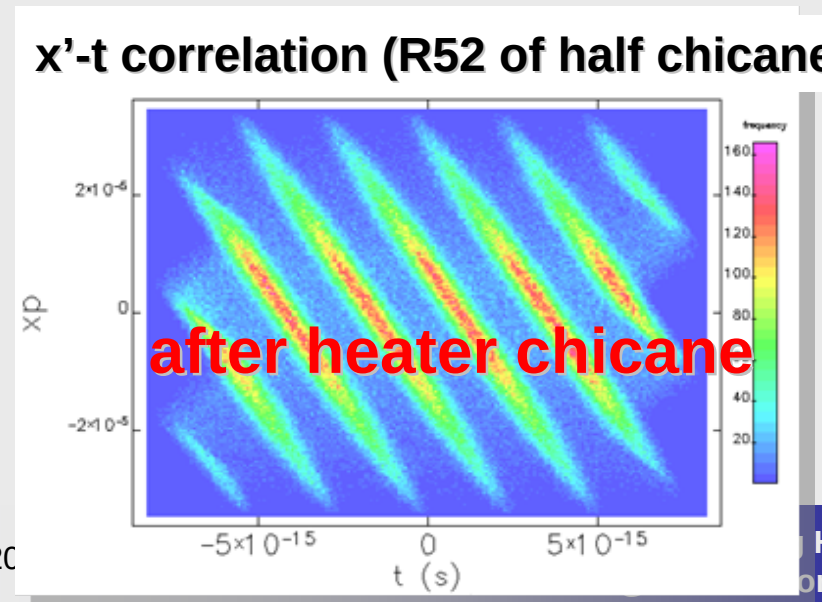
Laser Modulation Hidden in 4D Phase Space

- Laser heater at 0.5 μJ (Elegant simulation by Y. Ding)

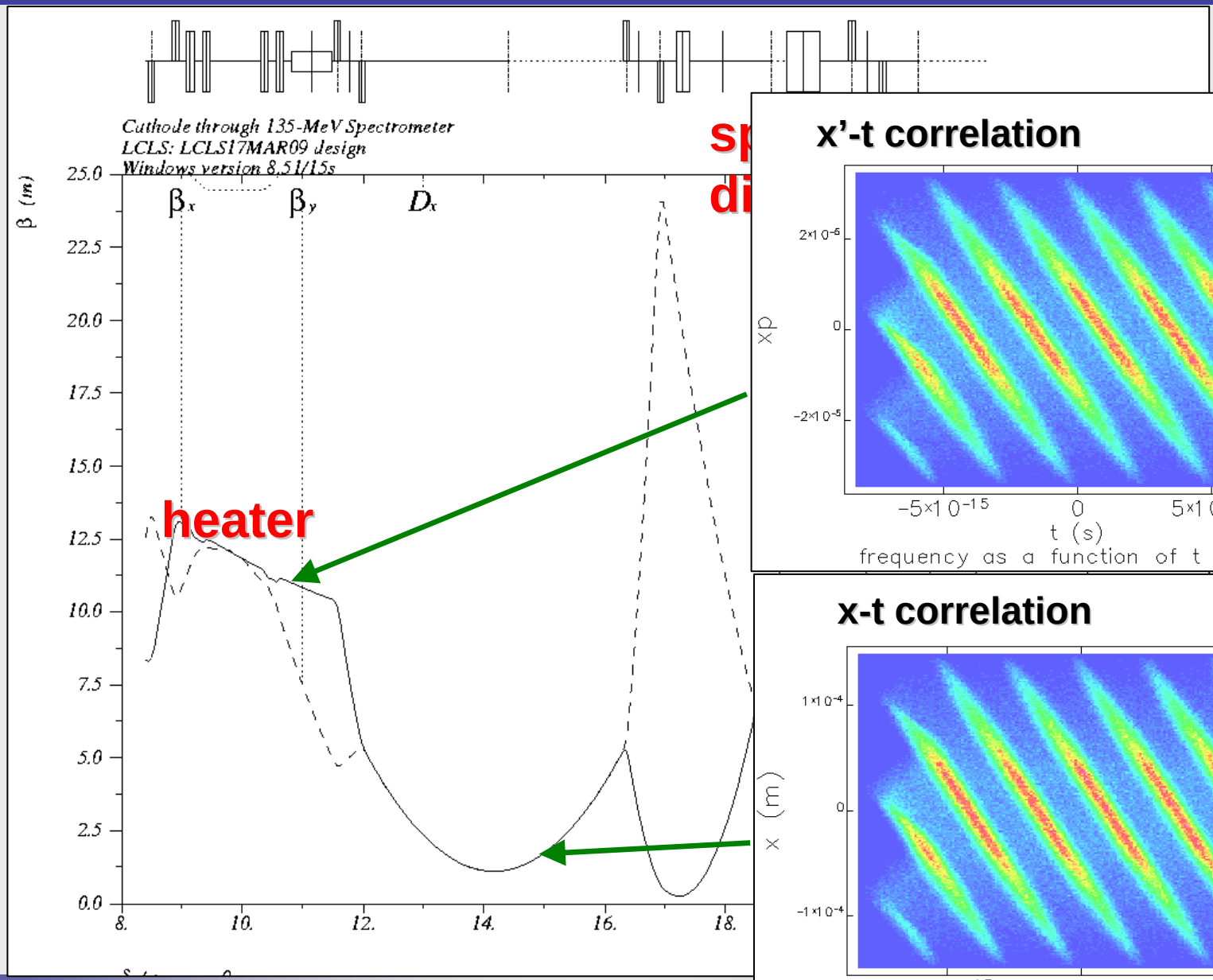






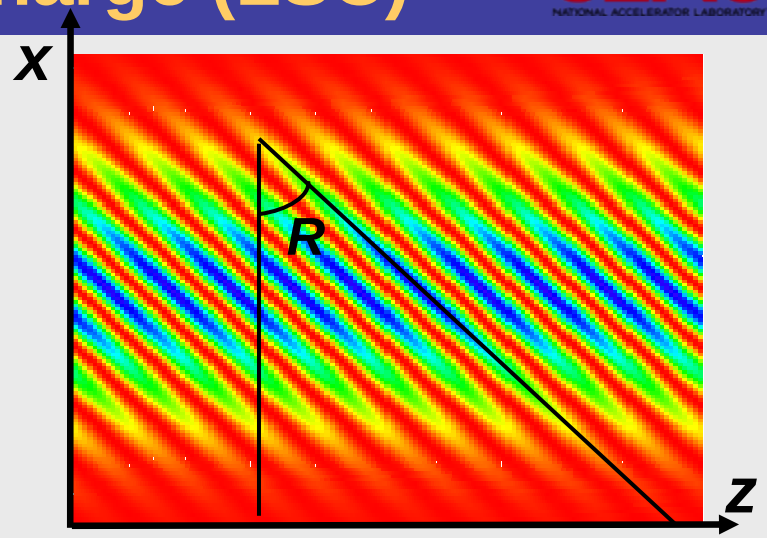


Modulation Recovered in Real Space



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 (exponentially if Gaussian distribution in x)

- In a 1D approach (as used in *Elegant*), longitudinal modulation multiply by 1D LSC impedance to compute energy modulation

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

modulation amplitude

LSC for Tilted Microbunching

- Beam clearly modulated for tilted microbunching in 3D density
- If beam size σ_x is much larger than $\gamma\lambda$, 3D calculation shows

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

G. Stupakov, private communications
D. Ratner, A. Chao, Z. Huang, FEL08

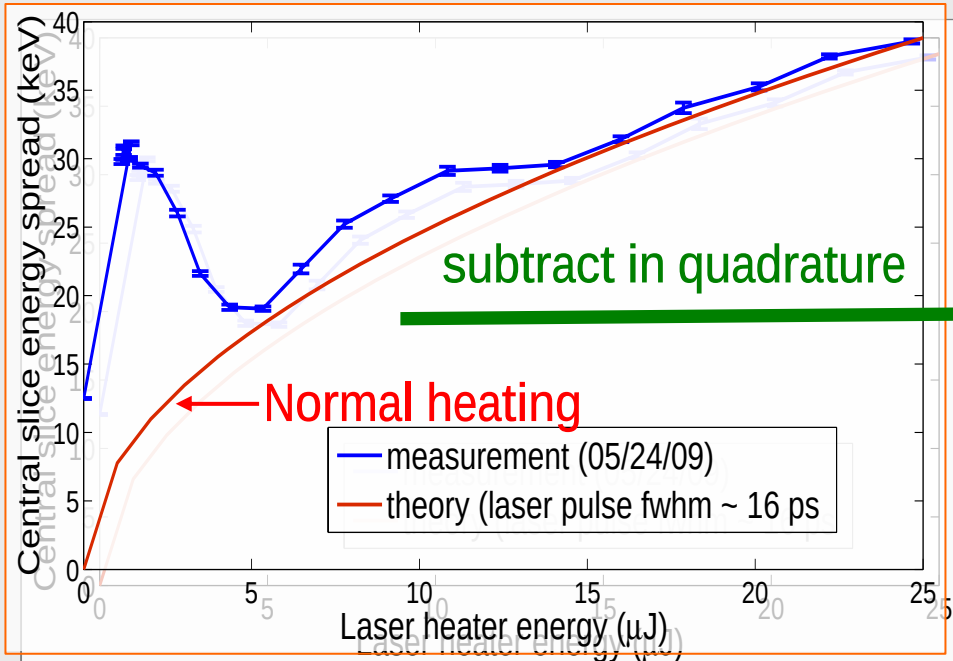
- LSC depends weakly on γR when $R<1/\gamma$
  ➔Tilted microbunching does not suppress LSC exponentially.
- 1D approach underestimates LSC by a large factor

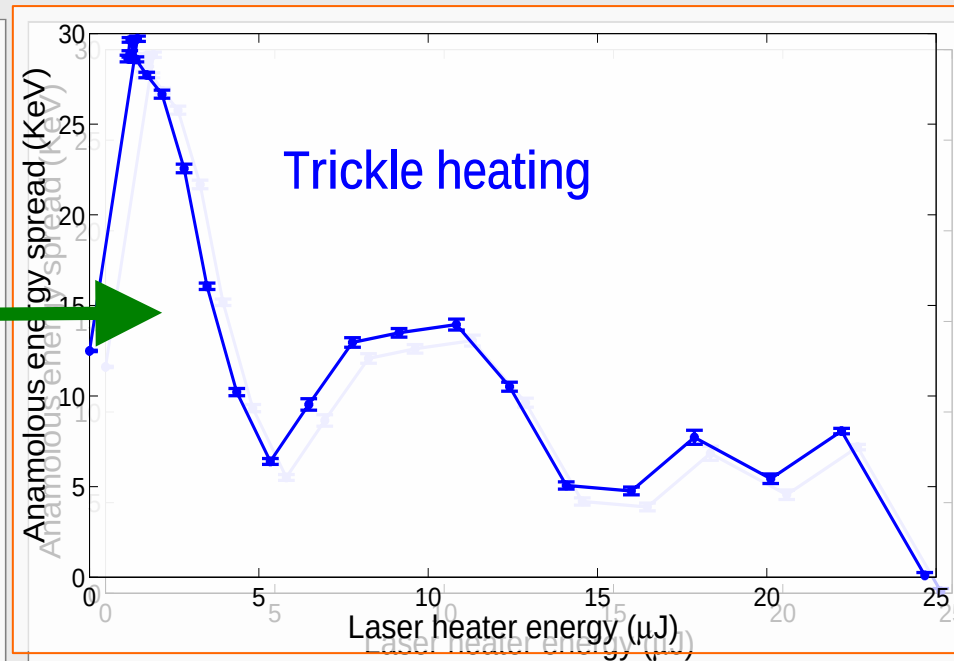
$$\frac{E_k}{E_k^{1D}} = \frac{e^{k^2 R^2 \sigma_x^2/2}}{1+\gamma^2 R^2}$$

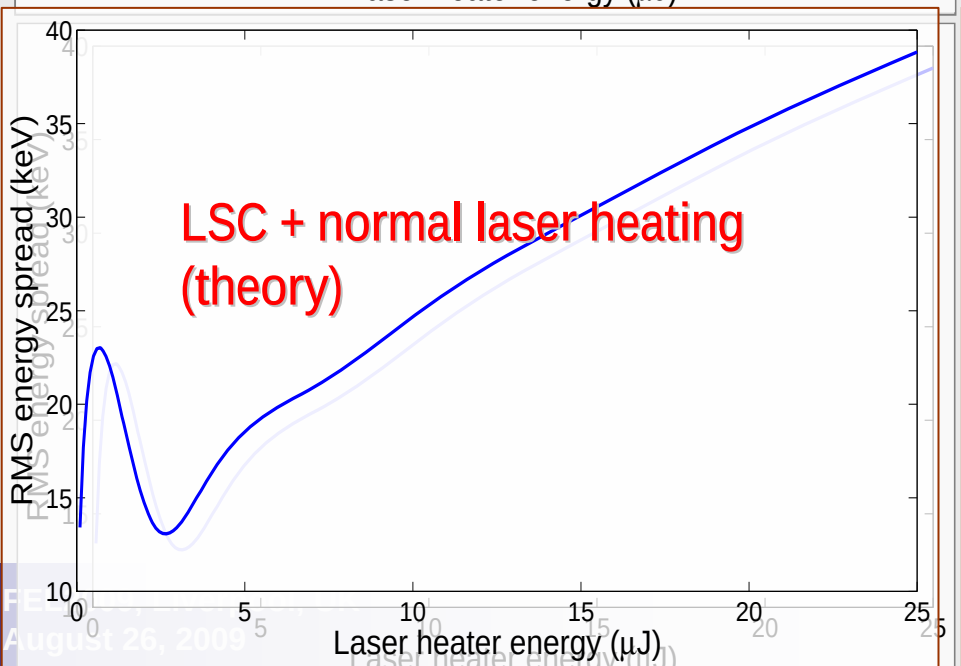
Take λ_L=758 nm, γ=264, σ_x=60μm, γR ~2,
1D underestimates LSC by a factor ~250!

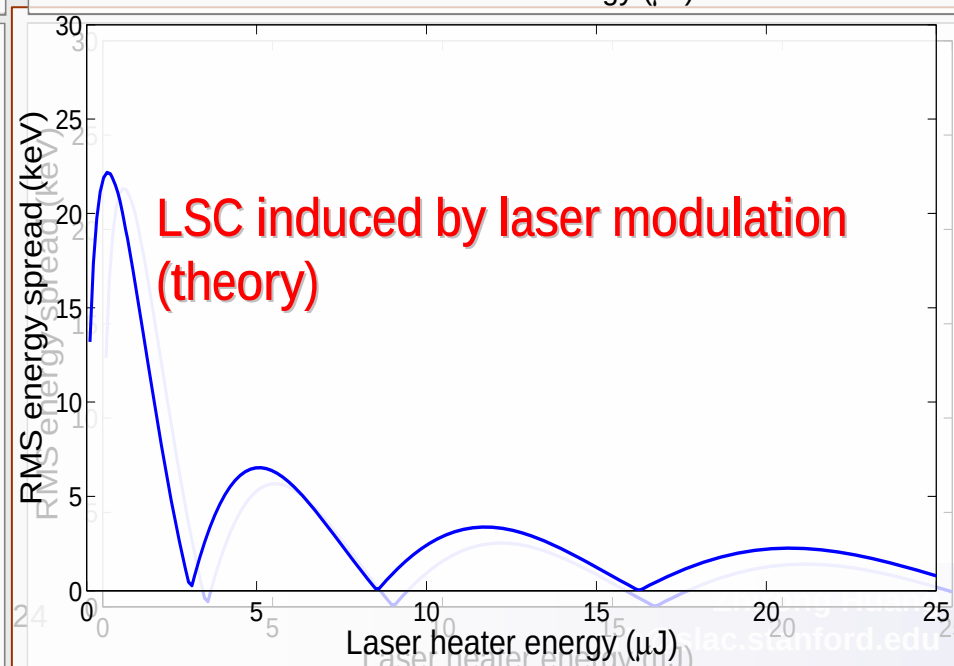
- Integrating 3D LSC over heater downstream beamline for total energy modulation

Comparison with measurements









Summary

- Laser heater is used in the LCLS to improve and optimize x-ray FEL performance at the nominal operating condition.
- Microbunching is suppressed but not all COTR is gone
  ➔ alternative diagnostics necessary (wire scanner etc…).
- Unexpected “trickle” heating explainable by a 3D LSC model
  (Preliminary estimation of 1D CSR effect is small, any 3D effect at play?)
- 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.

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Thanks to:

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all commissioning team members, and collaborators and visitors