High-resolution studies of microbunching phenomena in LCLS2

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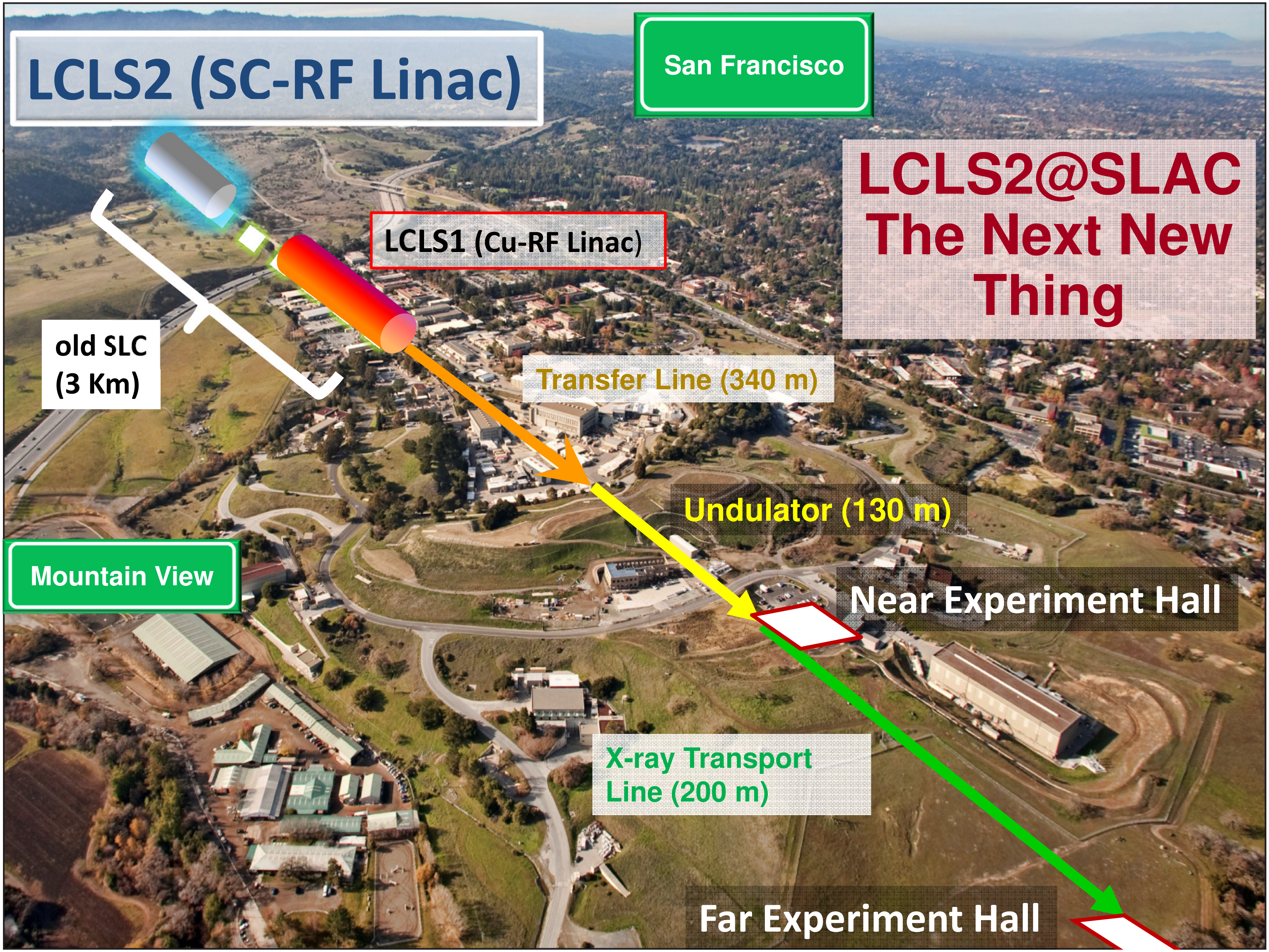
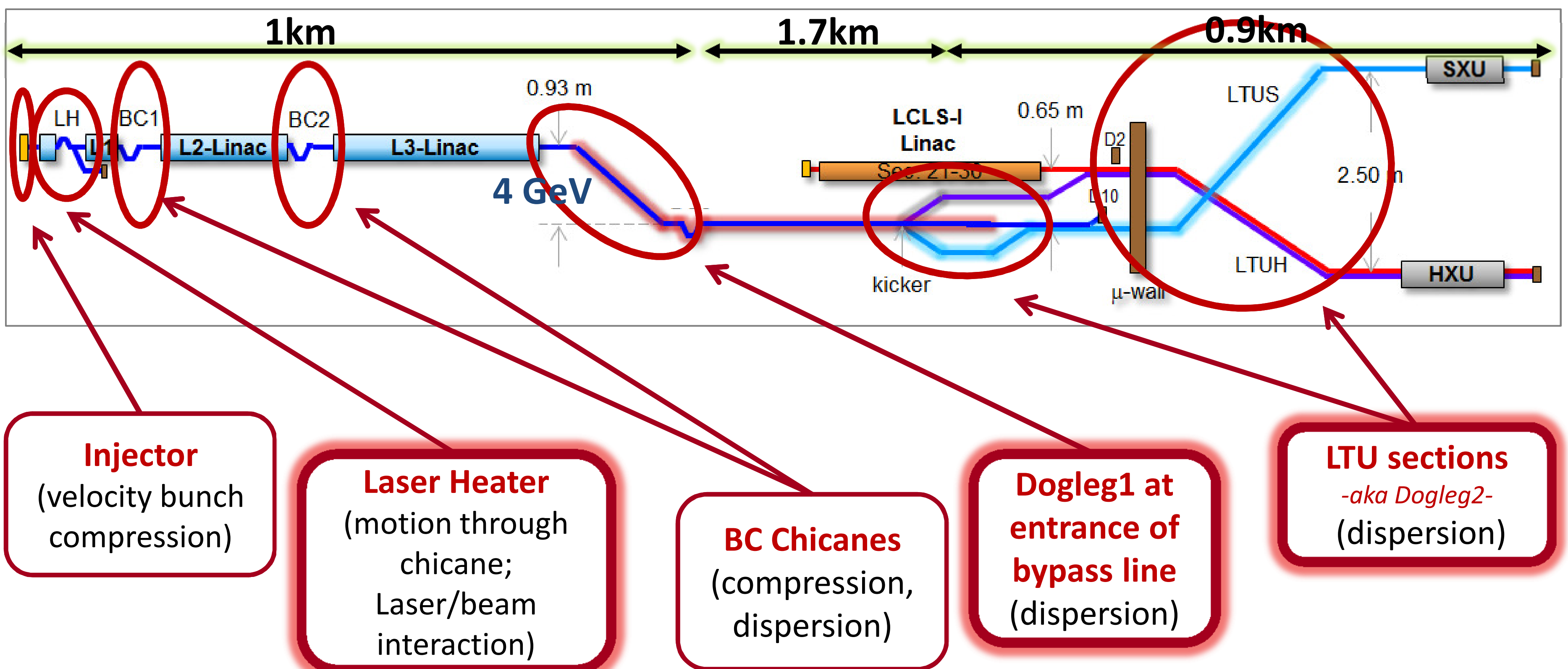


LCLS2 (SC-RF Linac)
San Francisco
LCLS2@SLAC
The Next New Thing
LCLS1 (Cu-RF Linac)
old SLC
(3 Km)
Transfer Line (340 m)
Undulator (130 m)
Mountain View
Near Experiment Hall
X-ray Transport
Line (200 m)
Far Experiment Hall

Not a boring machine: LCLS2 as a “microbuncher” paradise

- **Longitudinal Space Charge + z-Slippage = Microbunching instability**
  - Instability seeded by shot noise or other noise (e.g. in photo-cathode laser)
- **Other micro-structures from beam/laser interaction in LH**



Method: PIC code

- (Macro)particle simulations
  - IMPACT Pic Code + Access to NERSC computing facilities
- One electron, One macroparticle
- 3D space charge (+ 1D CSR, rf wakes)

- Two simulation approaches:
  - *Machine section-by-section studies; Track idealized macroparticle distribution representing short section of physical bunch; Higher grid resolution, faster run turn-around.*

  - *Cathode-2-undulator simulations of realistic whole beam (will not be shown here)*

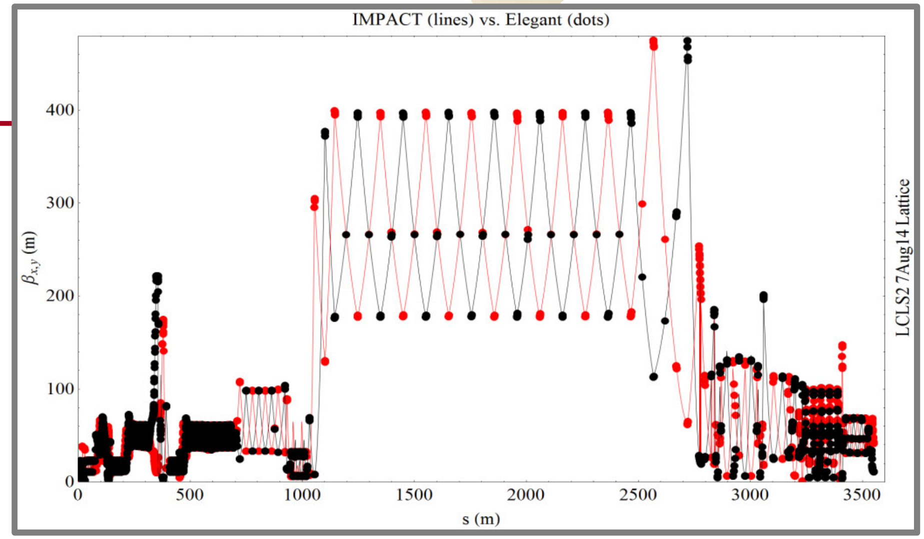
- Always try to make contact with analytical models when feasible

More on the code

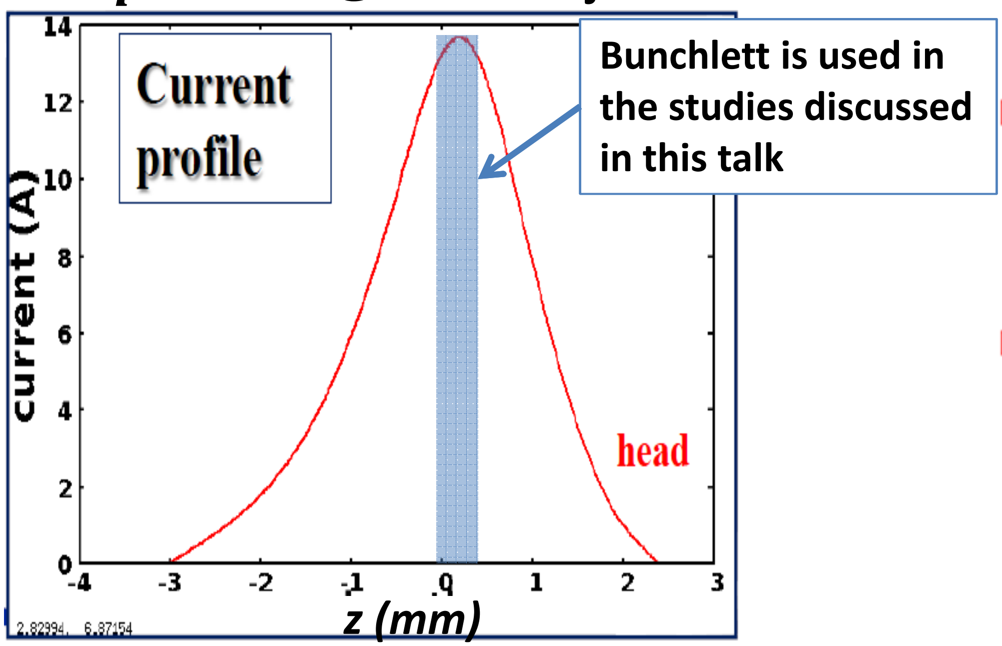
- **IMPACT = IMPACT-t (injector) + IMPACT-z (Linac)**
  - *written and maintained by J. Qiang (LBNL) et al.*

- Optimized for heavy-duty multi-processor runs (NERSC);
- Efficient 3D Poisson Solver; 1D CSR; rf wakes

Twiss functions: IMPACT vs Elegant



$100pC$ Beam @Exit of injector

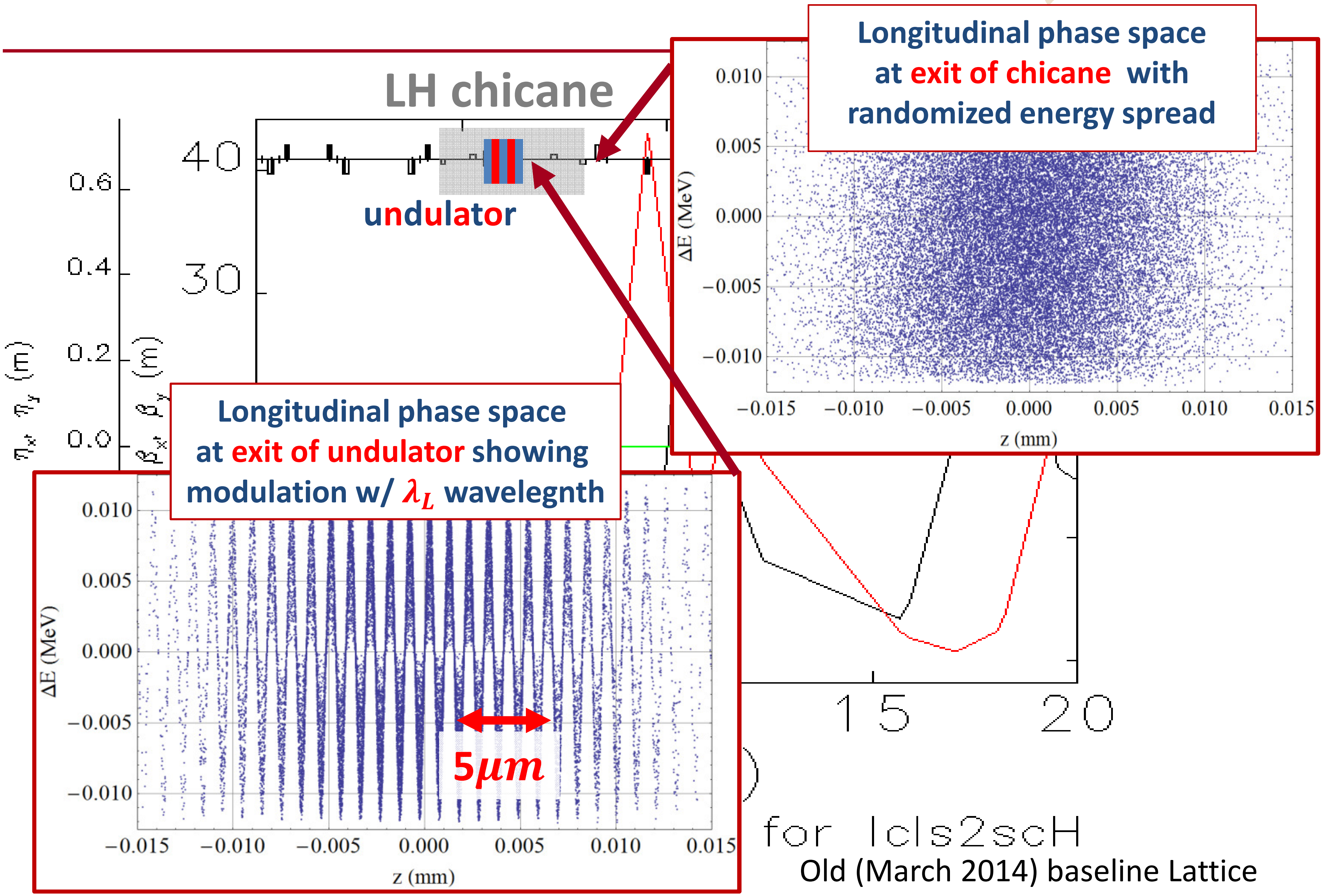


- **Uniform 3D grid** (follows bunch compression, transverse beam breathing)

- **Needed grid resolution can be demanding:**
  - Eg. in injected beam, ~20 grid points to resolve $1\mu m$ -> 100k z-grid nodes needed for ~5mm beam

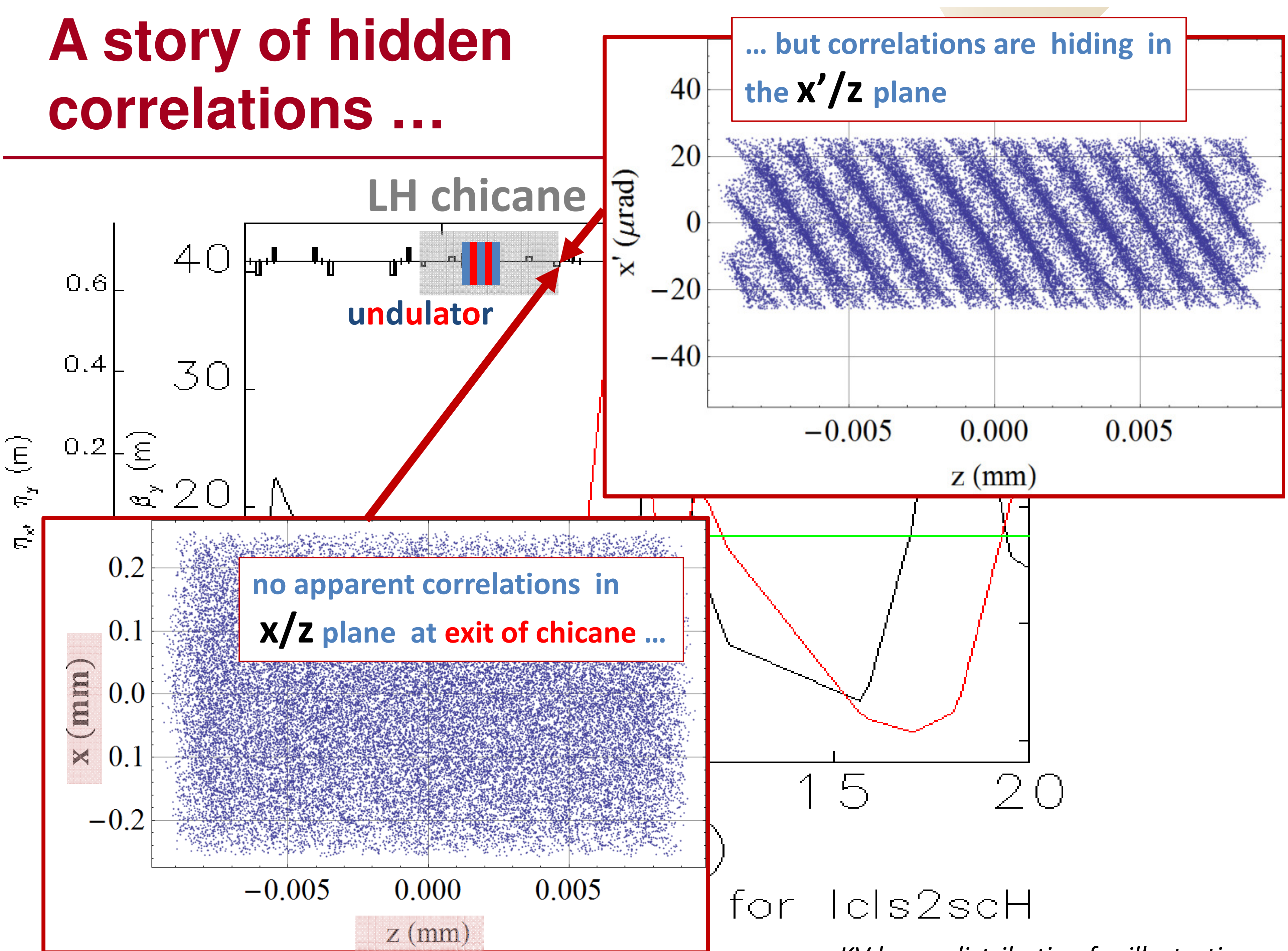
- **s2e runs, Linac, ~1B macroparticles, $n_x \times n_y \times n_z = 32 \times 32 \times 2048$ grid, take ~3 hours on 1000 processors; miss out some of the effects.**

The laser heater doing its job



Old (March 2014) baseline Lattice

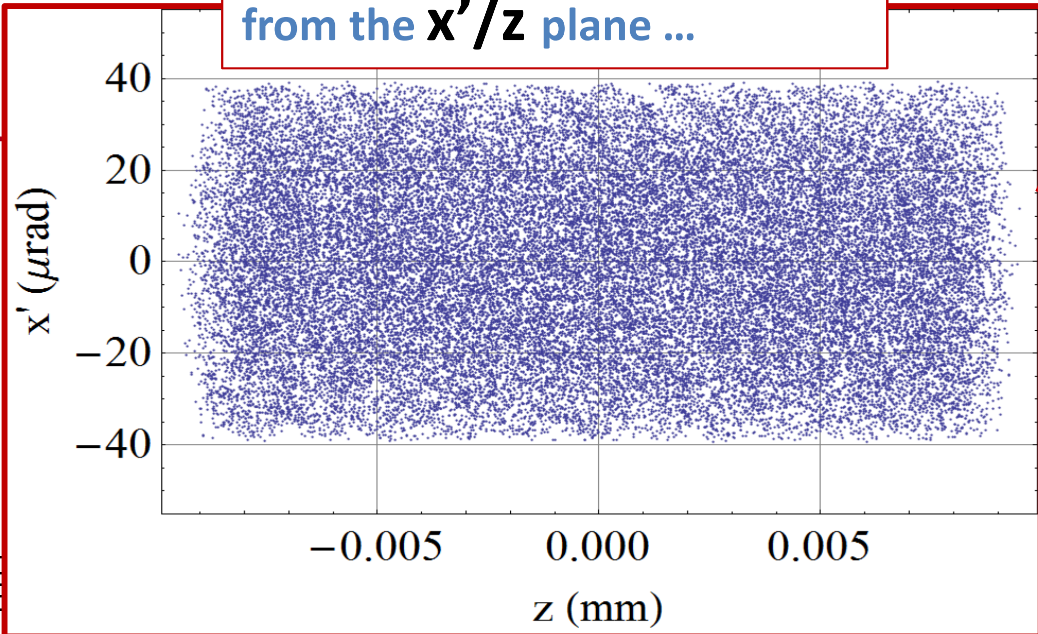
A story of hidden correlations …

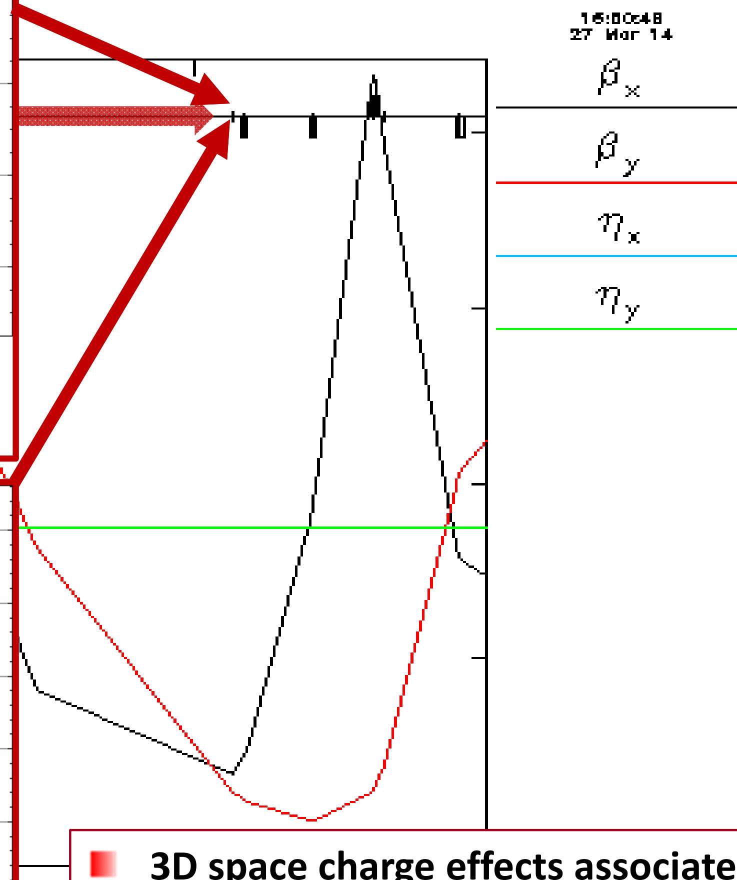


KV beam distribution for illustration

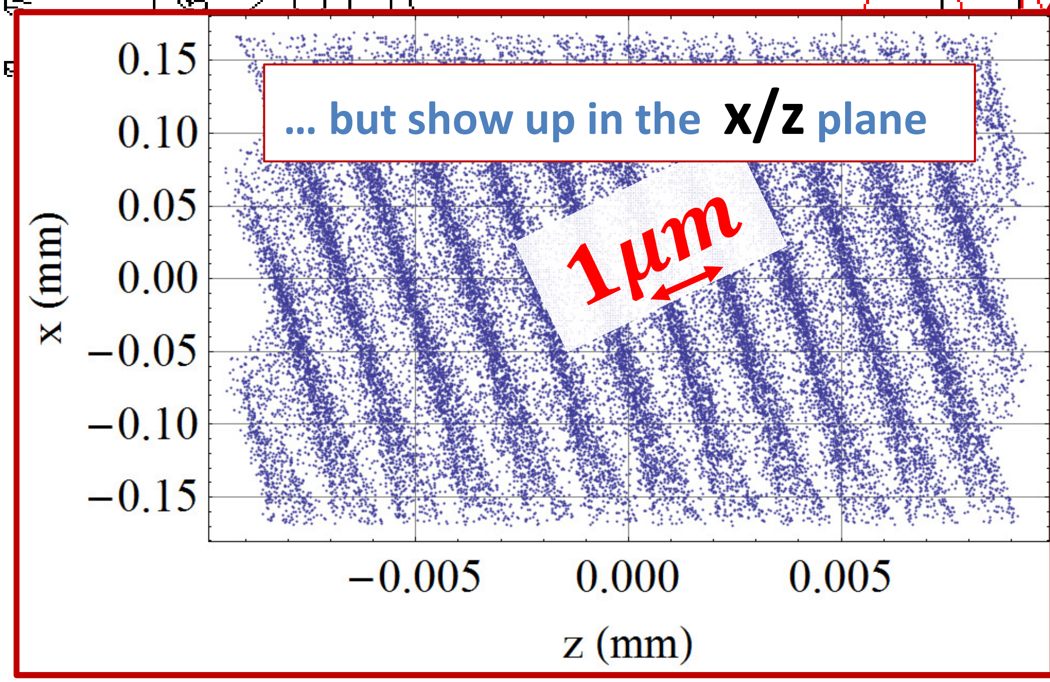
… $\pi/2$ phase-advance later

correlations have disappeared from the **x'/z** plane …





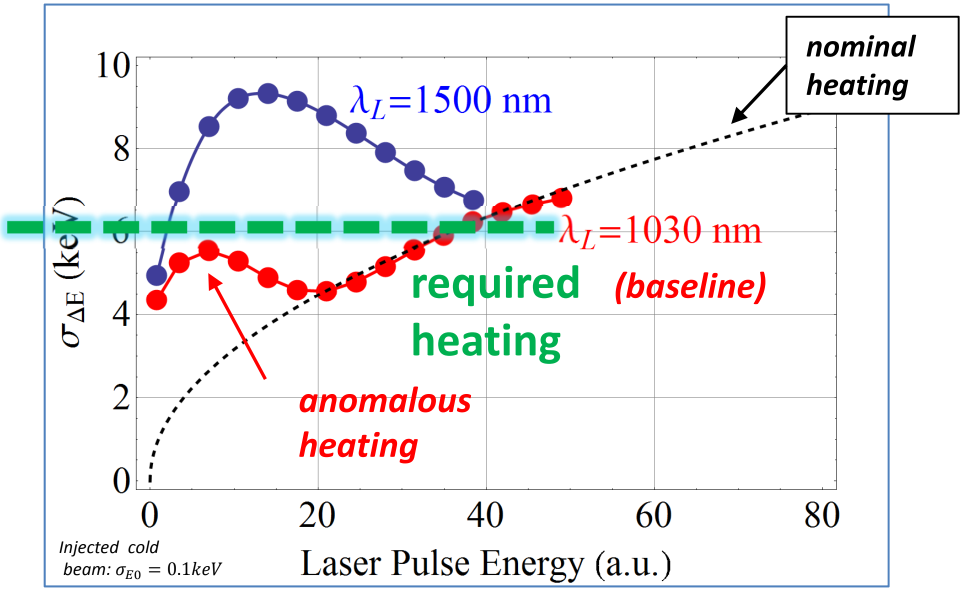
… but show up in the **x/z** plane



- **3D space charge effects associated with microstructure heat the beam**
- **Discovered during LCLS1 commissioning ("Trickle heating effect").**

The 'trickle' heating & shot-noise seeded heating

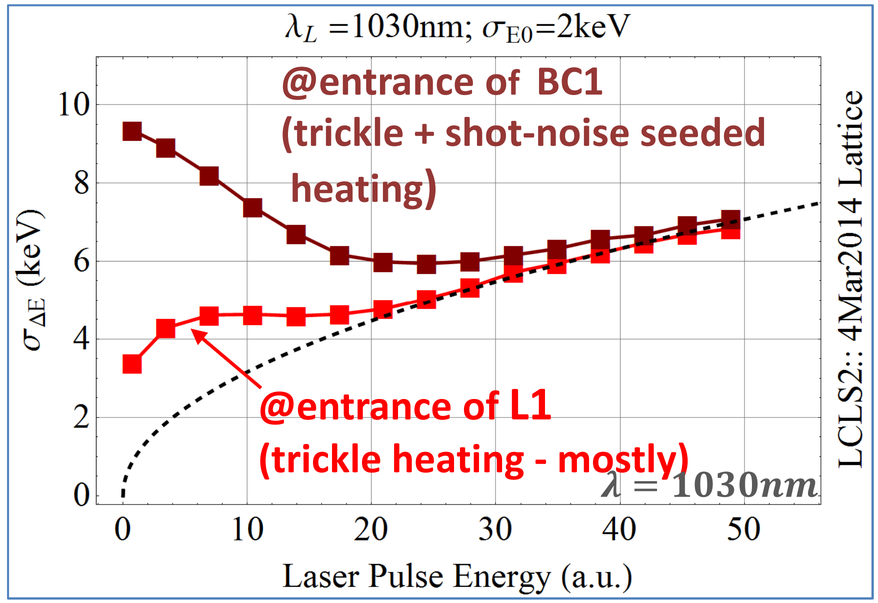
Trickle heating effect for two choices of laser wavelengths ($Q = 100pC$)



- **IMPACT** simulation. **Idealized flat-top** beam with $I_0 = 12A$ (100pC bunch). Gaussian energy and transverse beam distribution.
- **3D space-charge effects** add to nominal LH-heating
- Anomalous heating **limits tuning range** of heater

- Additional heating is caused by shot-noise seeded microbunching

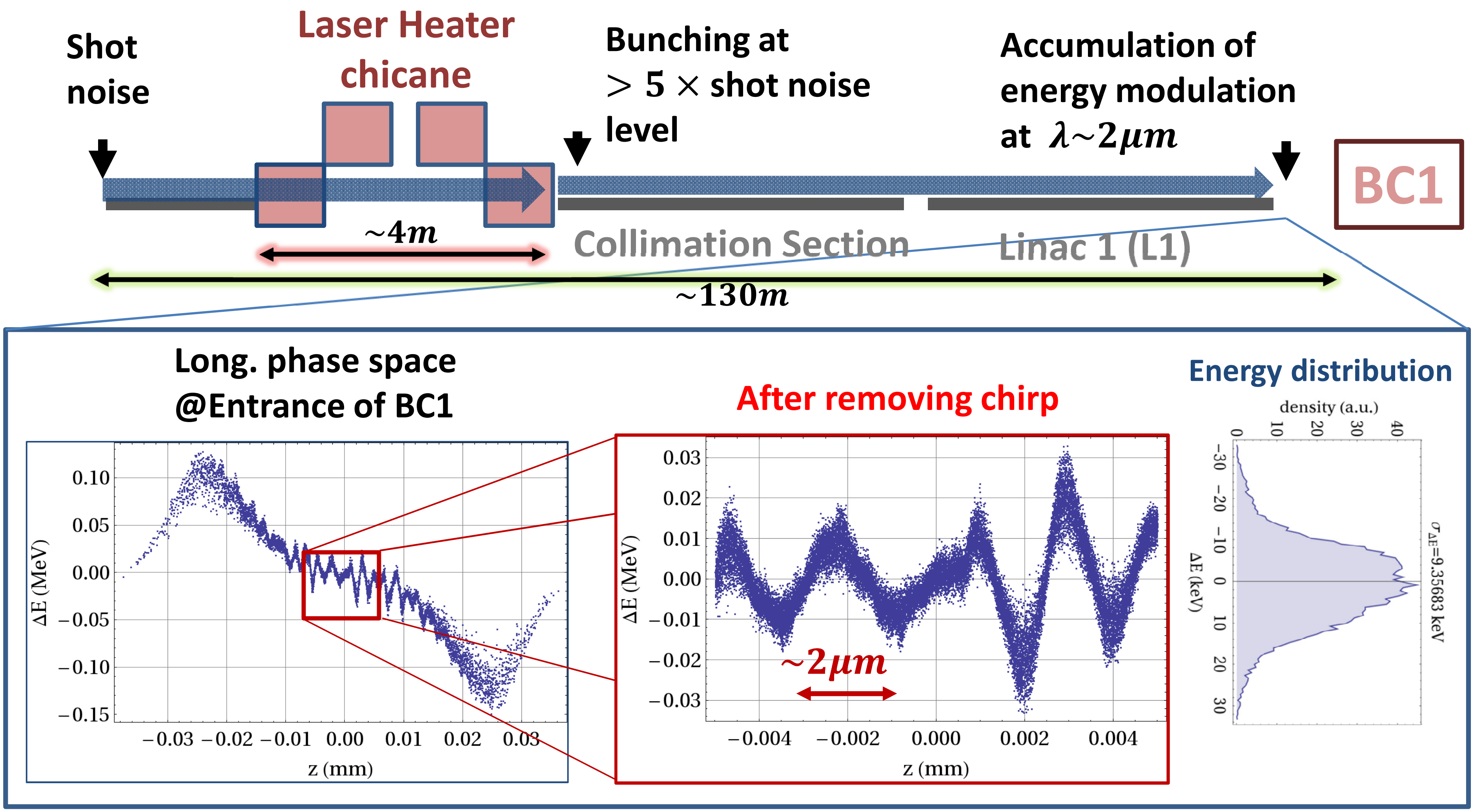
Observed heating at 2 locations along lattice



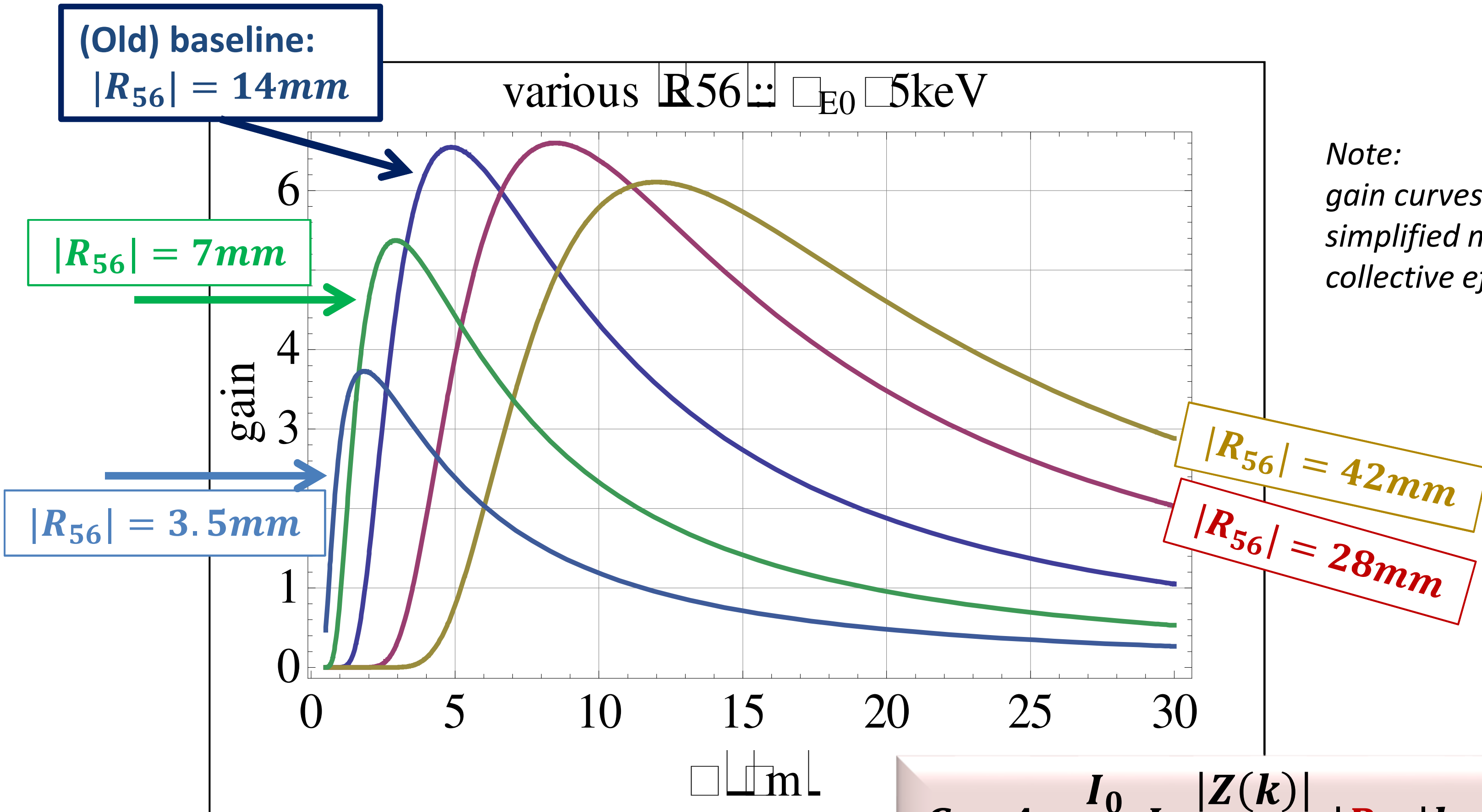
Injected warm beam: $\sigma_{E0} = 2keV$

Heating due to shot-noise seeded microbunching

- Microbunching induced by Laser Heater chicane causes energy modulation



μBI Gain curve through LH Chicane: choose R_{56} to reduce instability



Note:
gain curves based on simplified model excluding collective effects in chicane

$$G \simeq 4\pi \frac{I_0}{I_A} L_s \frac{|Z(k)|}{Z_0 \gamma_{BC}} |R_{56}| k\, e^{-(k R_{56} \sigma_\delta)^2/2}$$

- Old LH chicane baseline $|R_{56}|$ close to worst…
- Here, reducing (*vs.* increasing) $|R_{56}|$ is the more effective way to reduce gain

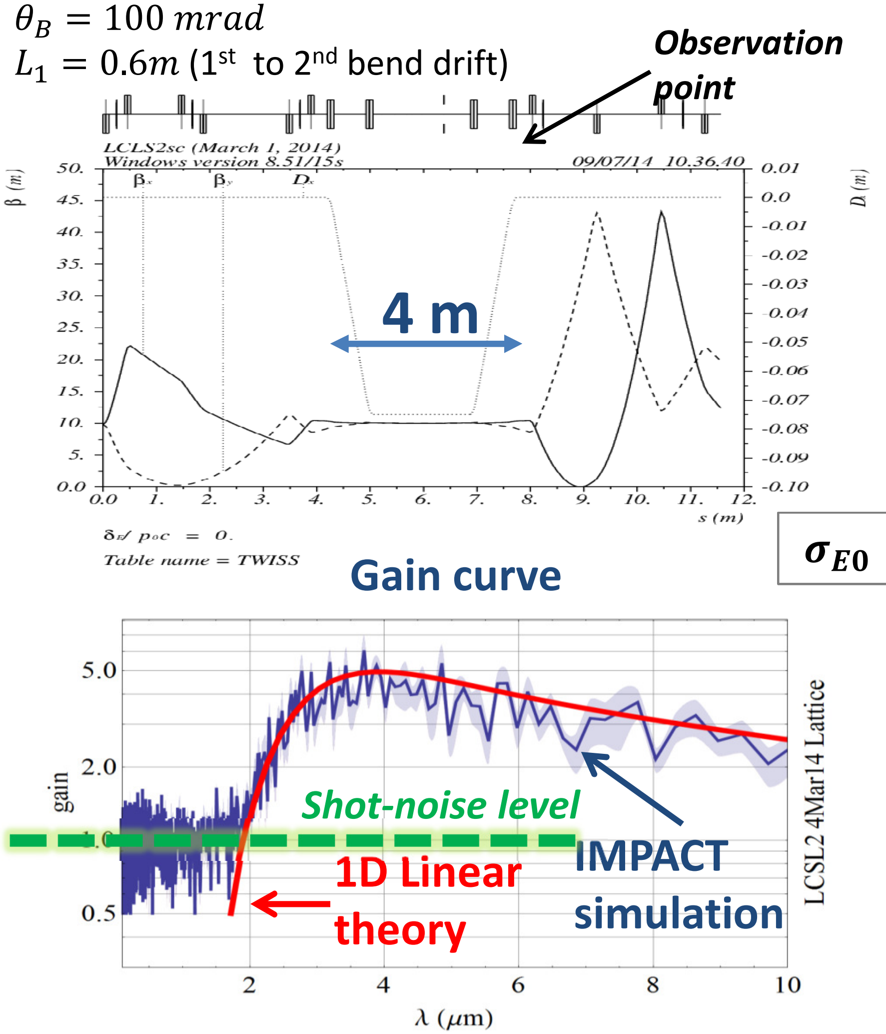
We redesigned the LH chicane to have a smaller $|R_{56}|$

- **Redesign chicane, keeping the same max $D_x = 7.5cm$ [lengthen drifts between 1-2 and 3-4 dipoles]**

Old baseline LHC $|R_{56}| = 14mm$

$\theta_B = 100\ mrad$

$L_1 = 0.6m$ (1st to 2nd bend drift)

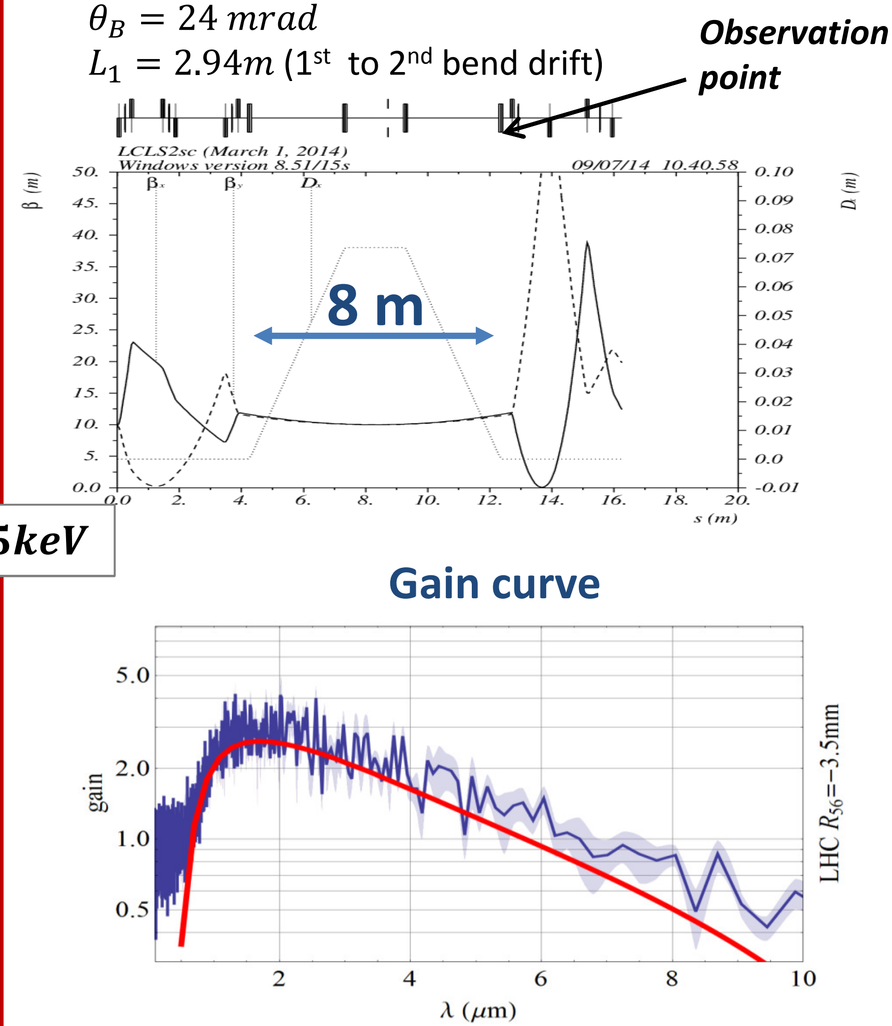


$\sigma_{E0} = 5keV$

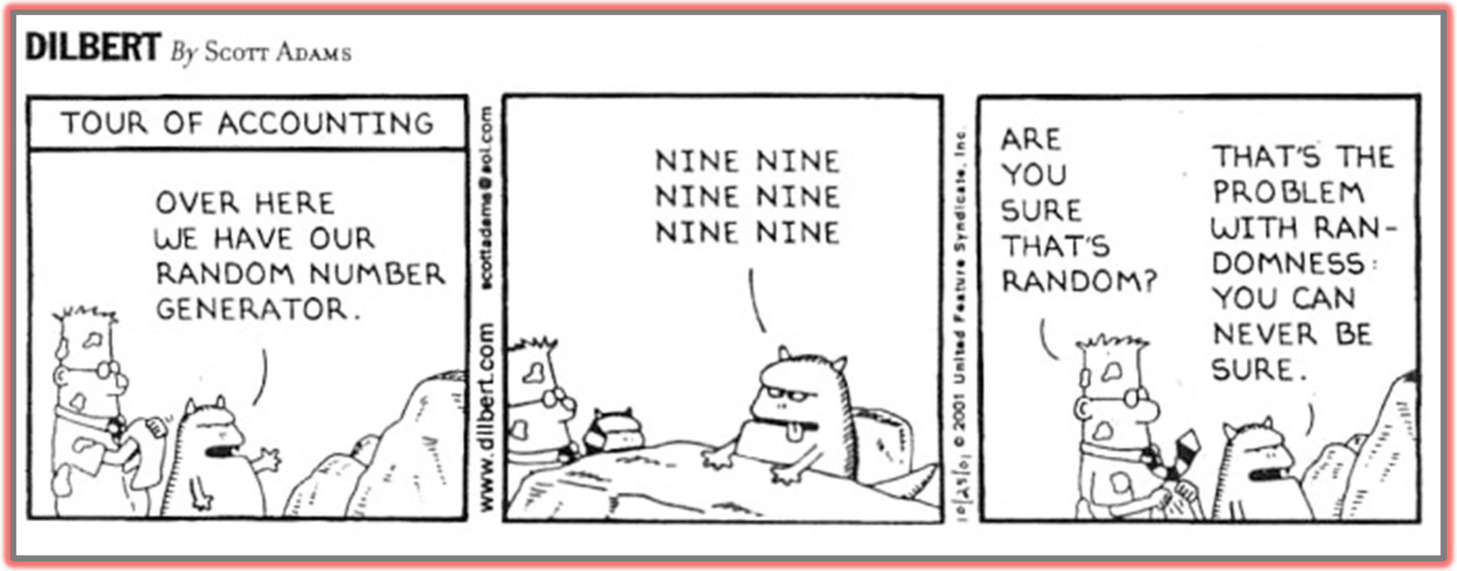
Redesigned LHC with $|R_{56}| = 3.5mm$

$\theta_B = 24\ mrad$

$L_1 = 2.94m$ (1st to 2nd bend drift)



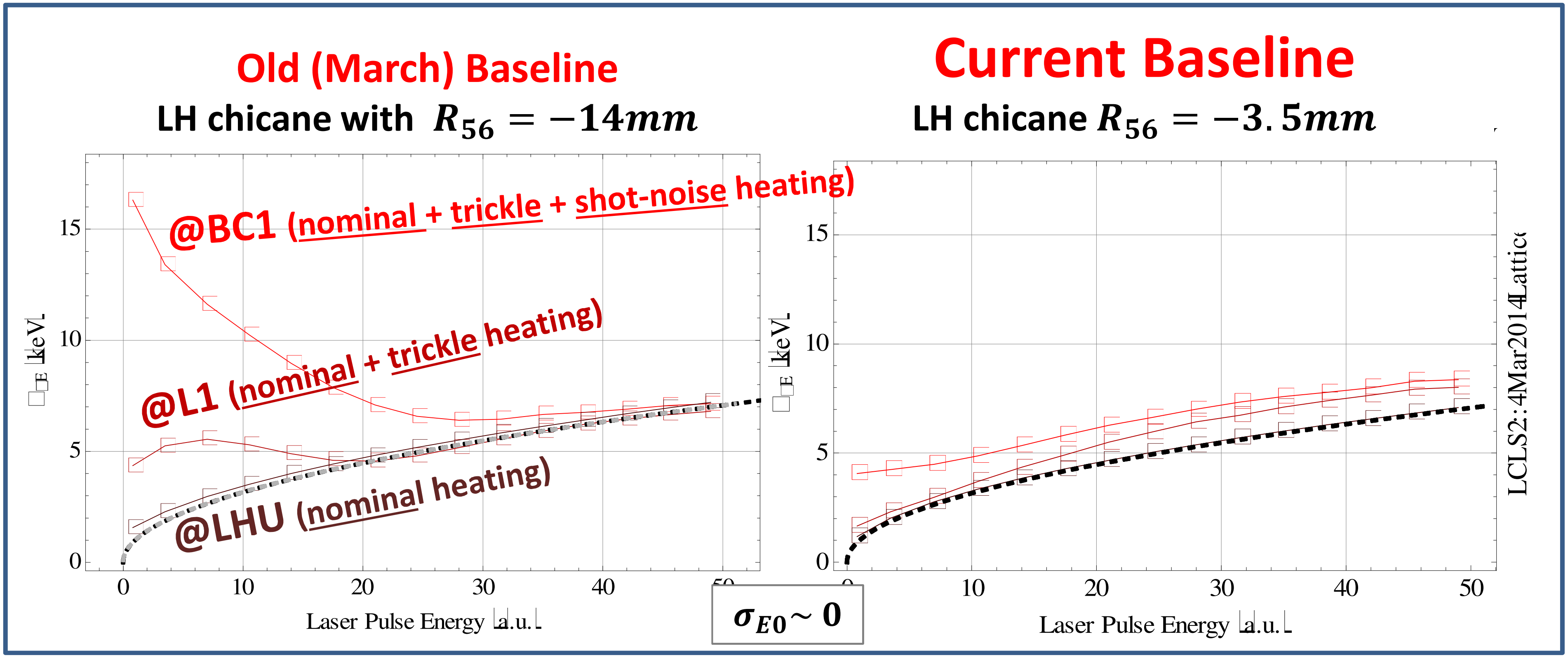
Aside note on randomness



- **Macroparticle distributions (~1B) are created by IMPACT using a pseudo-random generator. Is this good enough?**
  - As of now, no evidence of problems, but one should run randomness tests to be sure
  - Random numbers are for sale on WWW.RANDOM.ORG …

LH Chicane with smaller $|R_{56}|$ does indeed reduce shot-noise seeded heating

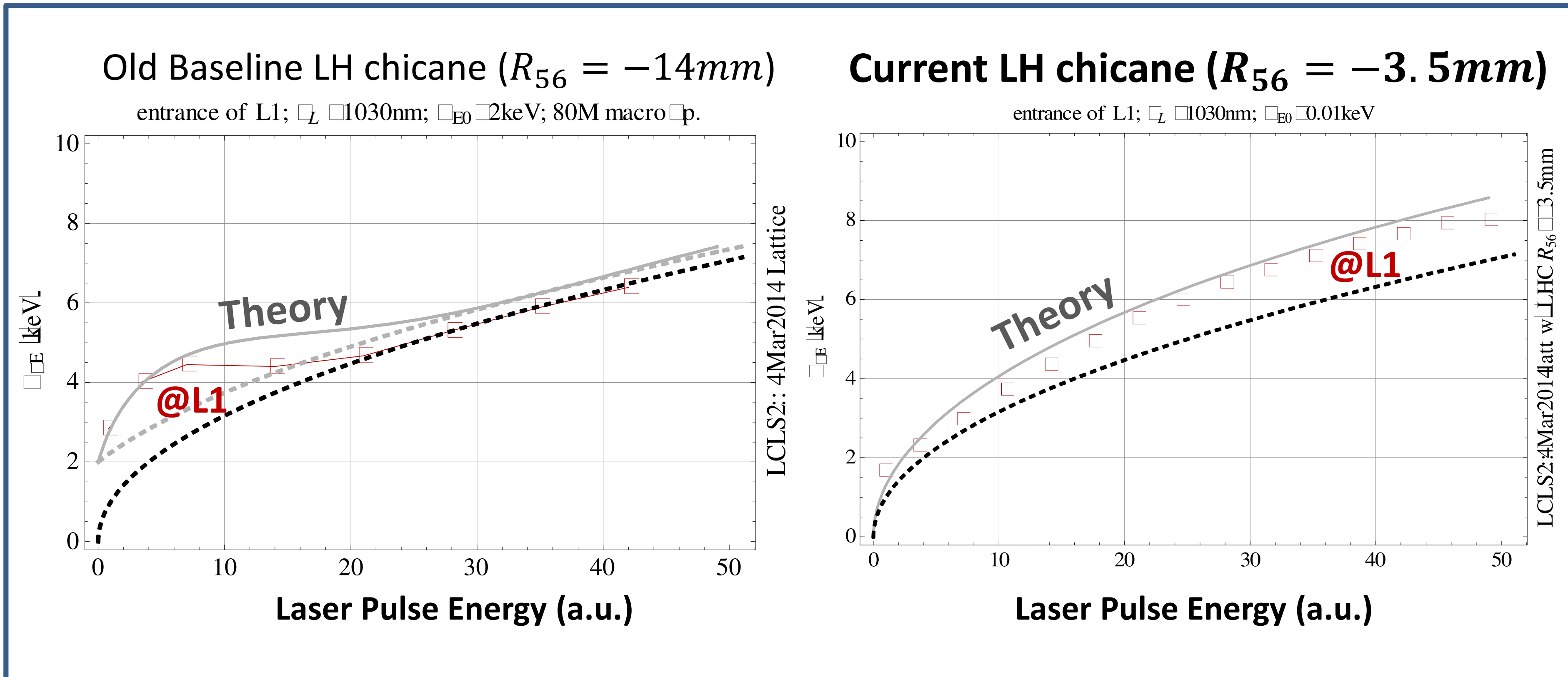
Observed energy spread *vs*. Laser Pulse Energy



- Note: here slice energy spread of injected beam $\sigma_{E0} \sim 0$
- **In modified LH chicane design trickle heating is somewhat larger at higher laser pulse energies (see next slide)**

Trickle heating: Compare simulation with analytical model (Z. Huang) *… and get reasonable agreement*

Observed energy spread *vs*. Laser Pulse Energy

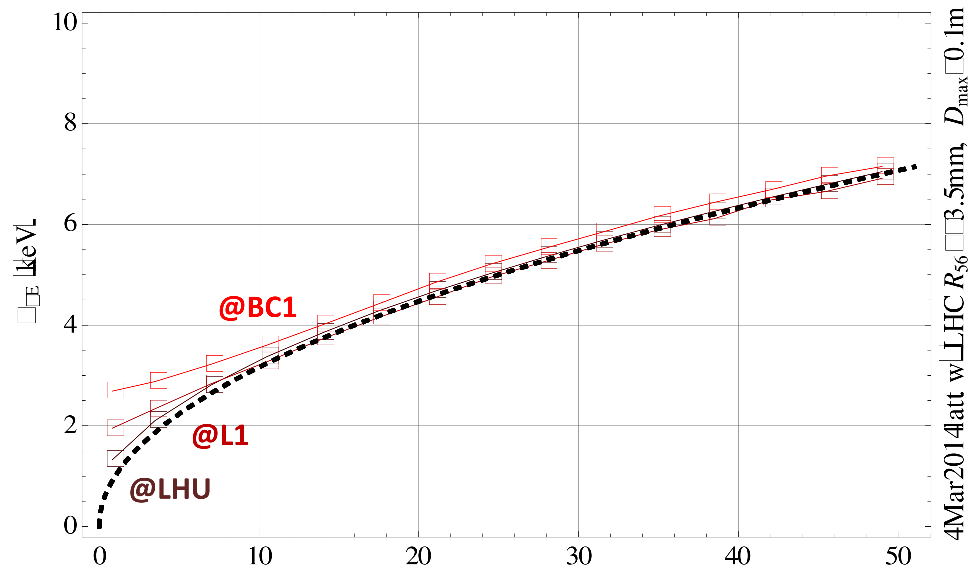


Trickle heating $\propto J_1(R_{56}k_L\delta_L)$

Further modification of LH chicane would almost eliminate trickle heating

Further modified LH chicane (not baseline)

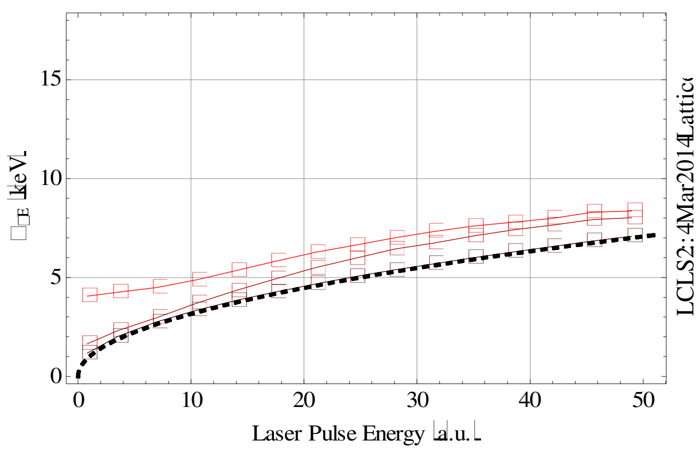
$(R_{56} = -3.5mm, D_{max} = 10cm)$



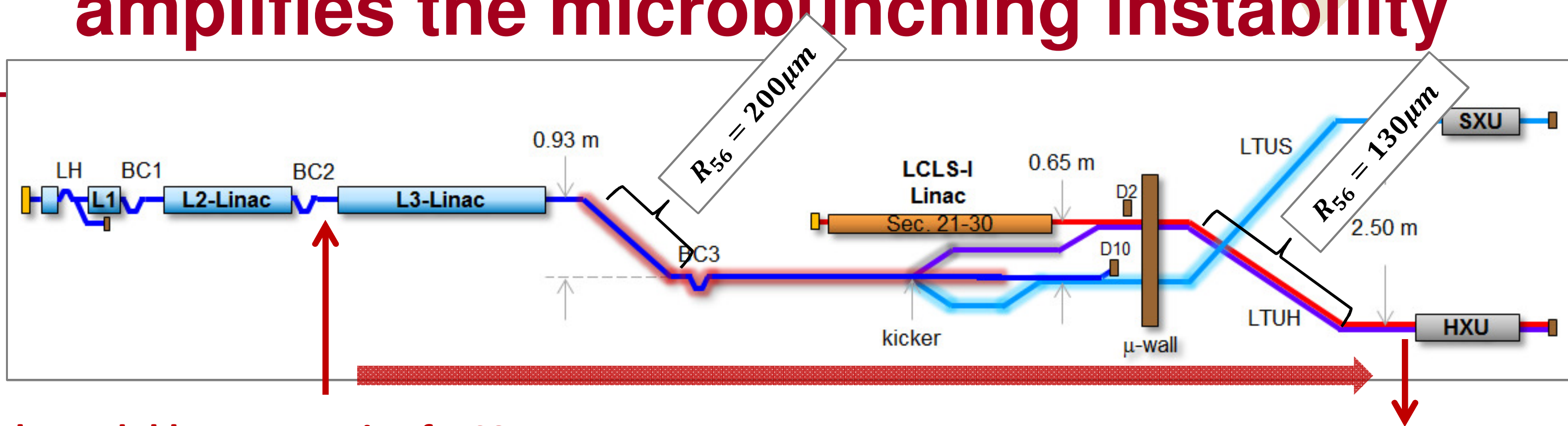
- **Trickle heating mostly gone**
- **Shot-noise induced μBI heating remains small**
- **Drawbacks:**
  - longer chicane (~12m)

Current baseline LH chicane

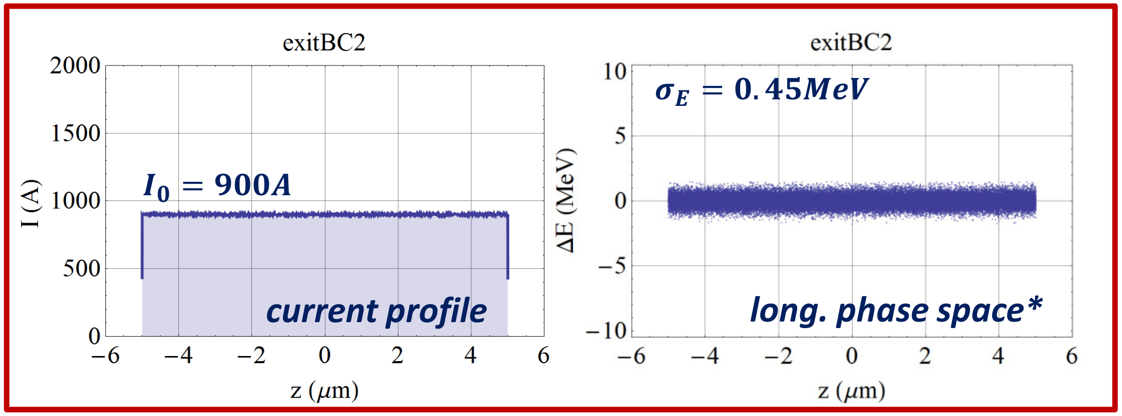
$(R_{56} = -3.5mm, D_{max} = 7.5cm)$



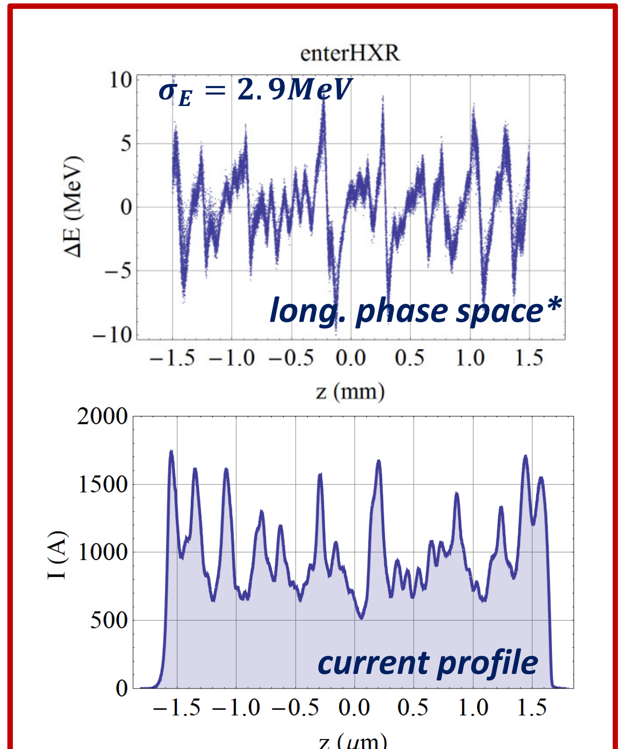
Transport through doglegs/bypass greatly amplifies the microbunching instability



Smooth model beam at exit of BC2



Beam as observed at HXU FEL is strongly microbunched

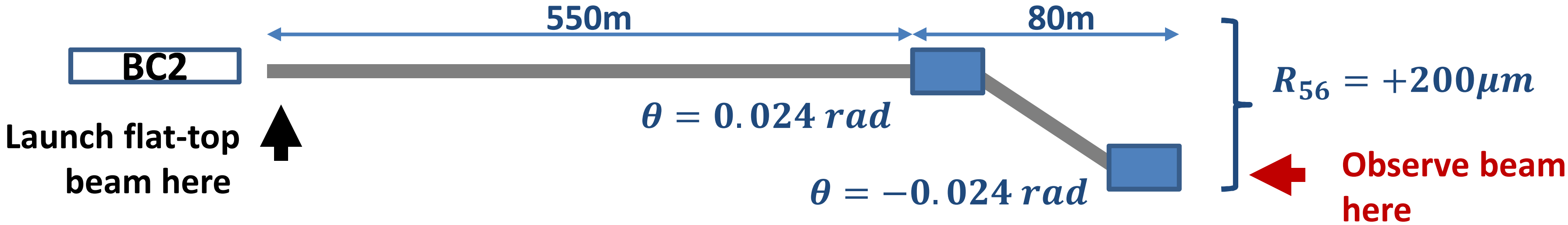


- Macroparticle simulation of **flat-top** model beam with **gaussian** uncorrelated energy spread at exit of BC2
  - representing short section of $Q = 100pC$ bunch with Laser Heater turned on.

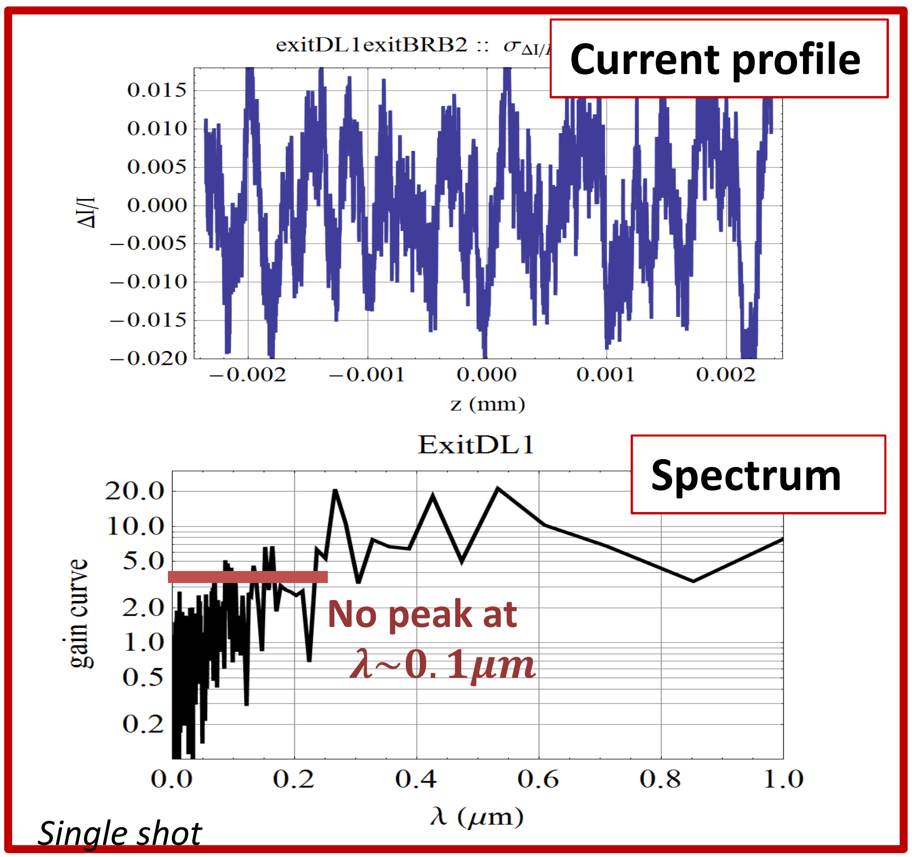
- Microbunching on **sub-μm scale** develops through DL (entrance of bypass) and transport section between μ-wall and FEL

** Correlated energy chirp removed*

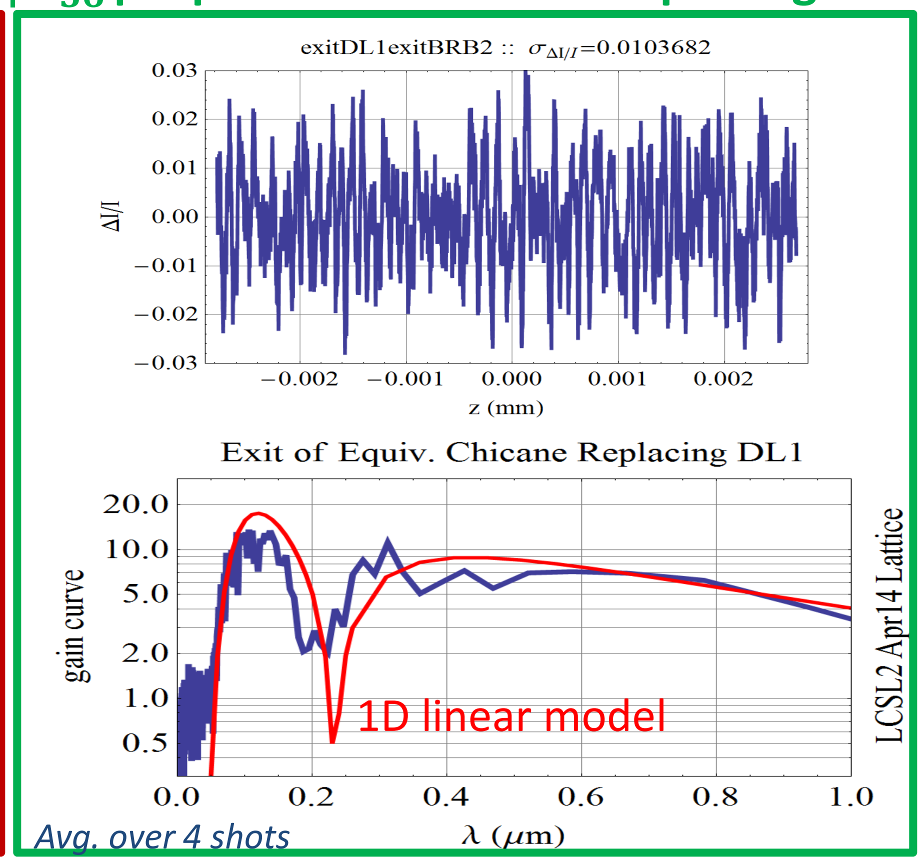
Problem starts with DL1: look at spectrum



DL1 baseline



$|R_{56}|$-equiv. short chicane replacing DL1



Aside on 1D vs. 3D
(and fine print too fine to read)

- **Linear theory of gain with 1D LSC model predicts essentially the same spectrum through DL1 as through a (short) 4-bend chicane with identical $|R_{56}|$.**
  - **Theory doesn't reproduce spectrum observed at exit of Dogleg (DL1) very well.**

- **We are still baking the cookies – not ready for last word.**
  - Limitation of the 1D LSC model within dogleg ?

- **Why the smoothing at higher spatial frequencies?** Longitudinal mixing induced by finite transverse emittance:

  Beam size in dogleg: $\sigma_x \sim 30\mu m$, $\sigma_{x'} \sim 1.2\mu rad$ Dogleg dipoles: $\theta = 0.024\, rad$, $L_{BRB} = 1m$

  Smoothing from finite transverse beam size: $\Delta z \sim R_{51}\sigma_x = \theta\sigma_x \sim 0.7\mu m$

  finite angular spread: $\Delta z \sim R_{52}\sigma_{x'} = \frac{L_{BRB}}{2}\,\theta\sigma_{x'} \sim 0.015\mu m$

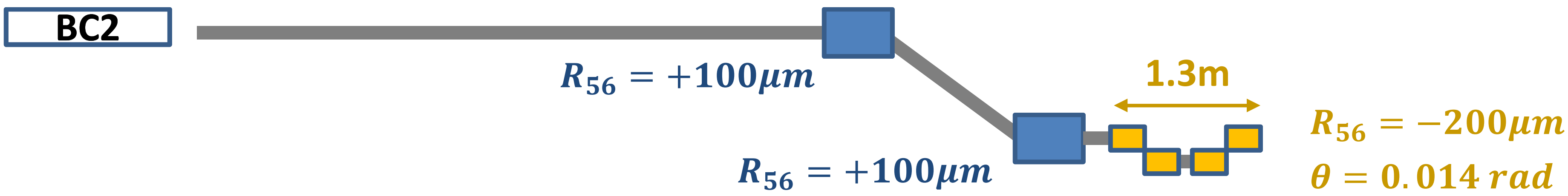
- **As the beam exits the 2nd bend in dogleg high-frequency components of energy modulations accrued within DL should be washed away and we would expect no additional contribution to the bunching observed at exit of DL1 (effectively, it is as if LSC was not active in DL; as predicted by 1D linear theory)**

- **However: if LSC 3D effects were important bunching induced by space charge within chicane may not be as strongly suppressed as expected based on a 1D model (Ref. experience with OTR measurements in LCLS1 downstream of DL at injector during commissioning, D. Ratner et al.)**

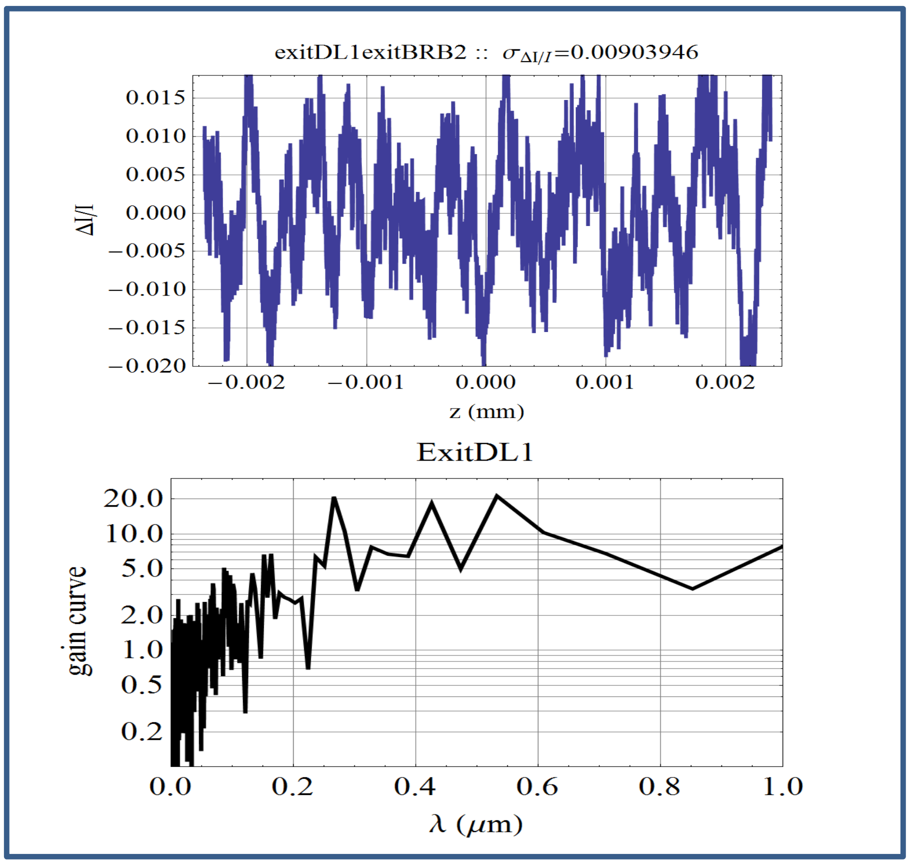
- **Are we in 3D regime?** $\frac{kr_b}{\gamma} \sim 0.4$ **for** $\lambda = 0.1\mu m$. **Is this large enough to claim 3D effects are important?**

BTW, energy-spread induced mixing is a bit smaller $\Delta z \sim 2\pi R_{56}\sigma_\delta \sim 0.14\mu m$

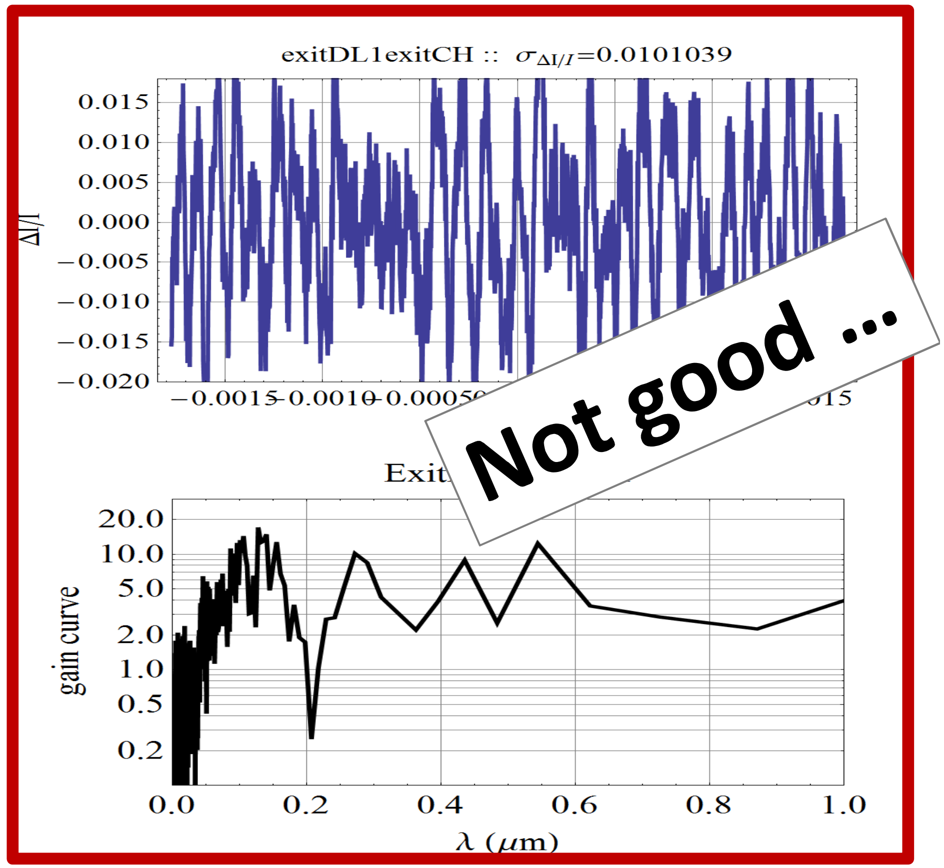
Non-local R_{56} compensation?



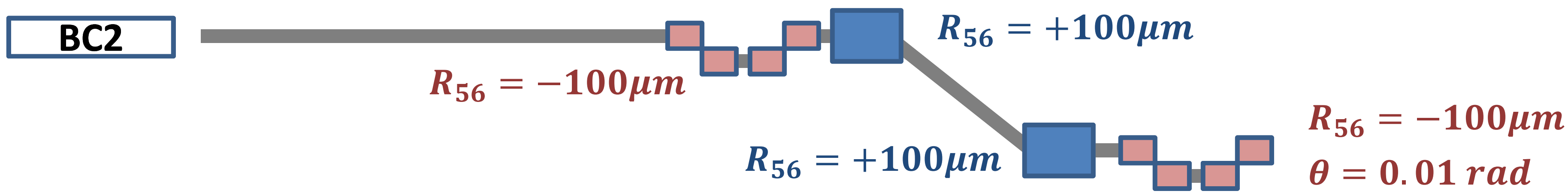
DL1 baseline



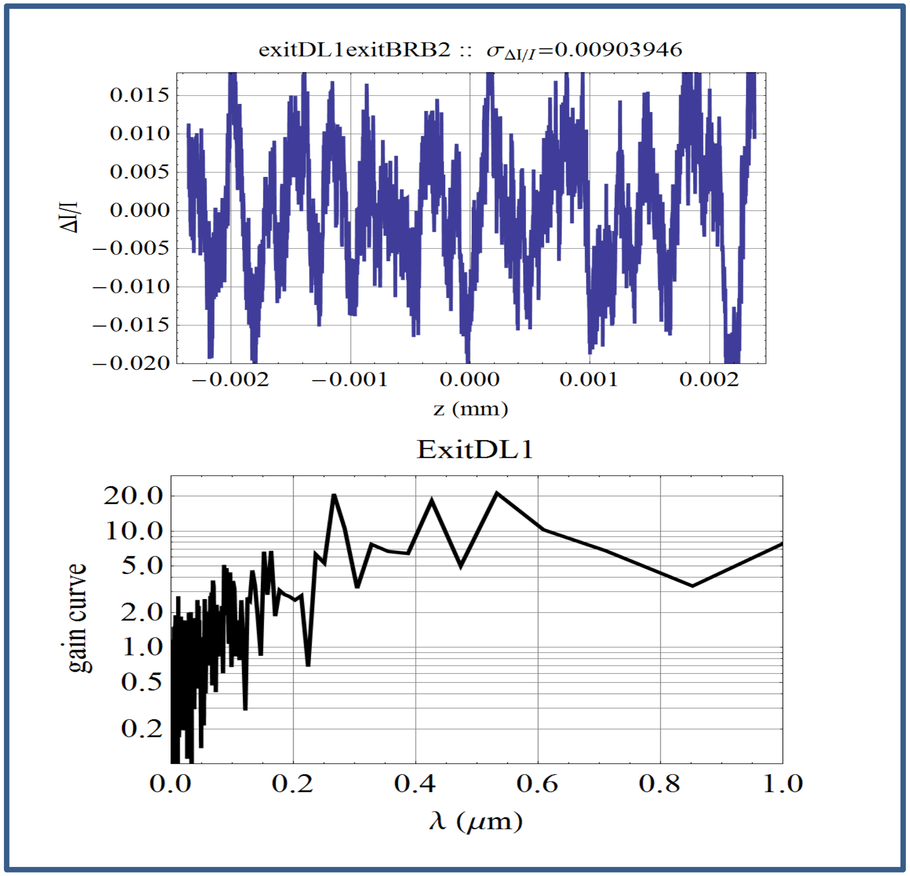
Baseline DL1 + equivalent chicane



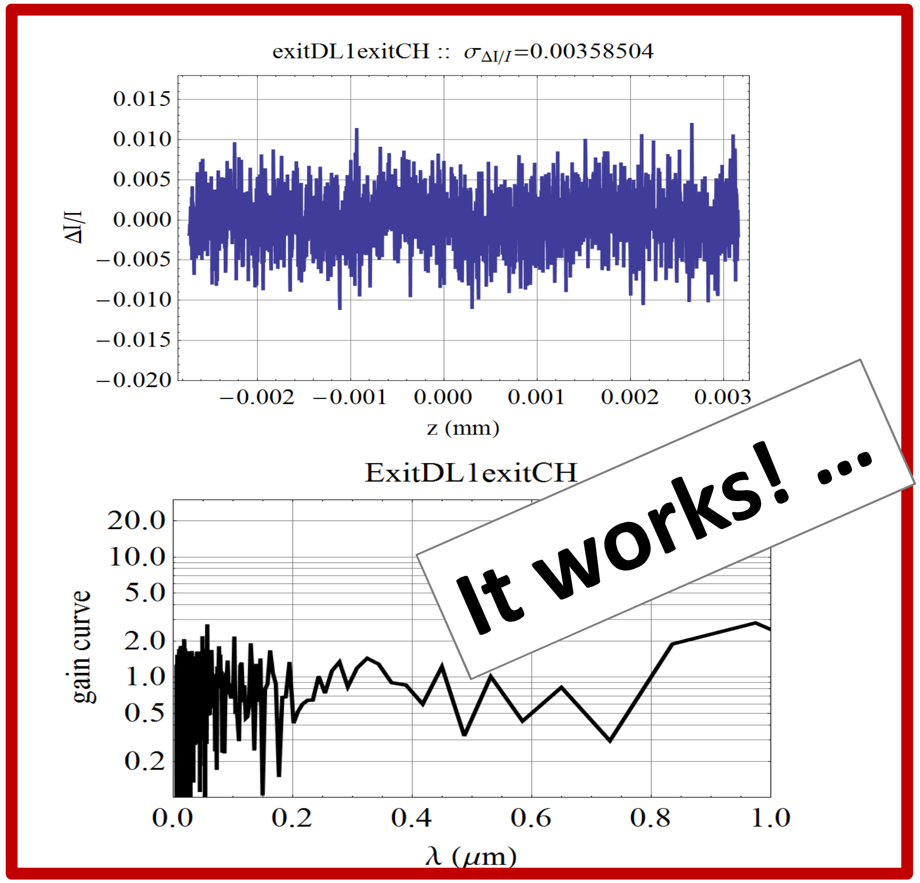
Try local R_{56} compensation



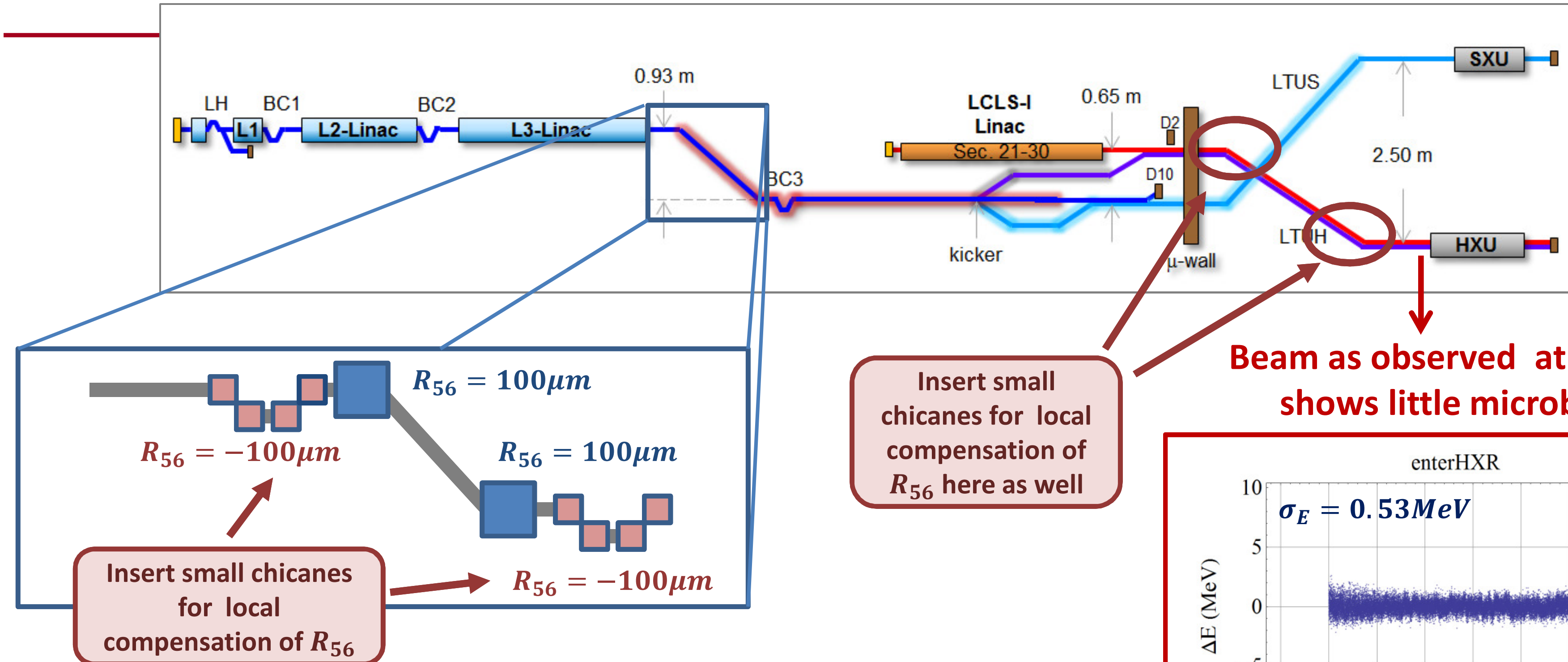
DL1 baseline



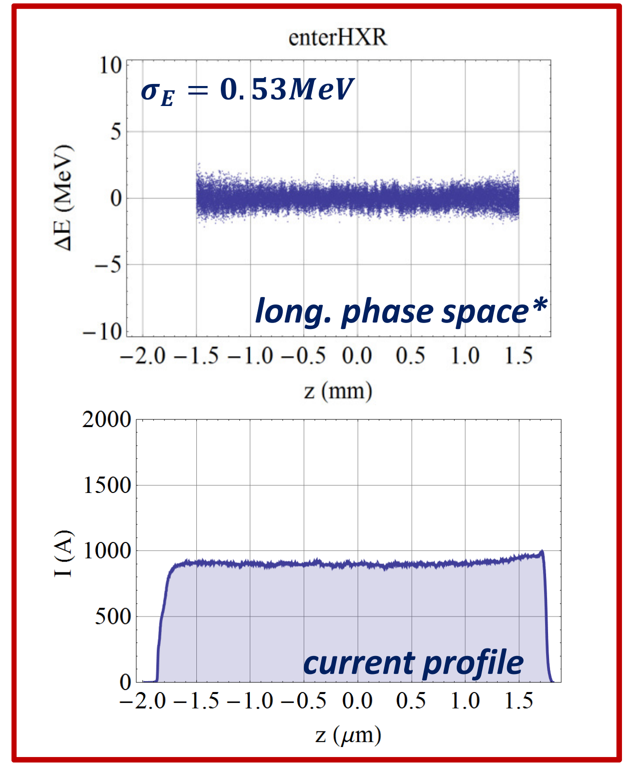
Baseline DL1 +2-compensating chicanes



Make all main doglegs locally isochronous (to HXR)



Beam as observed at HXU FEL shows little microbunching



- Non-local compensation of R_{56} not as effective.
- Alternate local compensation schemes may be possible
- Robustness against jitters, errors?
- Effect on transverse emittance?
- Delaying compression to exit of bypass would also be a way to reduce microbunching

** Correlated energy chirp removed*

Conclusions

- **The Laser Heater: watch out what you ask for!**
  - ***Anomalous heating (trickling, microbunching)***
- **Long transport lines are potential trouble makers.**
  - ***Making the transport lines locally isochronous as much as possible should fix the problem.***
- **After having taken the pain to try to avoid it,**
  Could we use the μBI for something good?

Acknowledgements

J. Qiang for support with IMPACT.
LCLS2 design team