The Microbunching Instability and LCLS-II Lattice Design

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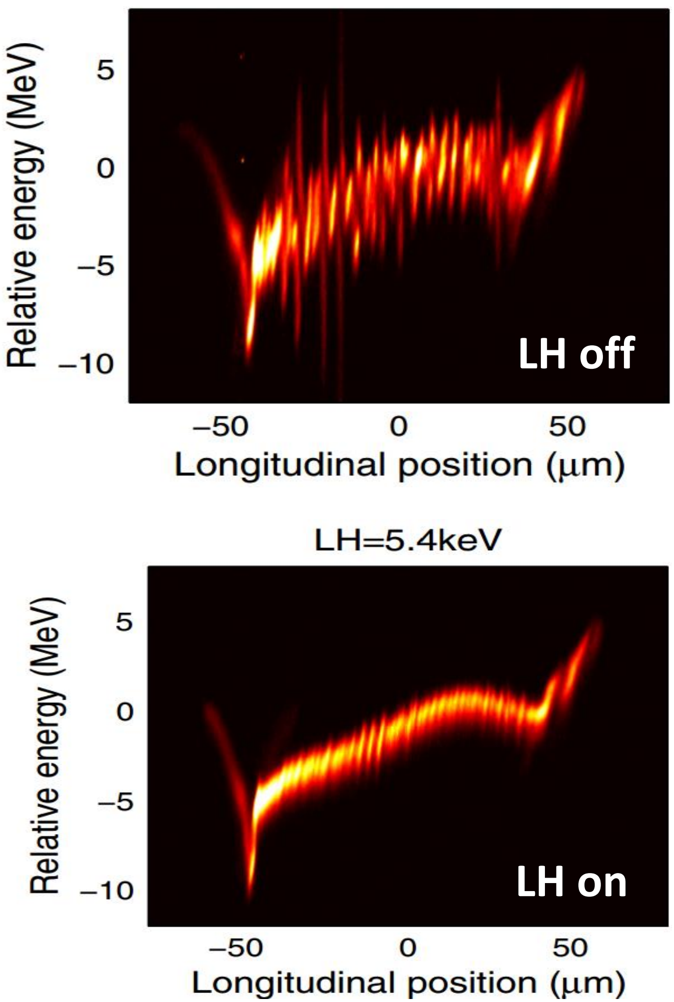
The microbunching instability (μBI): pervasive and unwanted

μBI in action:
LCLS beam measurements*



****D. Ratner, et al., PRST-AB, 18 030704 (2015)***

- **The μBI signature: micro E/z correlations, energy spread growth**
- **Consequences: reduced radiation output and/or degradation of radiation spectrum**
- **First identified by M. Borland, predicted by E. Saldin, *et al.*, early 2000s**
- **Of concern in all x-ray FELs ➔ Laser Heater**
- **A potential problem for LCLS-II**
  - ***Characterize instability***
  - ***Look for remedies that do not sacrifice beam brightness***

Two mechanisms drive the instability

- ***Longitudinal*** **self-fields + longitudinal slippage from R_{56}**
  (The conventional and prevalent mechanism)

- ***Transverse*** **self-fields + longitudinal slippage from R_{52}**
  (New !)

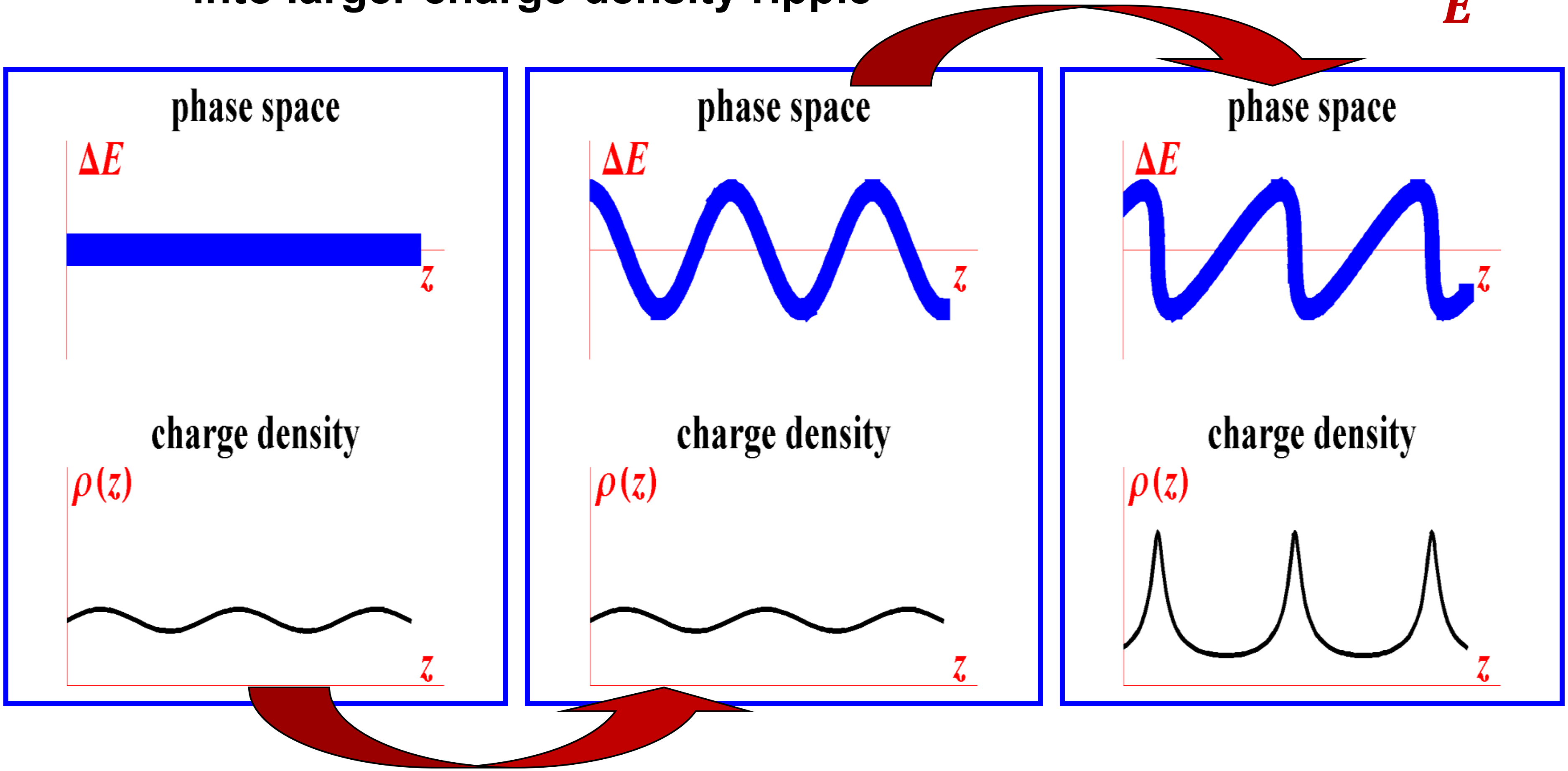
Focus on shot-noise seeded instability

- *Effect of non-uniformities in photo-cathode laser?*

Cartoon for the ‘conventional’ mechanism of μBI

Dispersion turns energy modulation into larger charge-density ripple

$$\Delta z = R_{56}\frac{\Delta E}{E}$$

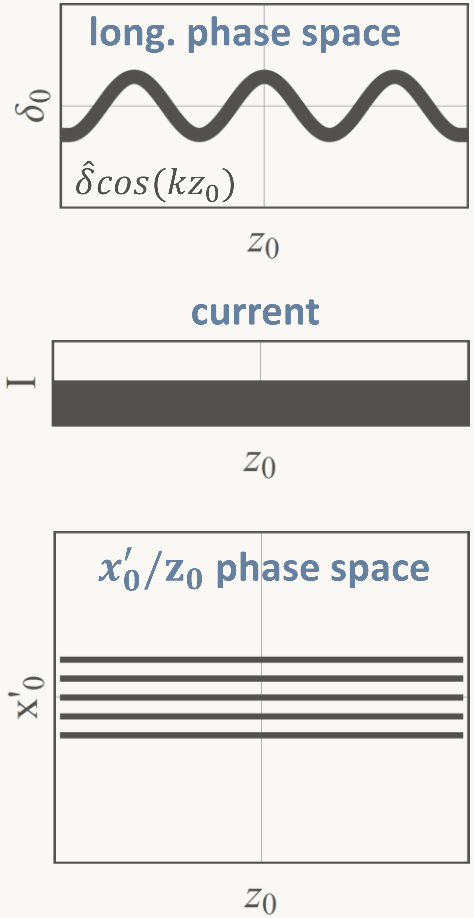


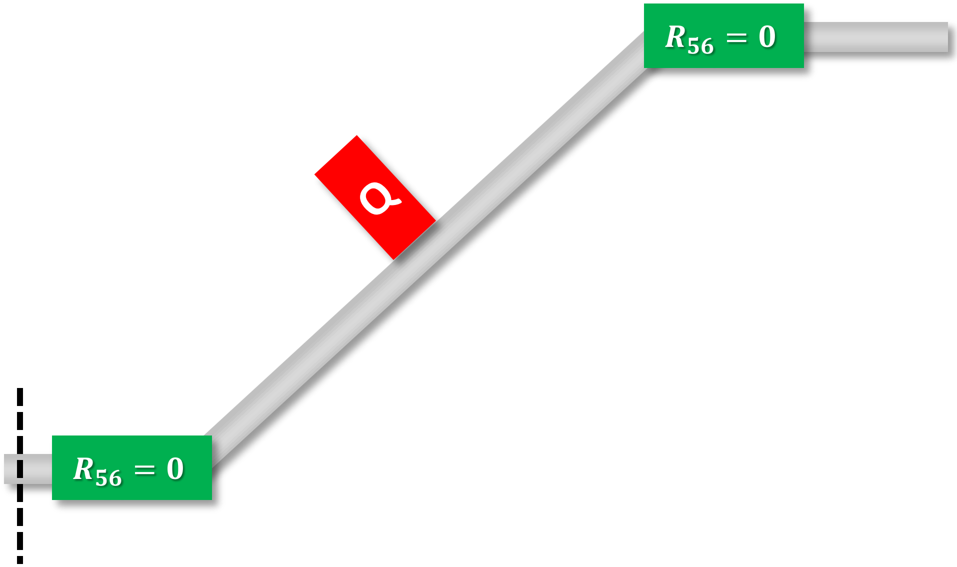
Collective effects turn charge-density ripple into energy modulation

$$\Delta E = \frac{4\pi I}{I_A} mc^2 \int \frac{|Z|}{Z_0} ds$$

The not-so conventional mechanism: *e.g.* transport through dogleg achromat

beam as a line charge
($x_0 = 0$, w/ energy modulation,
uniform current,
discrete angular spread)





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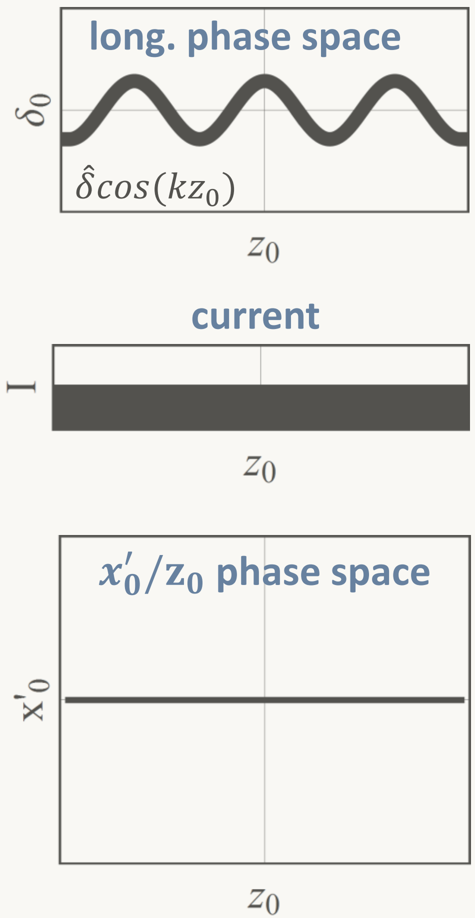

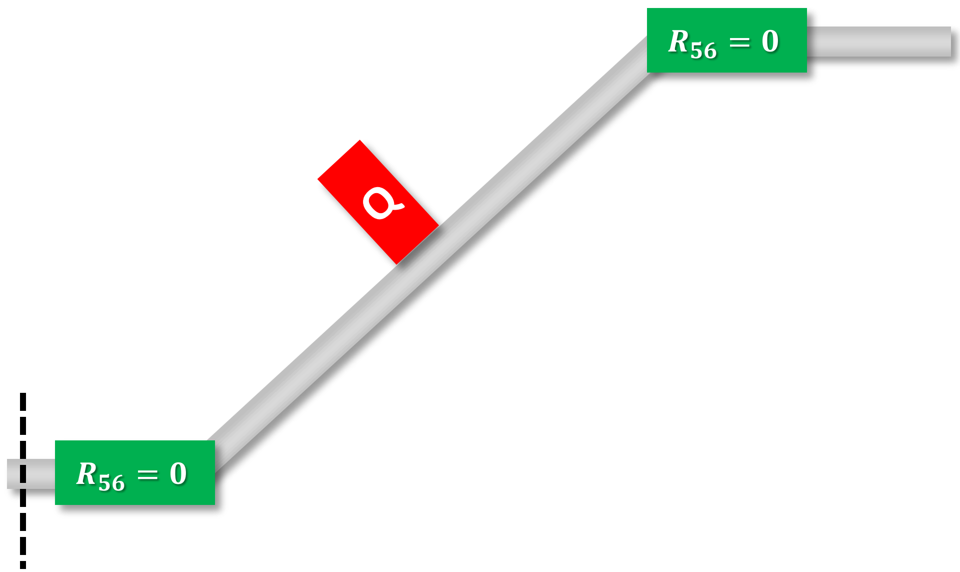

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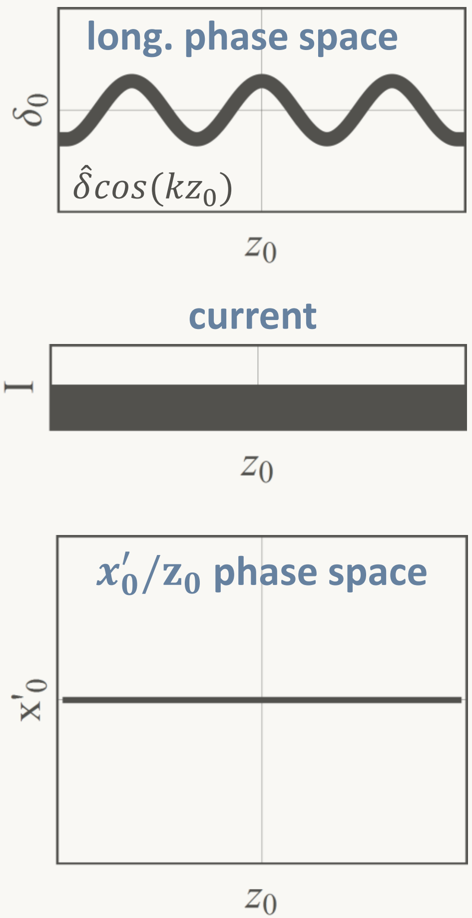

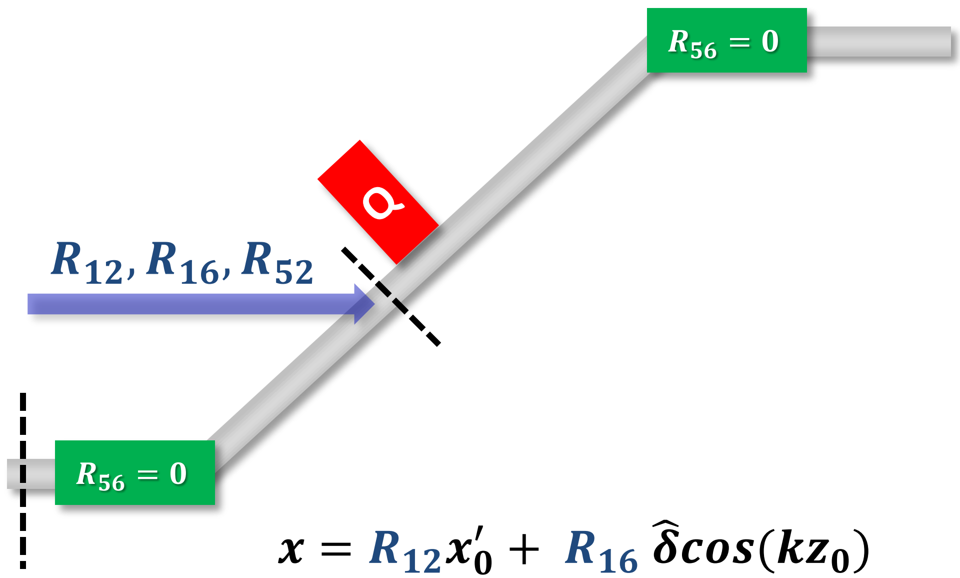

$$x = R_{12}x'_0 + R_{16}\,\hat{\delta}cos(kz_0)$$

$$z = z_0 + R_{52}x'_0$$

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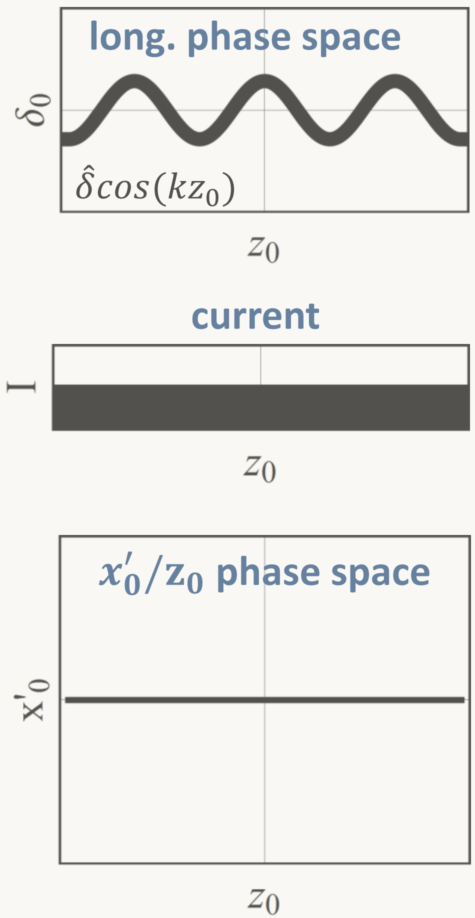

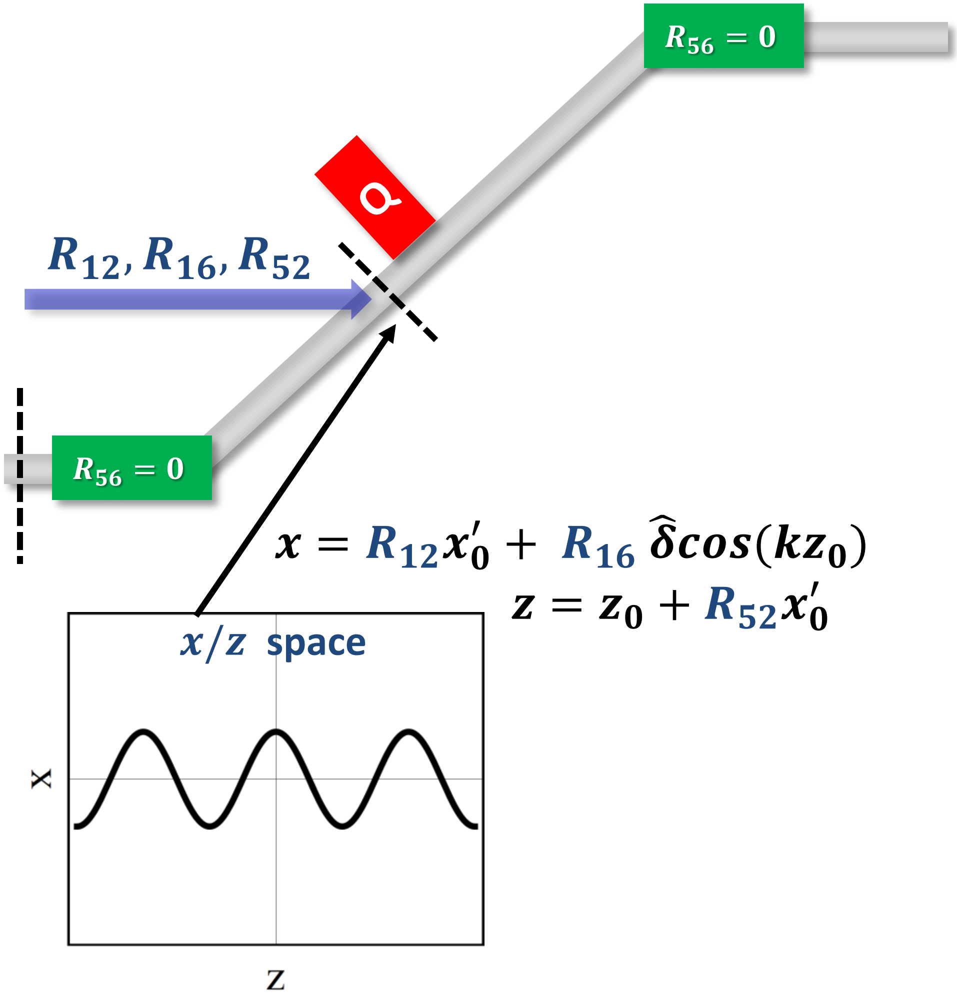

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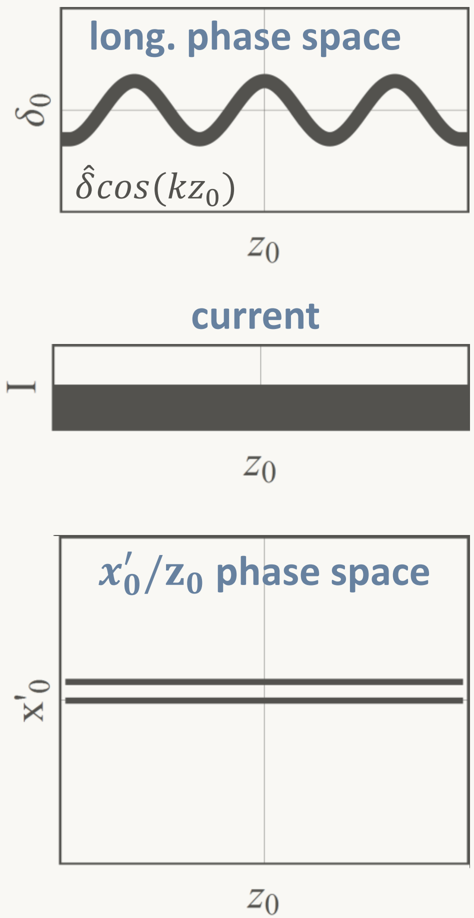

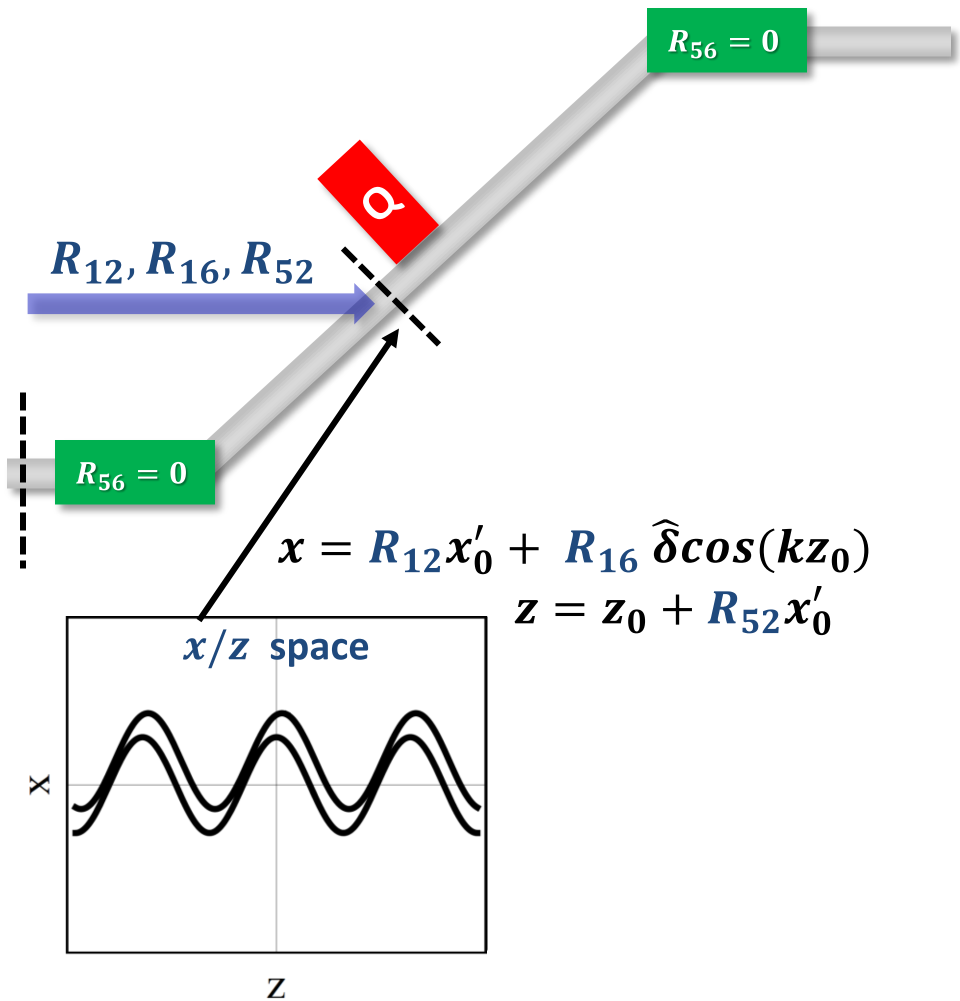

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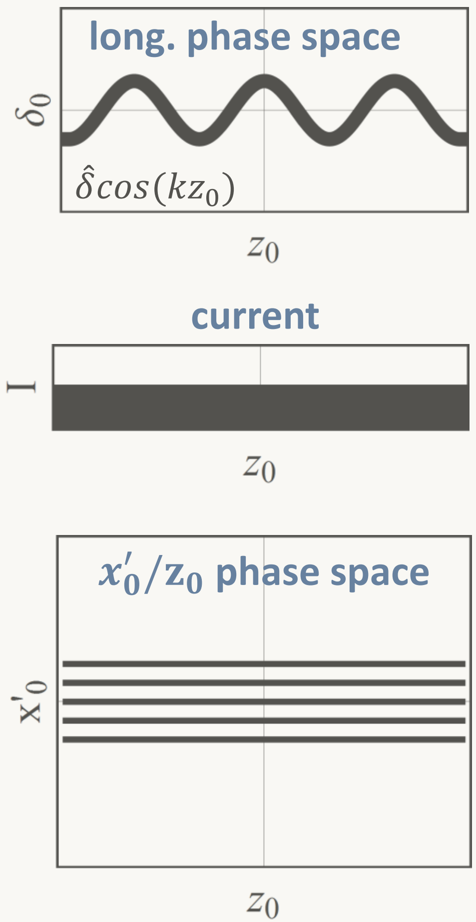

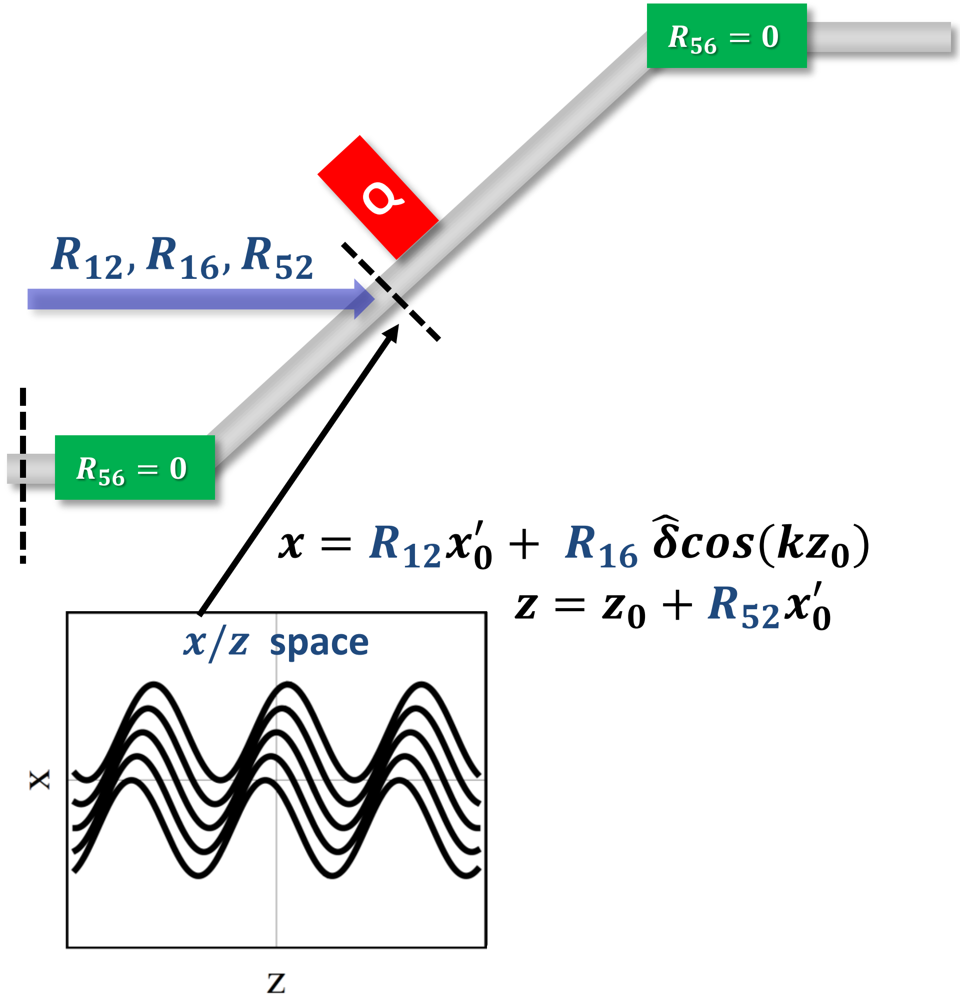

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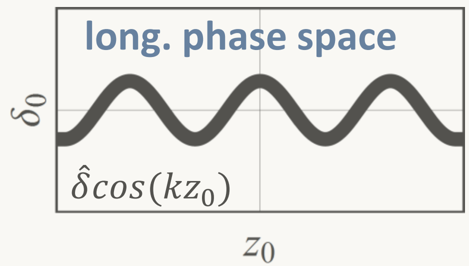

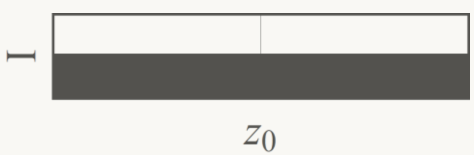

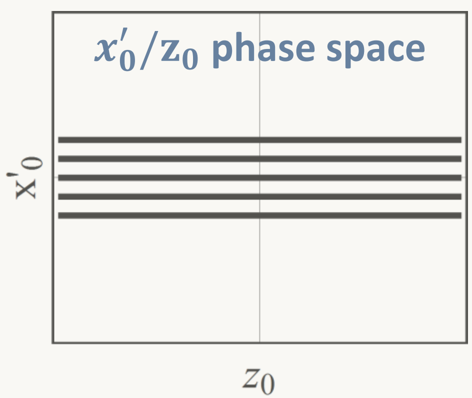

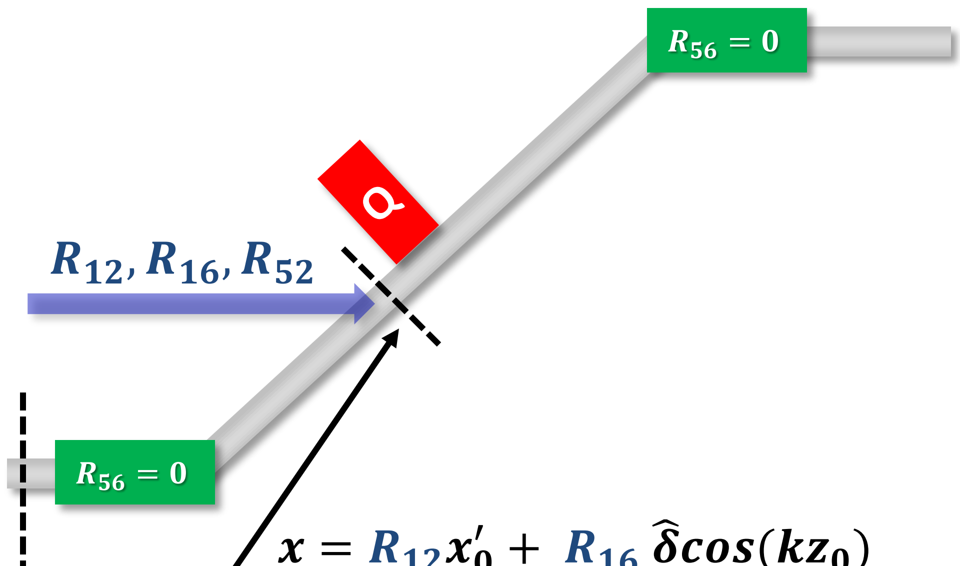

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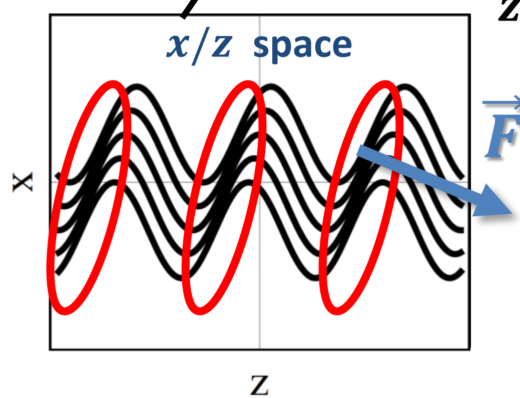
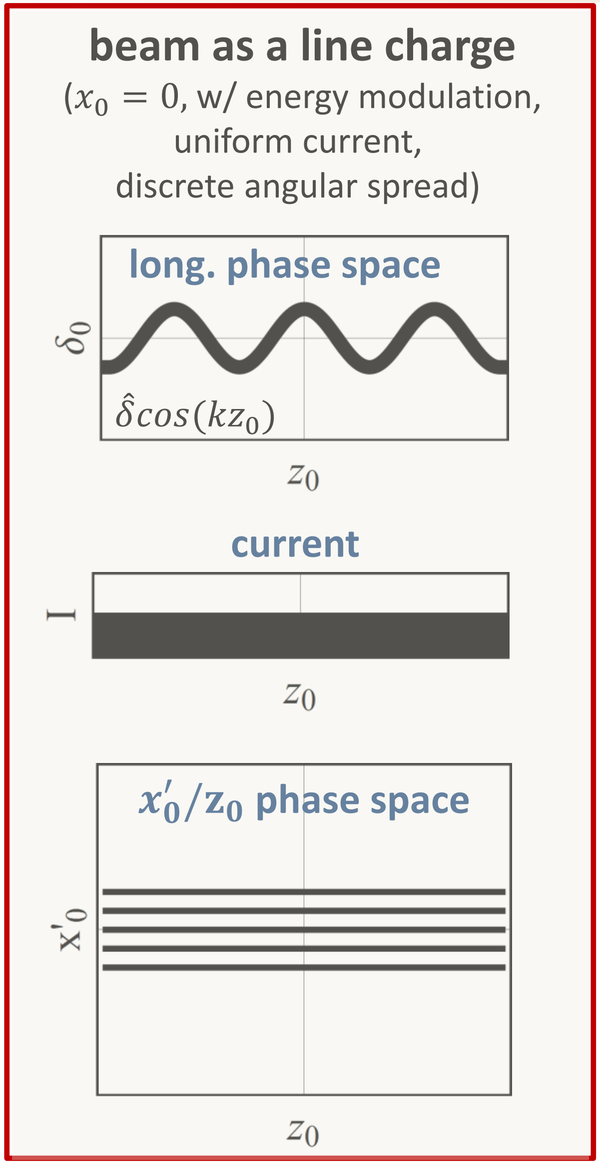
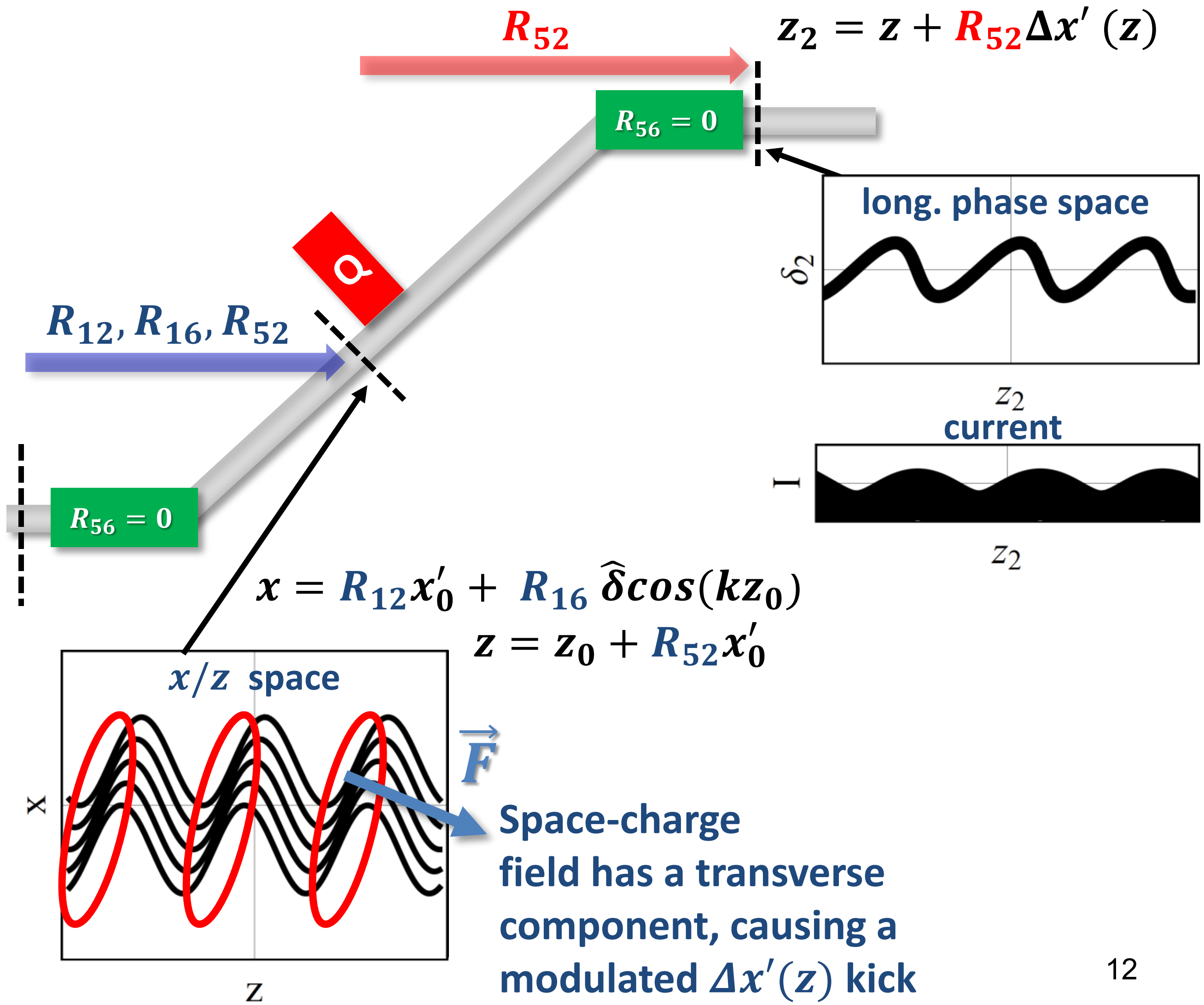


Space-charge field has a transverse component, causing a modulated $\Delta x'(z)$ kick

The not-so conventional mechanism: *e.g.* transport through dogleg achromat





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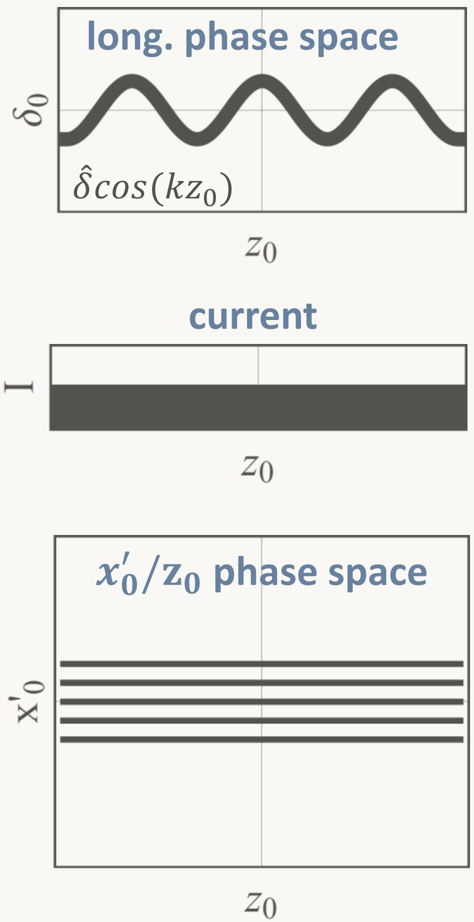
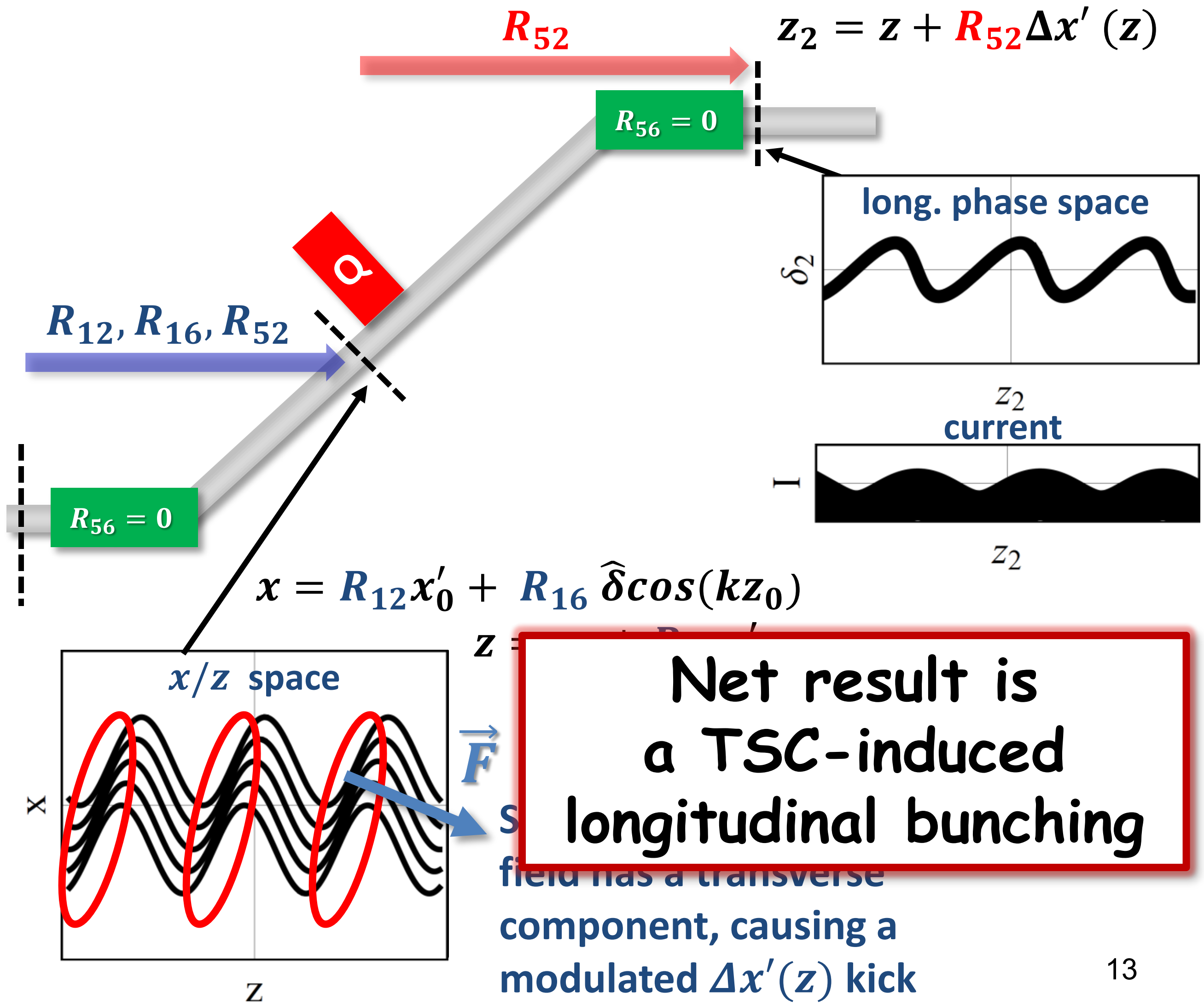




Net result is a TSC-induced longitudinal bunching

The tools of the trade for μBI analysis

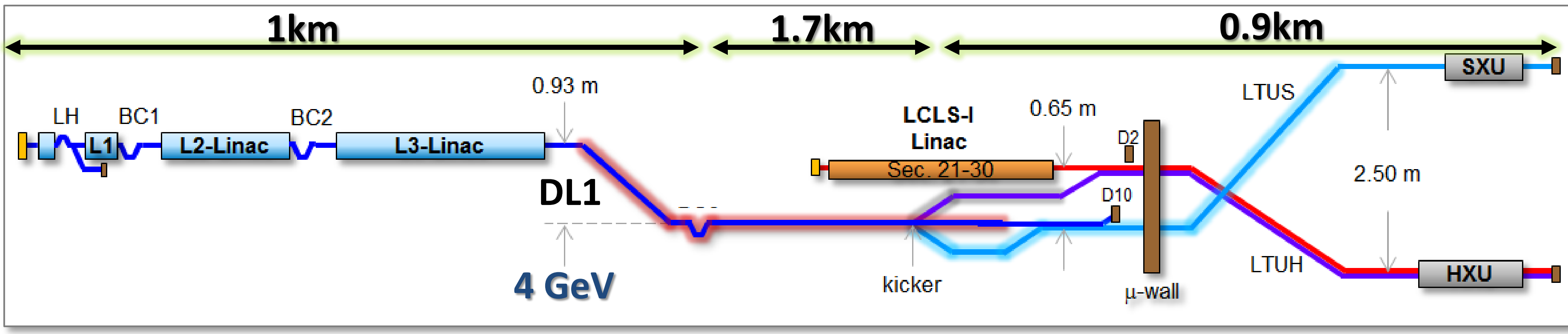
- **High fidelity macroparticle simulations (code IMPACT, by J. Qiang *et al., LBNL*)**
  - *Efficient **3D** Poisson solver for space-charge fields*
  - *5^{th} order single-particle dynamics + **1D CSR**, RF and RW **wakefields***
  - *Efficient **parallelization**; access to LBNL NERSC computing resources (1000+ processor runs)*
  - ***One** electron, **One** macroparticle*
  - *For this study: track **idealized beam** distributions to highlight μBI effects through various critical machine sections (excluding the injector).*

- **(Semi-)analytical linear models**
  - *Impedance-based or otherwise simplified representation of space-charge fields.*

Not a boring machine: the many μBI hot-spots along LCLS-II

LCLS-II Layout

Schematic (not to scale) by P. Emma



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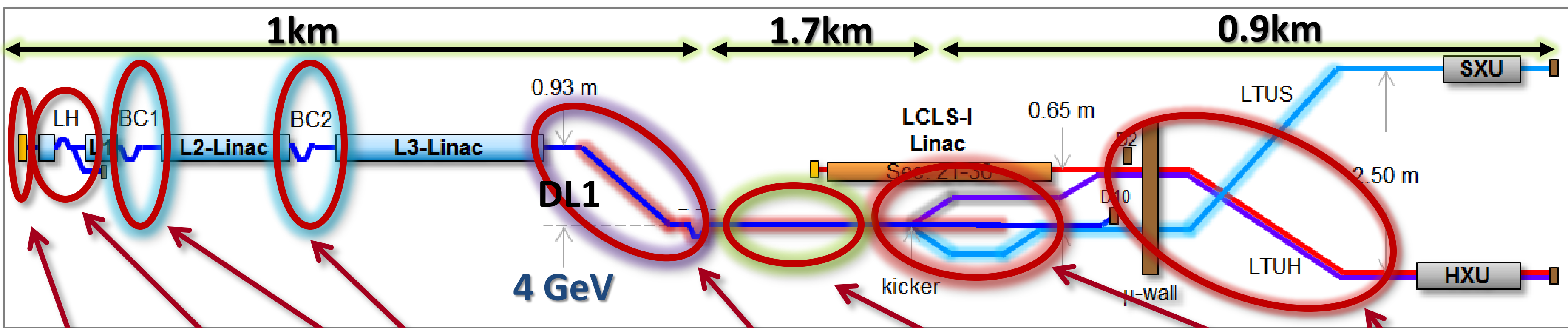


Injector
Velocity bunching

Laser Heater
Anomalous heating

BC Chicanes
Compression, dispersion

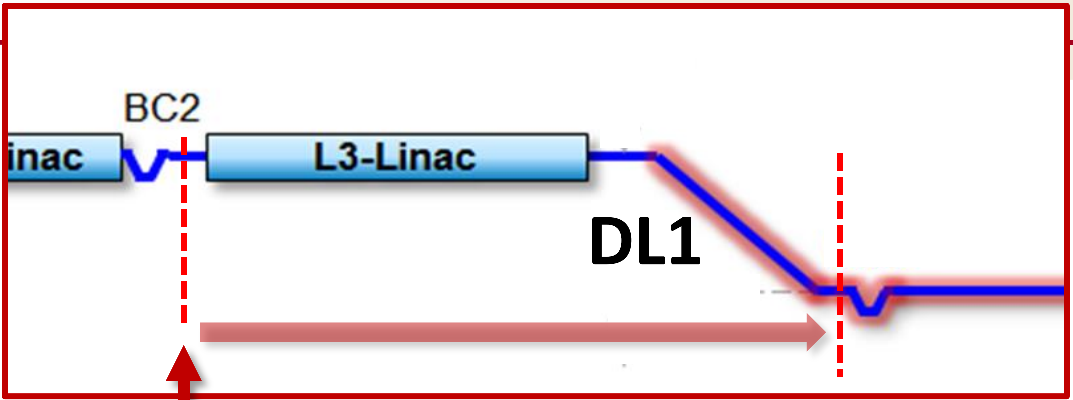
Dogleg at entrance of bypass line
Dispersion

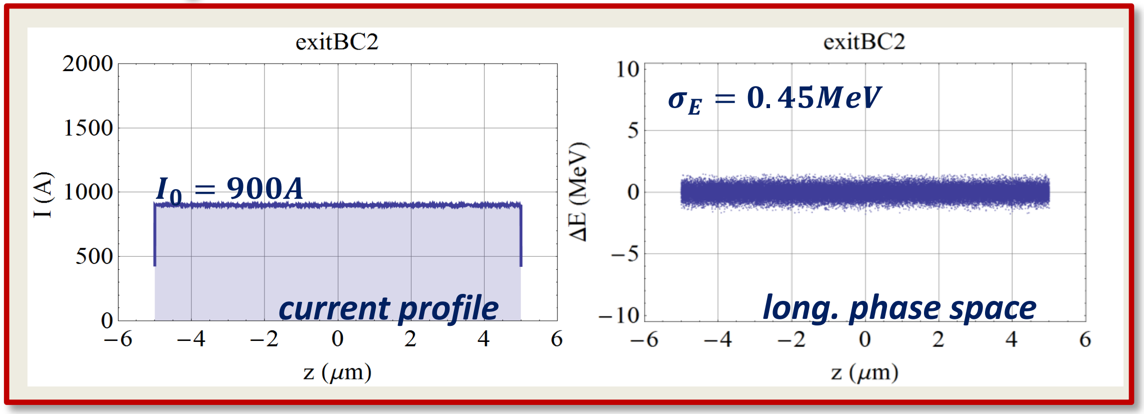
Bypass line
Long transport

LTU sections
Dispersion

- **Focus on transport to HXR FEL (baseline 100 pC bunches)**

Warming up the simulation muscles: track beam from BC2 to exit of DL1





- **Flat-top with nominal full compressed current $I = 900A$**
- *Track w/ <u>longitudinal</u> space charge only*
- **Compare with linear theory**
  - *LSC-Impedance*

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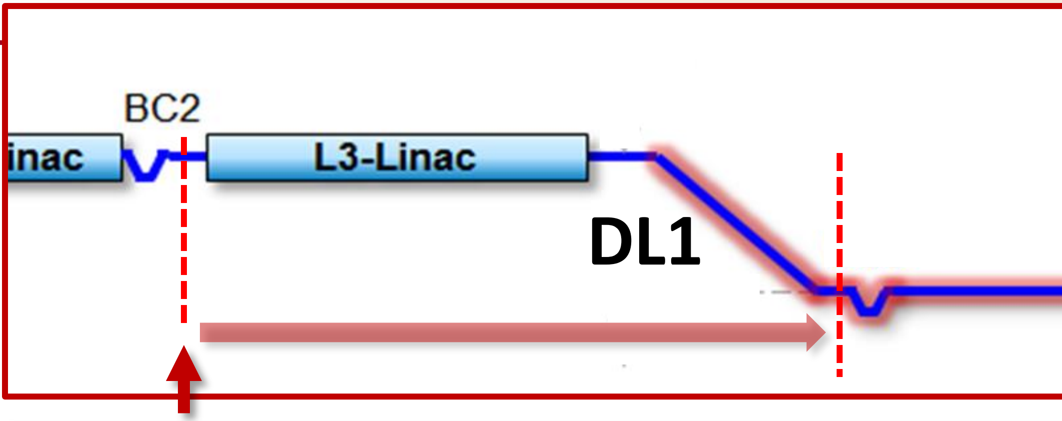

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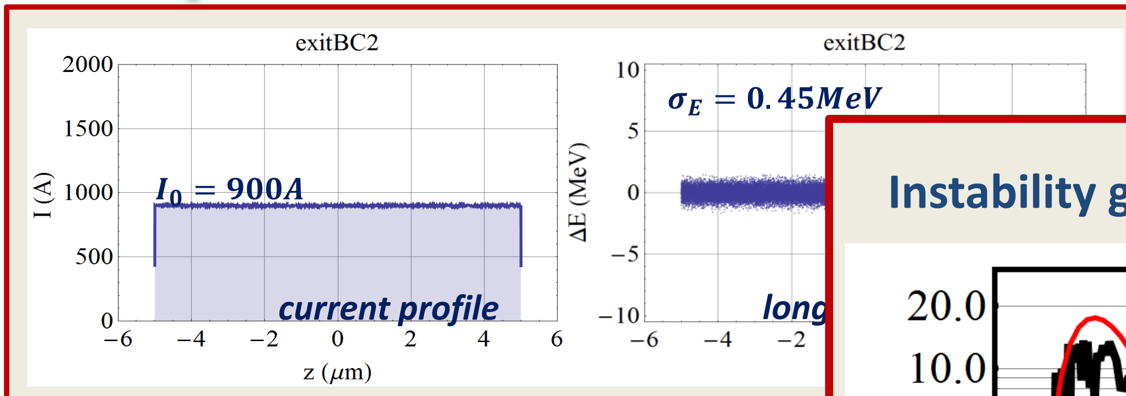
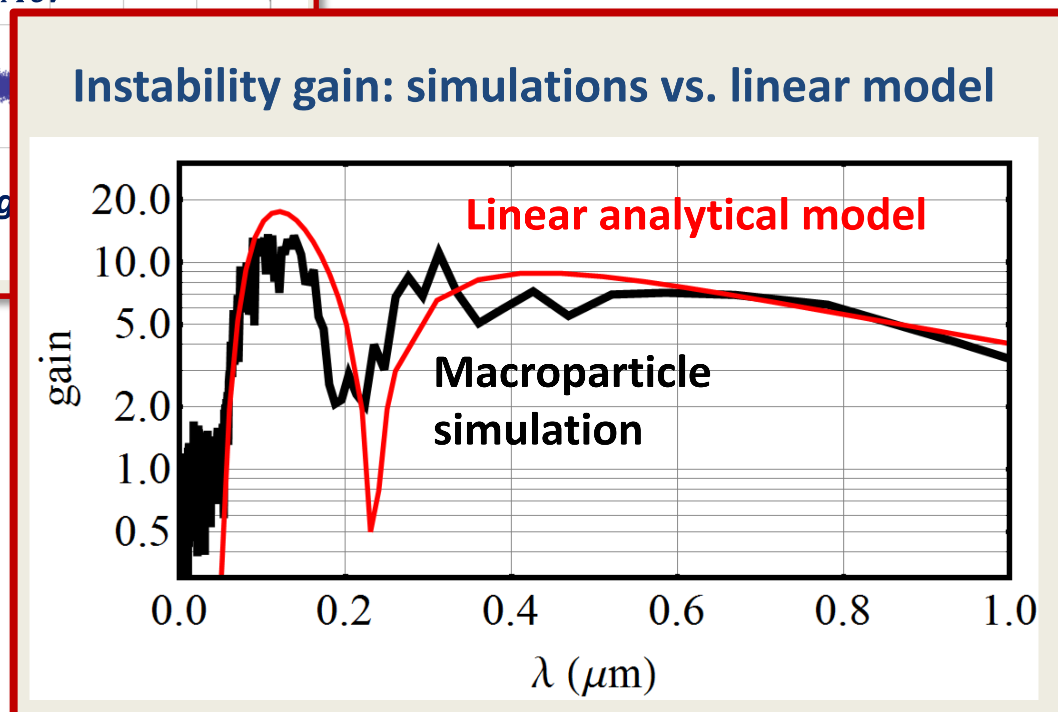
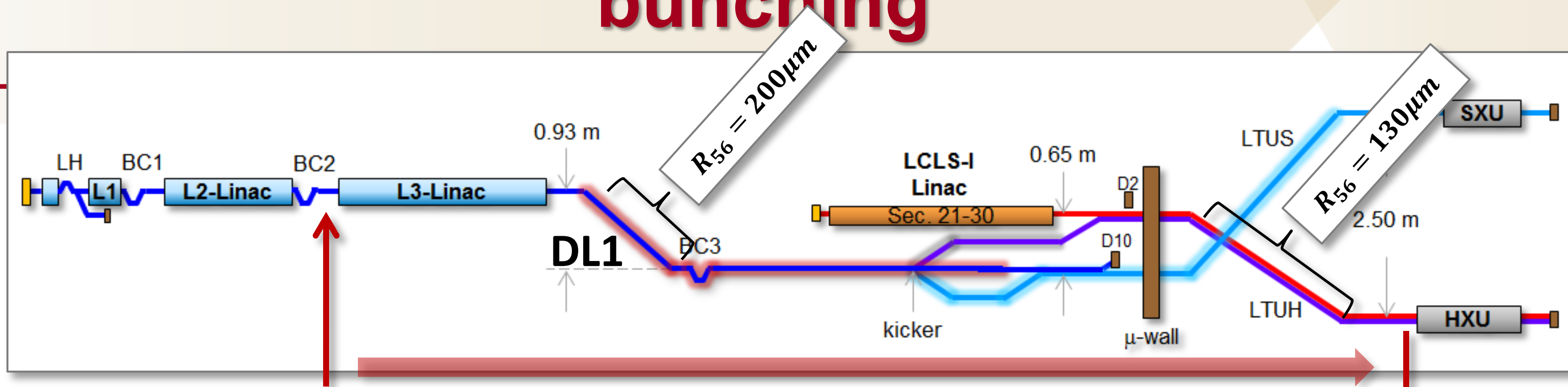


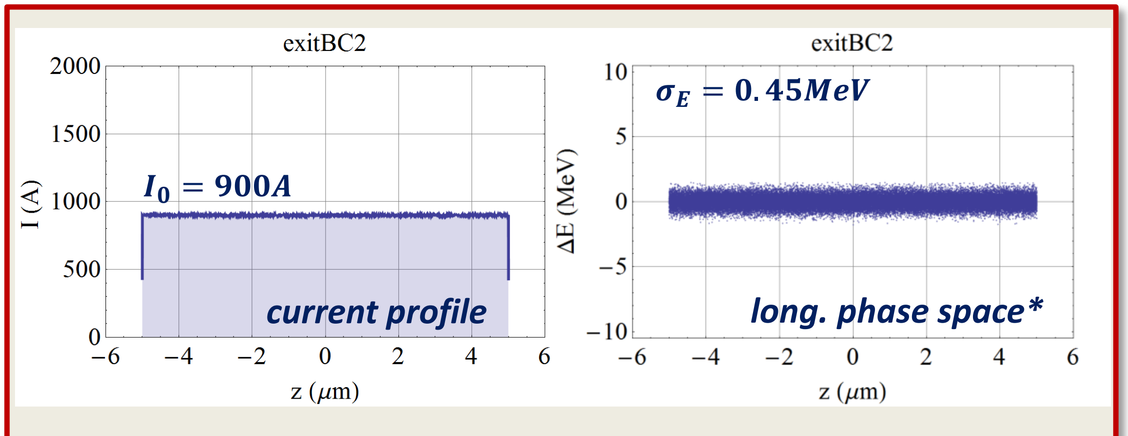


- **Gain = $|b_f/b_i|$**
  - $|b_i| = 1/\sqrt{N}$ *(shot noise)*
- **Good cross-validation simulation/theory**
  - *Theory includes effect from plasma oscillations in L3*
- ***peak gain @ sub-μm***

Follow the beam to the FEL and find spectacular bunching

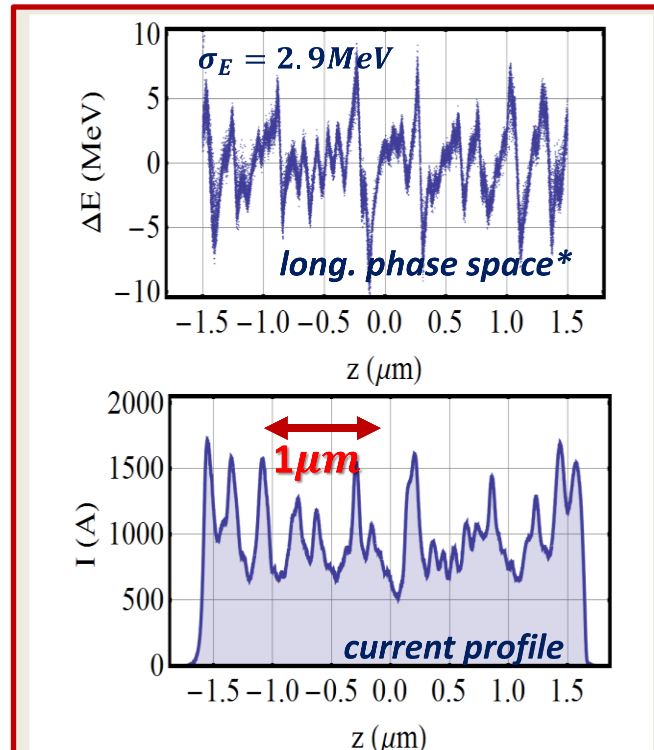


Start simulation with smooth beam model at exit of BC2



- **flat-top** model beam with **gaussian** uncorrelated energy spread
  - represents short section of $Q = 100pC$ bunch (laser heater on.)

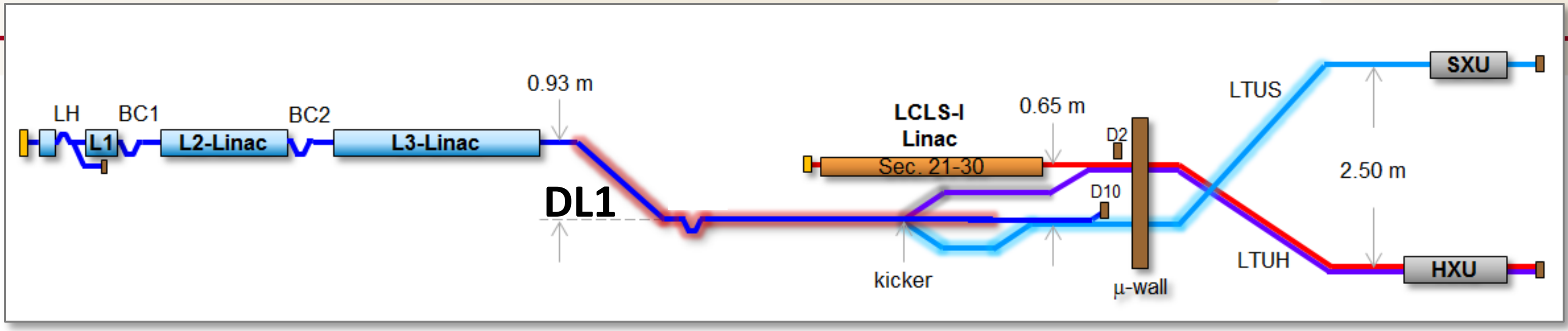
Beam as observed at HXU FEL is strongly microbunched



- Strong microbunching on sub-μm scale

** Correlated energy chirp removed*

What to do?
Introduce local cancellation of R_{56}



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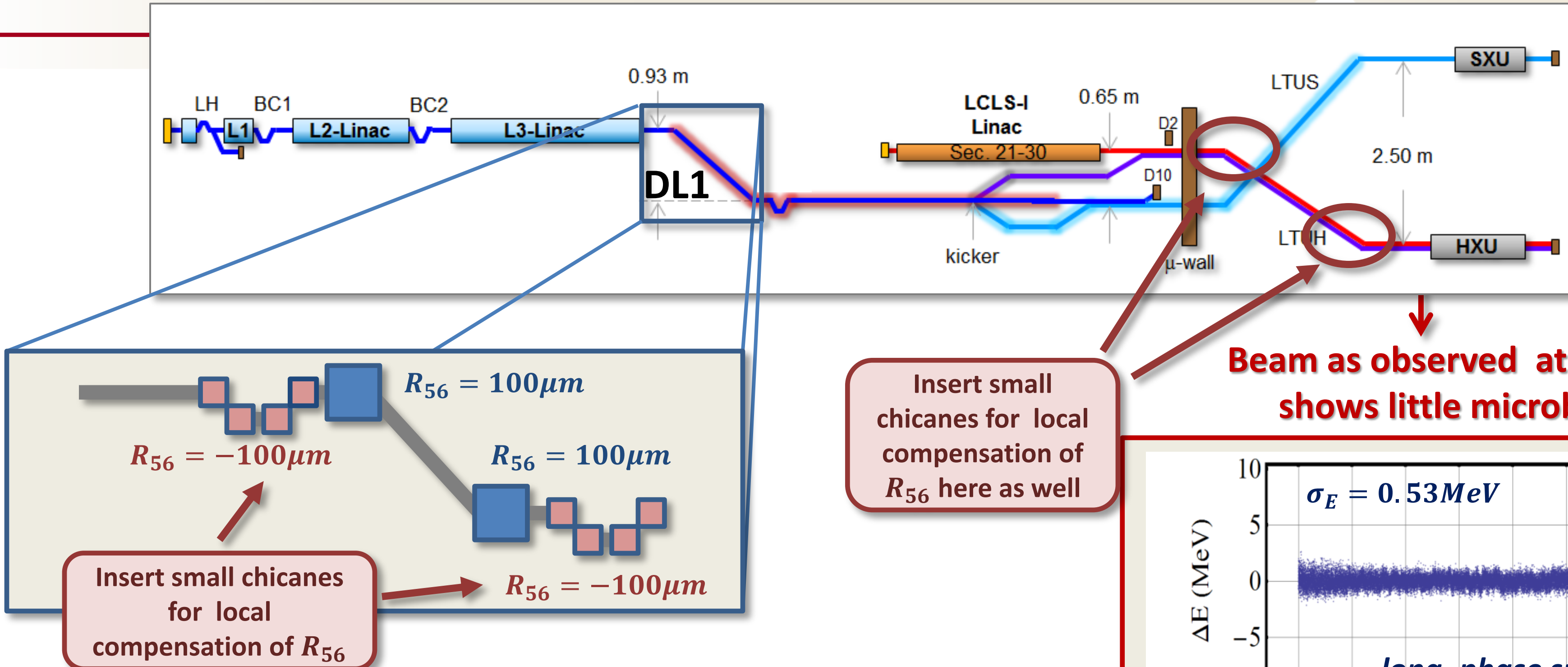
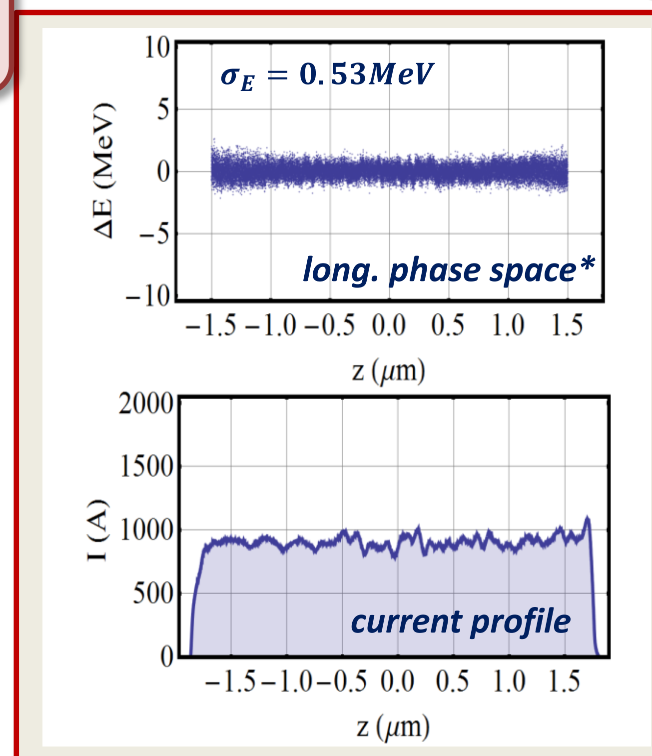


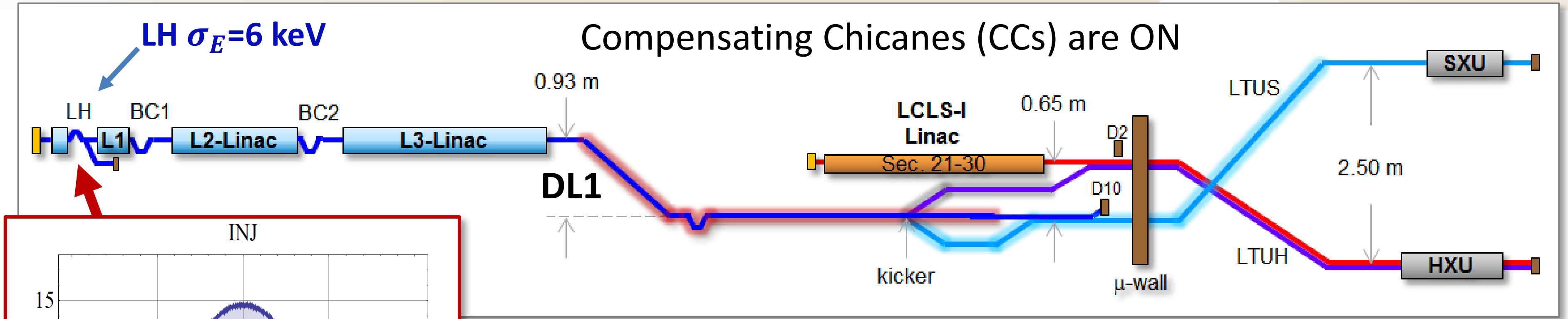
Beam as observed at HXU FEL shows little microbunching

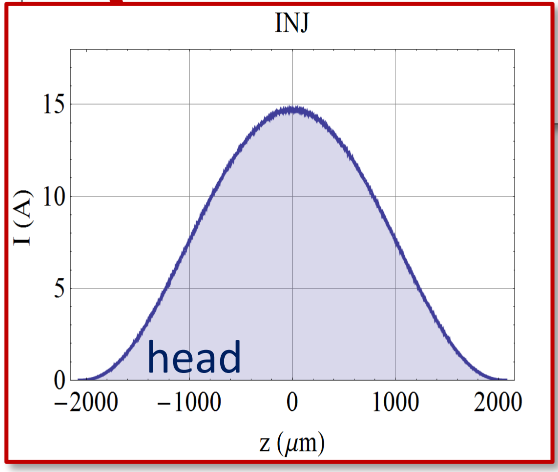


- Method appears to be highly effective
  - *Delaying compression to exit of bypass could also be a way to reduce microbunching but has drawbacks*
- Is everything all right, then ? Not quite …

** Correlated energy chirp removed*

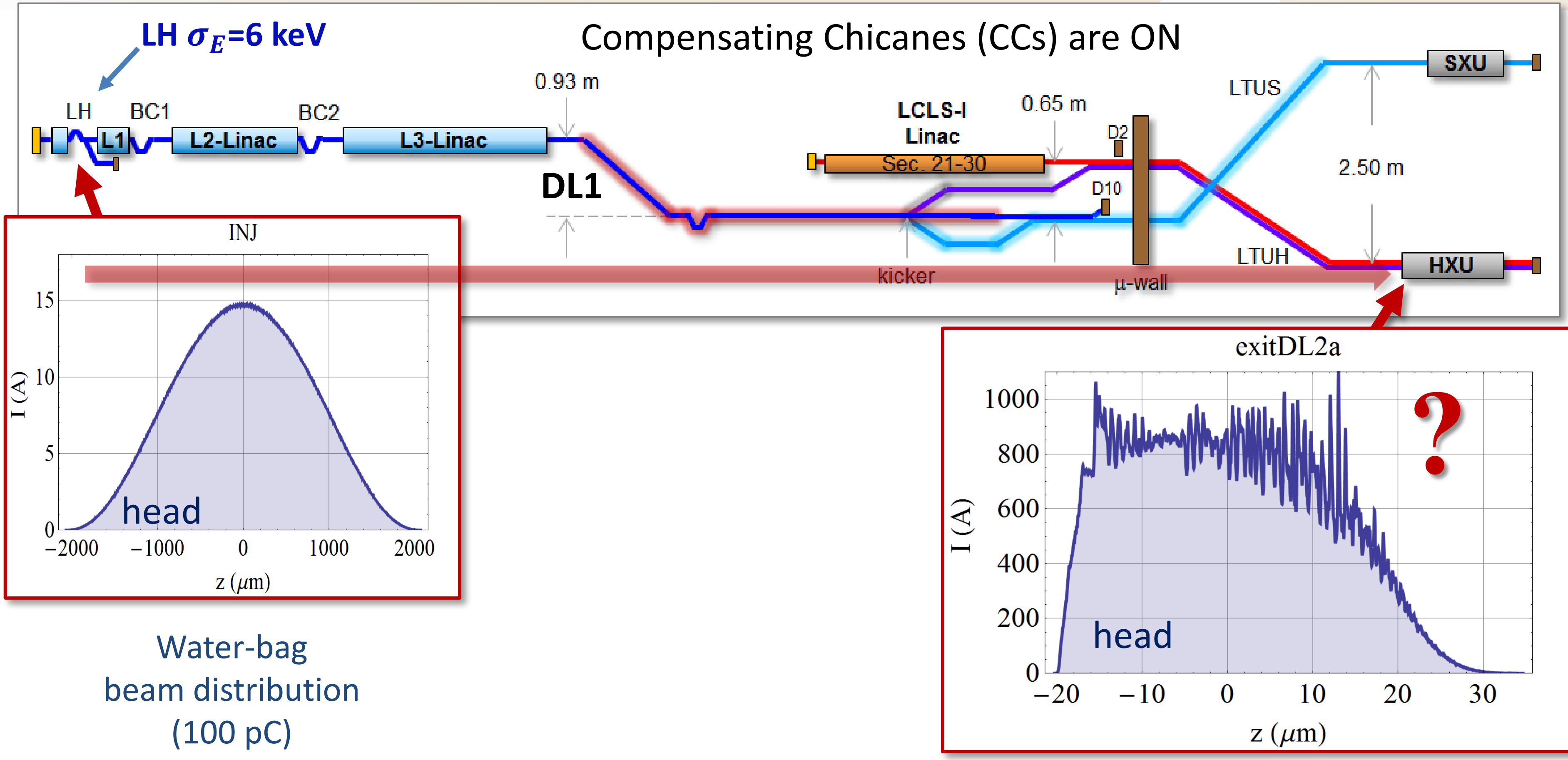
The μBI strikes back …





Water-bag
beam distribution
(100 pC)
E=100 MeV

The μBI strikes back …



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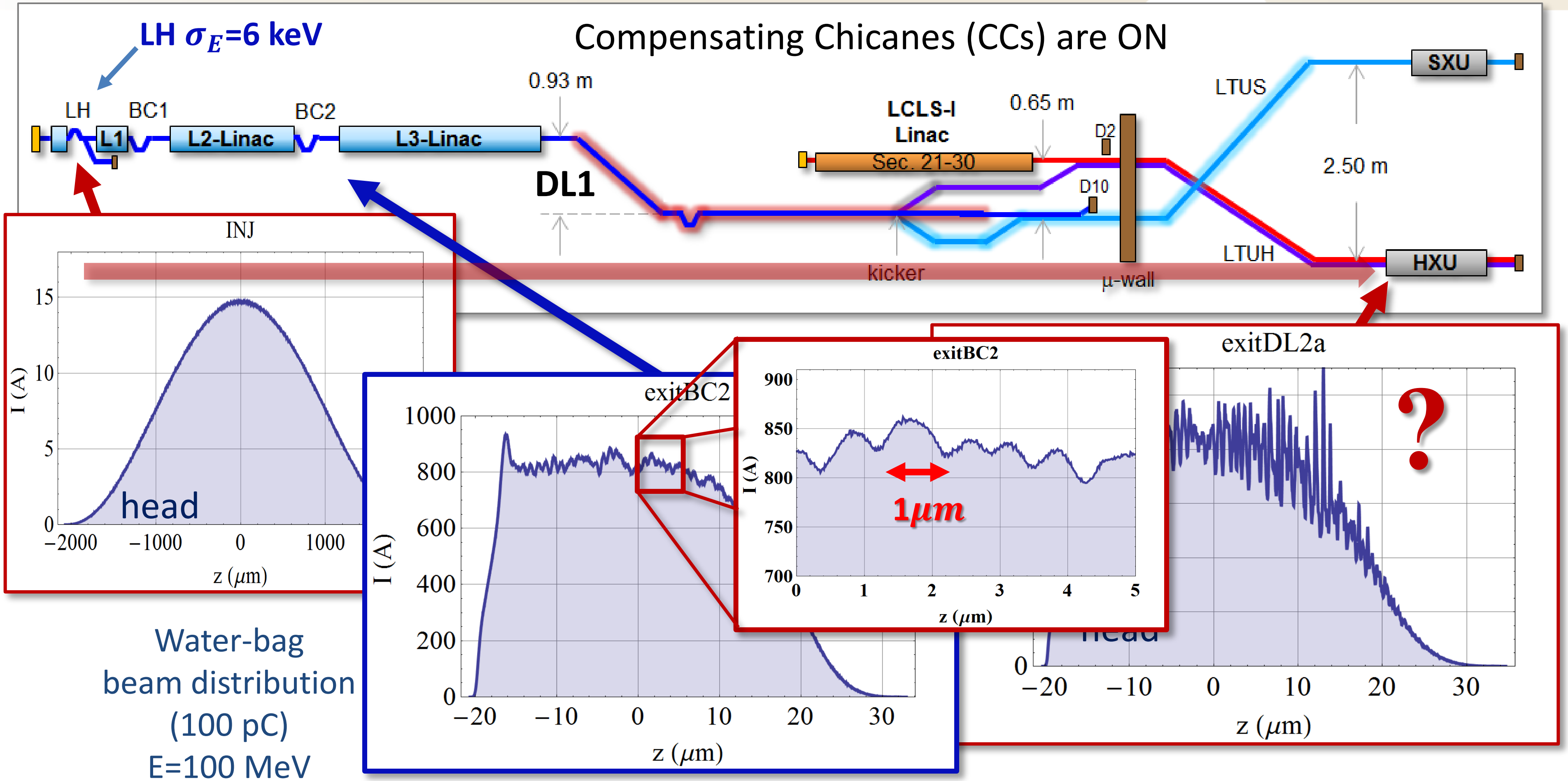
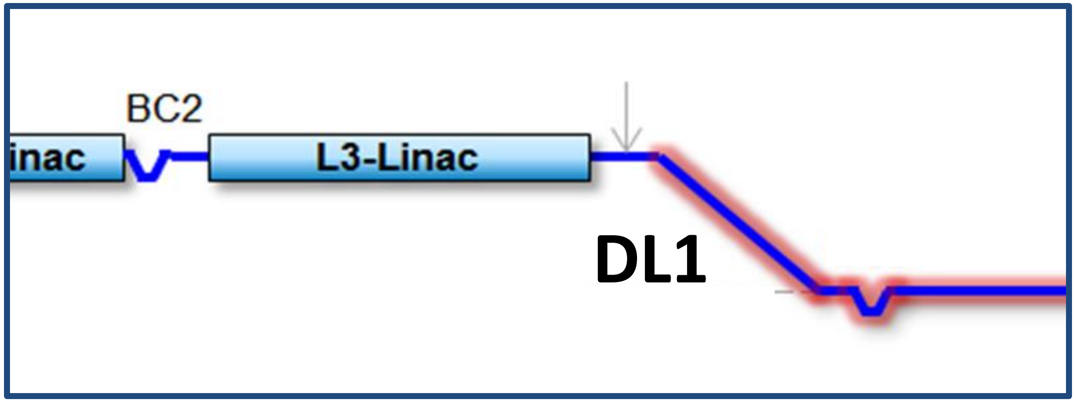


- **Quite a bit of gain is still happening through the bypass line.**
  - **What causes this gain?**

A close look at the dynamics through dogleg DL1 shows the effect from TSC

DL1 Compensating Chicanes
are ON



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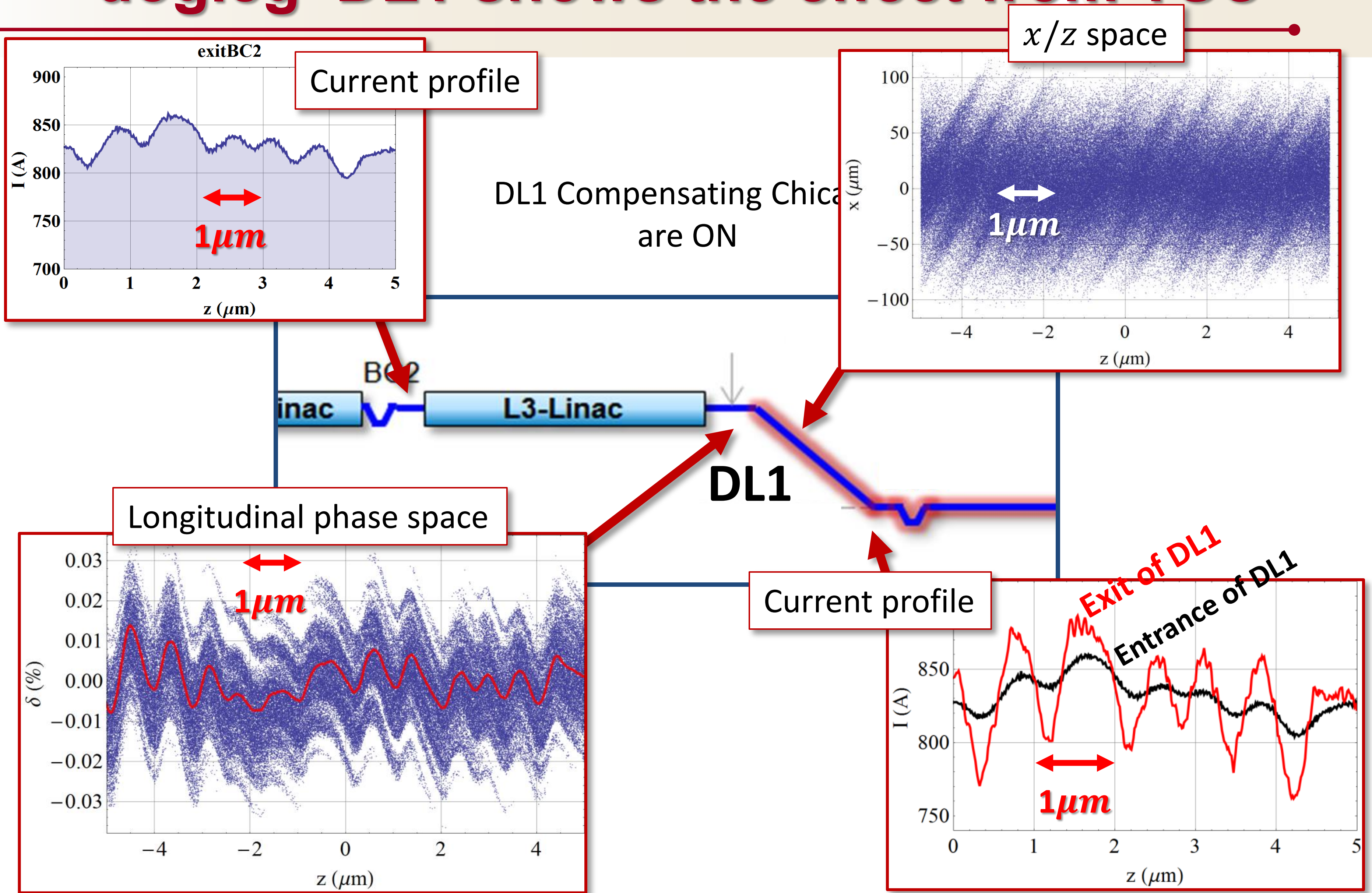

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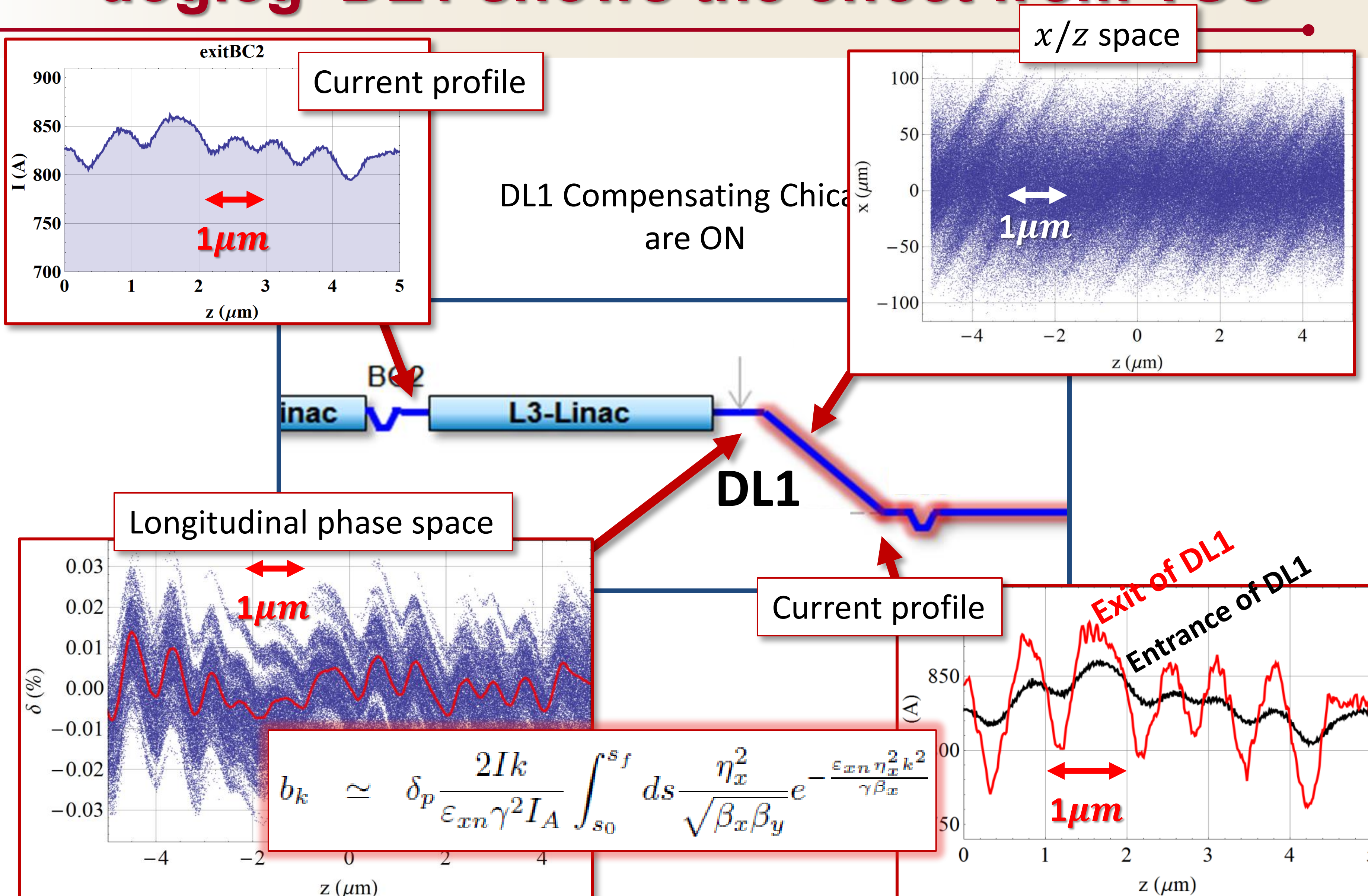
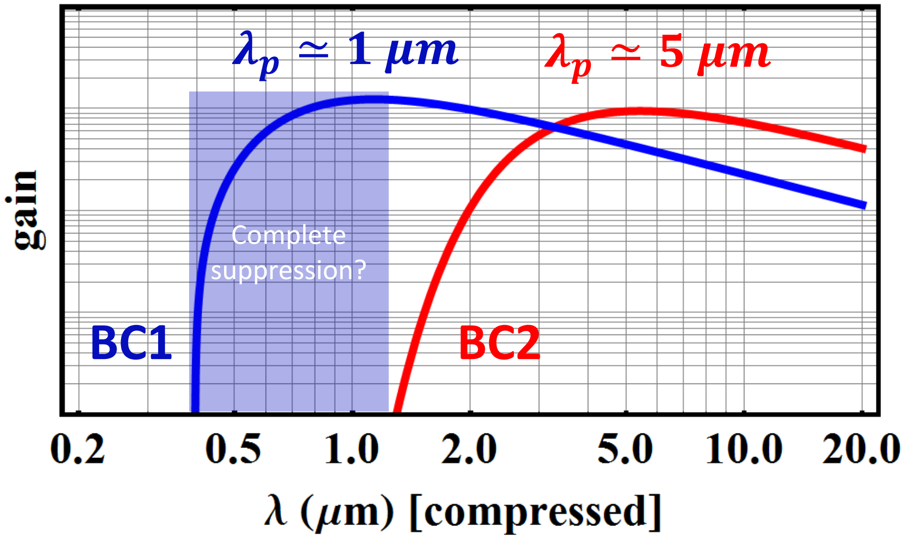


$$b_k \simeq \delta_p \frac{2Ik}{\varepsilon_{xn}\gamma^2 I_A} \int_{s_0}^{s_f} ds \frac{\eta_x^2}{\sqrt{\beta_x \beta_y}} e^{-\frac{\varepsilon_{xn}\eta_x^2 k^2}{\gamma\beta_x}}$$

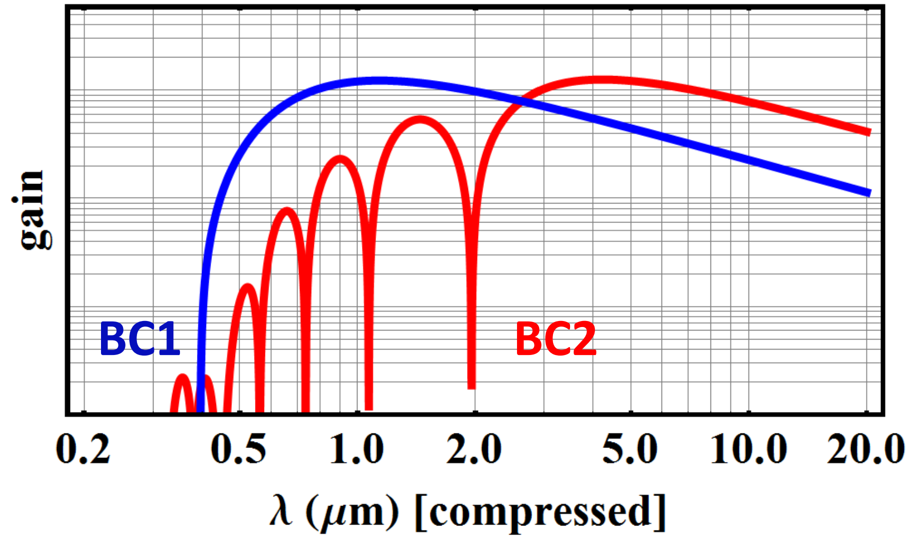
M. Venturini, et al., PRST-AB 18, 054401 (2015)

Instructive aside: why is there any bunching at 1 μm @ BC2 exit?

Beam model w/ gauss distribution in slice energy (too crude …)



More accurate account of Laser Heater effect on energy density



Expected peak gain @ $\lambda_p \simeq 2\pi |R_{56}| \sigma_\delta$

LH $\sigma_E = 6\ keV$

$R_{56}^{BC1} = 55mm;\ \sigma_\delta^{BC1} = 2.4 \times 10^{-5}$

$R_{56}^{BC2} = 38mm;\ \sigma_\delta^{BC2} = 2.2 \times 10^{-5}$

- Gain scales as $\sim J_1(ak)$ at large k*
  - *Shorter wavelength modes pass through*

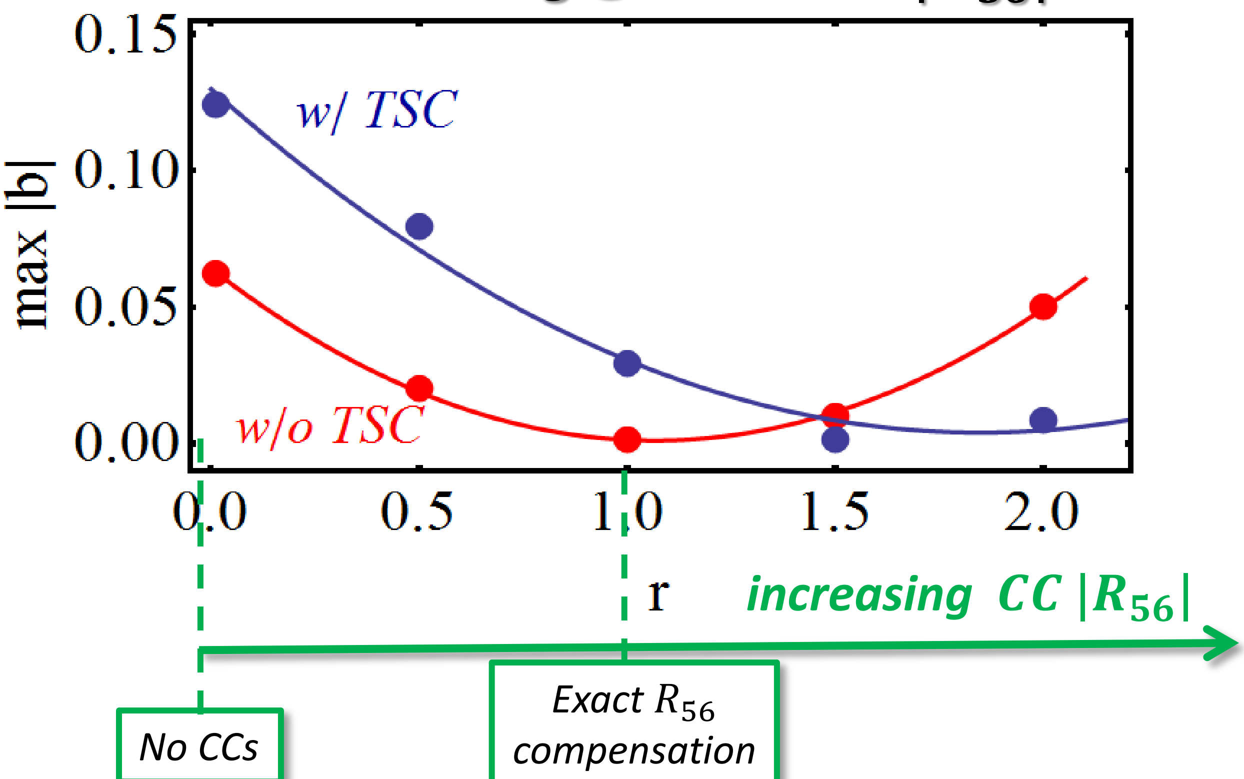
- Machine design strategy aiming at minimizing overlap between gain curves?
  - Freedom to set relevant parameters (R_{56}'s, BC energies, etc.) is limited

*Z. Huang, et al., PRST-AB, 2004

It gets better: Optimum tuning of compensating chicanes

- Exact cancellation of R_{56} by CCs minimizes LSC effects.
- With different CC setting we can get LSC- and TSC-effects to offset each other? Yes

Microbunching @FEL *vs.* CC $|R_{56}|$



$$\mathbf{r} = \frac{|R_{56}|_{CC}}{|R_{56}|_{DL-dipole(s)}}$$

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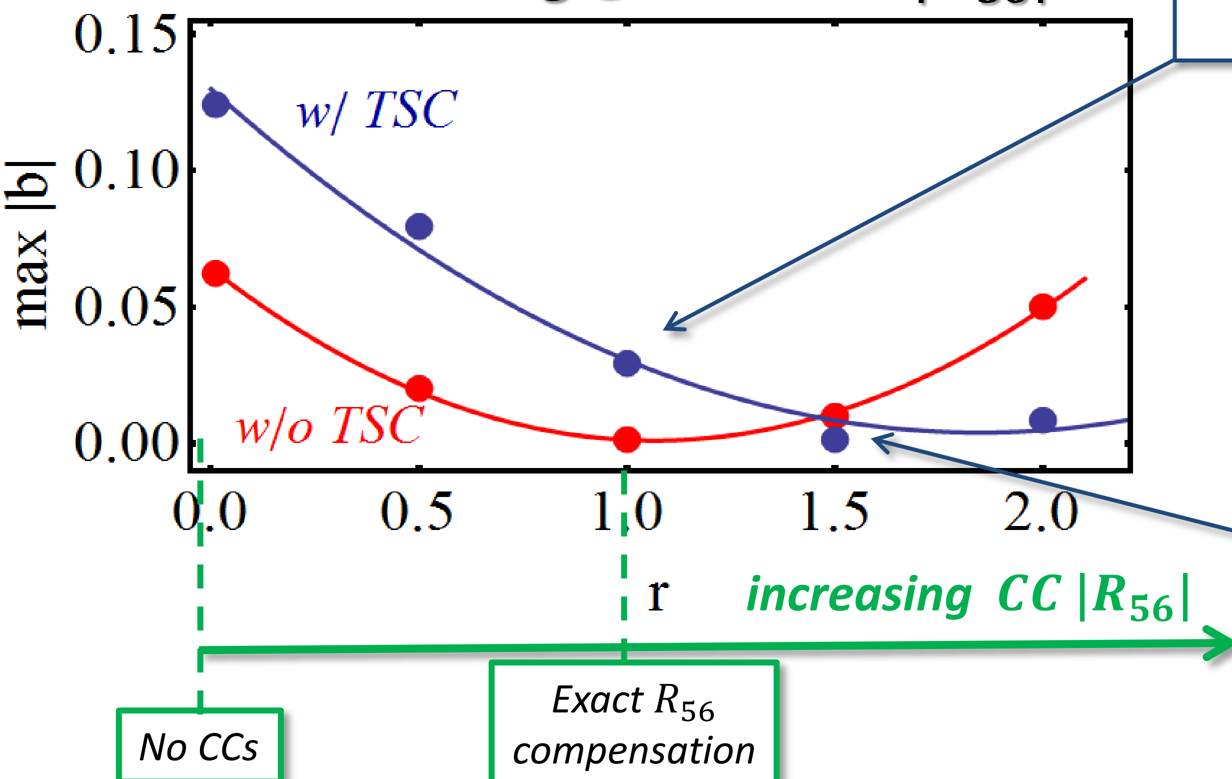

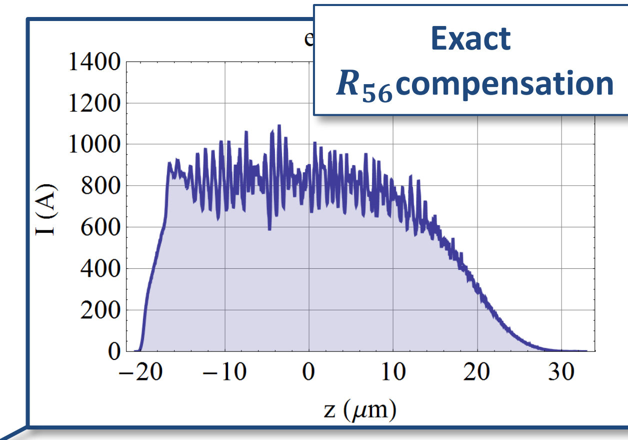

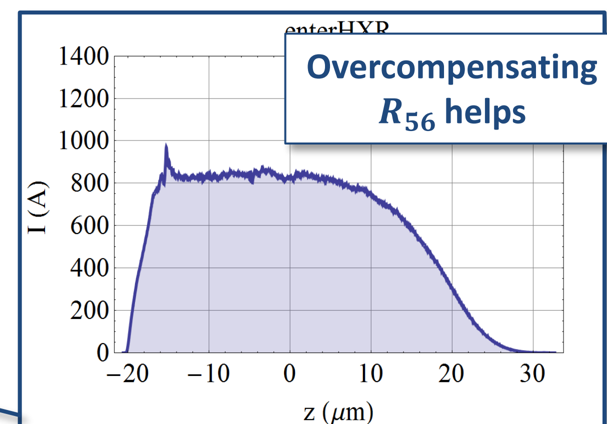

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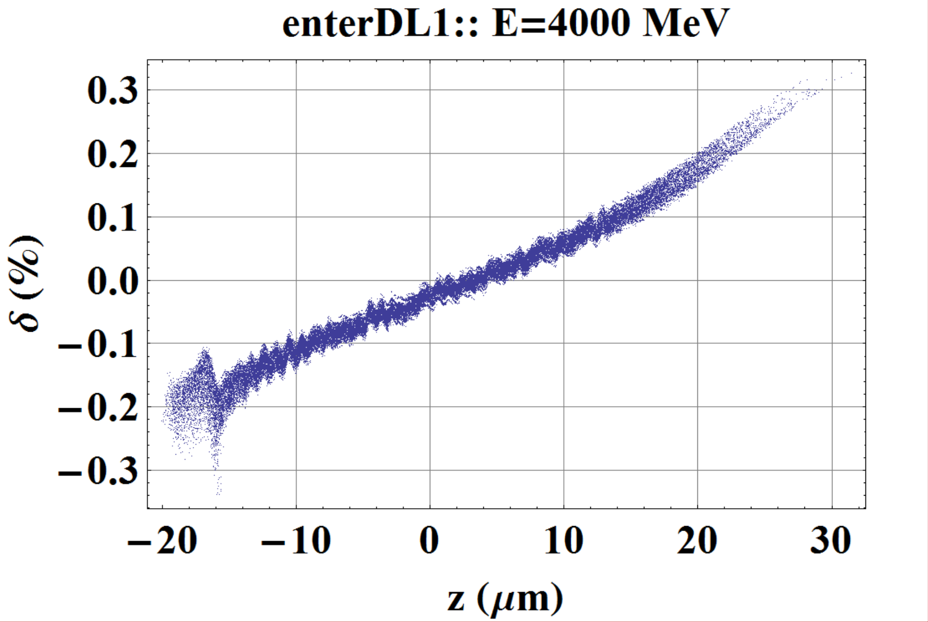
No T_{566}-effect here (see next slide)

Not the end of the story yet: Bunching from nonlinear momentum compaction T_{566}



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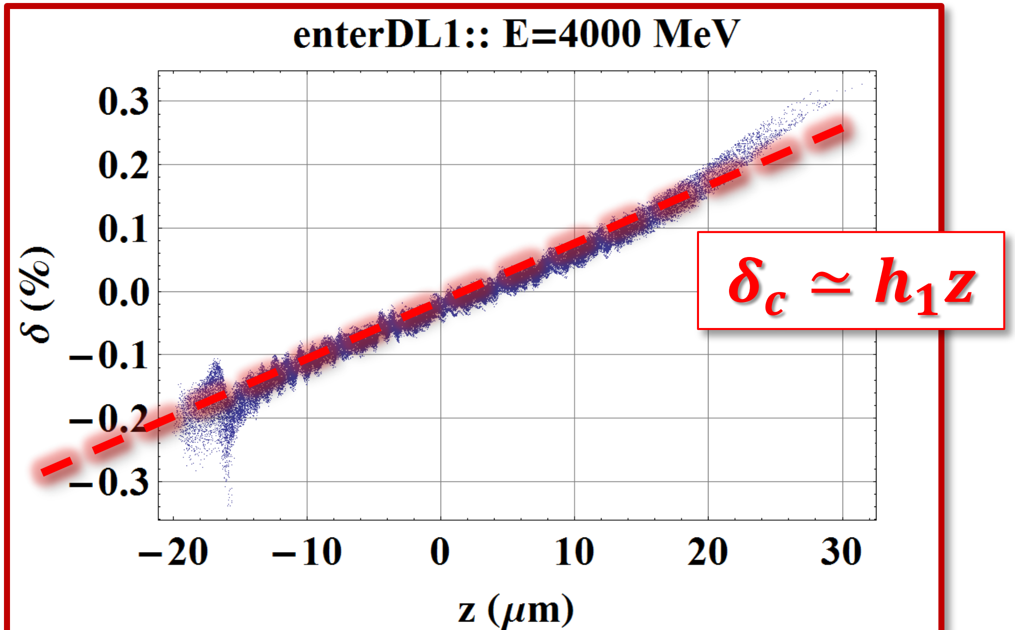
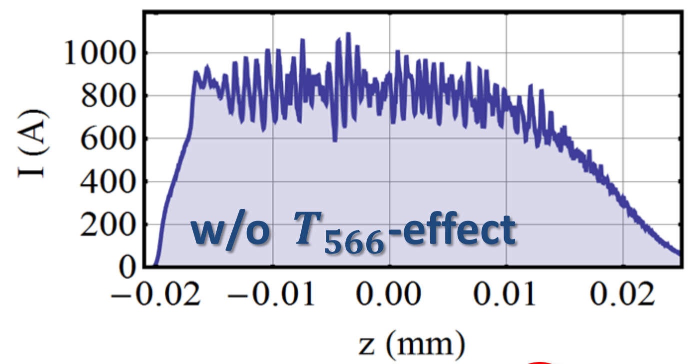
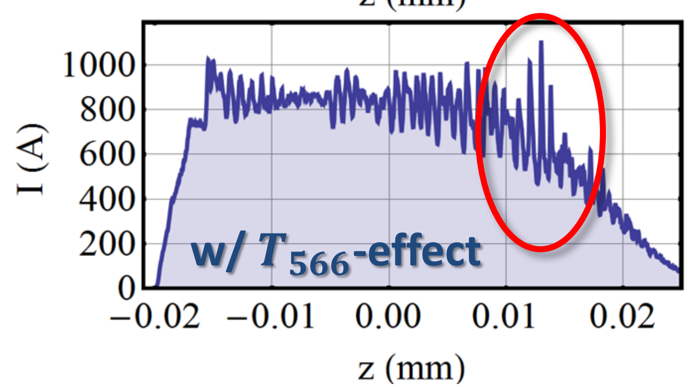


energy chirp + dogleg T_{566} ≡
effective $\mathbf{R_{56}^{eff}} \simeq 2T_{566}h_1 z \simeq 100\mu m$
(at $z = 10\mu m$)

- Away from bunch center **effective $\mathbf{R_{56}^{eff}}$** is comparable in magnitude to DL1 R_{56}

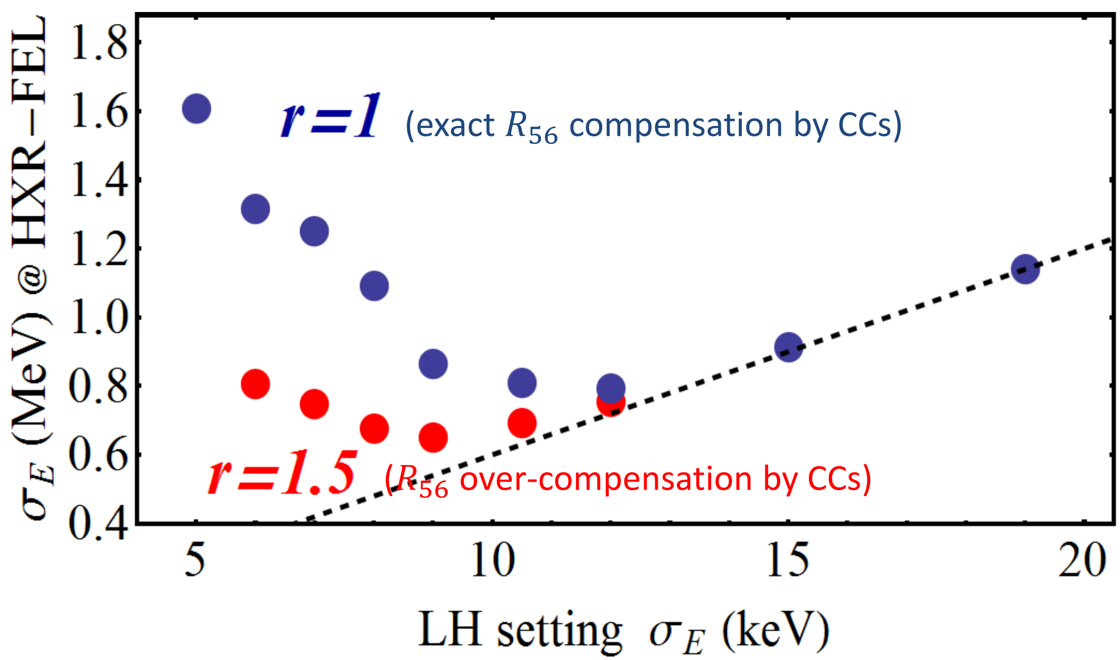
- At entrance of DL1 bunch has still a substantial energy chirp left over from compression
  - *'dechirping' will be completed by resistive-wall wake in bypass line*





Optimum setting for Laser Heater, minimum energy spread

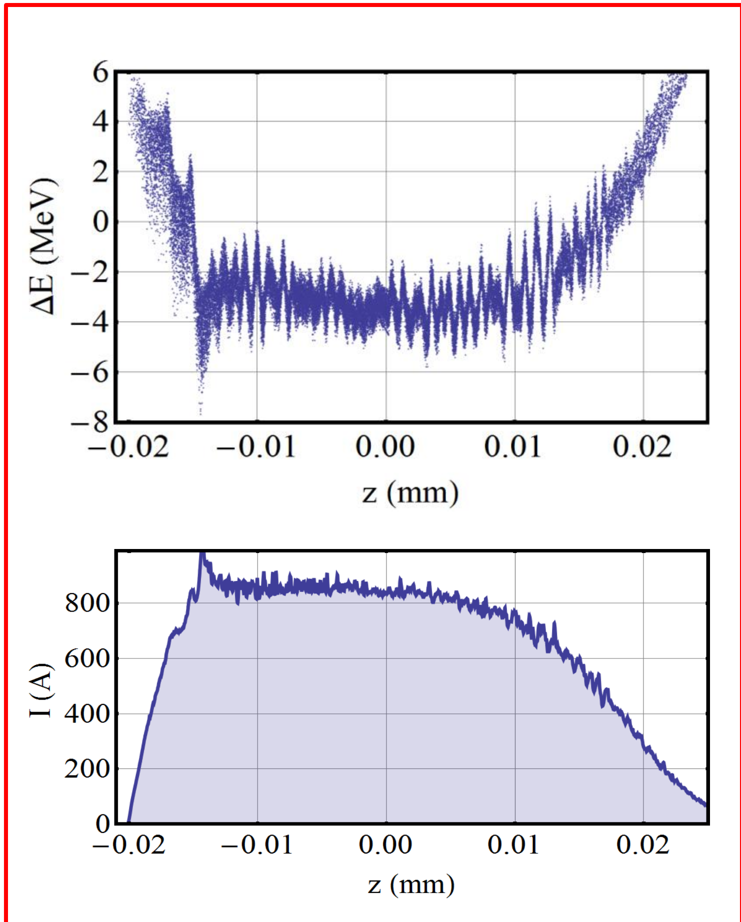
Energy spread @FEL vs. energy spread @LH

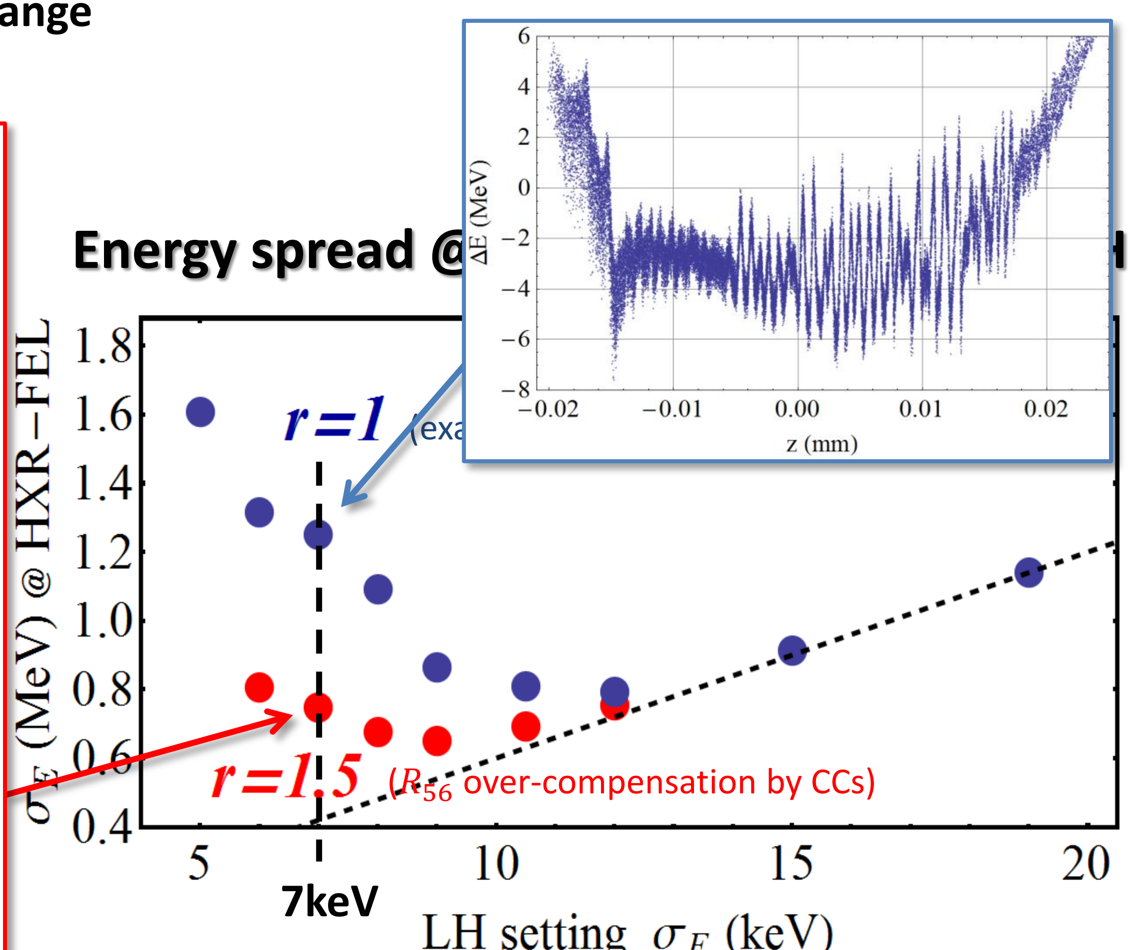


Note: σ_E @FEL is the projected rms spread in the beam core [-12μm, 20μm] upon removal of the (nonlinear) energy chirp.

Optimum setting for Laser Heater, minimum energy spread

- Confirm benefit of R_{56} overcompensation over range of LH setting





Note: σ_E @FEL is the projected rms spread in the beam core [-12μm, 20μm] upon removal of the (nonlinear) energy chirp.

Summary

- **LCLS-II as a fertile ground for the μBI**
- **Long transport lines between Linac and FELs have shown potential for large amplification of the instability**
- **New mechanism: microbunching generated by Transverse Space Charge (TSC) in high-brightness beams**
  - *Quite significant for LCLS-II*
- **Compensating Chicanes have been found to represent an effective remedy**
  - *Properly tuned they can be used to offset LSC and TSC-induced bunching against each other.*
- **Can we trust the predictions from our models?**
  - *Benchmarking against LCLS measurements are underway.*

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