VUV and X-ray Free-Electron Lasers

Bunch Compression, Laser Heaters, CSR

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Tuesday Schedule

- High-brightness beam techniques 09:00 – 10:00
- Break 10:00 – 10:10
- Injector beam dynamics 10:10 – 11:10
- Break 11:10 – 11:20
- Bunch compression, laser heater & CSR 11:20 – 12:00
- Lunch Break 12:00 – 13:30
- Electron beam properties and FODO 13:30 – 15:15
- Break 15:15 – 15:30
- FEL simulations with Genesis 15:30 – 17:30

Overview

Bunch Compression

- RF compression
- Magnetic Chicanes

Coherent Synchrotron Radiation (CSR)

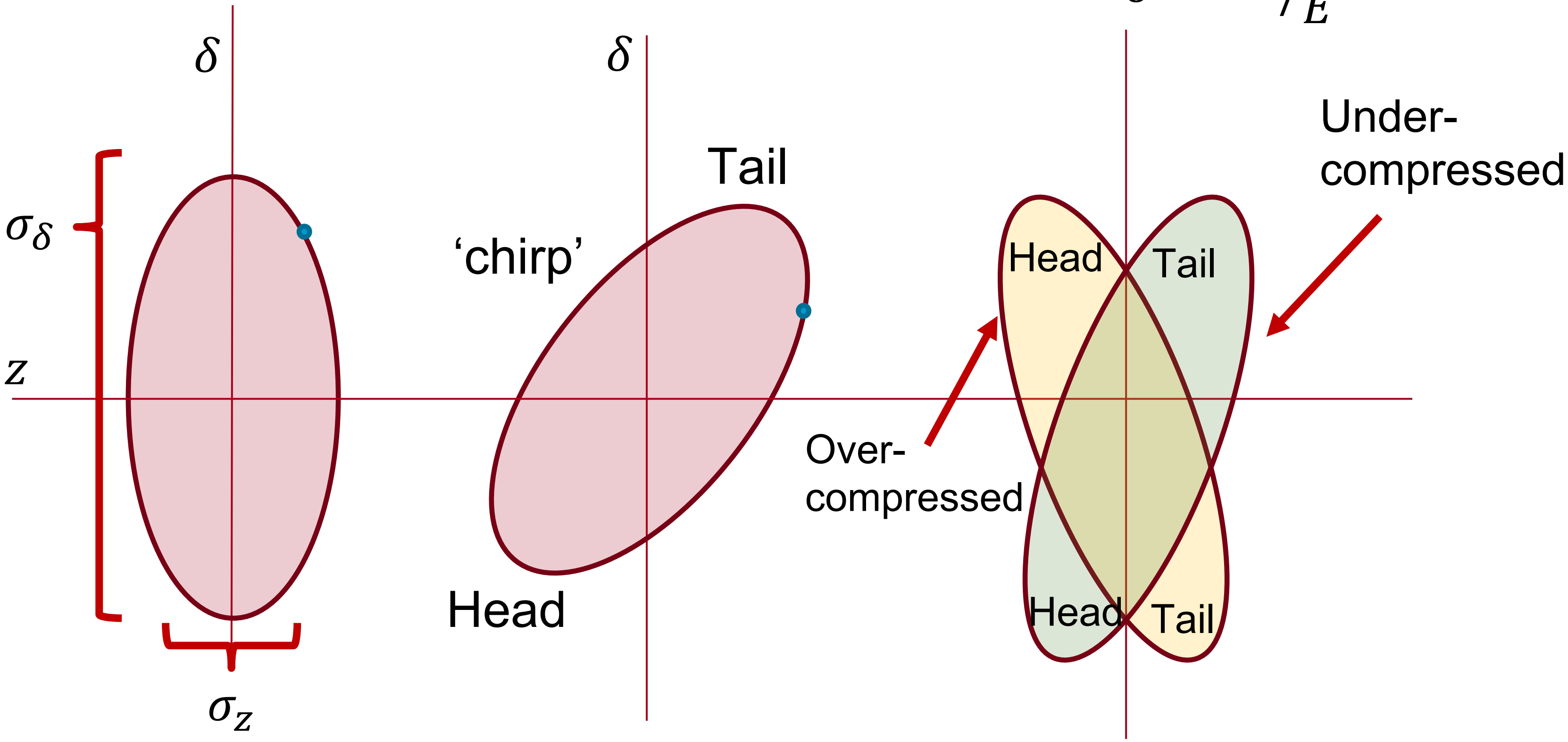
Laser Heaters and Microbunching

Bunch Compression

Bunch Compression

- Bunch compressors are used to reduce the longitudinal/temporal size of the beam of the beam and increase peak current.
- Usually happens in several locations for x-ray FELs, using both RF and magnetic fields.
- Chirp = energy spread/slope along the bunch (longitudinal)

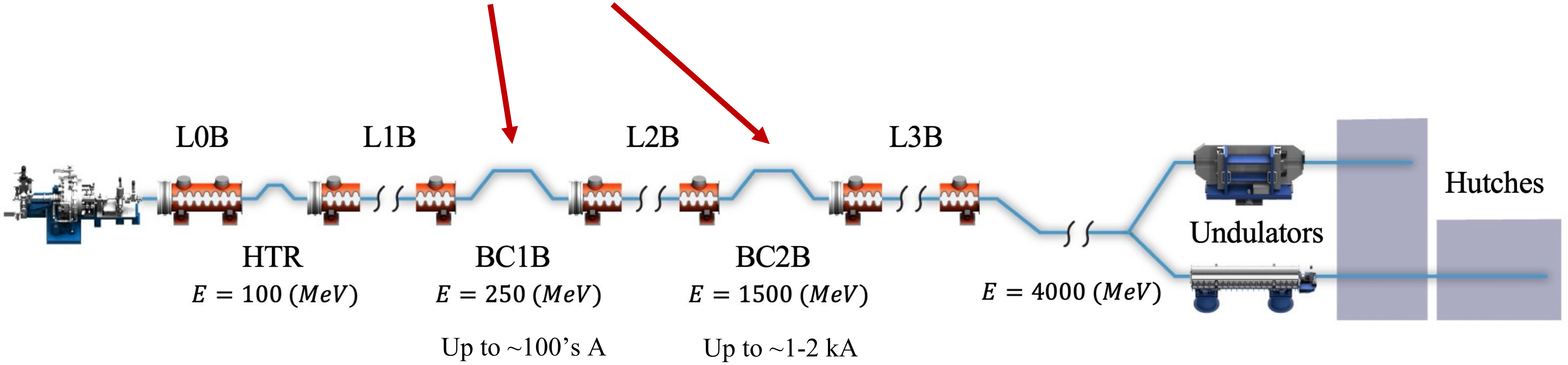
Looking at the longitudinal phase space: $\delta = {}^{\Delta E}/_{E}$



*in book notation:
$\sigma_z = \sigma_\zeta$

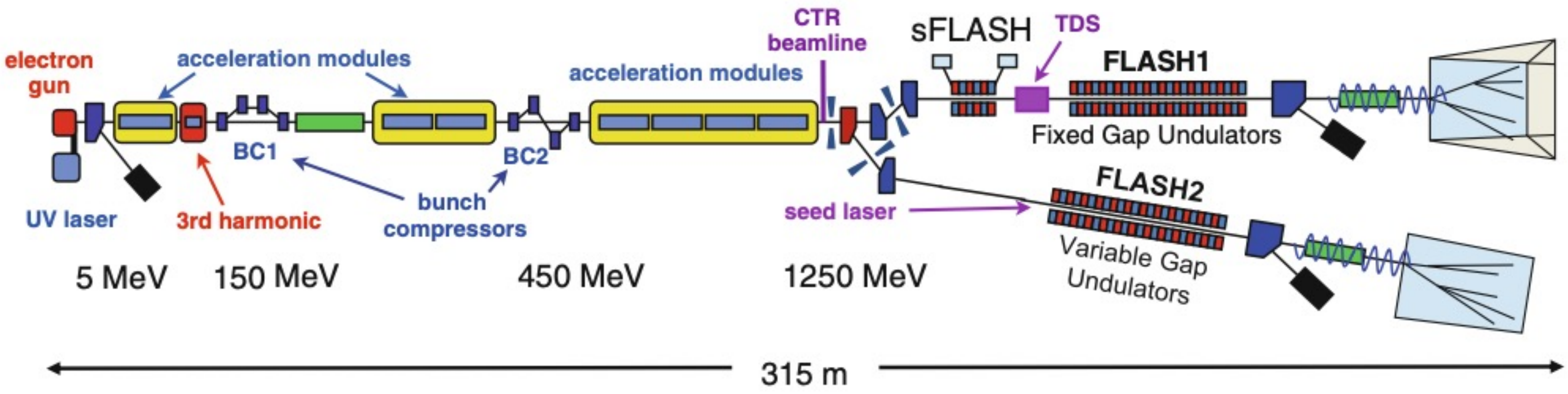
Bunch Compression

- This process is done at several energies throughout the machine to mitigate space charge, energy spread, jitter, and RF effects (bunch length).
- For example, in LCLS-II there are 4 bunching locations:
  - Bunching cavity after the gun.
  - 3.9 GHz superconducting cavities after L0B (linearizer).
    - Discussed in Sec. 8.6.2 of text.
  - Two chicanes (BC1B, BC2B).



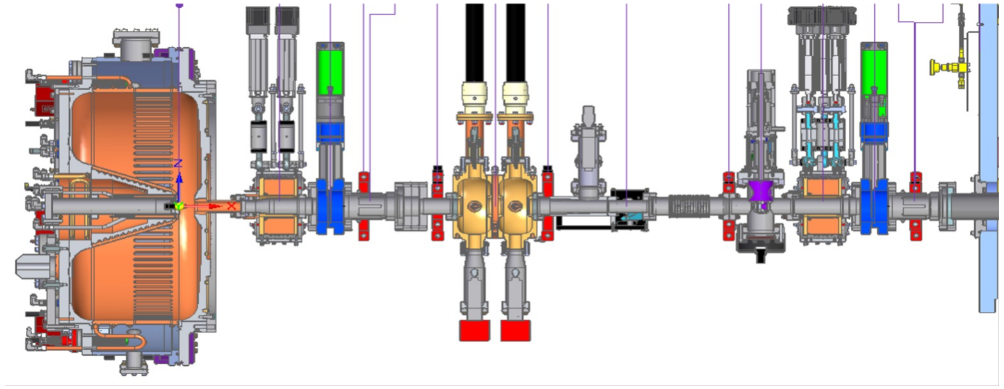
Bunch Compression in Stages

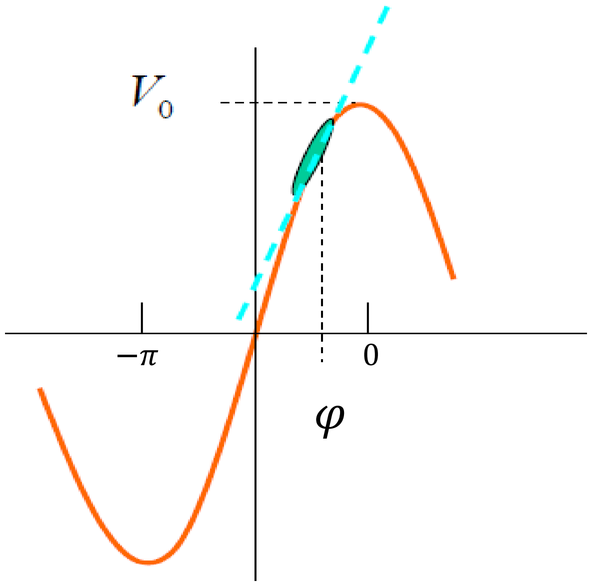
- FLASH Example, pg. 143 text.
- Two stage compression:
  - 150 MeV to 100A.
  - 450 MeV to several kAs.
- If compressed in one stage (BC1):
  - Emittance growth and beam blow up would negatively impact lasing.
- If compressed in one stage at (BC2):
  - Larger energy spread needed, which negatively impacts lasing.



Bunch Compression: RF Chirp

- When the bunch leaves the quarter wave gun, the temporal length is 20+ ps.
- This can be shortened with RF or magnets (if bunch is several % of RF curve).
- Off crest operation in the buncher cavity is used to shorten the bunch.
  - dz dependent change of dE



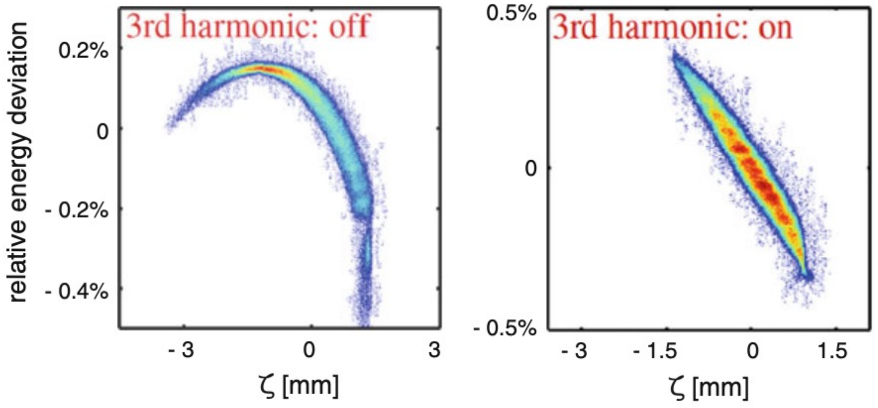


$$V = V_0 cos(kz + \varphi)$$

$$E(z) = E_0 + eV_0 cos(kz + \varphi)$$

$$\kappa = \frac{d\delta}{dz} = -\frac{keV_0 sin\varphi}{E_0 + eV_0 cos\varphi}$$

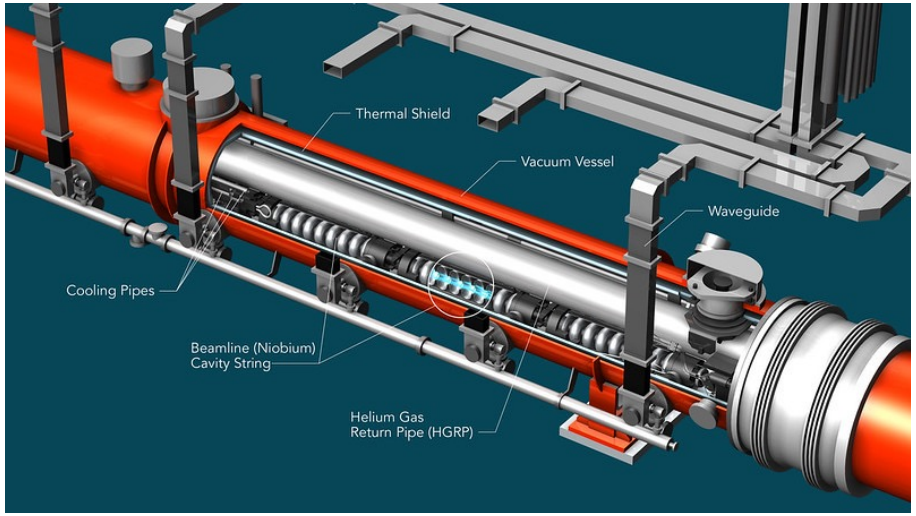
*Note, $\zeta = z$

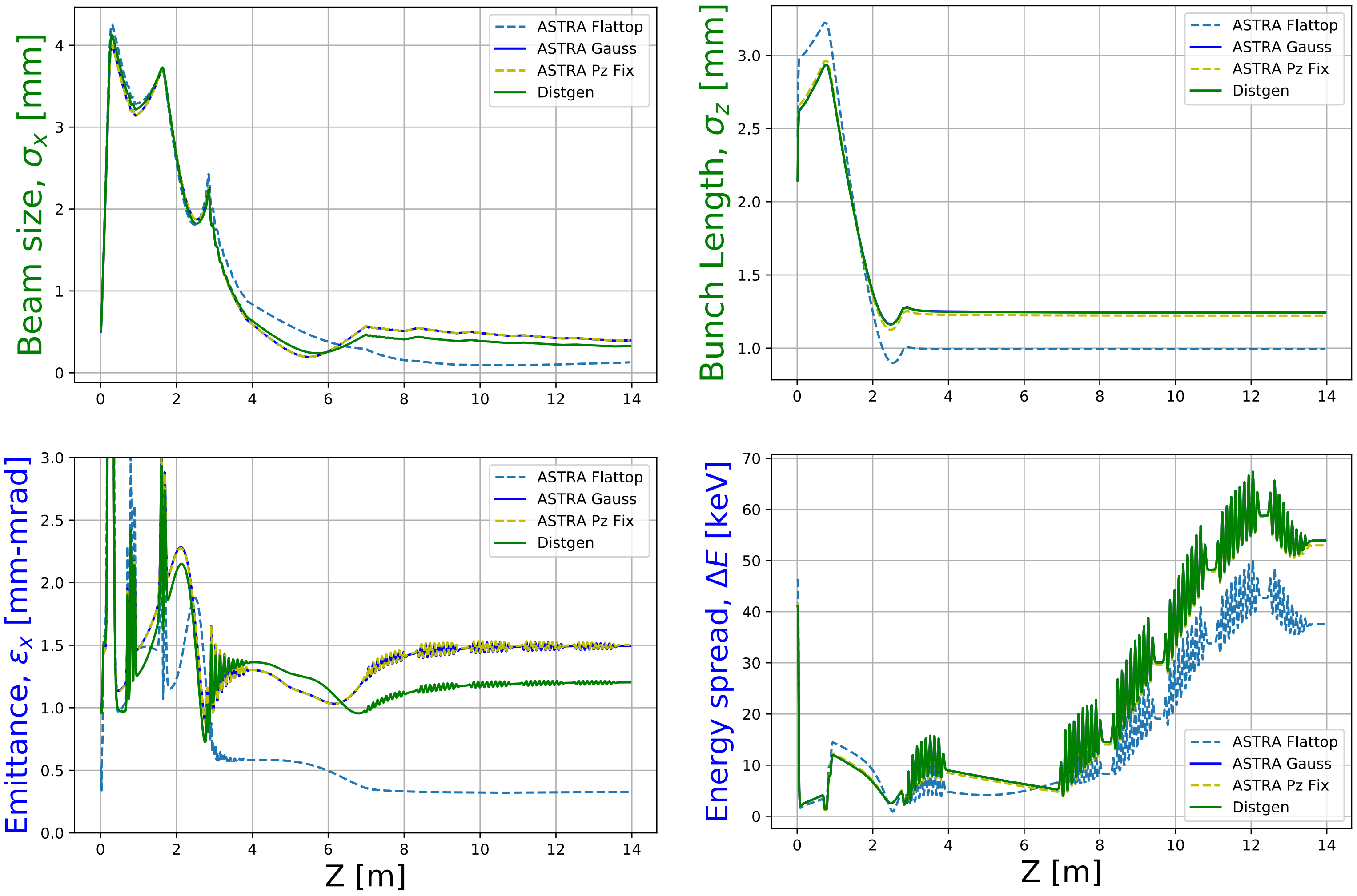


Pg. 144, text.

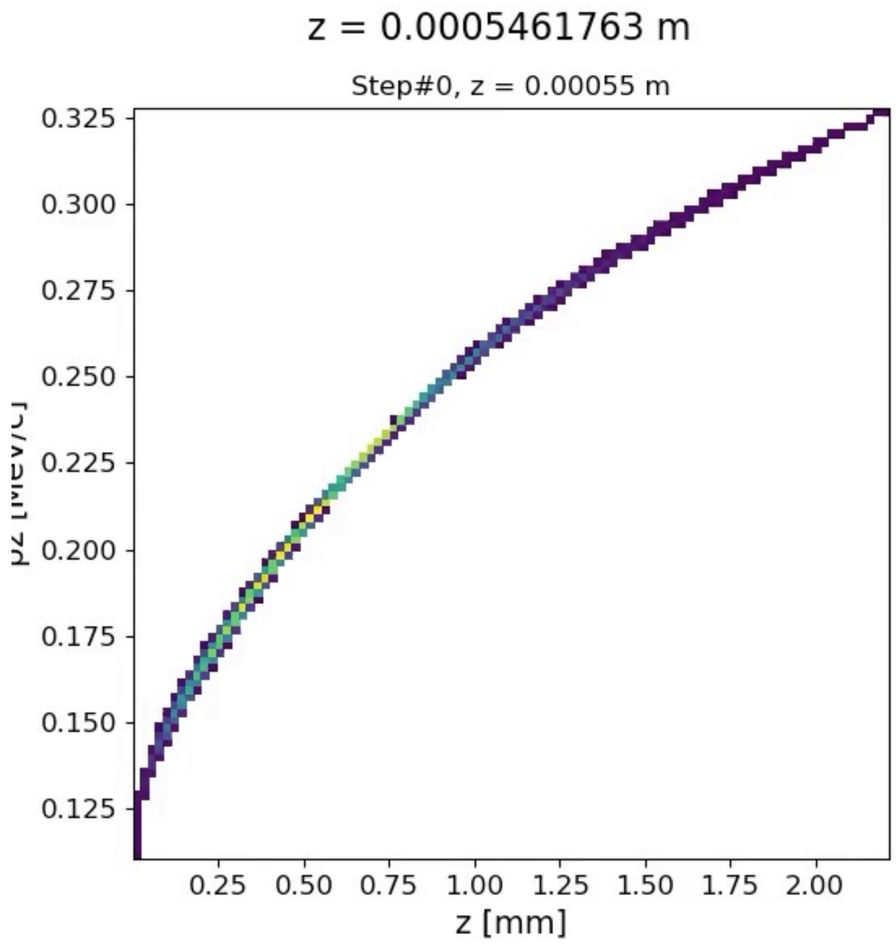
RF Chirp: LCLS-II simulation case

- Consider gun, buncher, solenoids + cryomodule 1

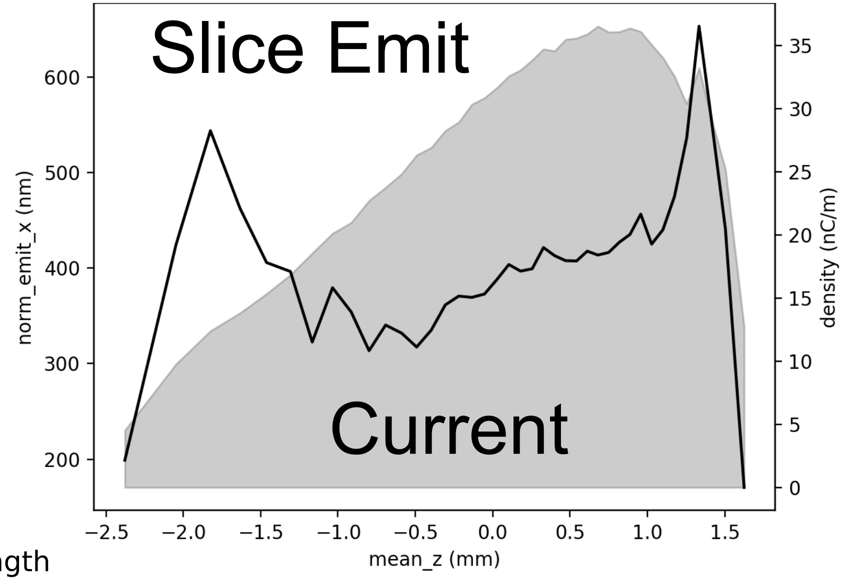


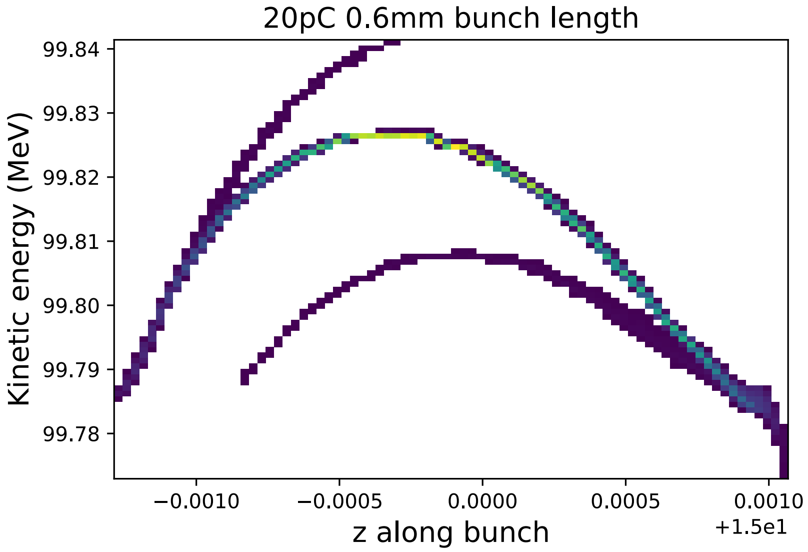


RF Chirp: LCLS-II simulation case



Change RF phases



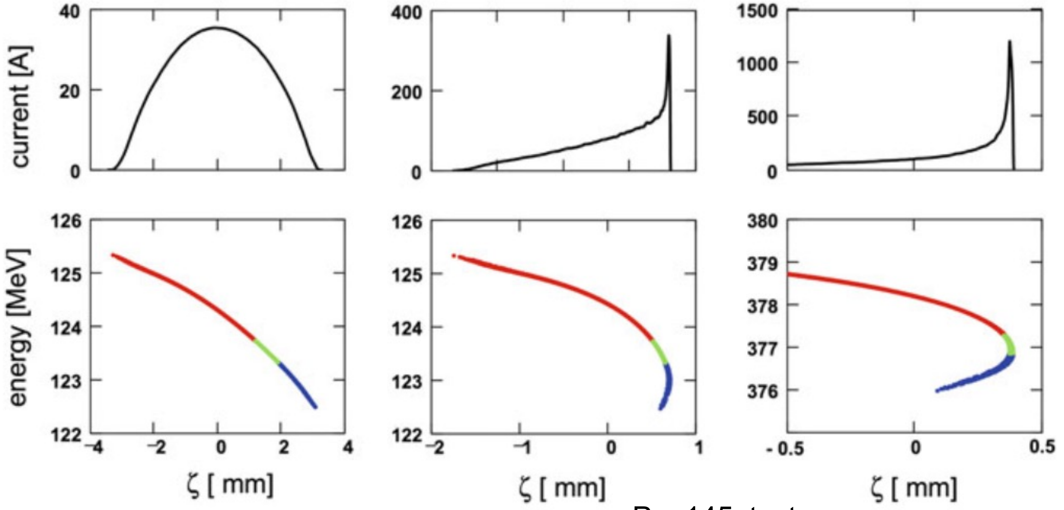


Slice emittance does not change

Bunch Compression: Chicane

- Chirp (energy slope) in the beam is used to force electrons to travel different paths in the bending magnets (chicane).
  - Lower energy = longer path.
  - dE dependent change of dz
  - Note, $\gamma \gg 1$ assumed in chicanes
- This increases peak current.

*Note, $\zeta = z$



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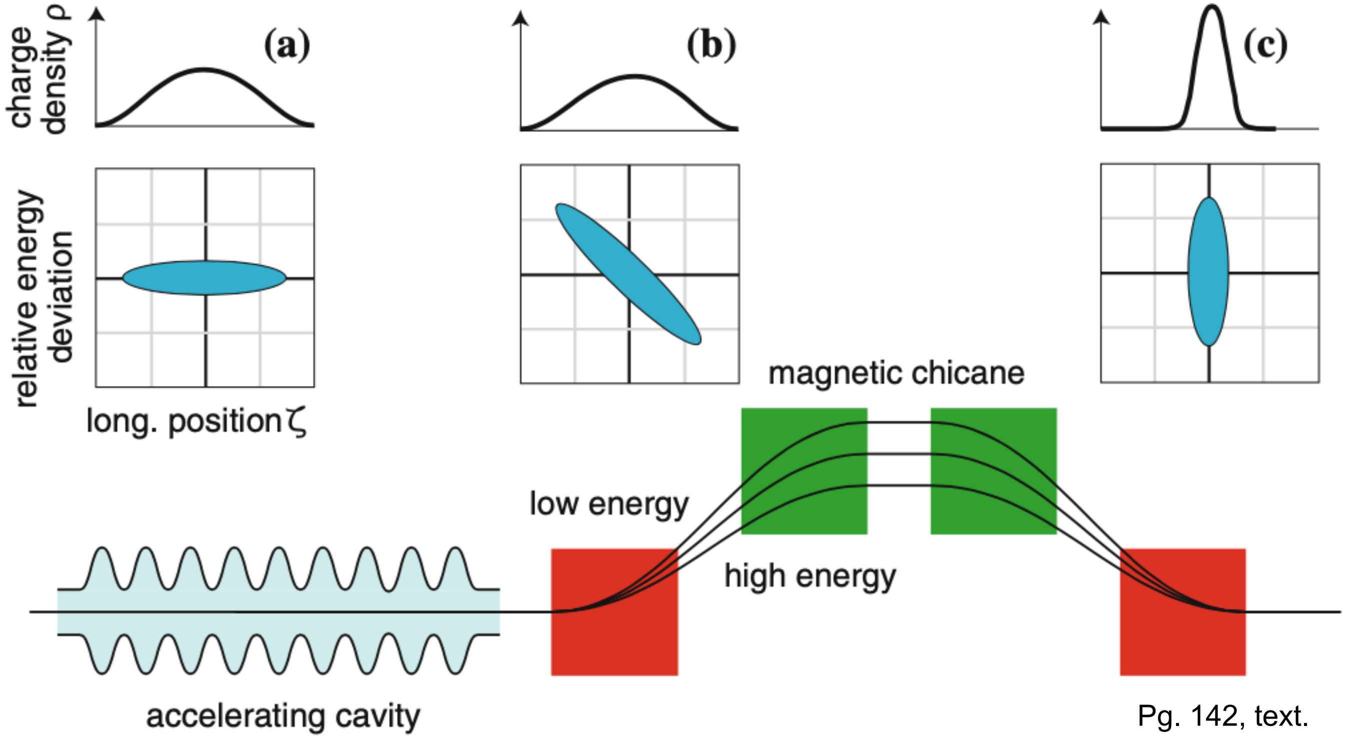


Pg. 142, text.

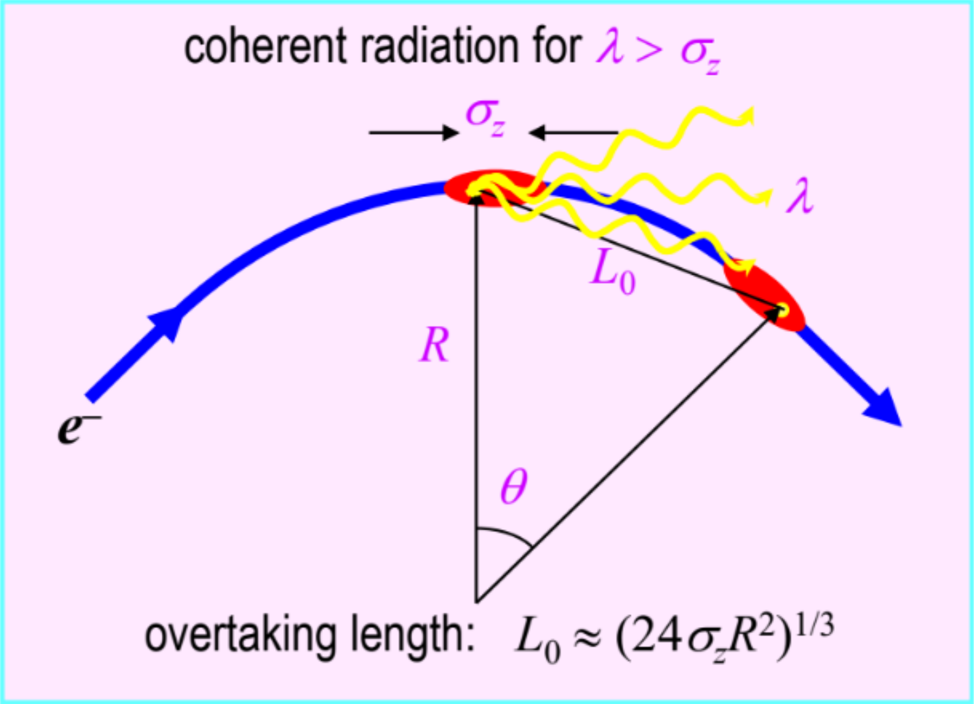
$$\Delta z = R_{56}\delta + T_{566}\delta^2 + \cdots$$

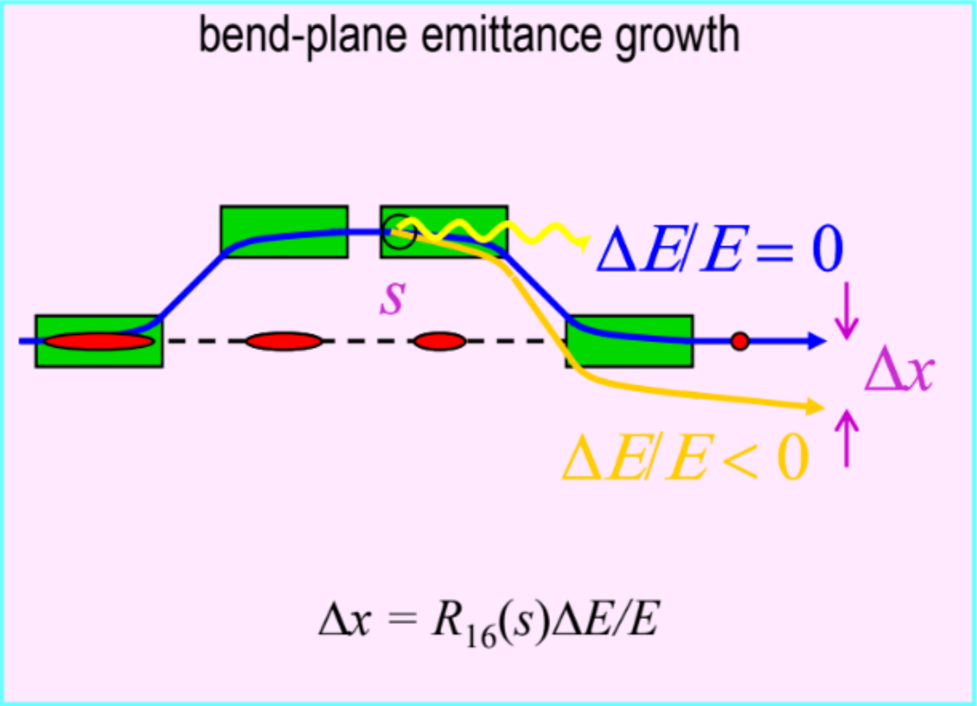
$$R_{56} = -\theta^2\left(\frac{4}{3}L + 2D\right)$$

Coherent Synchrotron Radiation

Coherent Synchrotron Radiation (CSR)

- CSR is radiation emitted by a relativistic beam as it goes through a curved trajectory (bend).
- Photons emitted by the back of the bunch can be absorbed/interact with the head of the bunch.
- This causes energy spread and emittance growth in the beam.

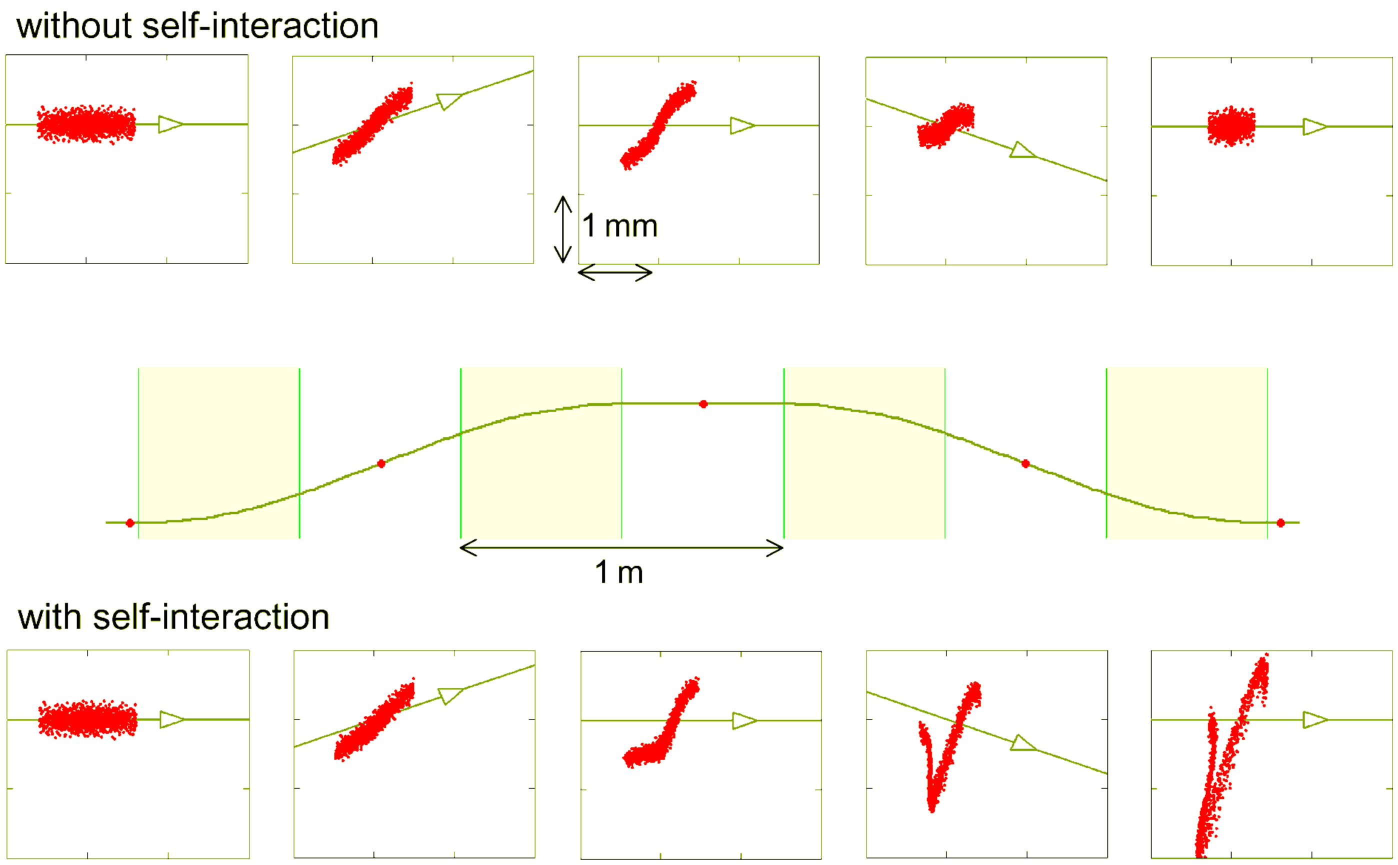




T. Maxwell

CSR Emittance Growth

- CSR can cause emittance growth and energy spread by raising/lowering the beam energy.
- Space charge plays a larger role when the beam is being compressed.
- These impact slices differently depending on the bunch length, etc.
- These are non-linear effects that impact the beam quality, and therefore the FEL.



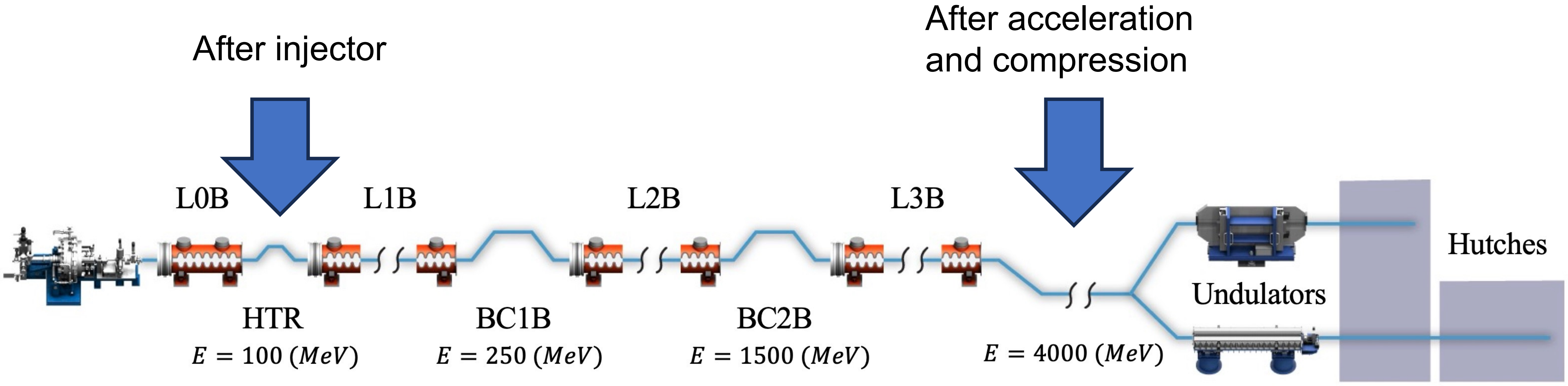
Energy loss due to CSR:

$$\left(\frac{\Delta E}{E}\right)_{CSR} \approx \left\{\frac{5\,Q\,R^{1/3}\,\theta}{\sigma_z^{4/3}\,E_c}\right\} Int\left(\frac{s}{\sigma_z}\right)$$

D. Nguyen

Chicanes + CSR: LCLS-II simulation case

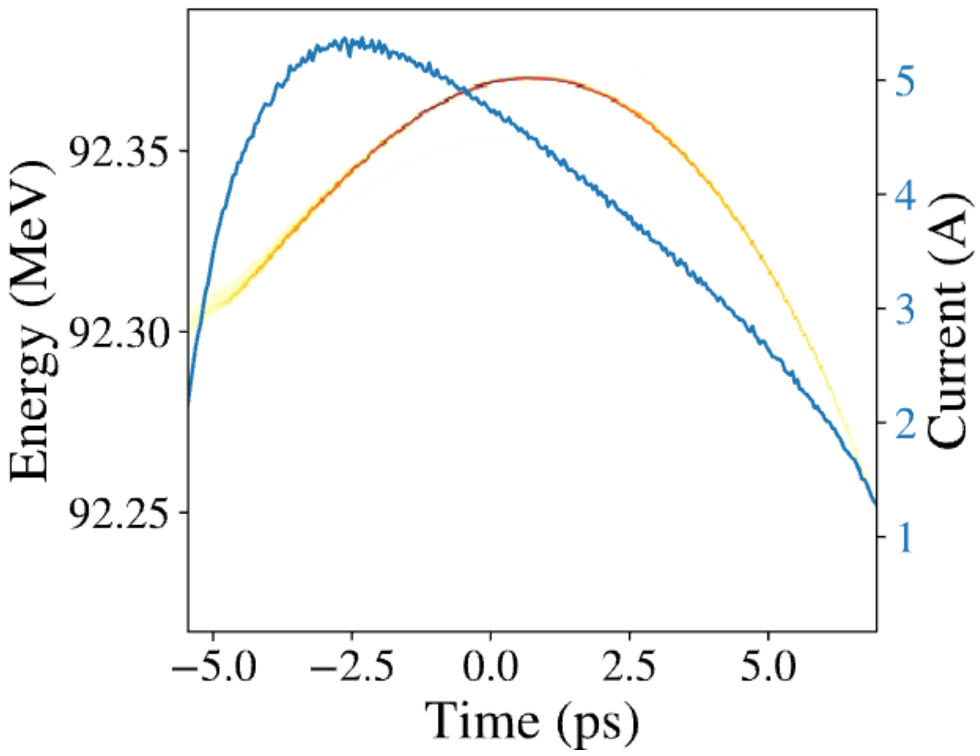
- Consider gun, buncher, solenoids + cryomodule 1 + linac + BC1/BC2
- Now phases in all cavities and the BC settings are at play



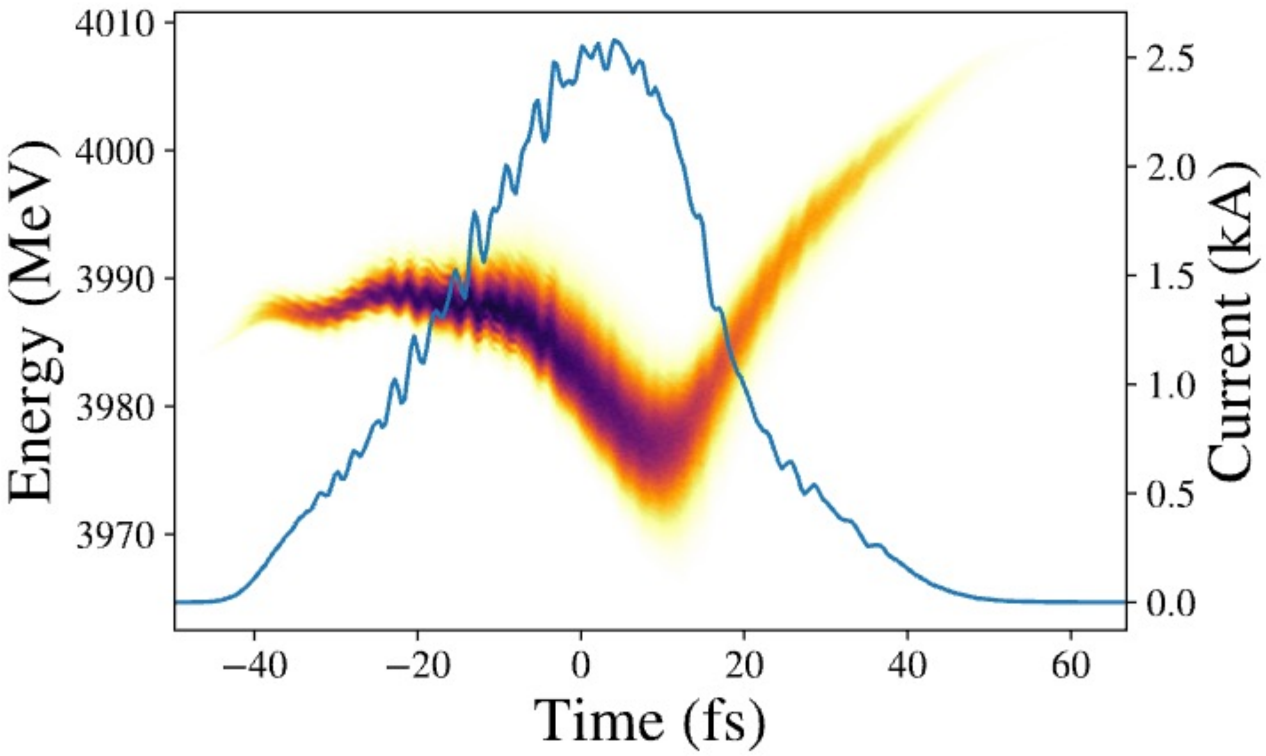
CSR Impact on slice emit

Back to the LCLS-II simulation case*

- After first cryomodule



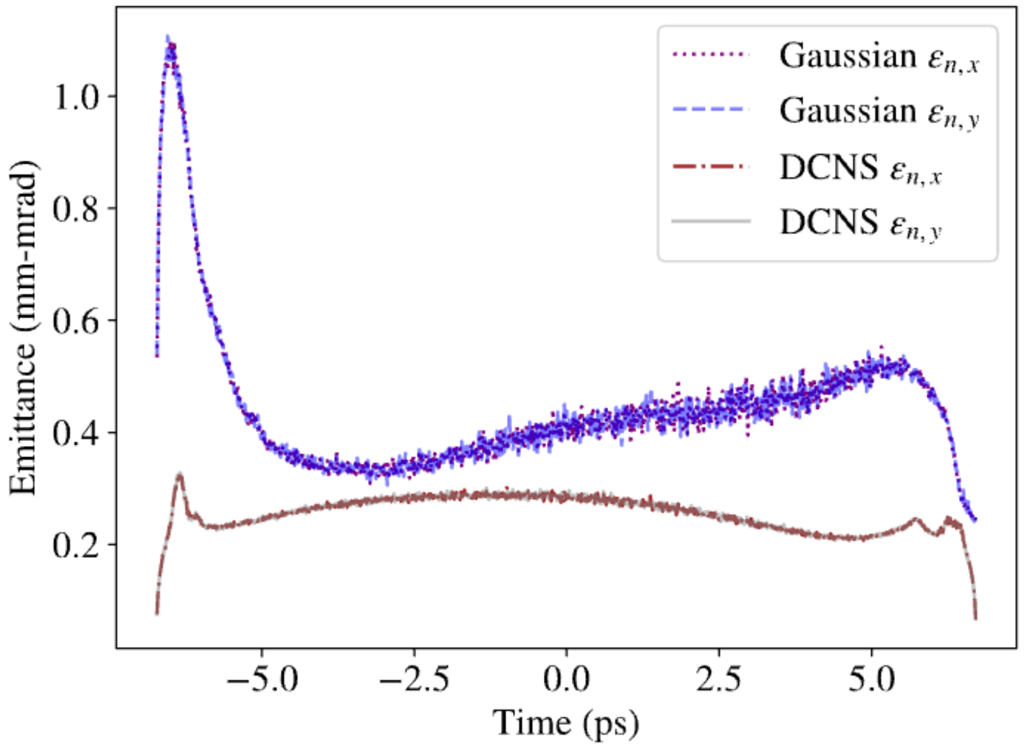
- After BC2



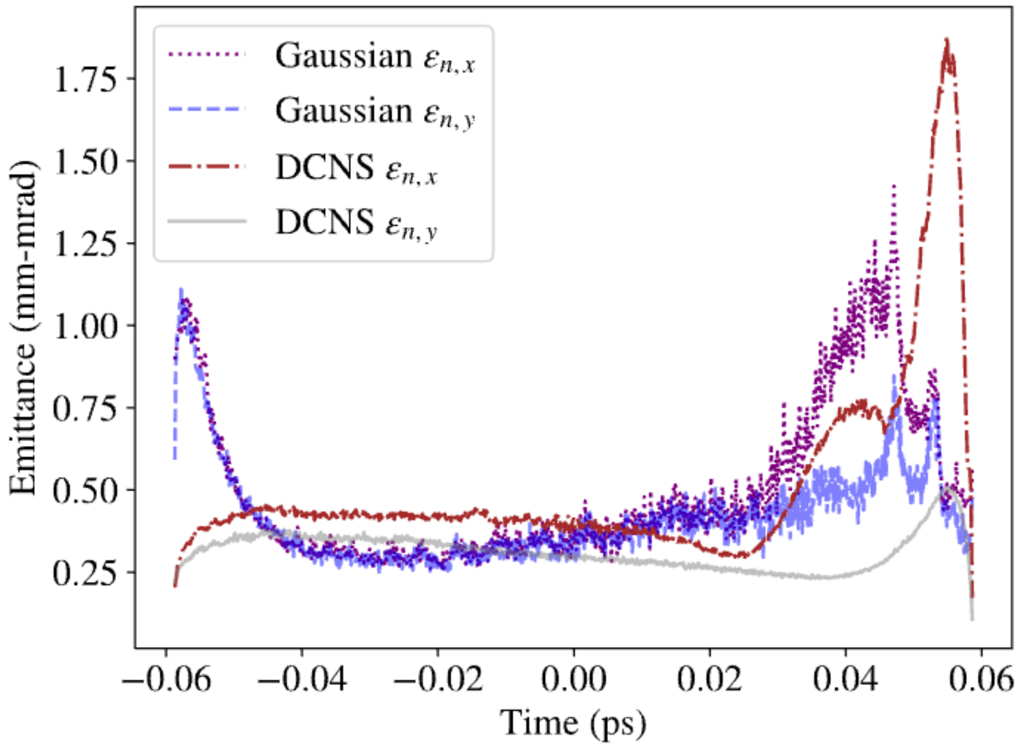
CSR Impact on slice emittance

Back to the LCLS-II simulation case*

- After first cryomodule

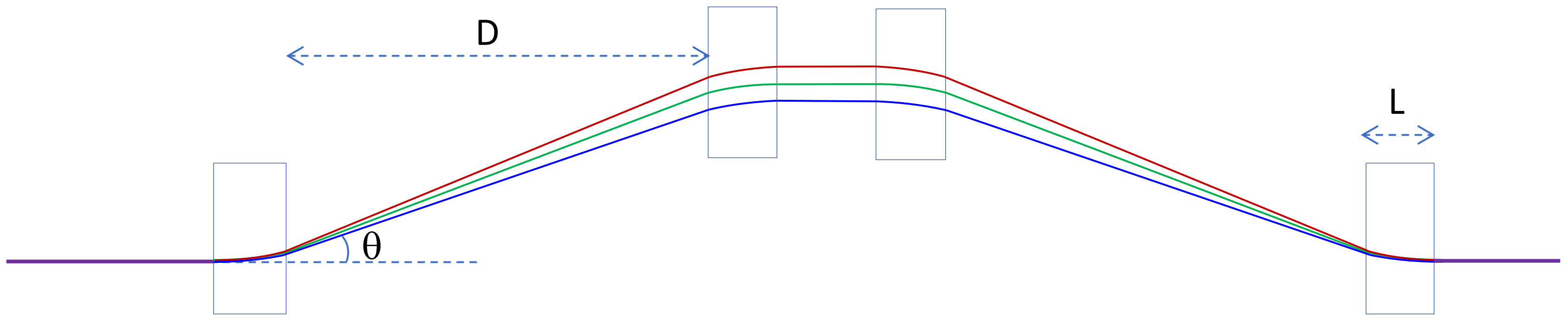


- After BC2



Discussion

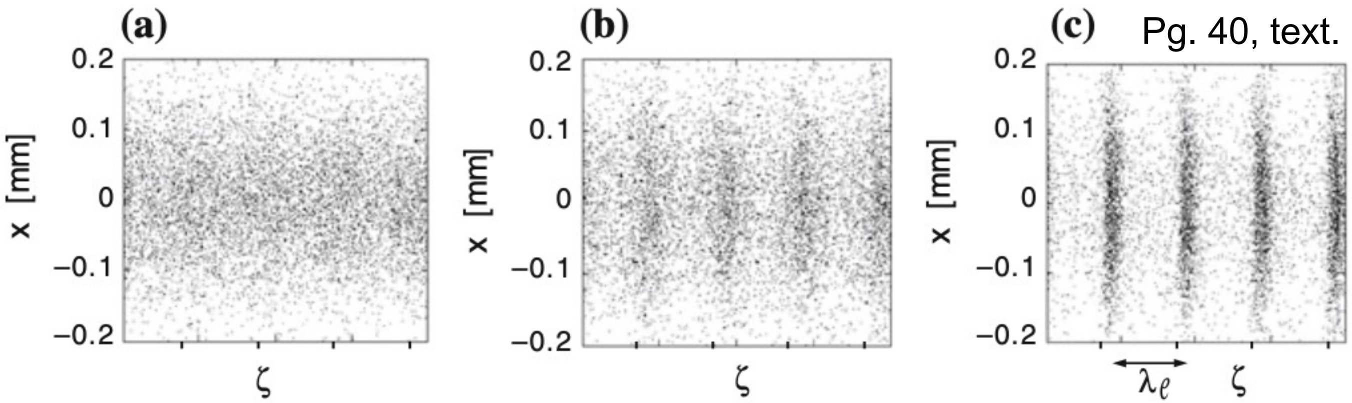
- How does a large energy spread after the injector impact compression?
- What is going on in a chicane?
- Why do we need a short bunch? Why do we compress in multiple locations?



Microbunching and Laser Heaters

Microbunching

- Microbunching naturally occurs when energy and density modulations are amplified by collective effects.
- Longitudinal space charge increase energy modulations.
- Chicanes convert energy modulations to density modulations.
- The bunches longitudinally group together (slices).



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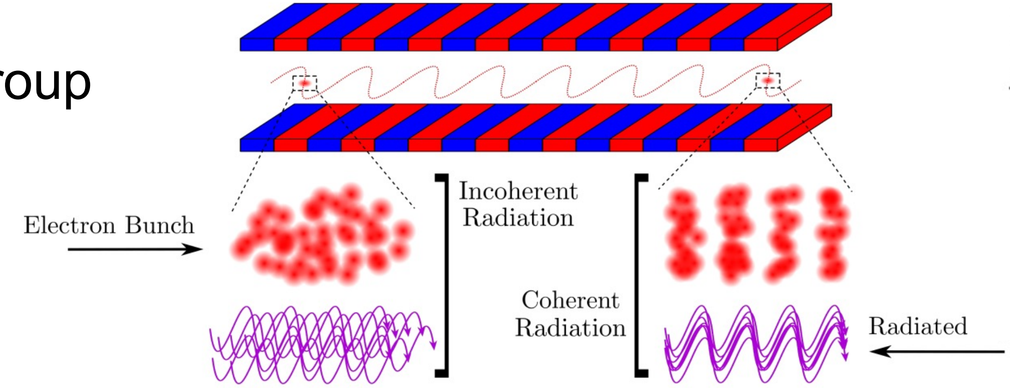
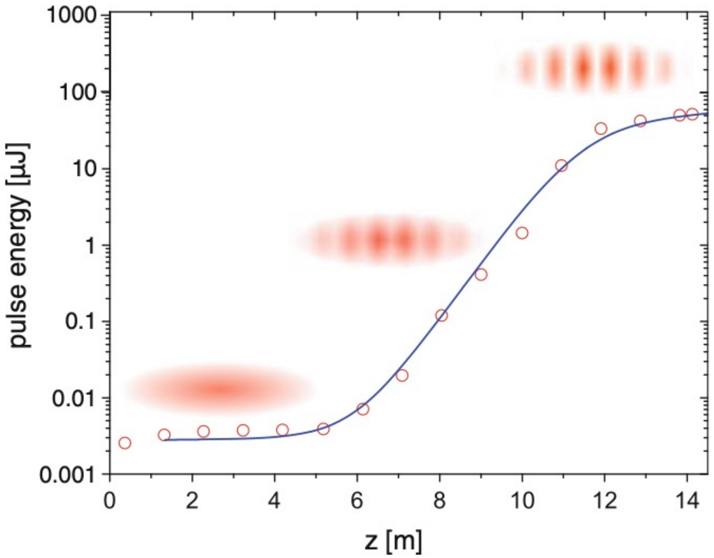




Pg. 41, text.

R. Lemons, Thesis

*Reminder slide…..

Bunched Beams Emit Coherent FEL Radiation

Bunching factor

$$b = \frac{1}{N_\lambda}\sum_{n}^{N_\lambda} e^{i\psi_n(z)}$$

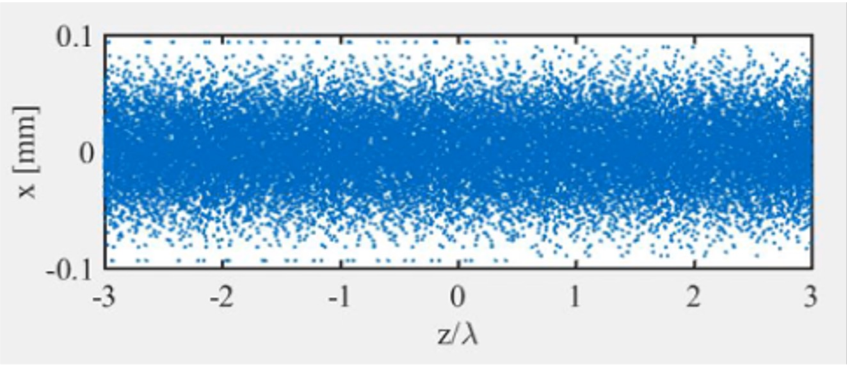
Radiation from an ensemble of N_λ electrons

N_λ is number of electrons in one wavelength

Coherent FEL emission

$$|E|^2_{FEL} = |\epsilon|^2\left[N_\lambda + N_\lambda^2\right]$$

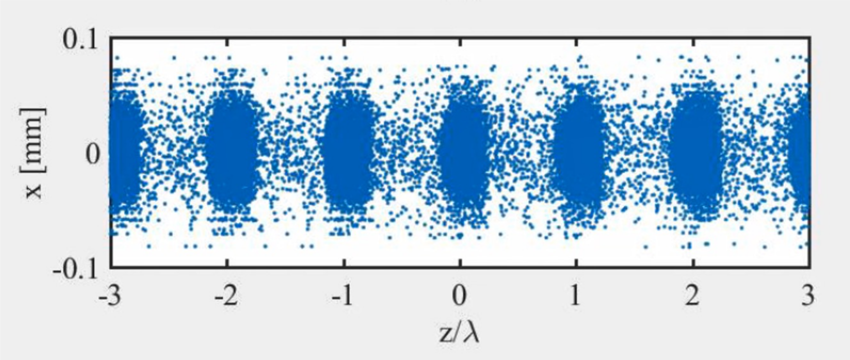
Unbunched beam



Bunching factor

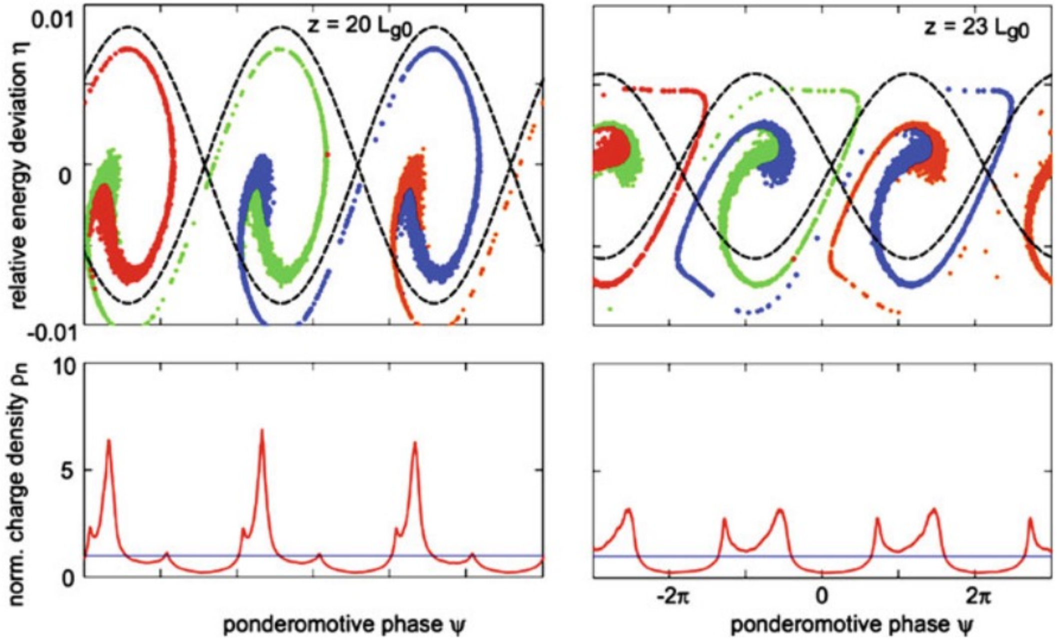
$$b = 0$$

Bunched beam



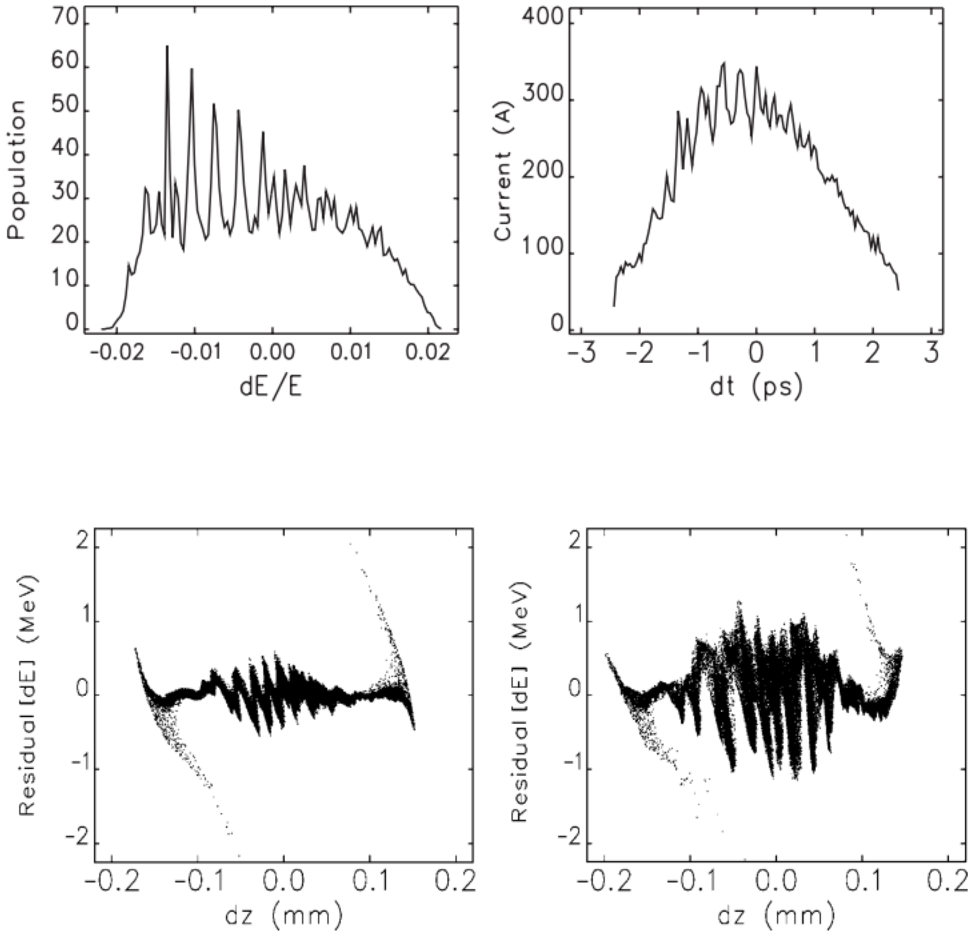
Bunching factor

$$b \sim 1$$



Microbunching Instability

- Longitudinal space charge, geometric wakes, and CSR acting on small slice emittances, can drive instabilities in the beam during acceleration and compression.
- Chicanes can convert energy modulation into density modulations. Modulations/radiation before we want them!
- This increases slice emit and energy spread, which impacts FEL performance.

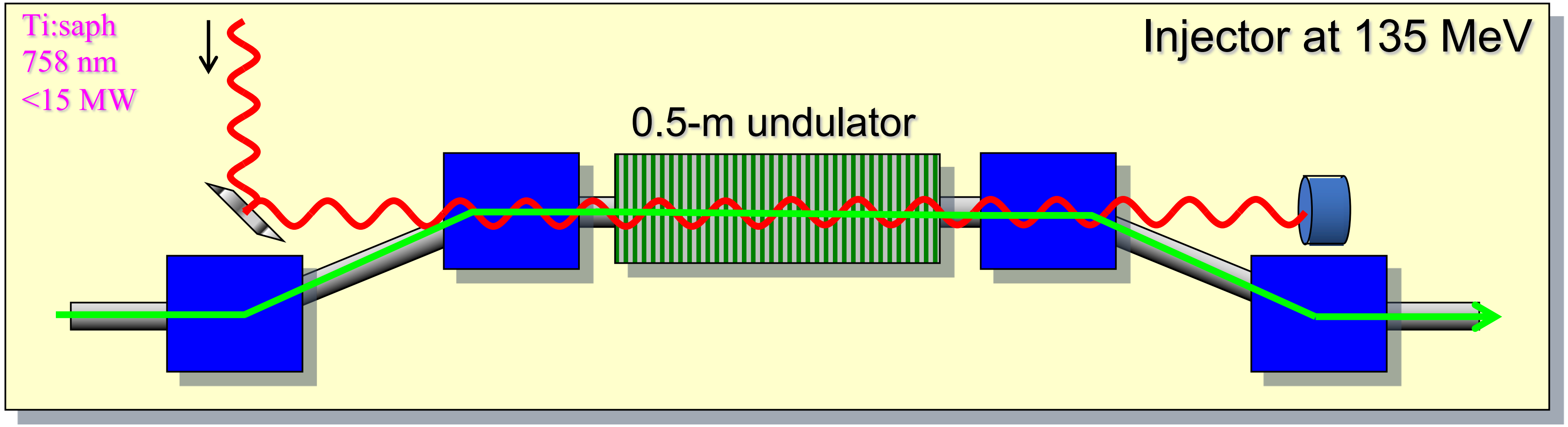


https://www.sciencedirect.com/science/article/pii/S0168900204007648

Laser Heaters

- Laser heaters are used to increase initial energy spread in the beam.
- This mitigates MBI downstream by preventing bunching before the undulators.
- Additional energy spread can not be too large or FEL will suffer.

LCLS copper, laser heater:

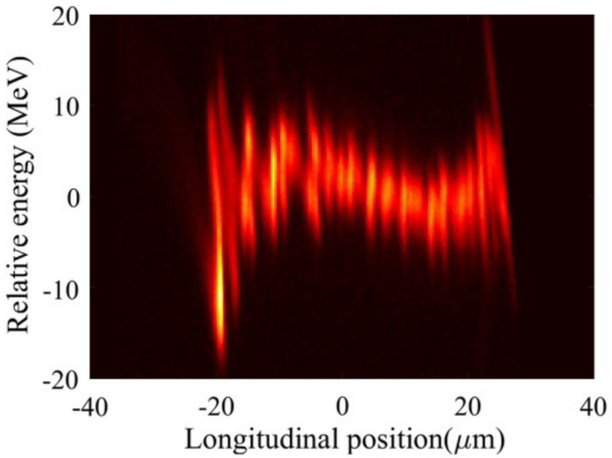


MBI + Laser Heater

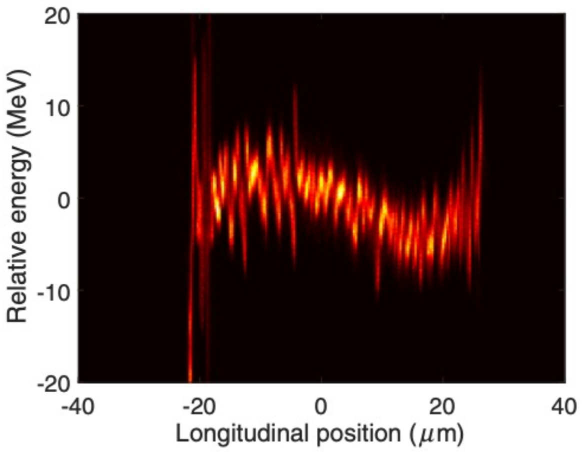
Laser heater OFF

Laser heater ON

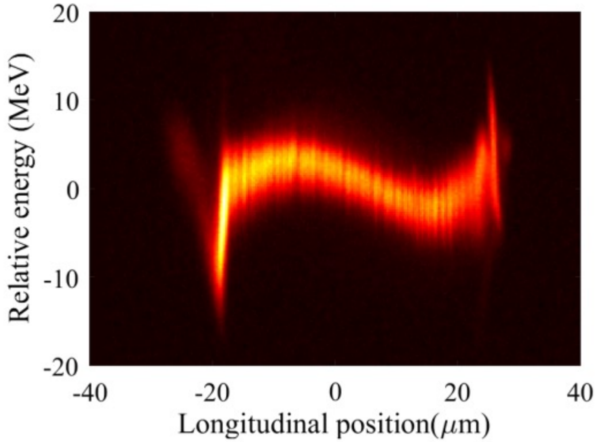
LCLS copper



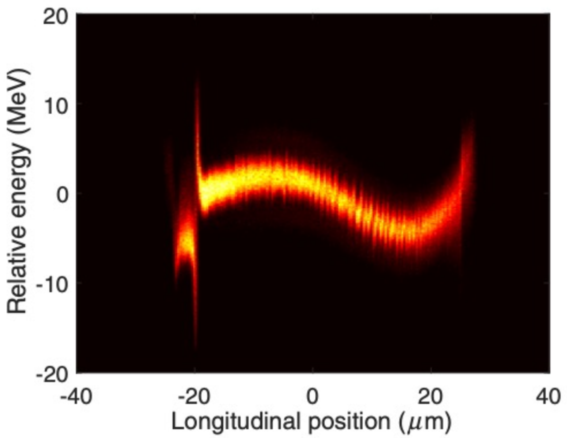
(a) measurement



(b) simulation



(a) measurement



(b) simulation

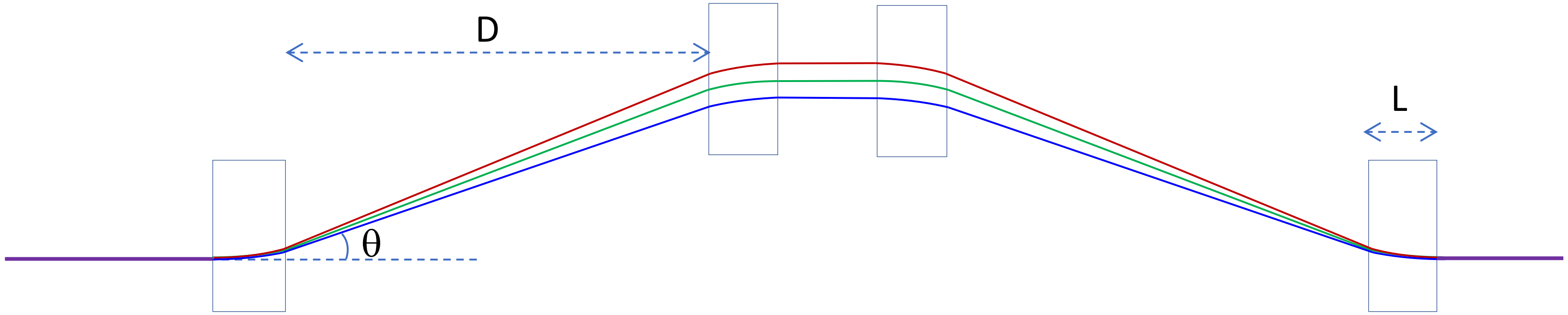
https://journals.aps.org/prab/pdf/10.1103/PhysRevAccelBeams.20.054402

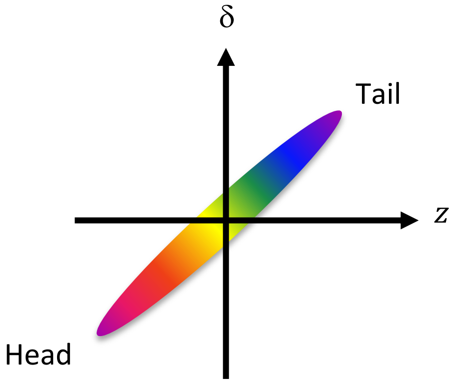
Summary

- X-ray FELs use bunch compression (often in multiple stages) to shorten the electron bunch and improve peak current.
- Buncher compression typically happens in magnet chicanes and/or bunching/chirper cavities.
- CSR is a non-linear effect and source of emittance growth and energy spread.
- Microbunching naturally occurs when electrons loose/gain energy to collective effects and longitudinally bunch together (slices).
- Laser heaters are used to mitigate microbunching instabilities.

Backup

Bunch Compression





Chirped electron bunch

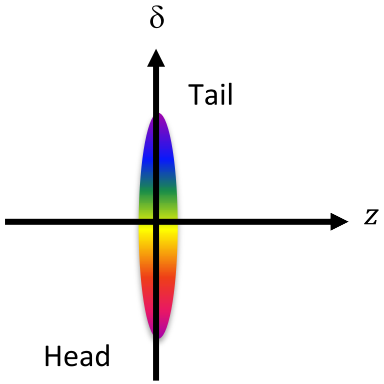
$$\Delta z = R_{56}\delta + T_{566}\delta^2 + O(\delta^3)\ldots$$

First-order momentum compaction

$$R_{56} = -\theta^2\left(\frac{4}{3}L + 2D\right)$$

Second-order momentum compaction

$$T_{566} \approx -\frac{3}{2}R_{56}$$



Compressed electron bunch

Combined Chirper-Chicane Transfer Matrix

Transfer matrix of the RF chirper cavity

$$\begin{pmatrix} z_1 \\ \delta_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \kappa & \dfrac{E_0}{E_{1c}} \end{pmatrix} \cdot \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix}$$

Transfer matrix of the chicane

$$\begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix} = \begin{pmatrix} 1 & R_{56} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} z_1 \\ \delta_1 \end{pmatrix}$$

$$\begin{pmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \end{pmatrix}_{n+1} = \begin{pmatrix} R_{11} & R_{12} & 0 & 0 & 0 & 0 \\ R_{21} & R_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{33} & R_{43} & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{55} & R_{56} \\ 0 & 0 & 0 & 0 & R_{65} & R_{66} \end{pmatrix} \begin{pmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \end{pmatrix}_{n}$$

$\boldsymbol{R_{z\delta}}$

Multiply these two matrices together, we obtain the combined chirper cavity-chicane transfer matrix

$$\begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix} = \begin{pmatrix} 1 + \kappa R_{56} & R_{56} \dfrac{E_0}{E_{1c}} \\ \kappa & \dfrac{E_0}{E_{1c}} \end{pmatrix} \cdot \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix}$$

Particle position at the end of the chicane

$$z_2 = (1 + \kappa R_{56}) z_0 + \left(\frac{E_0}{E_{1c}}\right) R_{56} \delta_0$$