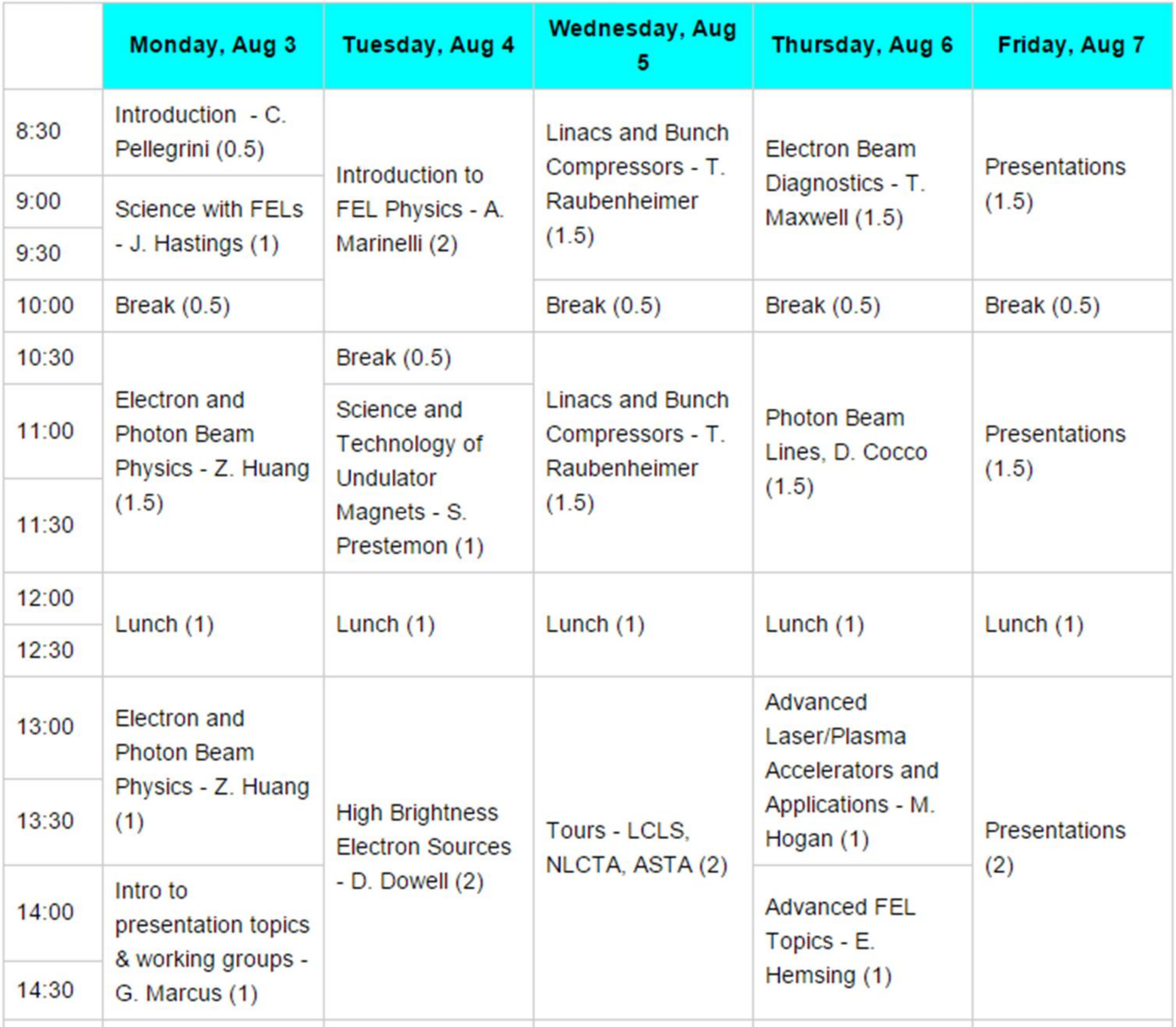
SSSEPB 2015
Linacs and Bunch Compressors

Lecture #2

8/5/2015

Tor Raubenheimer

Schedule



	Monday, Aug 3	Tuesday, Aug 4	Wednesday, Aug 5	Thursday, Aug 6	Friday, Aug 7
8:30	Introduction - C. Pellegrini (0.5)	Introduction to FEL Physics - A. Marinelli (2)	Linacs and Bunch Compressors - T. Raubenheimer (1.5)	Electron Beam Diagnostics - T. Maxwell (1.5)	Presentations (1.5)
9:00	Science with FELs - J. Hastings (1)				
9:30					
10:00	Break (0.5)		Break (0.5)	Break (0.5)	Break (0.5)
10:30	Electron and Photon Beam Physics - Z. Huang (1.5)	Break (0.5)	Linacs and Bunch Compressors - T. Raubenheimer (1.5)	Photon Beam Lines, D. Cocco (1.5)	Presentations (1.5)
11:00		Science and Technology of Undulator Magnets - S. Prestemon (1)			
11:30					
12:00	Lunch (1)	Lunch (1)	Lunch (1)	Lunch (1)	Lunch (1)
12:30					
13:00	Electron and Photon Beam Physics - Z. Huang (1)	High Brightness Electron Sources - D. Dowell (2)	Tours - LCLS, NLCTA, ASTA (2)	Advanced Laser/Plasma Accelerators and Applications - M. Hogan (1)	Presentations (2)
13:30					
14:00	Intro to presentation topics & working groups - G. Marcus (1)			Advanced FEL Topics - E. Hemsing (1)	
14:30					

Topics

- Acceleration
    - RF Cavities
    - NCRF and SCRF Technology
- Emittance Preservation
    - Phase Space and 6D Emittance
    - Synchrotron Radiation
    - Wakefields
- Bunch Compression
    - Linear and Nonlinear Optics
    - Space Charge and Wakefields
    - Micro-bunching effects

Beam properties

Zhirong Huang, Slide 25

- Second moments of beam distribution

rms size

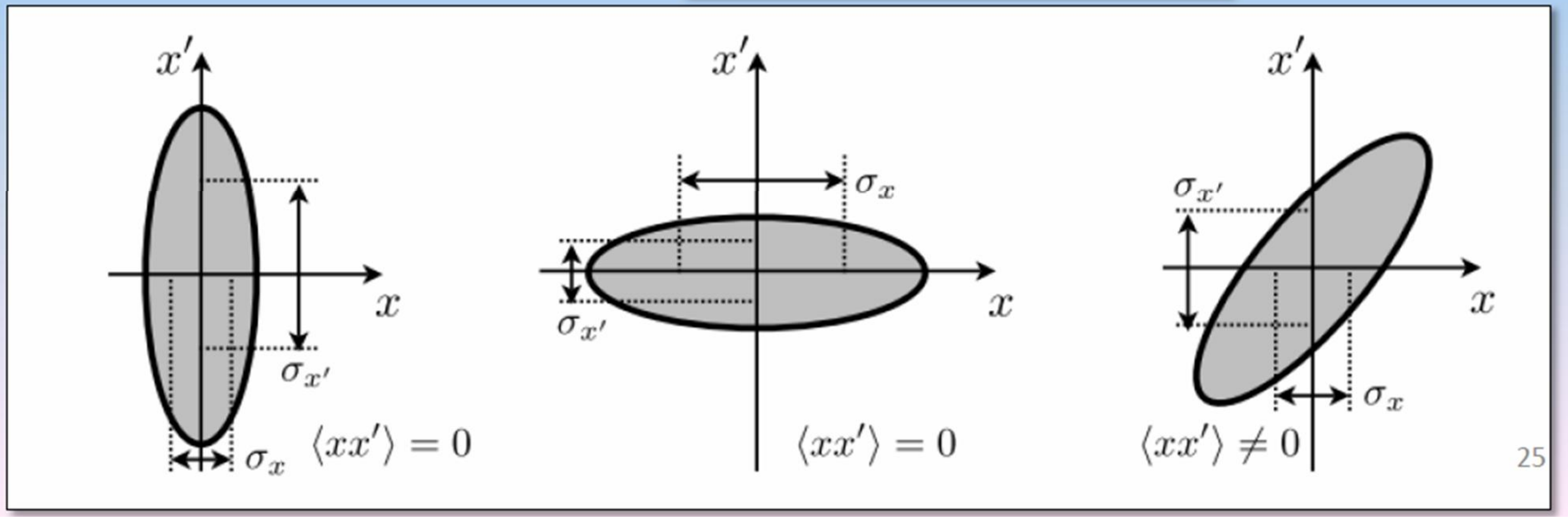
$$\sigma_x^2(z) = \langle x^2 \rangle = \frac{1}{N_e} \sum_j x_j^2 .$$

rms divergence

$$\sigma_{x'}^2(z) = \left\langle x'^2 \right\rangle = \frac{1}{N_e} \sum_j x_j'^2 .$$

correlation

$$\langle x\, x' \rangle = \frac{1}{N_e} \sum_j x_j x_j' .$$



Beam Emittance (2D projection)

$$\gamma\epsilon_x = \gamma\sqrt{\langle x_\beta^2\rangle\langle {x'_\beta}^2\rangle - \langle x_\beta x'_\beta\rangle^2}$$

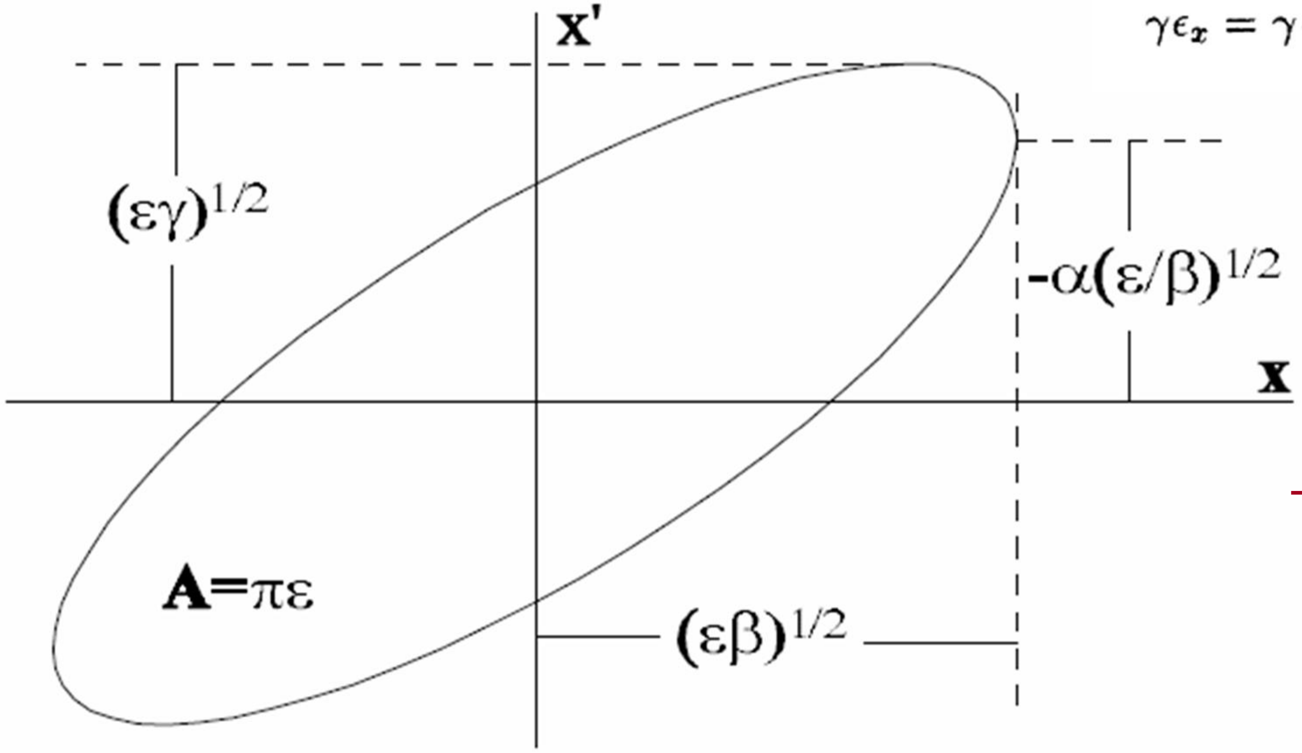


Fig. 6.5. Phase space ellipse with ellipse area A

$$\rho = \frac{1}{\sqrt{2\pi}\sigma_x}\exp\left[-\left(\frac{\gamma x^2 + 2\alpha x x' + \beta x'^2}{2\varepsilon}\right)\right]$$

Twiss Parameters

$$\alpha = -\frac{1}{2}\frac{d\beta}{ds}$$

$$\gamma = \frac{1+\alpha^2}{\beta}$$

Note not relativistic parameters γ and β

Phase Space

Map evolution of the beam

Liouville Theorem:

- conservative forces → 6D phase space density is conserved but …

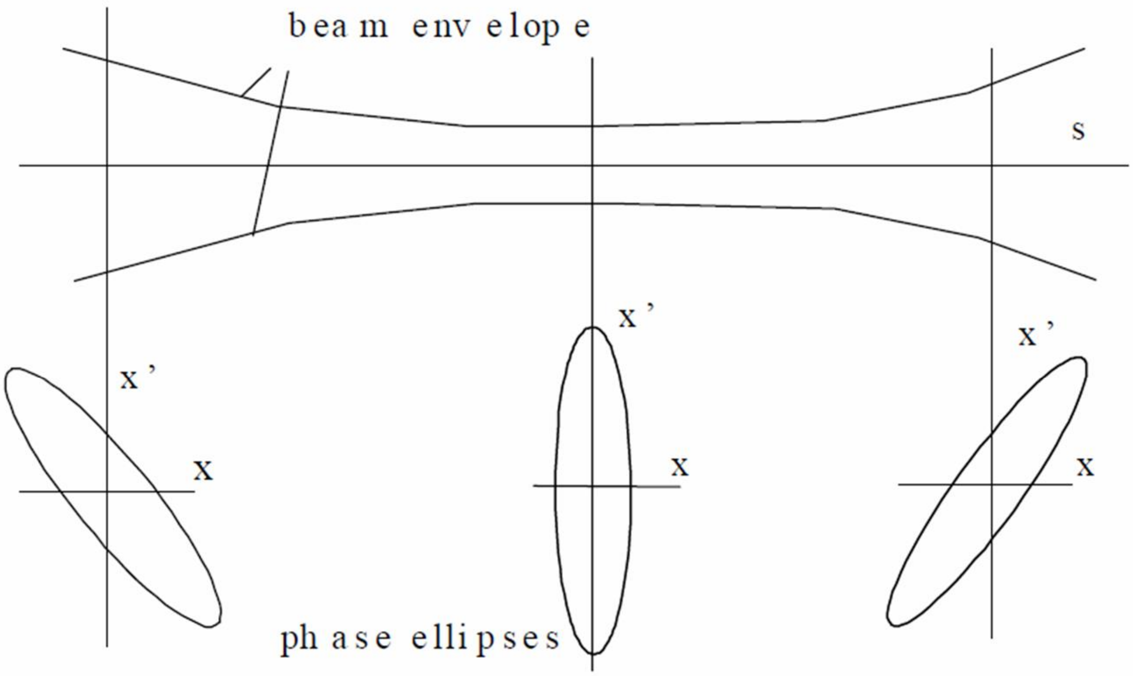


Fig. 6.6. Evolution of the phase ellipse along a drift space

Emittance Dilutions

Dave works very hard to make small emittance and Ago needs small emittance → better not screw it up

Non-Conservative dilutions – increase 6D ε

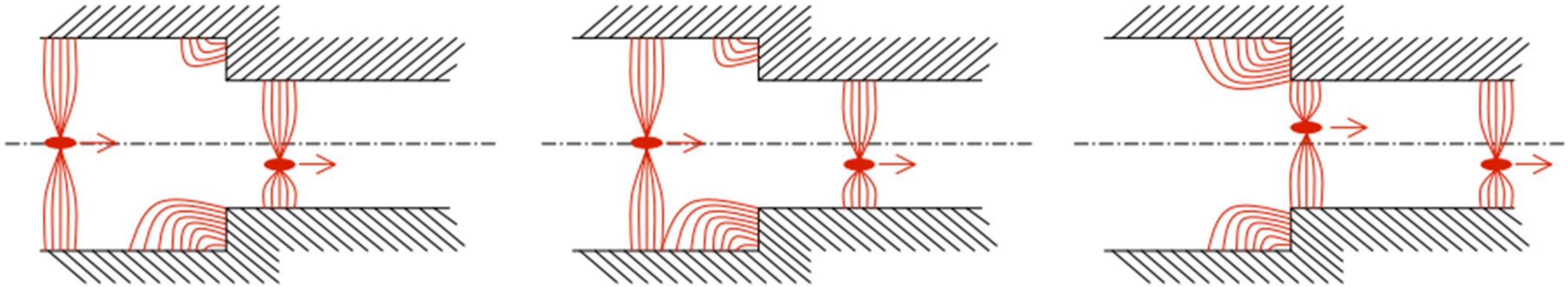
- Incoherent synchrotron radiation
- Scattering (beam gas or intra-beam)

Conservative diultions – increase projected ε

- Nonlinearities – wrap phase space around
- Transverse wakefields – couple x,y to z position
- Dispersion/chromaticity – couple x,y to δ energy offset

Wakefields

Beam is traveling near speed of light but beam will excite fundamental and higher-order modes along the metallic vacuum chamber boundary



First bunch losses energy (longitudinal and transverse) and fields impact subsequent bunches

Wakes are a strong function of the aperture with $W_{||} \sim 1/a^2$ and $W_{\perp} \sim 1/a^3$

Wakefields – Modal Representation

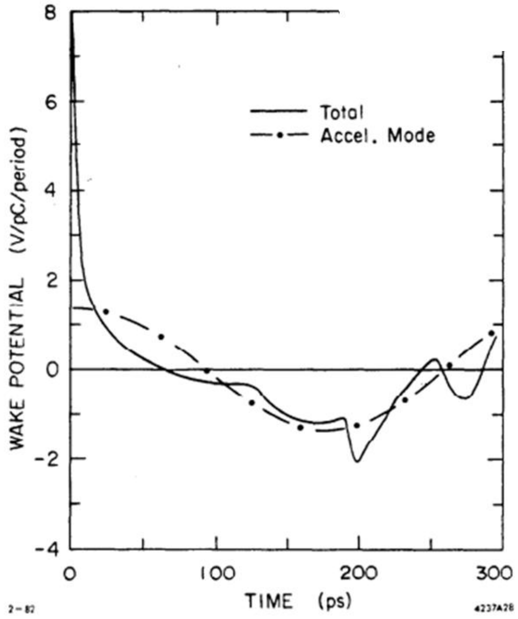
Beam is traveling near speed of light but beam will excite fundemental and higher-order modes in the cavity

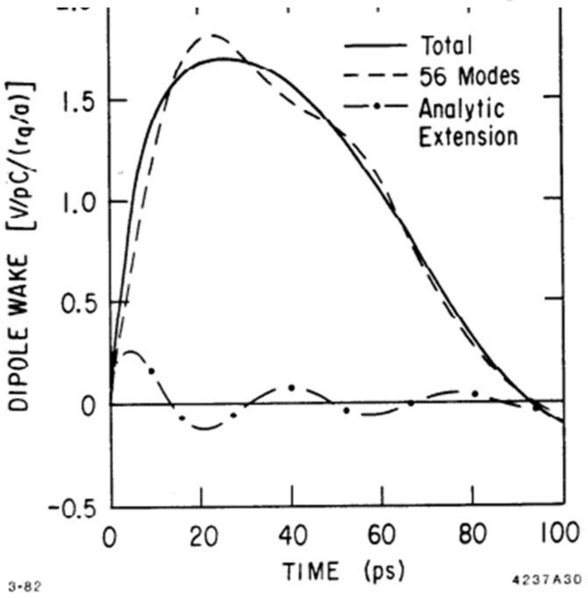
$$W_z \simeq \sum_n 2k_{0n}(a)\cos\frac{\omega_{0n}s}{c} \qquad s>0$$

Monopole modes

$$\mathbf{W}_\perp \simeq \left(\frac{r'}{a}\right)\hat{x}\sum_n \frac{2k_{1n}(a)}{(\omega_{1n}a/c)}\sin\frac{\omega_{1n}s}{c} \qquad s>0.$$

Dipole modes





A leading particle leaves a field that impacts trailing particles

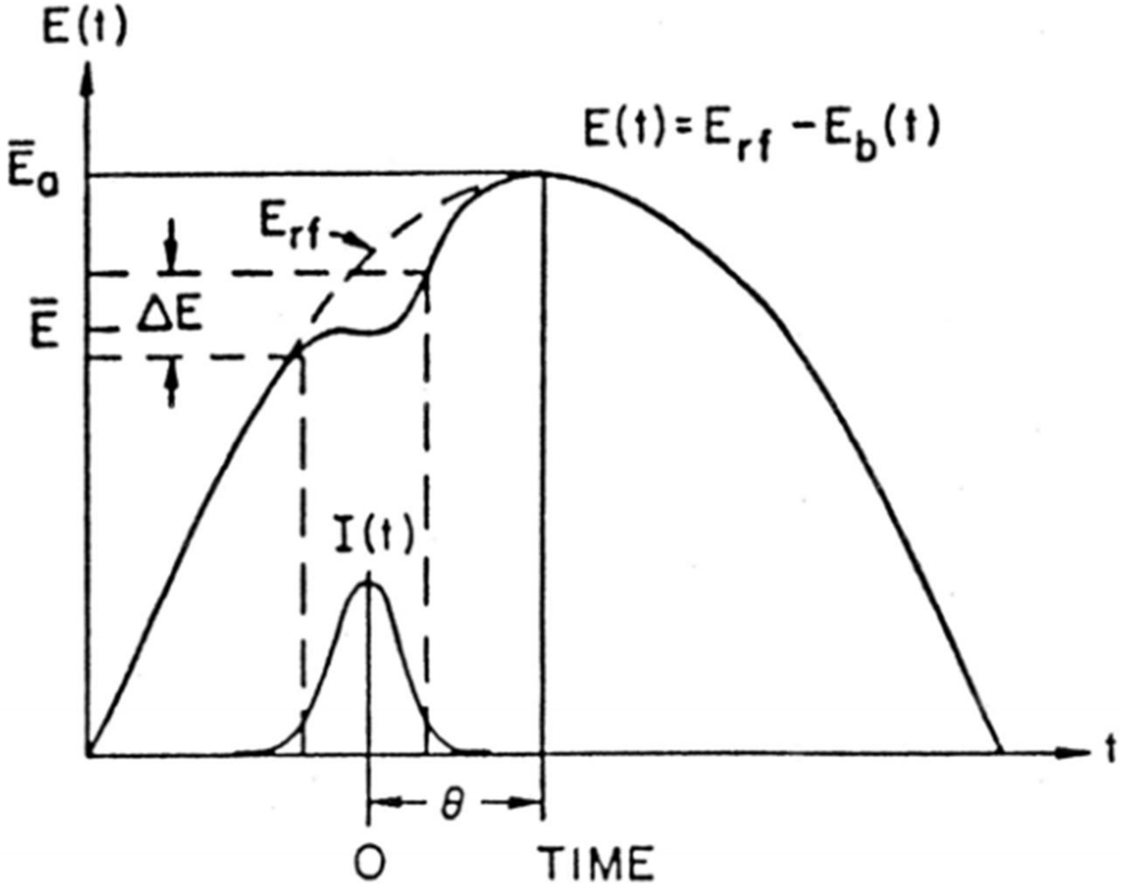
Suggestion: look up the Panofsky-Wenzel Theorem

Longitudual Wakefield Compensation

The longitudinal wakefield will generate an energy spread across the bunch distorting the rf acceleration field

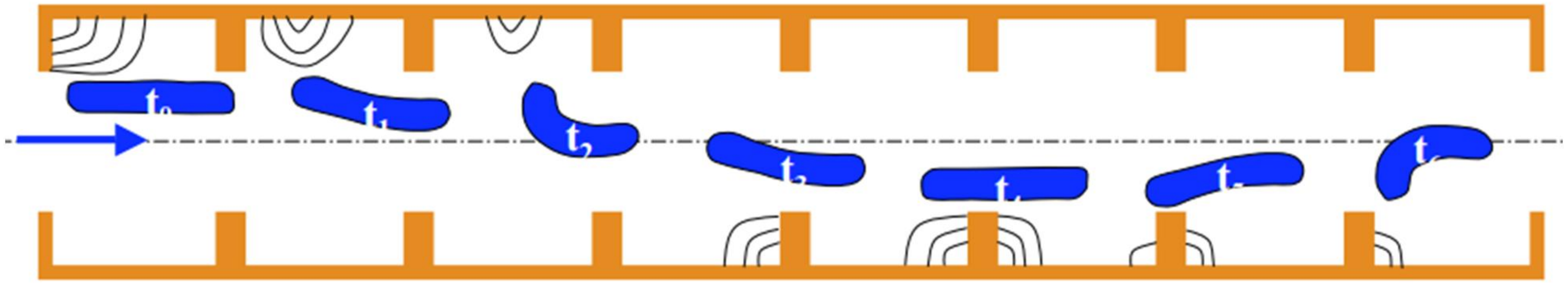
Choose the rf phase to compensate (or accentuate the effect of the wakefield)

Nonlinearity of wakefield is more difficult to fix



Transverse Wakefields

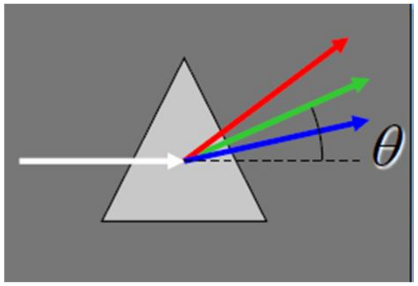
Example of transverse wakefields observed in the SLAC linac → single bunch beam breakup



There is no 6D emittance dilution but a strong nonlinear coupling between x and z that increases the projected emittance

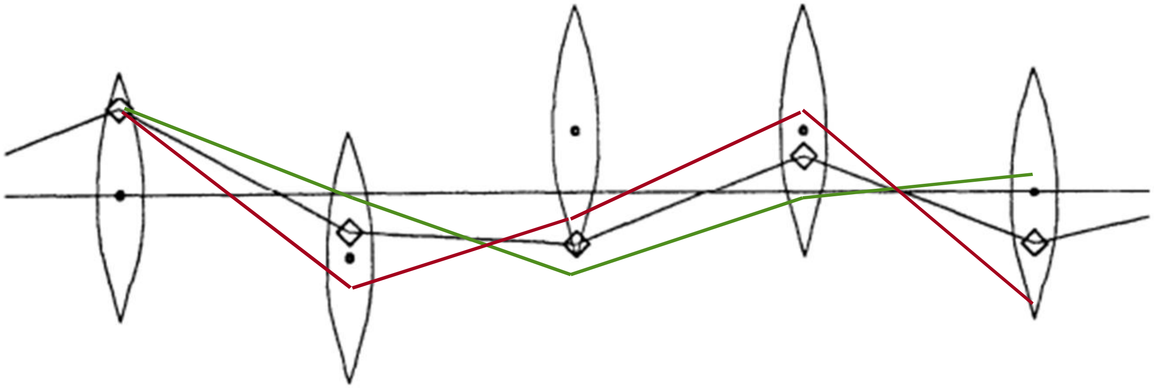
Dispersive Emittance Dilution

Deflections from magnetic fields are energy dependant. Dipole (steering) magnets are used to steer trajectory down linac and compensate for magnetic field and placement errors



→ energy dependent trajectory as if residual dispersion

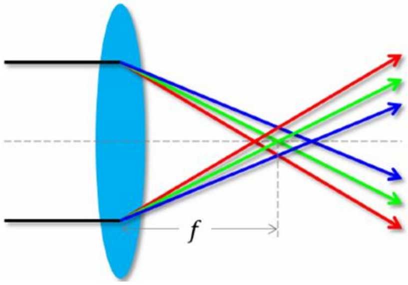
$$\Delta\varepsilon \sim \delta^2 \eta^2$$



Chromatic Dilution – Energy vs Focusing

We use Twiss parameters to describe both beam parameters and the beam optics (Twiss parameters depend on initial conditions)

- Usually matched to the accelerator so OK but can be confusing!



What happens when the beam is mismatched?

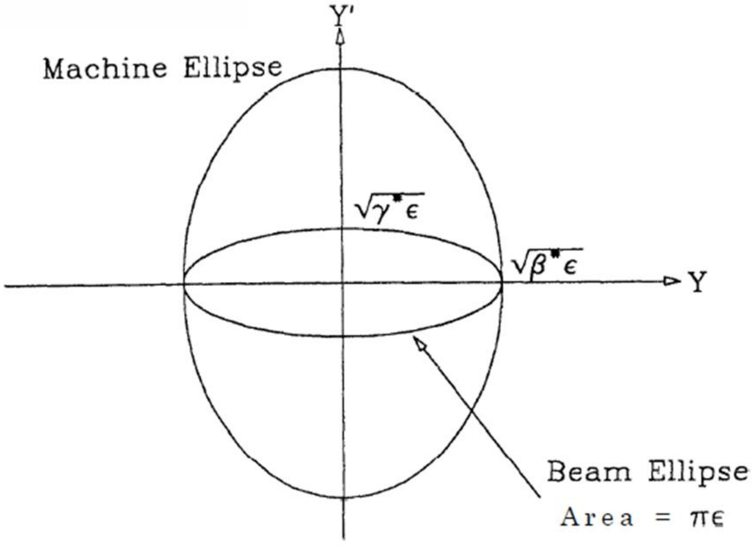


Fig. 48. Beam and machine ellipses for an unmatched beam.

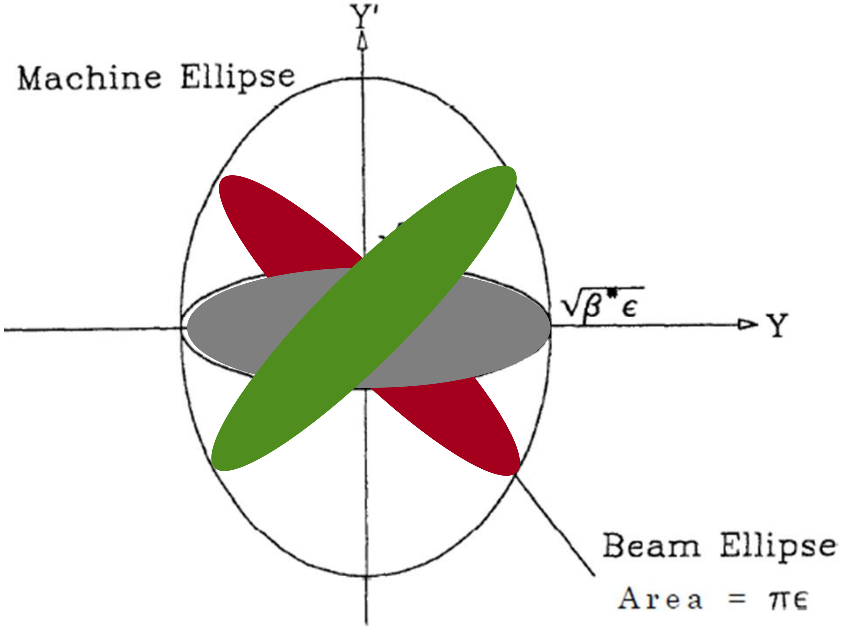


Fig. 48. Beam and machine ellipses for an unmatched beam.

Take-Away

Most processes will not dilute 6D phase space but there are many ways to couple the beam an increase projected emittance

Large energy spreads (few %) will lead to chromatic dilution and will drive tight tolerances to eliminate dispersive dilution

Longitudinal wakefields will add nonlinearity to longitudinal phase space making it hard to compress the beam to desired peak current (more later)

Transverse wakefields will couple x-z increasing projected emittance – depend on bunch length and apertures

Bunch Compression

Why compress bunch?

1. Peak current
2. Reduce energy spread from rf
3. Reduce transverse wakefields

How to compress the bunch?

Velocity bunch

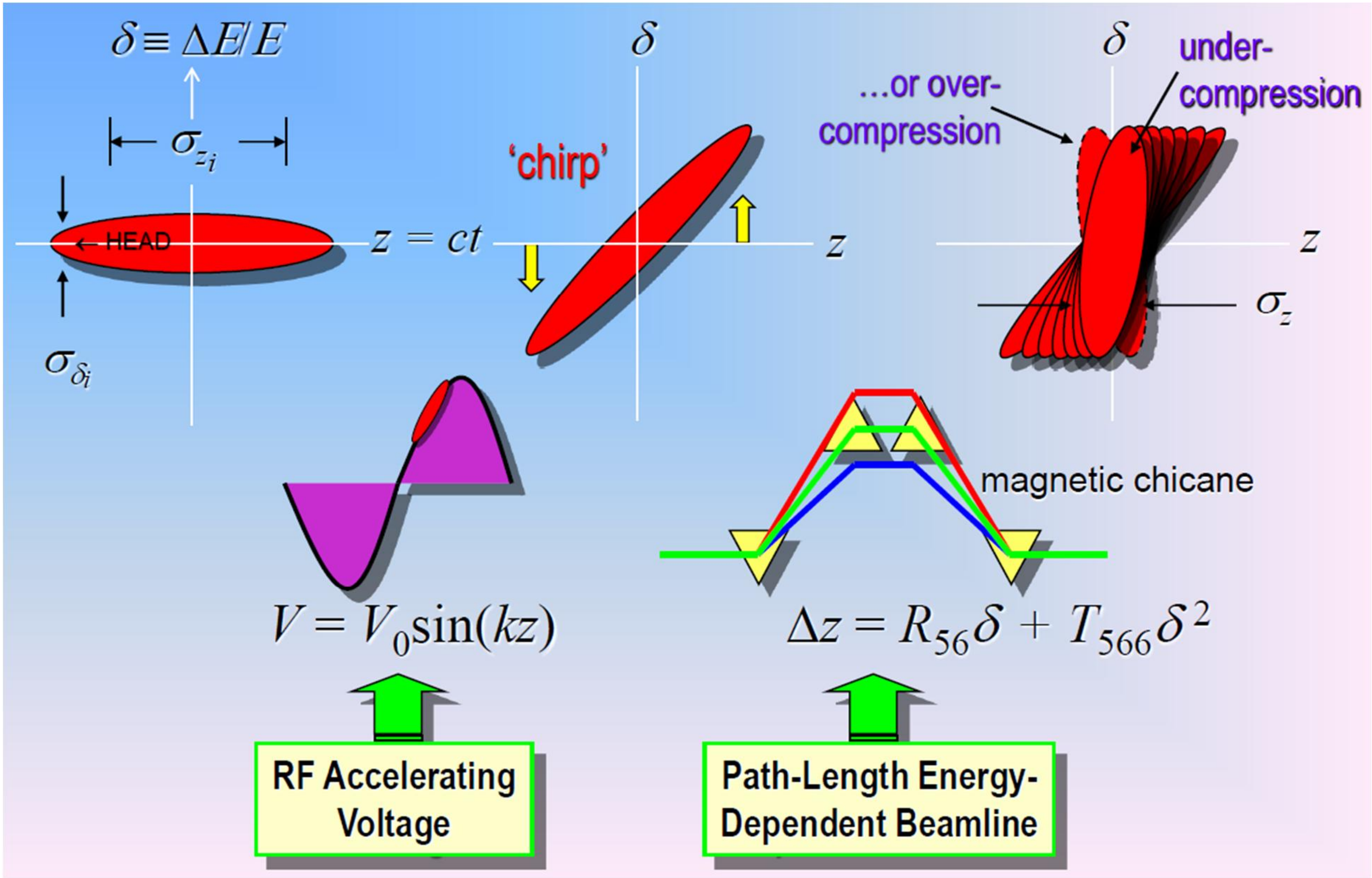
Path length variation

What is the velocity variation of relativistic particles $\Delta\beta/\beta$?

$$\Delta\beta/\beta = \Delta\gamma/\gamma \ 1 / 2\gamma^2$$

Longitudinal Motion ($\gamma >> 1$)

Bunch Rotation



$$V = V_0 \sin(kz)$$

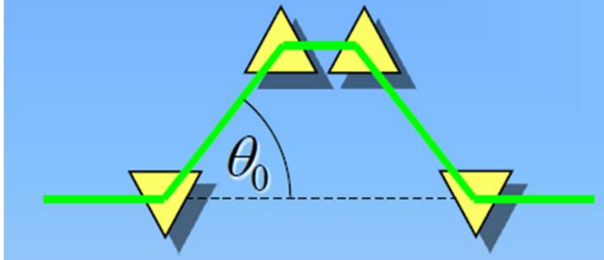
$$\Delta z = R_{56}\delta + T_{566}\delta^2$$

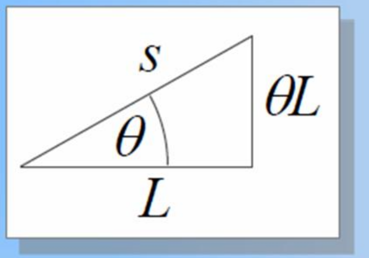
RF Accelerating Voltage

Path-Length Energy-Dependent Beamline

Magnetic Chicane – Path Length

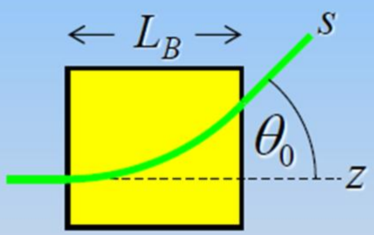
A 4-bend magnetic chicane introduces a path length increase depending on bend angle, θ, where $|\theta| << 1$ and $\gamma >> 1$.





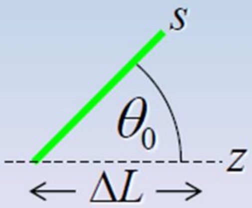
$$s = \sqrt{L^2 + (L\theta)^2}$$
$$\approx L\left(1 + \tfrac{1}{2}\theta^2\right)$$
$$ds = \tfrac{1}{2}\theta^2(z)dz$$

1) One bend magnet



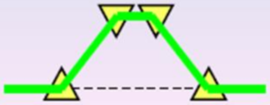
$$\theta(z) = \tfrac{z}{L_B}\theta_0$$
$$\Delta s_1 \approx \frac{\theta_0^2}{2L_B^2}\int_0^{L_B} z^2 dz = \tfrac{1}{6}\theta_0^2 L_B$$

2) Drift between bends



$$\Delta s_2 \approx \tfrac{1}{2}\int_0^{\Delta L} \theta_0^2 dz = \tfrac{1}{2}\theta_0^2 \Delta L$$

3) 4 bends + 2 drifts



$$\Delta s = 4\Delta s_1 + 2\Delta s_2 = \theta_0^2\left(\Delta L + \tfrac{2}{3}L_B\right)$$

Magnetic Chicane – Path Length Variation

Now allow a small relative energy deviation, $\delta = \Delta E/E_0$

$$\Delta s = \theta_0^2\left(\Delta L + \tfrac{2}{3}L_B\right) \rightarrow \left(\tfrac{\theta_0}{1+\delta}\right)^2\left(\Delta L + \tfrac{2}{3}L_B\right)$$

$$\approx \theta_0^2\left(\Delta L + \tfrac{2}{3}L_B\right)\left(1 - 2\delta + 3\delta^2 - \ldots\right)$$

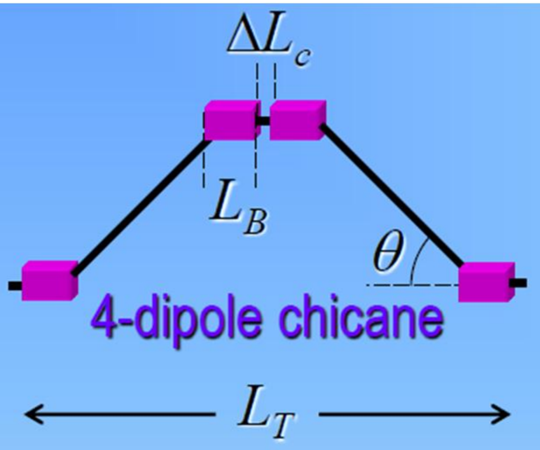
$$= \Delta s_0 + R_{56}\delta + T_{566}\delta^2 + \ldots$$

$$\boxed{R_{56} \approx -2\theta_0^2\left(\Delta L + \tfrac{2}{3}L_B\right)}$$ linear energy term

$$T_{566} \approx -\tfrac{3}{2}R_{56}$$ 2nd-order energy term (chicane only)

Types of Path Length Compressors

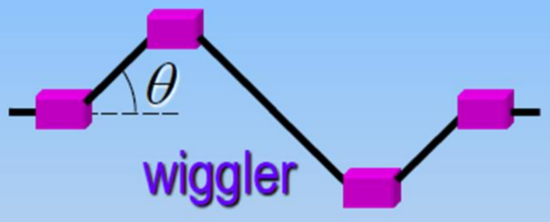
(bunch head at $z < 0$)



LEUTL,…
LCLS,
TTF-BC1,2,
TESLA-BC1

$$\boxed{R_{56} \approx -2\theta^2\left(\frac{L_T}{2} - \frac{4}{3}L_B - \frac{\Delta L_c}{2}\right)} < 0$$

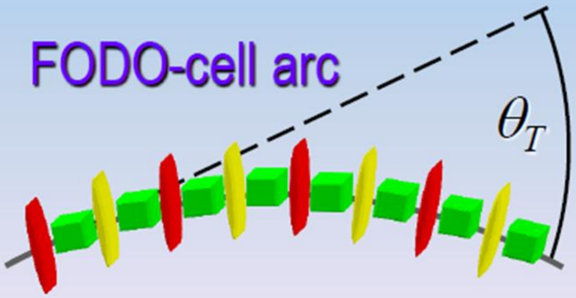
simple, achromatic



TESLA-BC2,3

$$\boxed{R_{56} \approx -2\theta^2\left(\frac{L_T}{2} - \frac{4}{3}L_B\right)} < 0$$

achromatic, CSR cancellation?



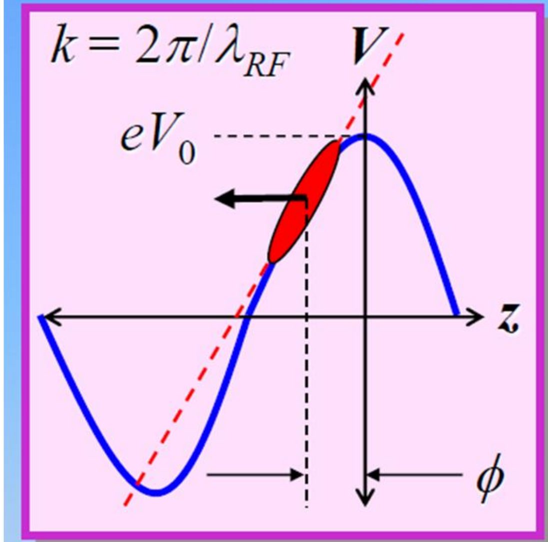
SLC RTL,
SLC arcs
NLC BC2

$$\boxed{R_{56} \approx \frac{\theta_T^2 L_T}{4N_c^2\sin^2(\mu_x/2)}} > 0$$

reverse sign R_{56}

Linear Bunch Compressor

$\phi = 0$ at accelerating crest



$$E(z_i) = E_i + eV_0\cos(\phi + kz_i)$$

$$\delta(z_i) \equiv \frac{E(z_i)-E(0)}{E(0)} = \frac{\Delta E}{E_0} \approx \text{chirp (slope)}$$

$$-\left(k\frac{eV_0}{E_0}\sin\phi\right) z_i + a\delta_i = \overset{\downarrow}{h}z_i + a\delta_i$$

(with $a \equiv \frac{E_i}{E_0} \le 1$, and $|kz_i| \ll 1$)

$$z = z_i + R_{56}\delta = (1 + hR_{56})z_i + aR_{56}\delta_i$$

for initially uncorrelated z_i and δ_i, the final rms bunch length is…

$$\sigma_z = \langle z^2 - \langle z\rangle^2\rangle^{1/2} = \sqrt{(1 + hR_{56})^2\,\sigma_{z_i}^2 + (aR_{56}\sigma_{\delta_i})^2} \approx |1 + hR_{56}|\sigma_{z_i}$$

energy spread: $\sigma_\delta = \langle \delta^2 - \langle\delta\rangle^2\rangle^{1/2} = \sqrt{h^2\sigma_{z_i}^2 + a^2\sigma_{\delta_i}^2} \approx |h|\sigma_{z_i}$

Choose coordinates with bunch head at $z < 0$, then if $R_{56} < 0$ (chicane) a chirp with $h > 0$ ($\pi < \phi < 0$) will compress the bunch.

Impact of Nonlinearities (Rf and Optical)

Write bunch length coordinate after compressor to 2nd order …

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

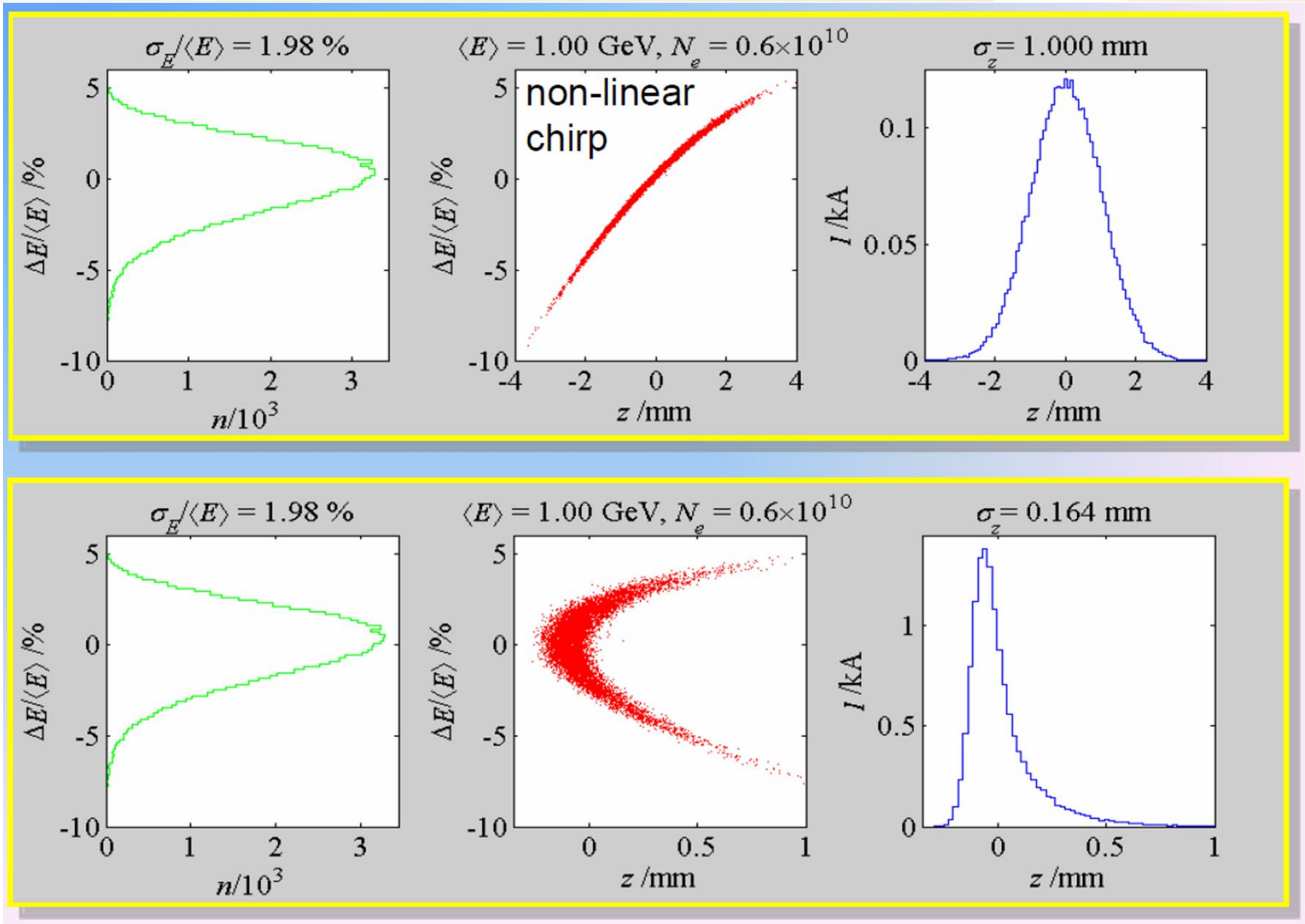
Now add 2nd order term of sinusoidal rf accelerating voltage...

$$\delta = a\delta_i + hz_i + \frac{\pi h}{\lambda \tan\phi} z_i^2$$

Using a Gaussian z-distribution [$\langle z_i^4 \rangle = 3\sigma_{z_i}^4$] and $\langle z_i \delta_i \rangle = 0$, the rms bunch length is…

$$\sigma_z^2 = \underbrace{a^2 R_{56}^2 \sigma_{\delta_i}^2}_{\text{limit}} + \underbrace{(1 + hR_{56})^2 \sigma_{z_i}^2}_{\text{linear term}} + \underbrace{2h^2 R_{56}^2 \left(h\frac{T_{566}}{R_{56}} - \frac{\pi}{\lambda \tan\phi}\right)^2 \sigma_{z_i}^4}_{\text{2nd-order limit}}$$

Nonlinear Effects

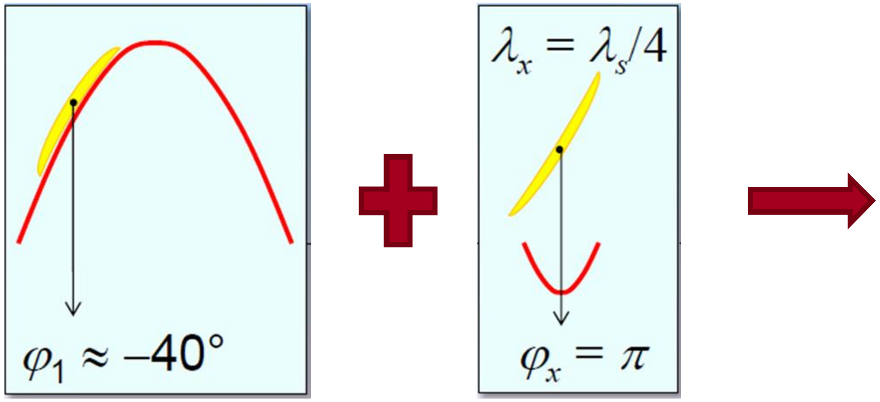


2nd-order Compensation

$$\sigma_z^2 = \underbrace{a^2 R_{56}^2 \sigma_{\delta_i}^2}_{\text{limit}} + \underbrace{(1 + hR_{56})^2 \sigma_{z_i}^2}_{\text{linear term}} + \underbrace{2h^2 R_{56}^2 \left(h\frac{T_{566}}{R_{56}} - \frac{\pi}{\lambda \tan\phi}\right)^2 \sigma_{z_i}^4}_{\text{2nd-order limit}}$$

2nd-order term from T566 and rf curvature. How to compensate this?

1. Choose arc-style compressor to flip sign of R56
2. Add rf with opposite curvature



Linearize Compressed Bunch

LCLS-II Bunch Compressor Configuration

Two stages of bunch compression to limit compression factor and peak current at low energy and reduce sensitivity to phase jitter

L0
$\varphi \approx 0$
$V_0 \approx 97$ MV

L1
$\varphi = -26°$
$V_0 = 235$ MV

HL
$\varphi = -170°$
$V_0 = 40$ MV

L2
$\varphi = -28°$
$V_0 = 1448$ MV

L3
$\varphi = 0$
$V_0 = 2460$ MV

GUN
0.75 MeV

LH
98 MeV
$R_{56} = -5$ mm
$I_{pk} = 12$ A
$L_b = 2.0$ mm
$\sigma_\delta = 0.006$ %

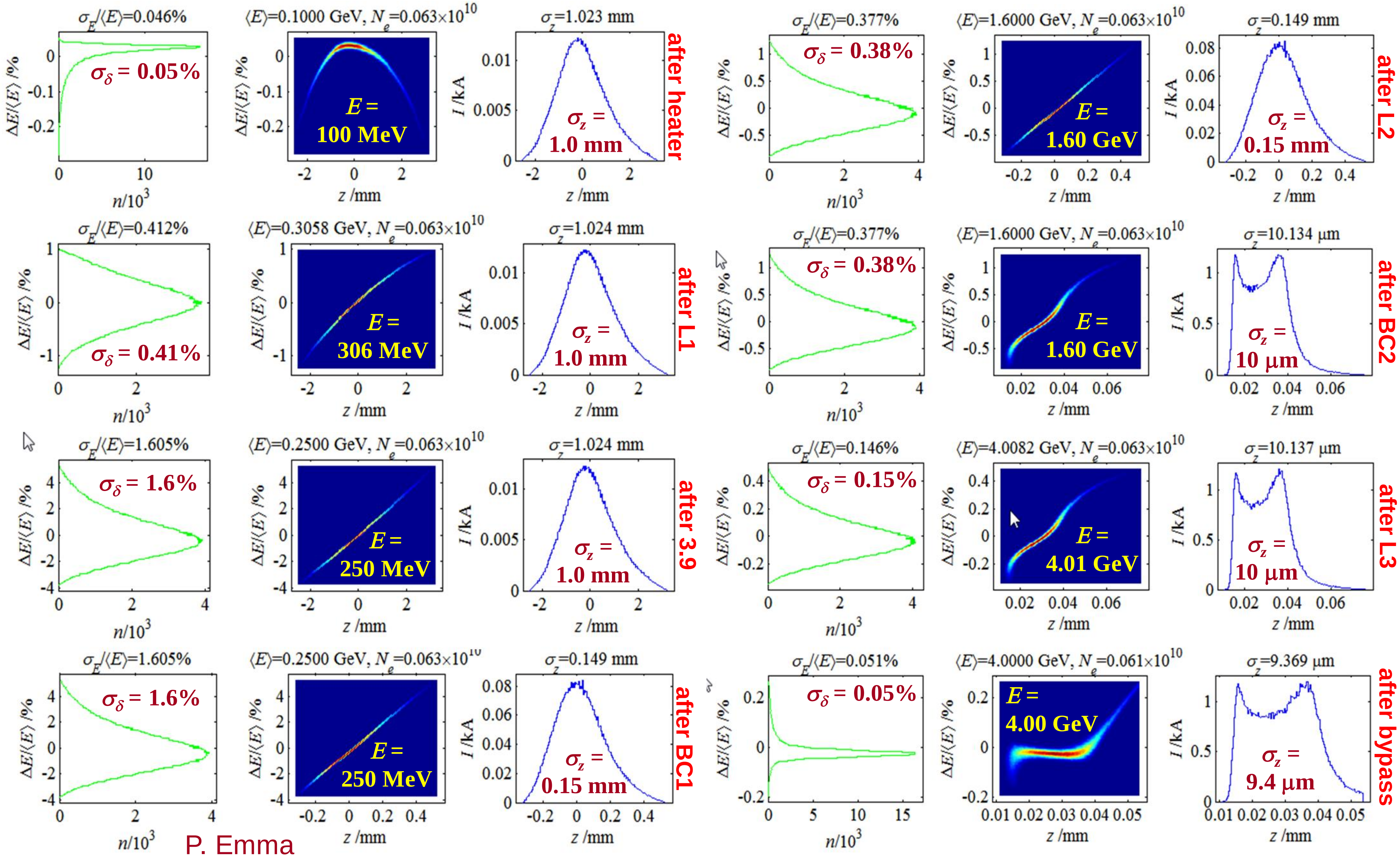
BC1
270 MeV
$R_{56} = -65$ mm
$I_{pk} = 60$ A
$L_b = 0.40$ mm
$\sigma_\delta = 1.4$ %

BC2
1550 MeV
$R_{56} = -65$ mm
$I_{pk} = 1000$ A
$L_b = 0.024$ mm
$\sigma_\delta = 0.50$ %

LTU
4.0 GeV
$R_{56} = 0$
$I_{pk} = 1000$ A
$L_b = 0.024$ mm
$\sigma_\delta \approx 0.02$ %

Energy chirp manipulation is performed primarily with rf phases (wakes are weak) but final chirp on short bunch is removed using resistive wall wake

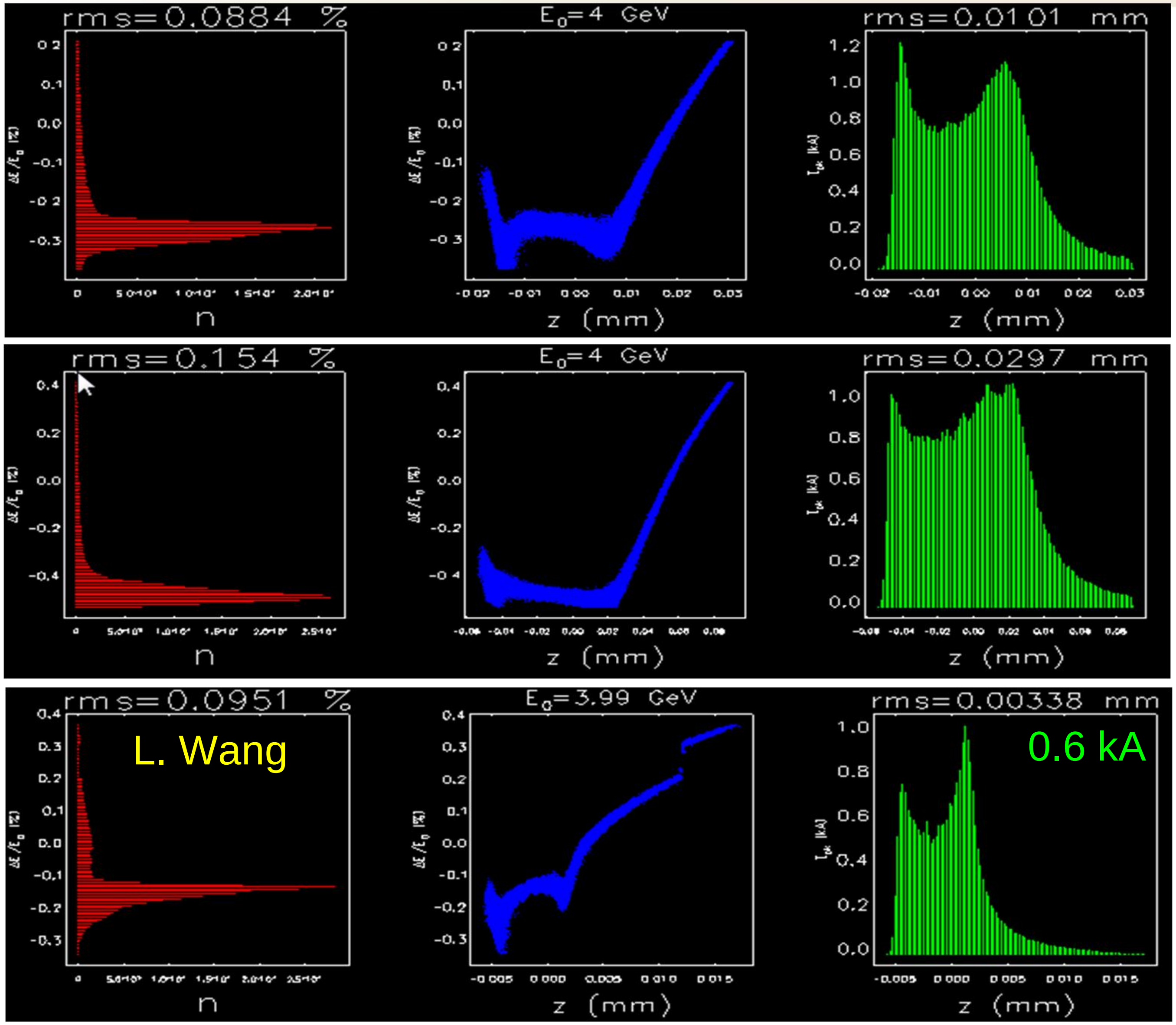
Evolution of the LCLS-II Bunch Along the Linac



P. Emma

Tracking a 100, 300, and 20 pC Bunch Charge

(with CSR, long. wakes, and separate injector runs – *ASTRA* & *Elegant*)



Q = 100 pC

$\gamma\varepsilon_x$=0.35→0.42 μm (20%)

heater = 5.5 keV rms

φ_{L1} = -12.7 deg

$V_{3.9}$ = 64.7 MV

$\varphi_{3.9}$ = -150 deg

$R_{56\text{-BC2}}$ = -37.0 mm

Q = 300 pC

$\gamma\varepsilon_x$=0.61→0.77 μm (26%)

heater = 11 keV rms

φ_{L1} = -14.0 deg

$V_{3.9}$ = 58.0 MV

$\varphi_{3.9}$ = -150 deg

$R_{56\text{-BC2}}$ = -36.7 mm

Q = 20 pC

$\gamma\varepsilon_x$=0.09→**0.13** μm (44%)

heater = 2.0 keV rms

φ_{L1} = -21.0 deg

$V_{3.9}$ = 55 MV

$\varphi_{3.9}$ = -165 deg

$R_{56\text{-BC2}}$ = -62 mm

Take-Away

Want to manipulate the bunch length along the linac but relativistic bunch is ‘frozen’ → vary energy dependent path length and ‘chirp’ the beam by adding position dependent energy variation with RF and wakefields

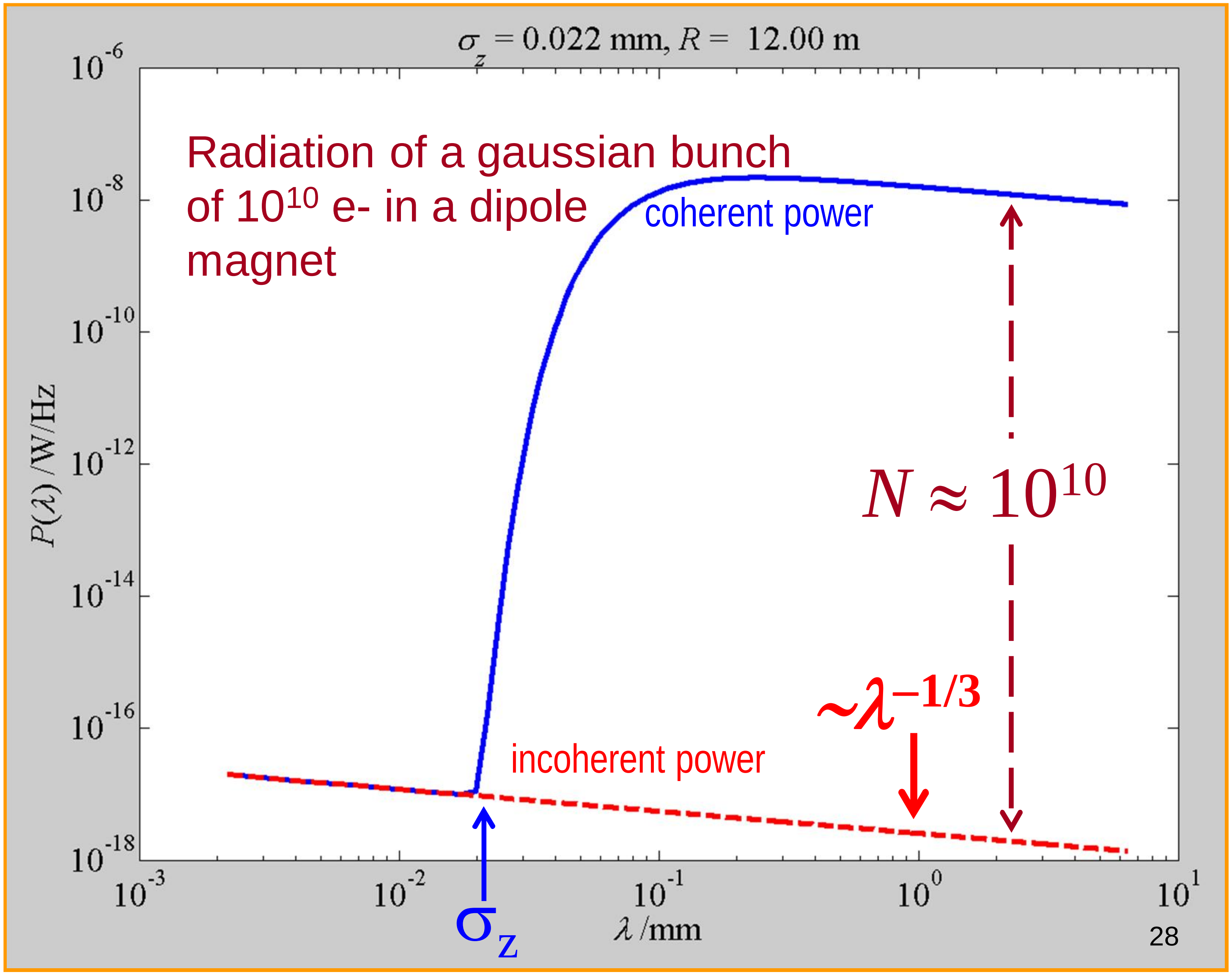
Two styles of compressors, one where high energy particles have shorter path and one with a longer path (think earth orbit)

Nonlinearities of longitudinal phase space limit compression. Can try to compensate these optically, using wakefields (wrong sign for chicanes), or harmonic rf

Multi-stage compression is used to reduce sensitivity of an single stage and reduce peak currents at low energy

Coherent Synchrotron Radiation

Bunch radiates coherently at wavelengths longer than the density modulation



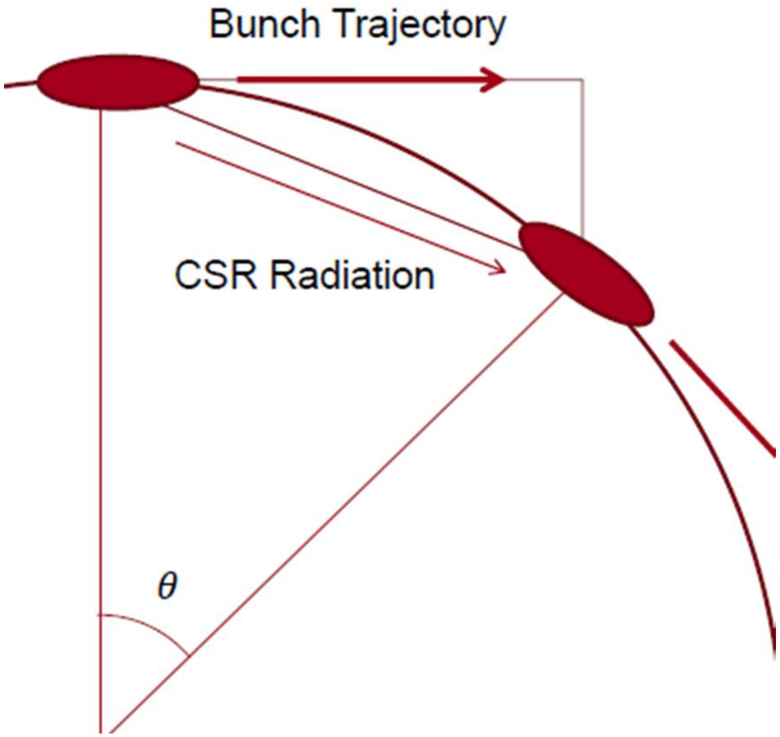
Radiation of a gaussian bunch of 10^{10} e- in a dipole magnet

ISR & CSR In Dipoles

- ISR: Radiation from a beam of e^- radiating **independently** while undergoing uniform circular motion: **Weak.**

- CSR: Radiation from a beam of e^- radiating **in phase** with each other while undergoing uniform circular motion: **Strong**.

  Becomes an issue after bunch compression where:
  - $\lambda \gtrsim \sigma_z$
  - Radiation from tail catches up to head; energy spread:



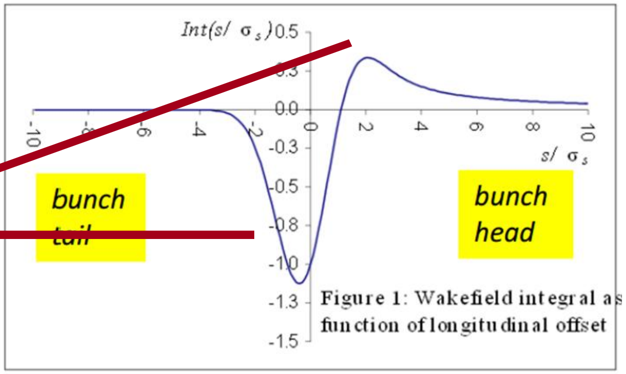


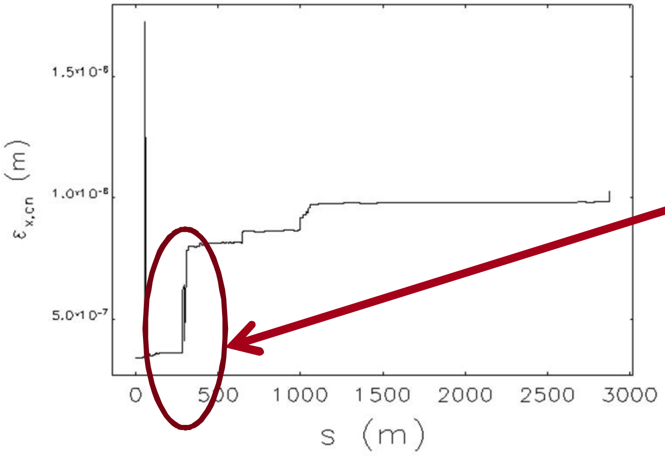
Figure 1: Wakefield integral as function of longitudinal offset

Peaks intensify as σ_z gets smaller!

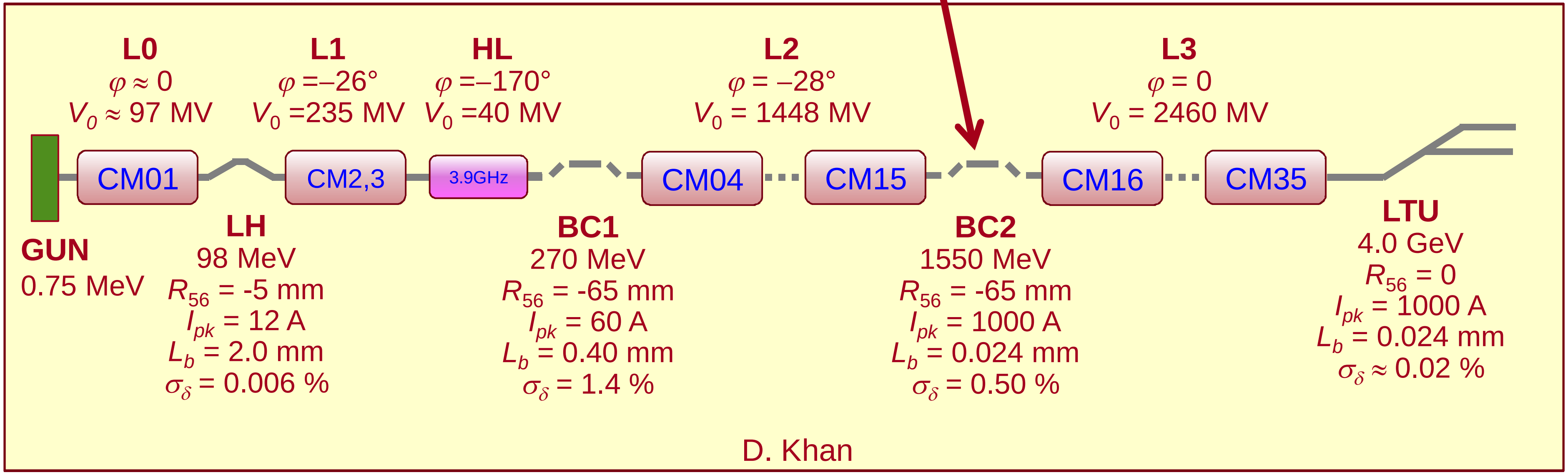
D. Khan

LCLS II Beamline: Area of Interest

- Specific areas of interest: anywhere there is a dipole/bend & where $\lambda \gtrsim \sigma_z$



CSR



L0
$\varphi \approx 0$
$V_0 \approx 97$ MV

L1
$\varphi = -26°$
$V_0 = 235$ MV

HL
$\varphi = -170°$
$V_0 = 40$ MV

L2
$\varphi = -28°$
$V_0 = 1448$ MV

L3
$\varphi = 0$
$V_0 = 2460$ MV

CM01 CM2,3 3.9GHz CM04 CM15 CM16 CM35

GUN
0.75 MeV

LH
98 MeV
R_{56} = -5 mm
I_{pk} = 12 A
L_b = 2.0 mm
σ_δ = 0.006 %

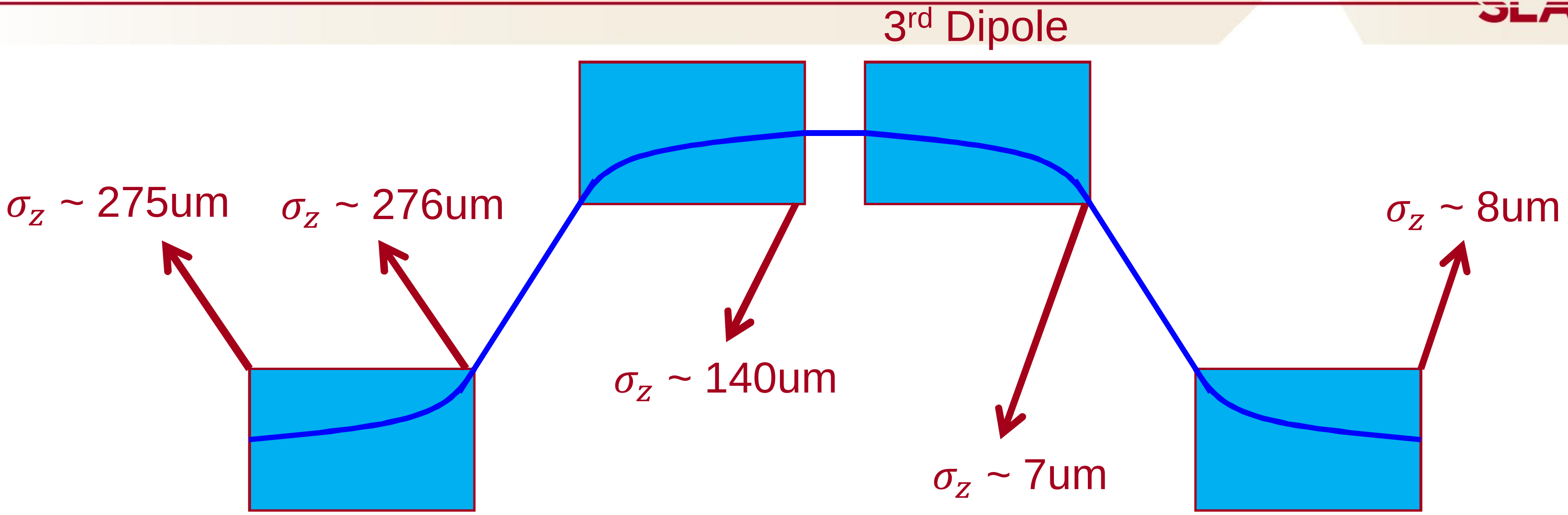
BC1
270 MeV
R_{56} = -65 mm
I_{pk} = 60 A
L_b = 0.40 mm
σ_δ = 1.4 %

BC2
1550 MeV
R_{56} = -65 mm
I_{pk} = 1000 A
L_b = 0.024 mm
σ_δ = 0.50 %

LTU
4.0 GeV
R_{56} = 0
I_{pk} = 1000 A
L_b = 0.024 mm
$\sigma_\delta \approx 0.02$ %

D. Khan

A Closer Look At BC2 From Current LCLS2



3rd Dipole

σ_z ~ 275um

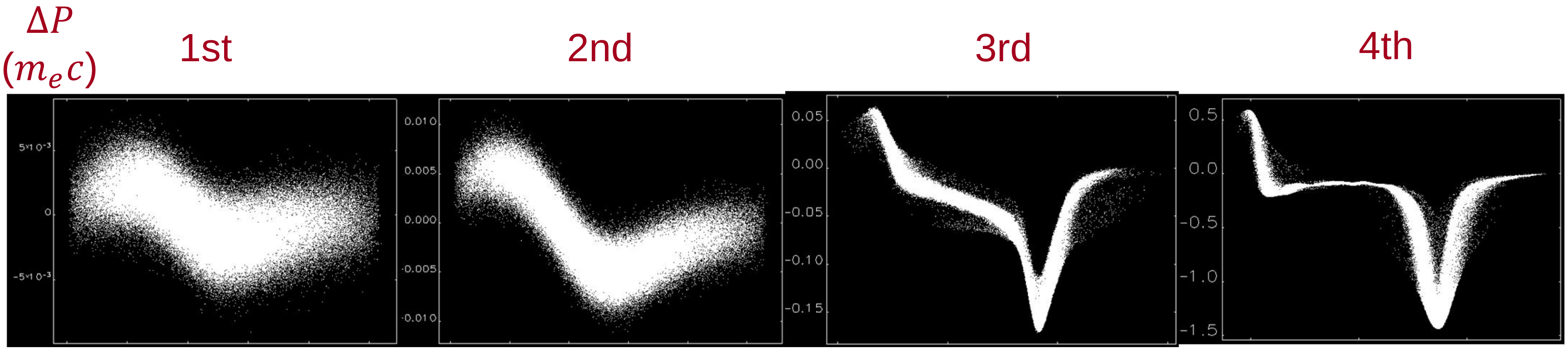
σ_z ~ 276um

σ_z ~ 8um

σ_z ~ 140um

σ_z ~ 7um

The 3rd bend is where the CSR effect really begins to surface (ELEGANT):

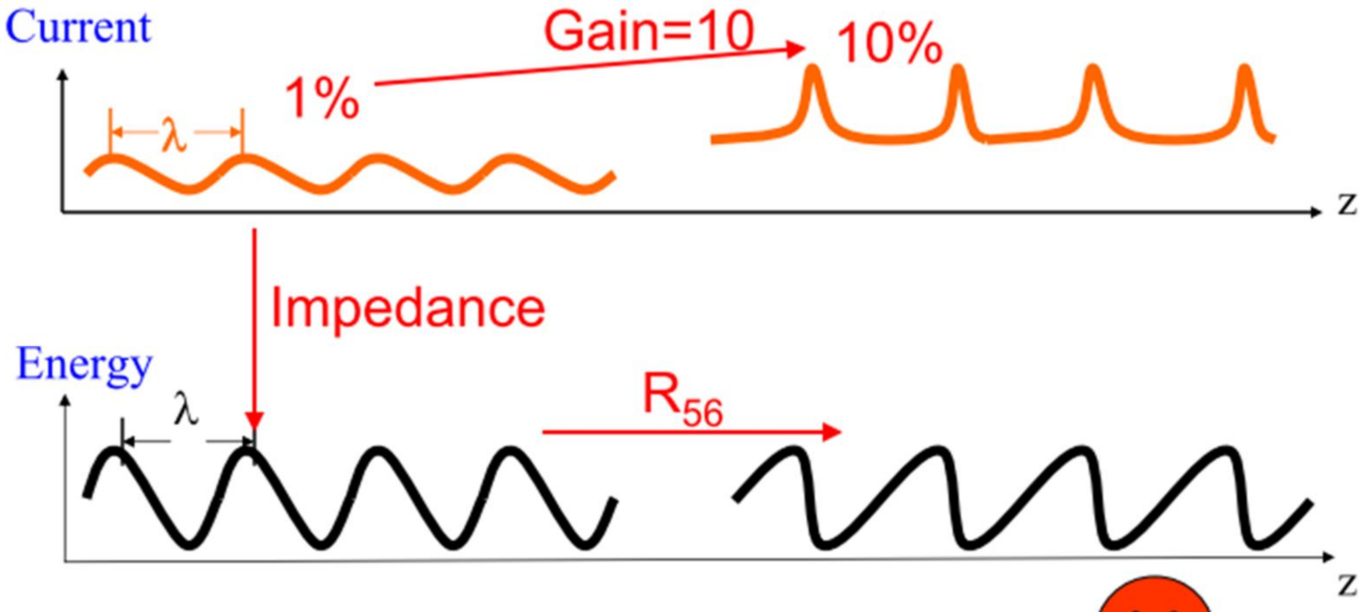


σ_z ~ 276um σ_z ~ 140um D. Khan σ_z ~ 7um σ_z ~ 8um

Density Variations → Microbunching

CSR will also radiate due to density variation along the bunch

→ Leads to energy variation along with density perturbation



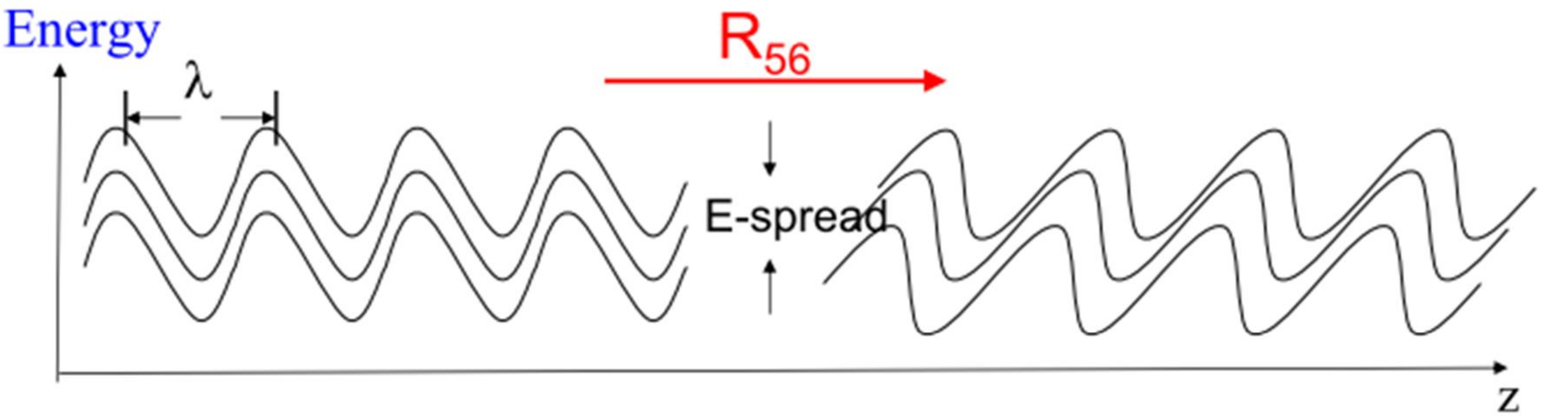
→ growth of slice energy spread (and emittance)

Microbunching Gain

- Gain due to upstream impedances (LSC, linac wake)

$$G \equiv \left|\frac{b_f}{b_0}\right| = \frac{I_0}{\gamma I_A}\left|k_f R_{56}\int_0^L ds Z(k_0;s)\right| \exp\left(-\frac{1}{2}k_f^2 R_{56}^2 \underbrace{\sigma_\delta^2}_{\text{local energy spread}}\right)$$

- No emittance damping!



- All beams have finite incoherent (uncorrelated) energy spread, smearing of microbunching occurs if

$$R_{56}\left(\frac{\Delta E}{E}\right)_{inc} \sim \lambda/(2\pi)$$

Longitudinal Space Charge Force

The longitudinal space charge force is suppressed as $1/\gamma^2$ for wavelengths long compared to the bunch radius in the beam rest frame

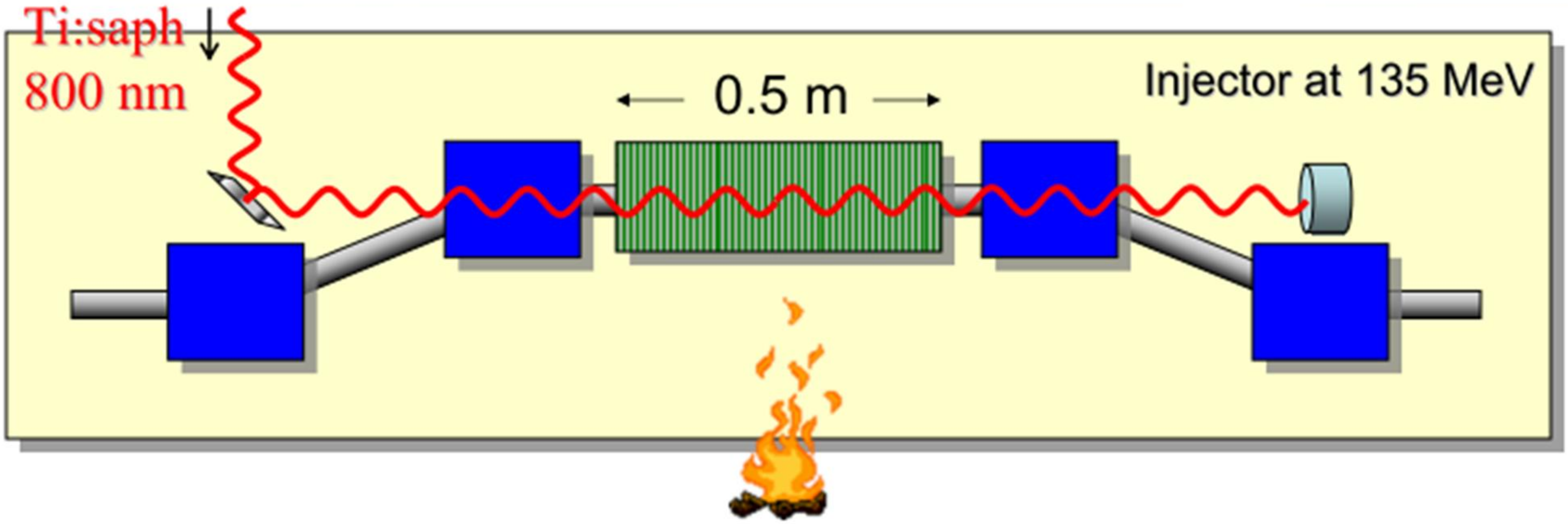
BUT

At wavelengths comparable to the radius, the cancellation is incomplete

→ LSC is the largest impedance source in the long drifts of the LCLS-II

Suppression of Microbunching

Increase beam energy spread



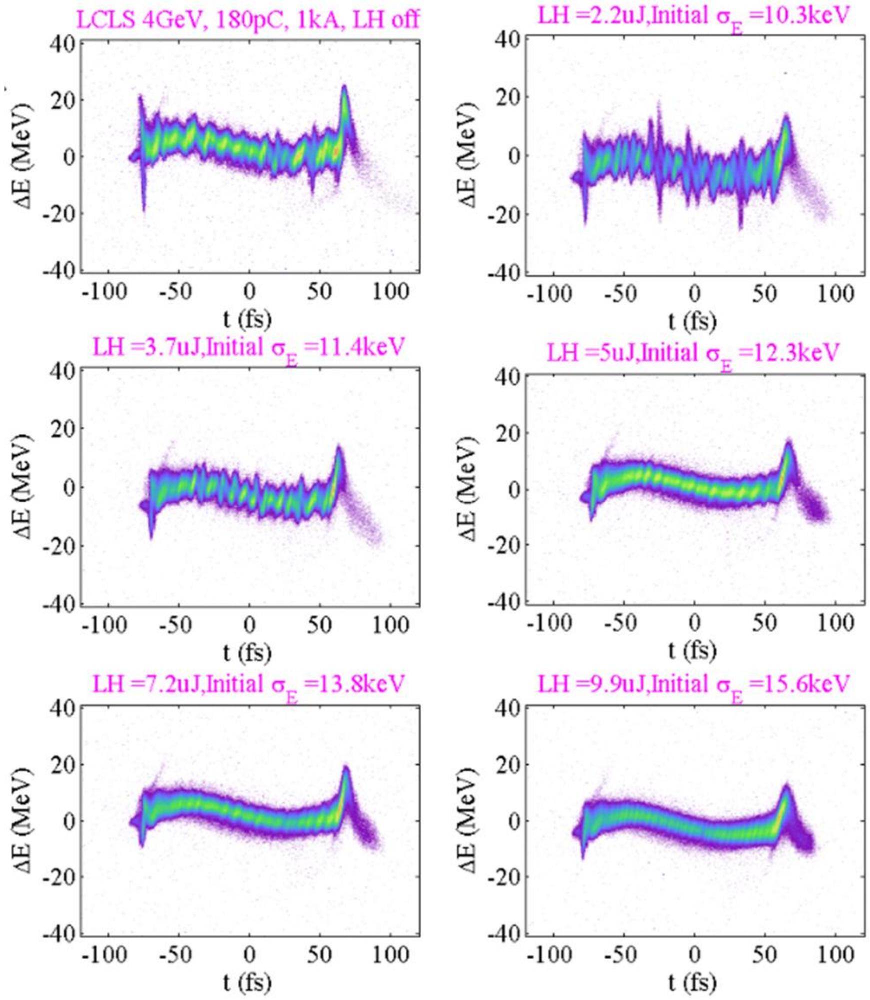
- Laser-electron interaction in an undulator induces rapid energy modulation (at 800 nm), to be used as effective energy spread before BC1 (3 keV→ 40 keV rms)
- Inside a weak chicane for easy laser access, time-coordinate smearing (Emittance growth is negligible)

Huang et al., PRST-AB 7, 2004

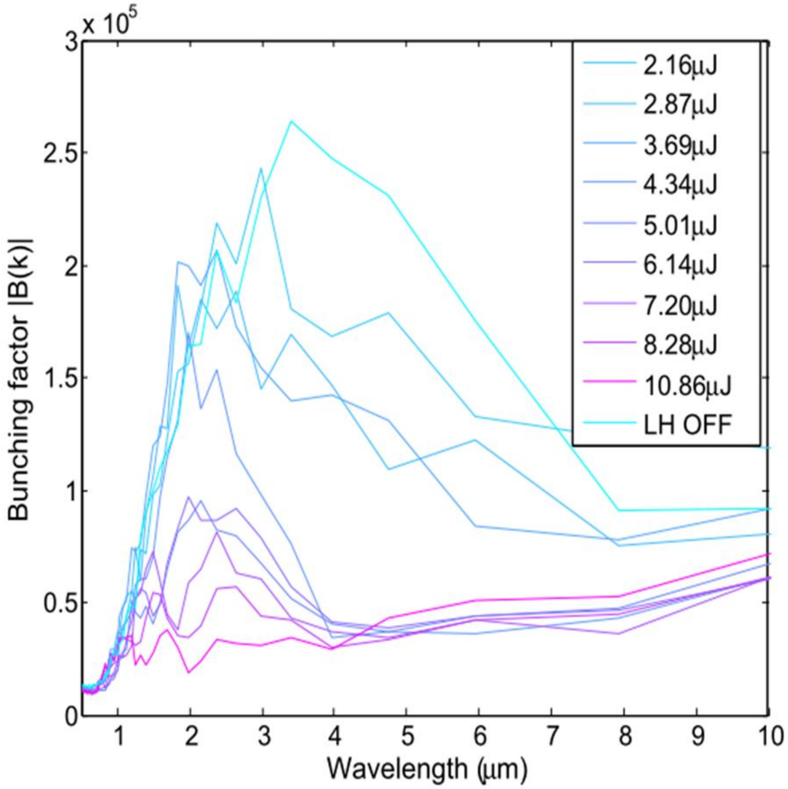
Microbunch Effects in LCLS

LCLS microbunching studies: 4GeV, 180pC, 1kA

Measured final t-p phase space vs laser heater

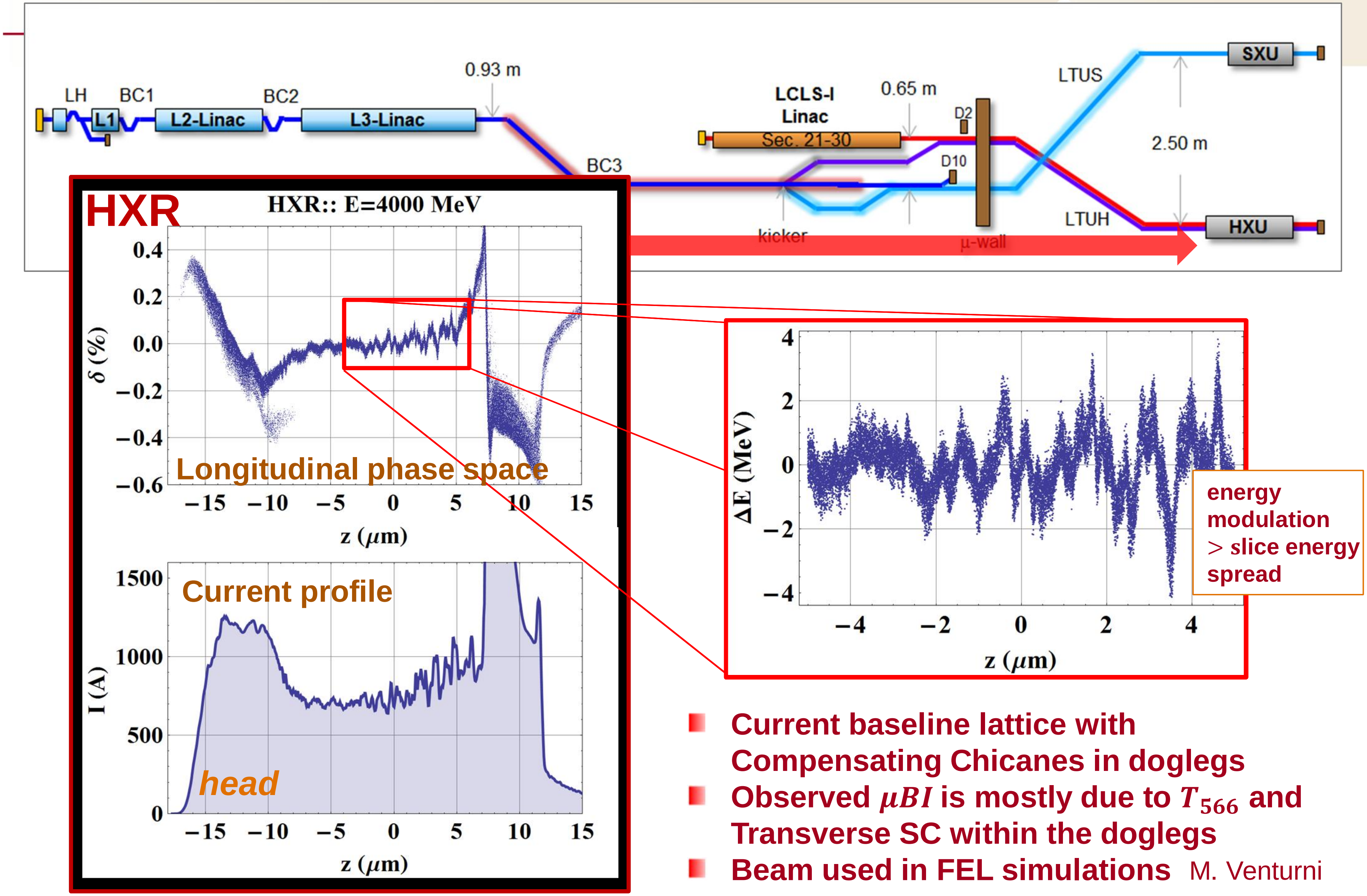


preliminary analysis of bunching factor



(D. Ratner, Y. Ding, et al.)

s2u simulations: 100 pC, LCLS-II HXR



- Current baseline lattice with Compensating Chicanes in doglegs
- Observed μBI is mostly due to T_{566} and Transverse SC within the doglegs
- Beam used in FEL simulations M. Venturni