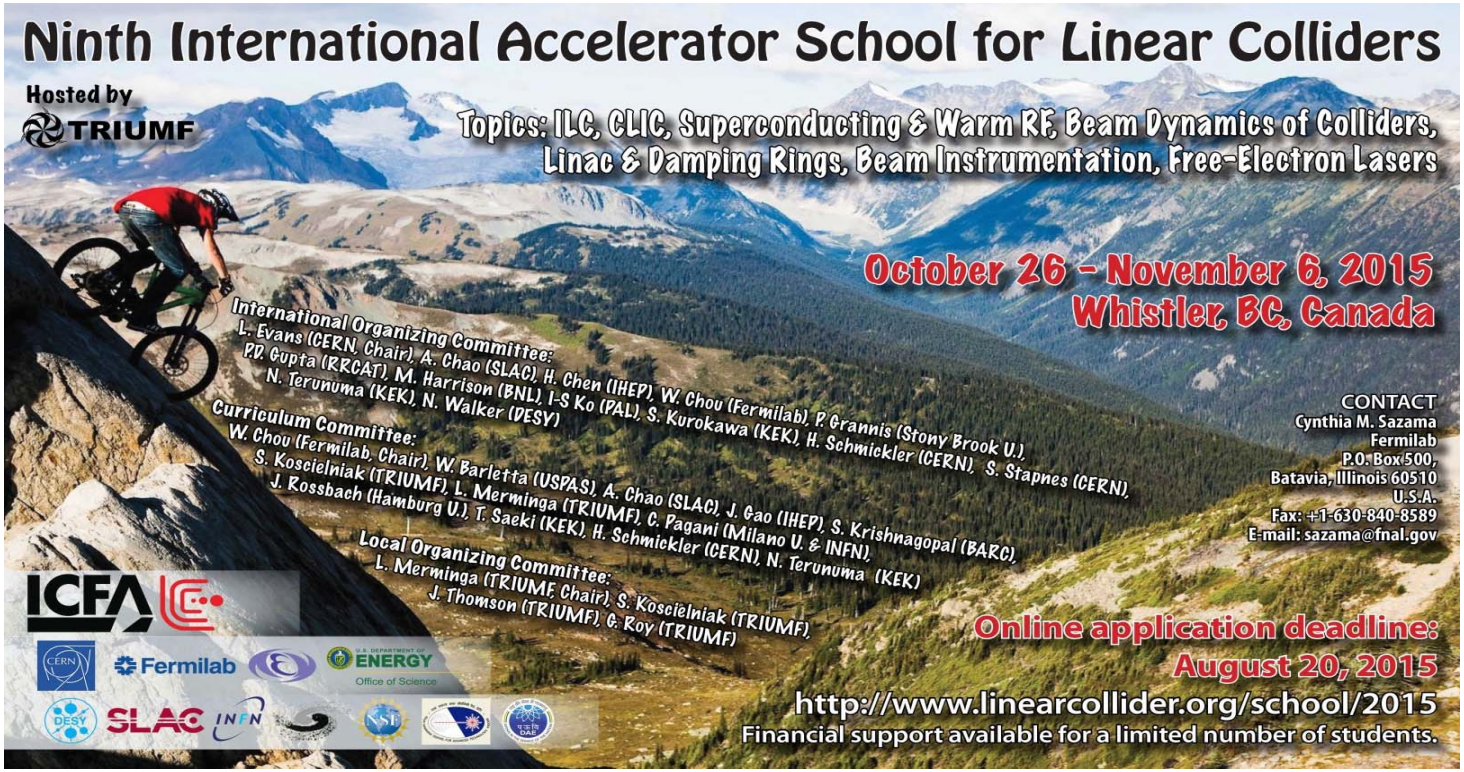


XFEL Beam Physics

10/31/2015

Tor Raubenheimer

STANFORD UNIVERSITY

SLAC NATIONAL ACCELERATOR LABORATORY

Missing

Y. Sun paper PRSTAB 17

FEL dependence on mismatch or projected emittance

Mismatch Distribution

CSR formula – see Emma – AP324

Longitudinal space charge force – see Huang, 2005

Transverse Space Charge

Trickle heating

Topics

LCLS-II introduction

- Will use examples from LCLS-II where relevant

Bunch Compression

- Linear and Nonlinear Optics

Emittance Preservation

- Non-conservative dilutions
- Wakefields and Dispersion

CSR and Space Charge

- Micro-bunching effects

FEL Requirements

Performance is strongly dependent on incoming beam 6D phase space

Want to have high peak current with small transverse emittance and small energy spread.

FEL cares about slice emittance / energy spread → too large ε or $\Delta E/E$ causes particles to slip buckets (page 10 of Panos' slides or Ming Xie fit)

BUT projected emittance matters also → oscillation of beam tail or betatron mismatch of a slice degrades output

Beam Energy Spread and Emittance

For gain, beam energy spread need to be small compared to ρ:

$$\sigma_{\Delta E/E} < \rho \approx \frac{1}{4}\left(\frac{1}{2\pi^2}\frac{I}{I_A}\frac{\lambda_u{}^2}{\beta\gamma\varepsilon}\left(\frac{K}{\gamma}\right)^2\right)^{1/3}$$

Transverse emittance has two effects:

1. Increase the longitudinal slipage.

$$\beta_z \approx 1 - \frac{1+K^2/2}{2\gamma^2} - \frac{J_x}{\beta_x} - \frac{J_y}{\beta_y} \Rightarrow \left.\frac{\Delta\gamma}{\gamma}\right|_{eff} \approx \gamma\varepsilon\frac{\gamma}{\beta_{x,y}(1+K^2/2)}$$

   where β_x and β_y are the accelerator optical functions NOT velocity and J_x and J_y are the particle transverse amplitudes

2. Match the e- beam to the radiation size and minimize diffraction

$$\Rightarrow \gamma\varepsilon < \frac{\gamma\lambda}{4\pi}$$ want similar Rayleigh and betatron lengths

FEL Beam Physics Challenge

FEL performance is strongly dependent on incoming beam 6D phase space

Higher phase space density → shorter gain length

Typical X-ray FEL parameters:

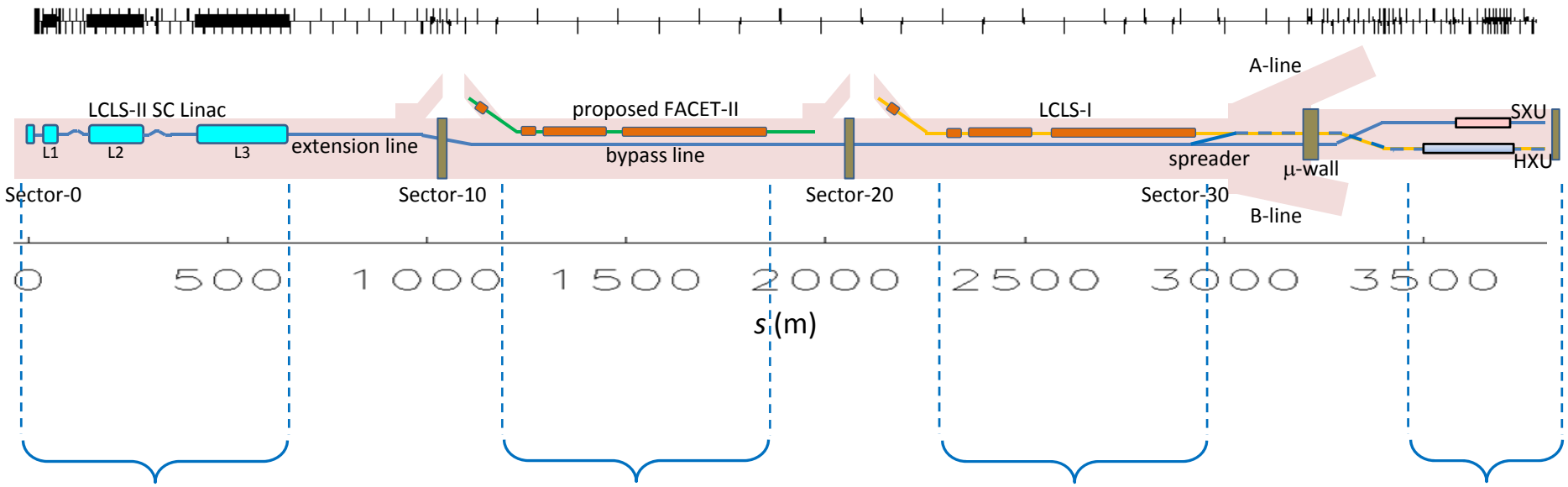
$\gamma\varepsilon_{x,y}$ < 1 um; I > 1 kA; N ~ 100 pC; $\sigma_{\Delta E/E}$ < 0.1%; E > few GeV

Challenge:

Compress beam by factors of ~100 from injector to increase peak current while preserving high phase space density.

LCLS-II Layout in SLAC Linac Tunnel

(only approximately to scale)



New SCRF Linac (4 GeV)

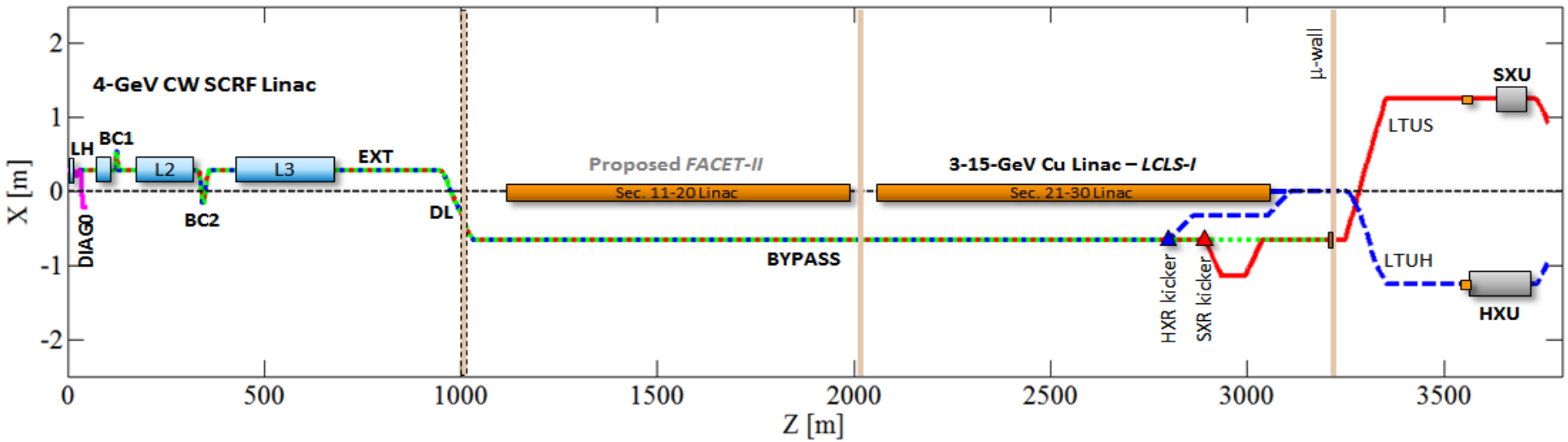
Proposed FACET-II and Bypass Line

Existing LCLS-I

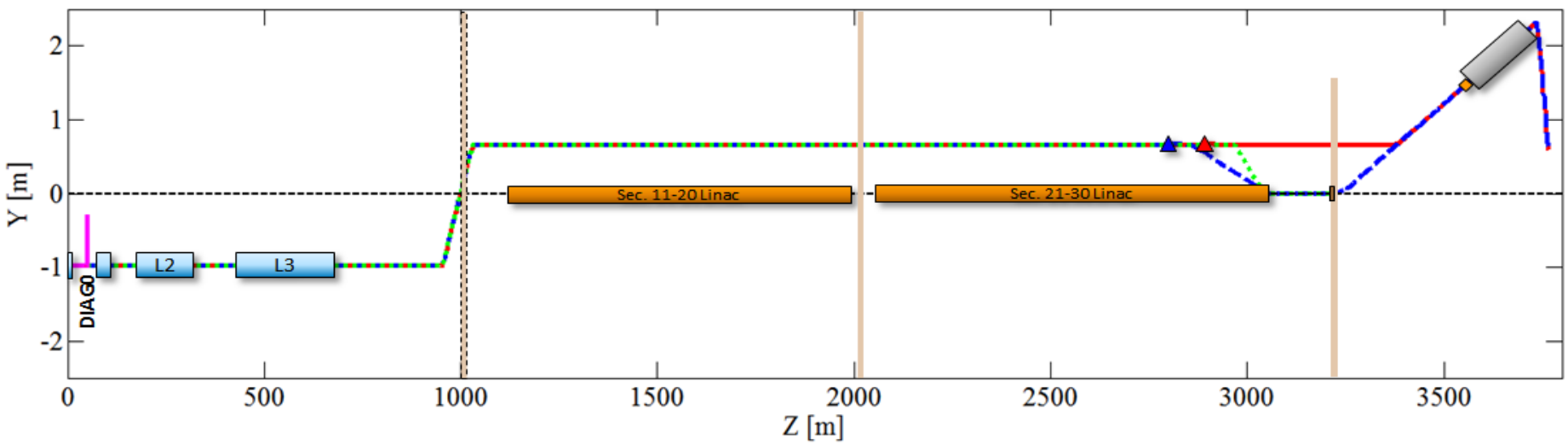
Undulators (LCLS-I & -II)

What is beam frame view of LCLS-II?

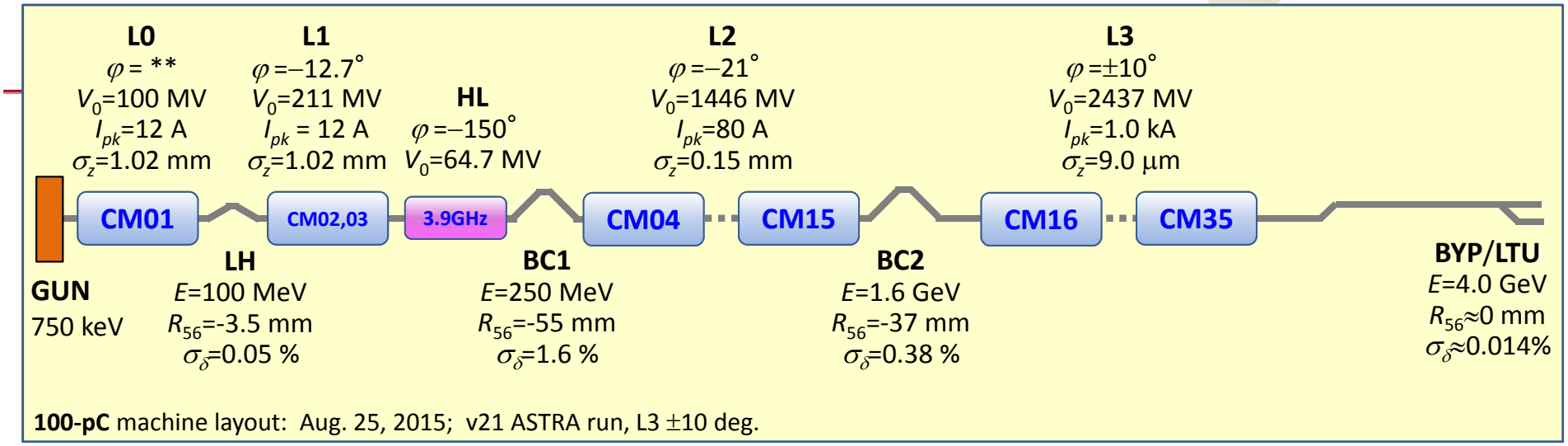
LCLS-II Scaled Layout (01OCT15 design)



blue-dash=***HXR***, **red**-solid=***SXR***, **green**-dot=***BSY-Dump***, ***magenta***=***DIAG0***



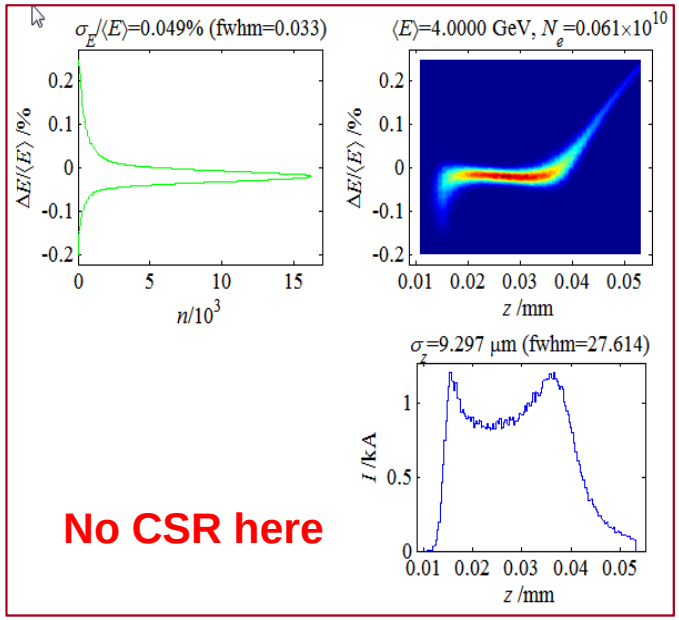
Linac RF and Compression



Linac Sec.	V_0 (MV)	φ (deg)	Acc. Grad.* (MV/m)	No. Cryo Mod's	No. Avail. Cav's	Spare Cav's	Cav's per Amp.
L0	100	**	16.3	1	8	0	1
L1	211	-12.7	13.6	2	16	1	1
HL	-64.7	-150	13.4	2	16	2	1
L2	1446	-21.0	15.5	12	96	6	1
L3	2437	±10	15.7	20	160	10	1

* Nom. crest grads. averaged over powered cavities (worst phasing requires 16 MV/m)
** L0 cav. phases: ~(–4.0°, 0, 0, 0, 0, 0, 1.25°, 3.0°), with cav-1 at 50%, cav-2 & -3 off.

Includes 2.5-km RW-wakes



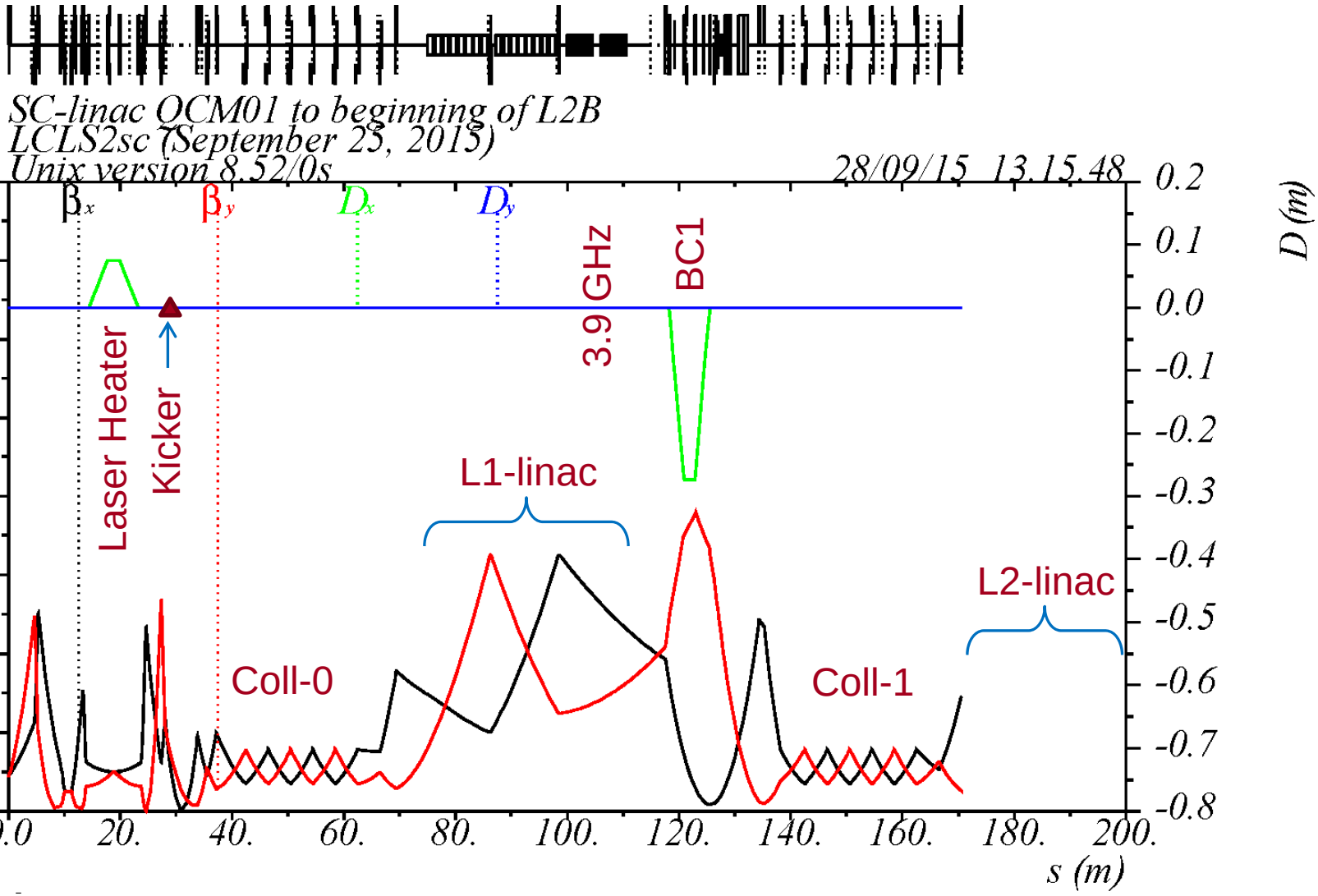
Electron Parameters (100 pC nominal)

Electron Beam Parameters	symbol	nominal	range	units
Final electron energy (operational)	E_f	**4.0**	2.0-4.5 [a]	GeV
Max. upgrade energy (or if reduced duty factor) [b]	E_{max}	**7.5**	-	GeV
Electron bunch charge (limited by beam power)	Q_b	**0.10**	0.01-0.3	nC
Max. bunch repetition rate in linac (CW) [c]	f_b	**0.62**	0-0.93	MHz
Average electron current in linac	I_{av}	**0.062**	0-0.3 [d]	mA
Average electron beam power at linac end (limit)	P_{av}	**0.25**	0-1.2 [e]	MW
Norm. rms transverse slice emittance at undulator	$\gamma\varepsilon_{\perp\text{-}s}$	**0.45**	0.2-0.7 [f]	μm
Final peak current (at undulator)	I_{pk}	**1000**	500-1500	A
Final rms bunch length (at undulator)	σ_{zf}	**8.3**	0.6-52	μm
Final estimated useable bunch duration (FWHM)	$\Delta\tau_f/\tau_f$	**50**	-	%
Total magnetic compression (cathode to undulator)	C_T	**85**	25-150	-
Final slice energy spread (rms, with heater)	σ_{Es}	**500**	125-1500	keV
Estimated RMS Beam Stability Goals:				
Relative rms electron energy stability (at und.)	$(\Delta E/E_f)_{rms}$	< **0.01**	-	%
Relative rms peak current stability (at und.)	$(\Delta I/I_{pk})_{rms}$	< **5**	-	%
Bunch arrival time stability (rms, at und.)	$(\Delta t_b)_{rms}$	< **20**	-	fs
Transverse centroid stability (rms, at und., 100 pC)	$\Delta x_{rms}/\sigma_x$	< **10** [g]	-	%

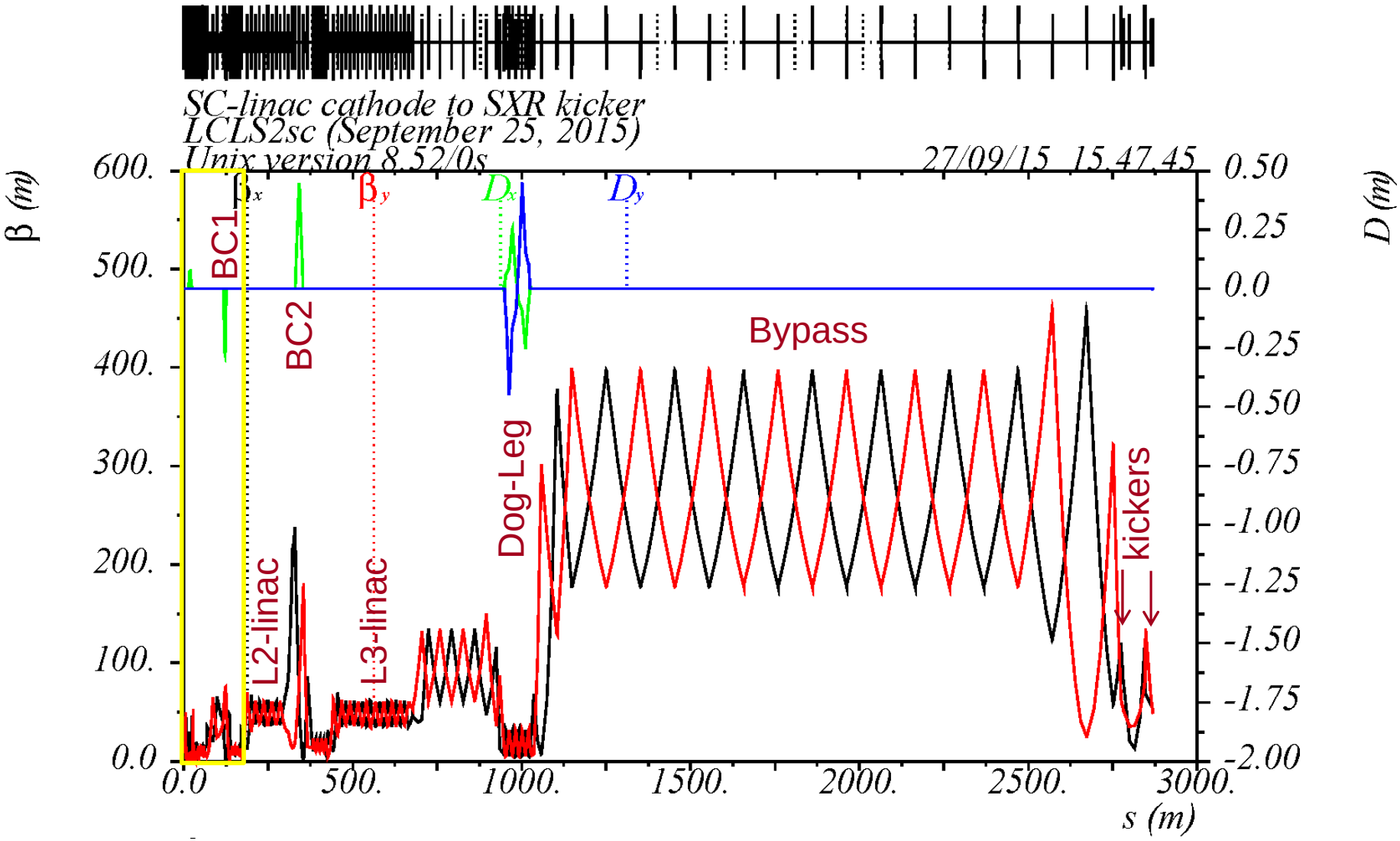
Nominal charge is 100 pC, but we also have configurations for 20 pC and 300 pC

Rate must change to limit e^- main-dump power to < 120 kW

SC-Linac: CM01-exit to L2 Start



SCRF-Linac: Cathode to SXR & HXR Kickers



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

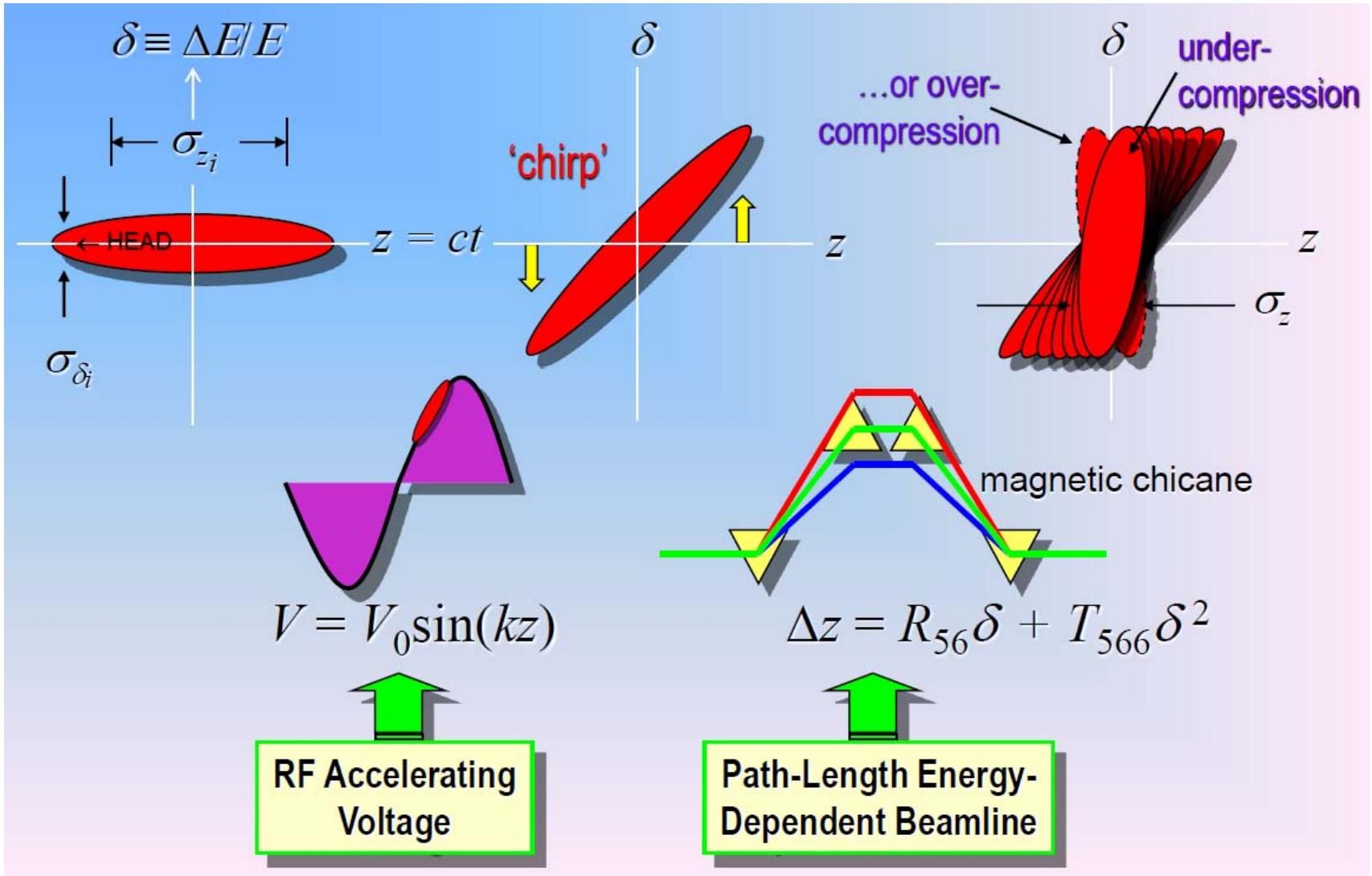
Path length variation

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

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

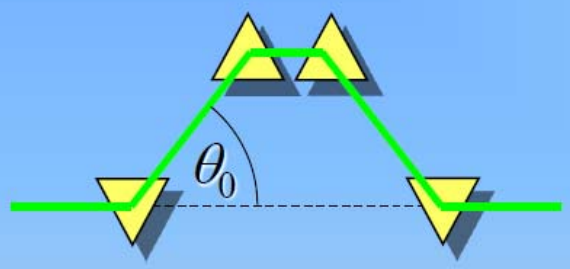
Longitudinal Motion (γ >> 1)

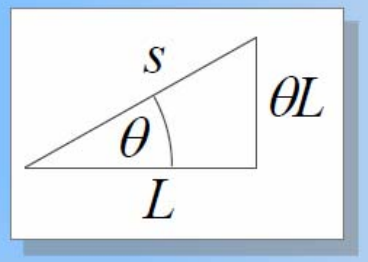
Bunch Rotation



Magnetic Chicane – Path Length

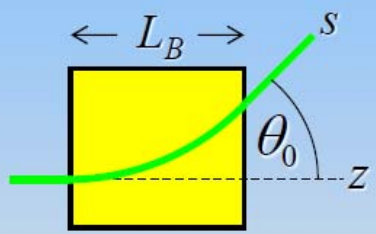
A 4-bend magnetic chicane introduces a path length increase depending on bend angle, θ, where $|\theta| << 1$ and $\gamma >> 1$.





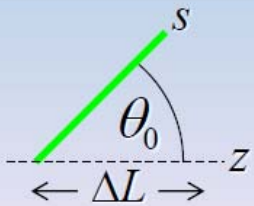
$$s = \sqrt{L^2 + (L\theta)^2}$$
$$\approx L\left(1 + \tfrac{1}{2}\theta^2\right)$$
$$ds = \tfrac{1}{2}\theta^2(z)dz$$

1) One bend magnet



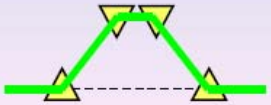
$$\theta(z) = \frac{z}{L_B}\theta_0$$
$$\Delta s_1 \approx \frac{\theta_0^2}{2L_B^2}\int_0^{L_B} z^2 dz = \frac{1}{6}\theta_0^2 L_B$$

2) Drift between bends



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

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, $\delta = \Delta E / E_0$

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

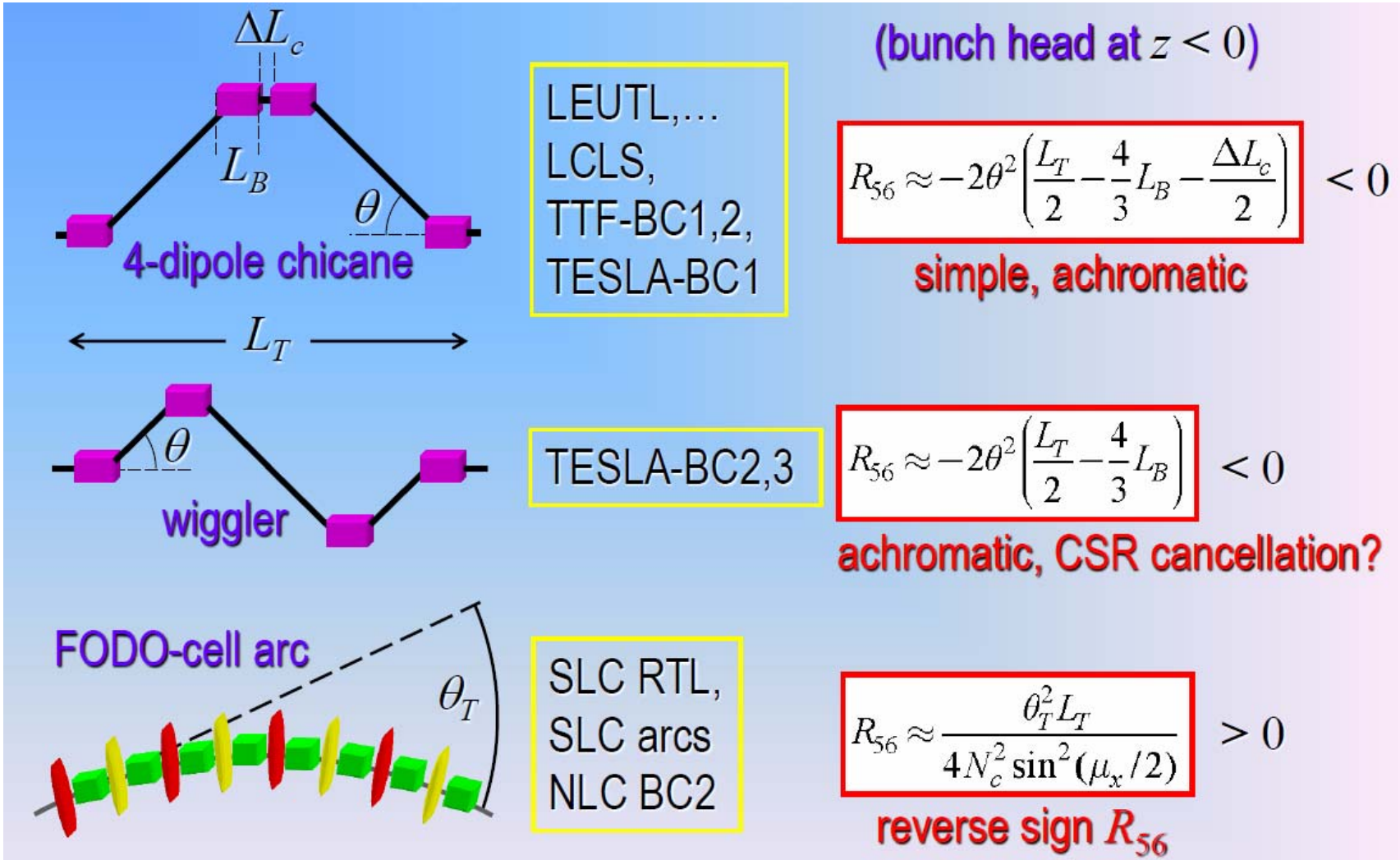
$$\approx \theta_0^2 \left(\Delta L + \tfrac{2}{3} L_B\right) \left(1 - 2\delta + 3\delta^2 - \ldots\right)$$

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

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

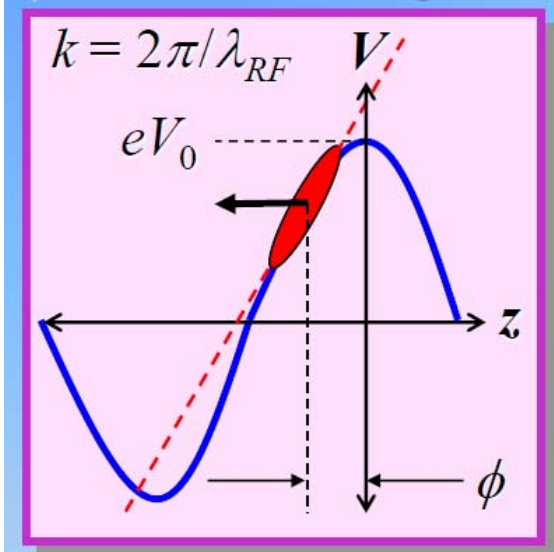
$$T_{566} \approx -\tfrac{3}{2} R_{56}$$ 2nd-order energy term (chicane only)

Types of Path Length Compressors



Linear Bunch Compressor

$\phi = 0$ at accelerating crest



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

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

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

$$\left(\text{with } a \equiv \frac{E_i}{E_0} \leq 1, \text{and } |kz_i| \ll 1\right)$$

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

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)

SLAC

Write bunch length coordinate after compressor to 2nd order …

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

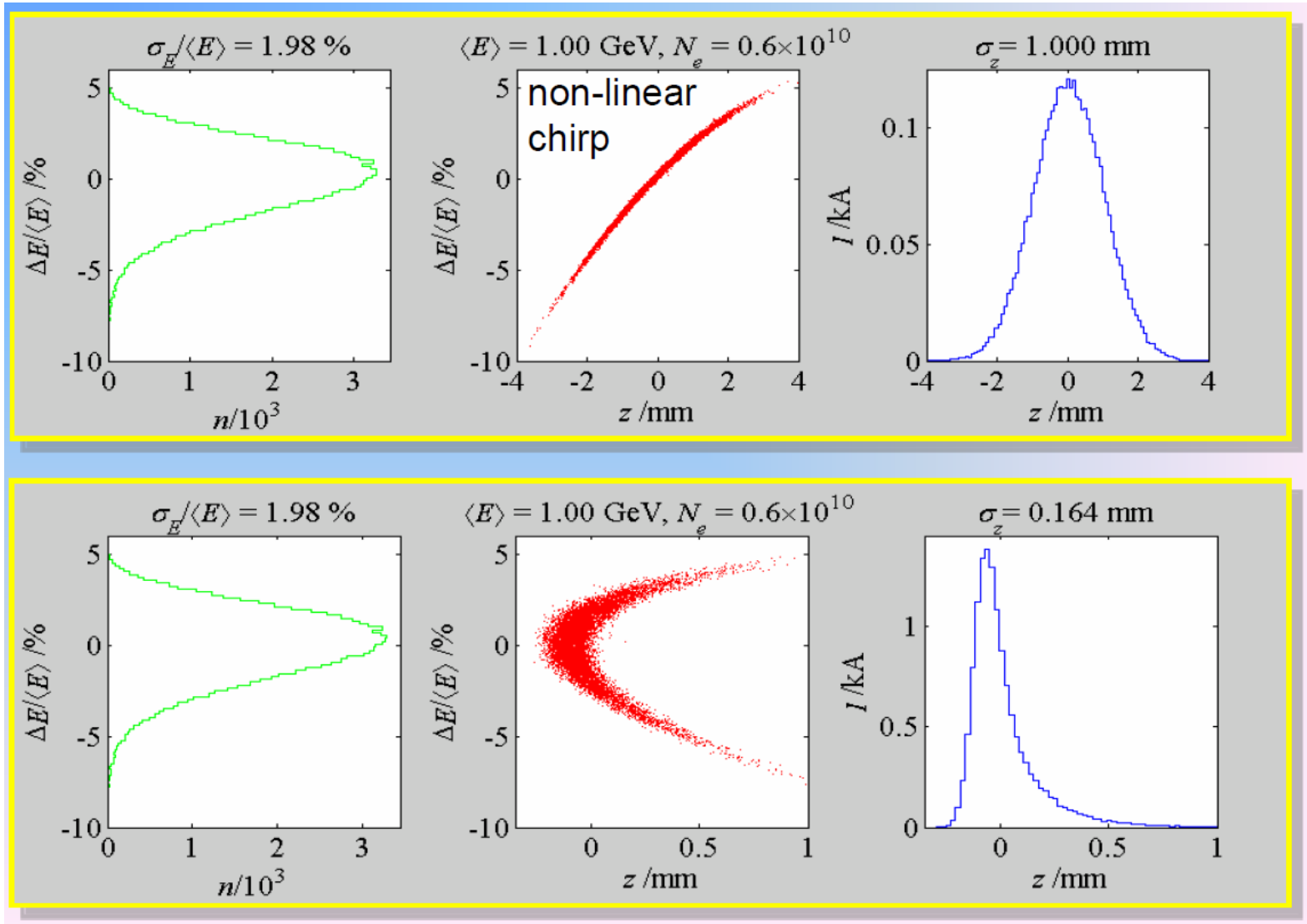
Now add 2nd order term of sinusoidal rf accelerating voltage...

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

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…

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

Longitudinal Nonlinear Effects



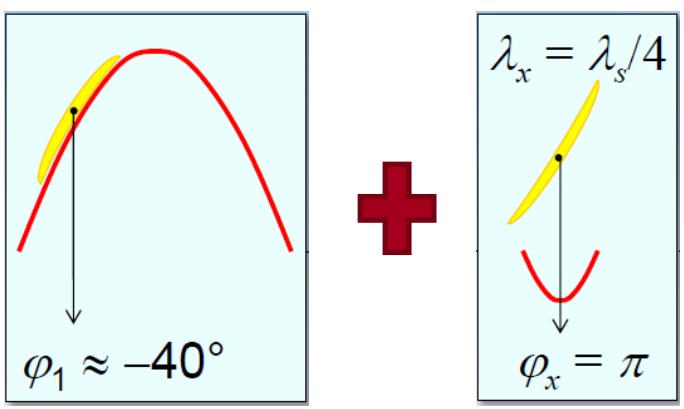
2nd-order Compensation

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

Paul Emma

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

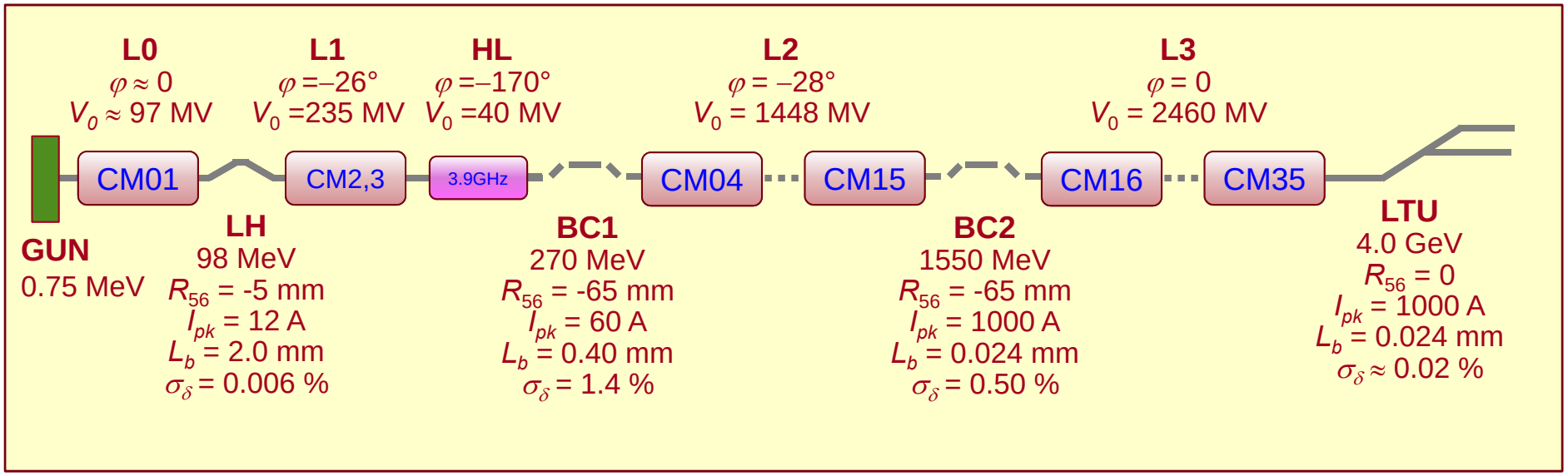


Linearize Compressed Bunch

Homework

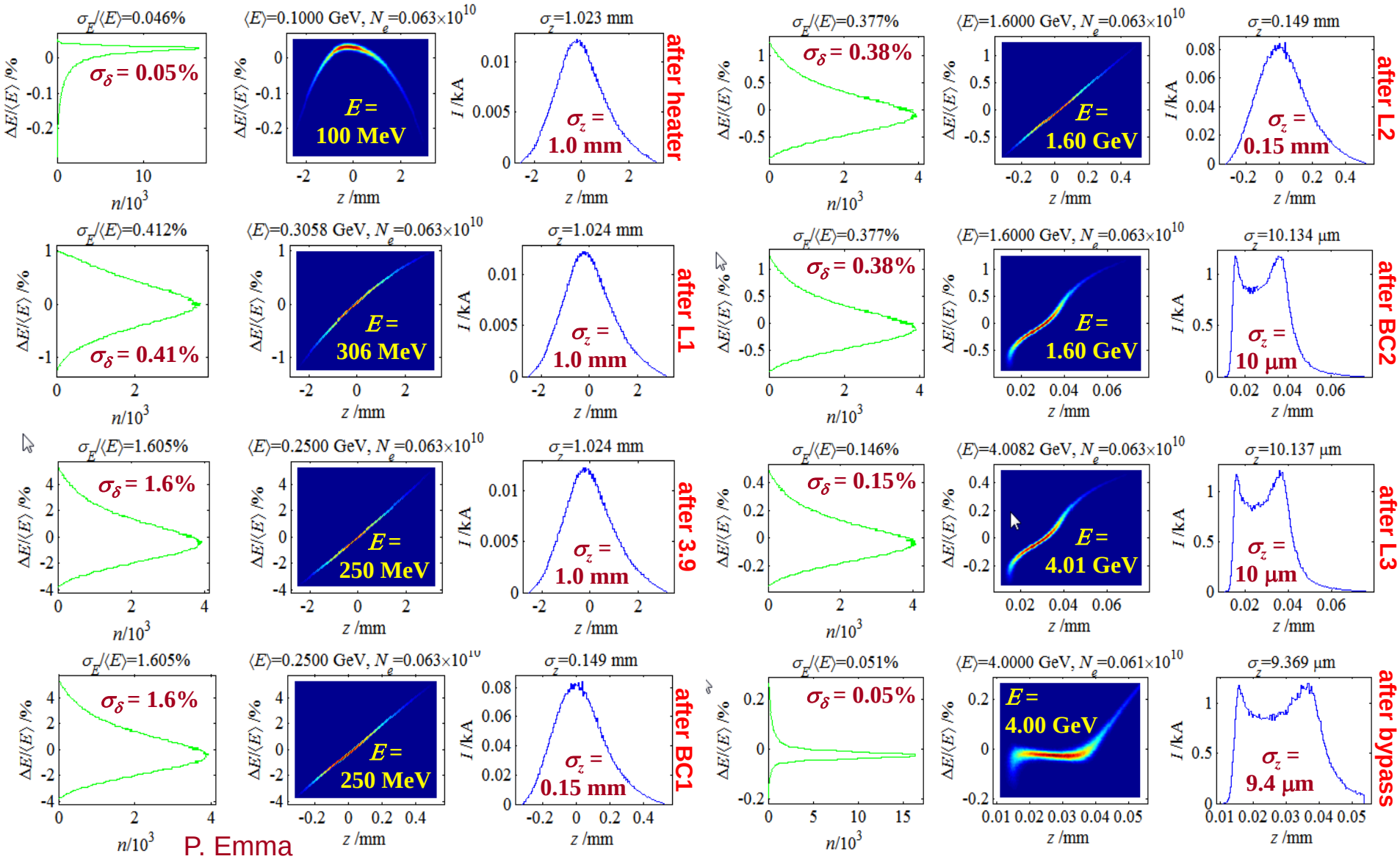
LCLS-II Bunch Compressor Configuration

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



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

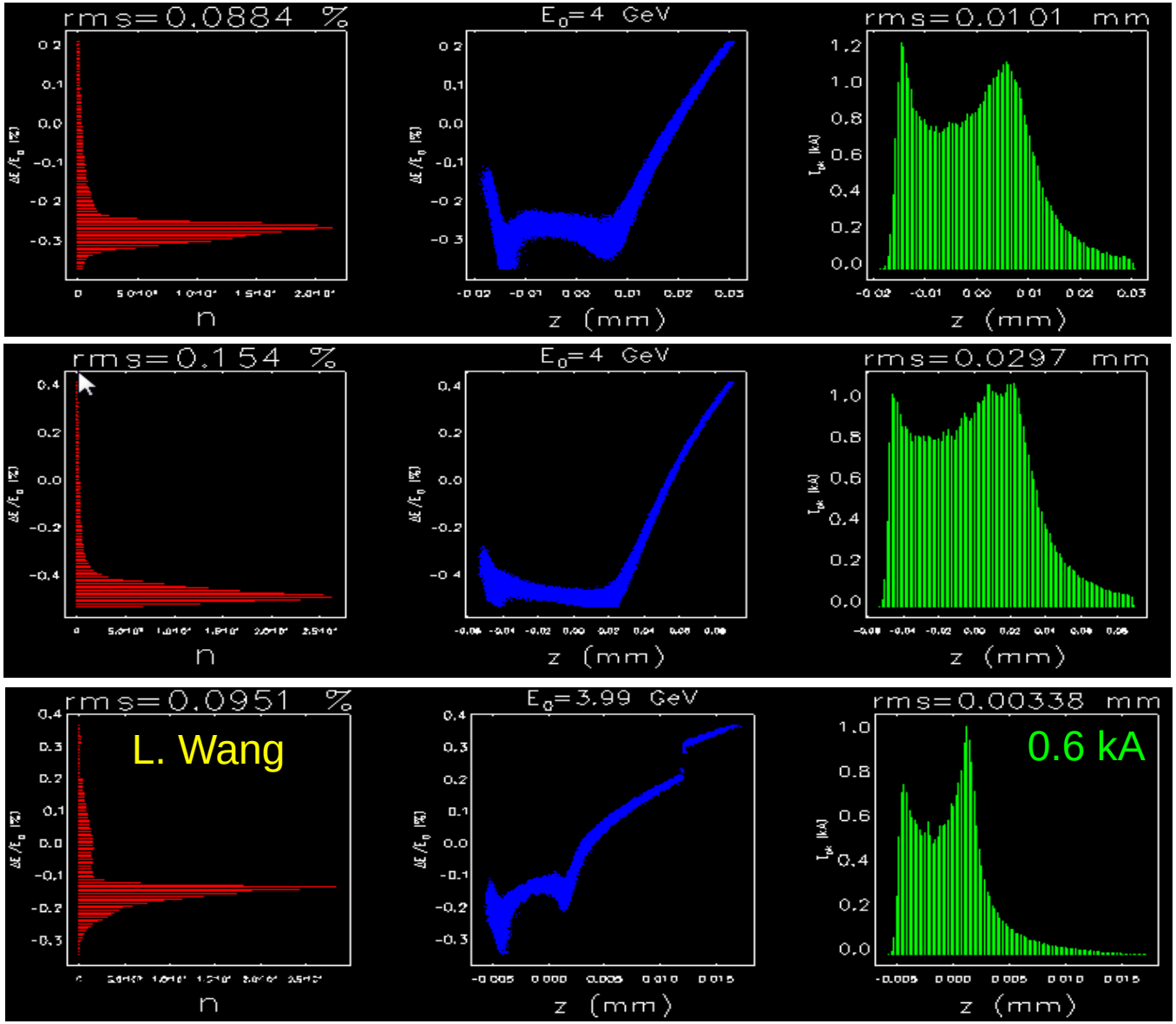
Evolution of the LCLS-II Bunch Along the Linac



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

Emittance Dilutions

Injector works very hard to make small emittance and the FEL needs bright beams → better not screw it up

Non-Conservative dilutions – increase 6D ε

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

Conservative dilutions – increase projected ε

- Transverse wakefields – couple x,y to z position
- Dispersion/chromaticity – couple x,y to δ energy offset
- Betatron coupling – couple x and y – insignificant with round beams
- Nonlinearities – wrap phase space around
- Space charge – combination of linear and nonlinear forces

Incoherent Synchrotron Radiation

Incoherent SR will lead to emittance growth when passing through bending magnets, chicanes, doglegs, ... Usually relatively easy to minimize but strong function of energy.

$$\Delta\gamma\varepsilon \approx 4 \times 10^{-8} E^6 \int ds \frac{\mathcal{H}}{\rho^3} \quad [m^2 GeV^{-6}]$$

Energy spread and damping terms are usually much smaller.

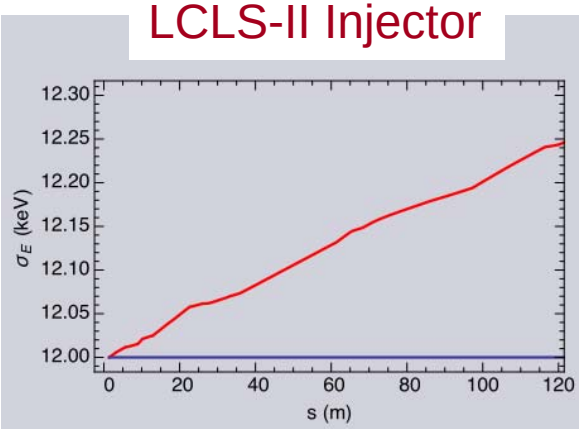
Intrabeam Scattering

The high brightness beams for the FEL are intrinsically dense and they have anisotropic temperature distribution (in beam frame) with

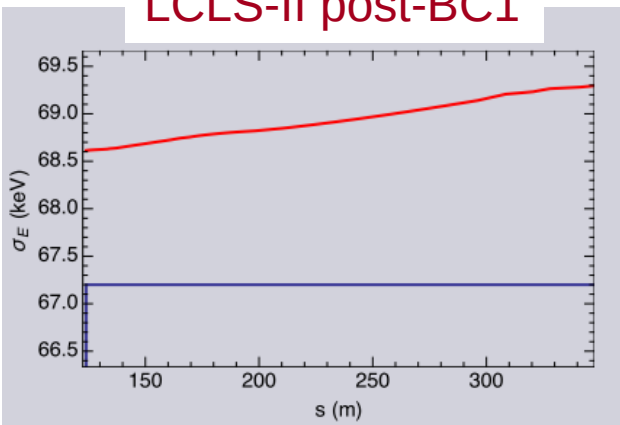
$T_{||} << T_x, T_y << mc^2$ → scattering increases $\sigma_{\Delta E/E}$

$$\frac{d\sigma_{\Delta E}^{\ 2}(s)}{ds} \approx \frac{\pi^{1/2}\Lambda\,(m_e c^2)^2 r_e}{2\gamma\left(\sigma_{\Theta x}\sigma_{\Theta y}\right)^{1/2}\left(\sigma_x\sigma_y\right)}\frac{I(s)}{I_A} \sim \frac{I(s)}{\gamma(\gamma\varepsilon)^{3/2}}$$

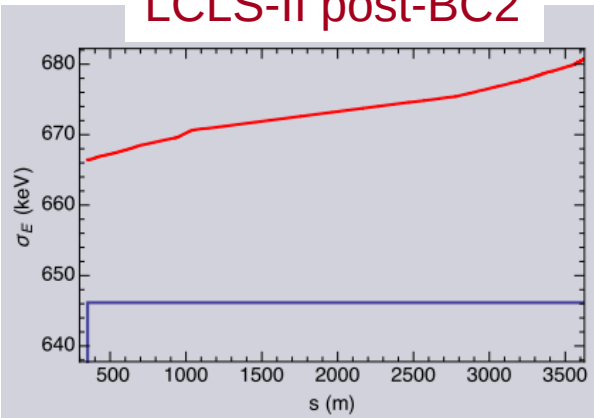
LCLS-II Injector



LCLS-II post-BC1



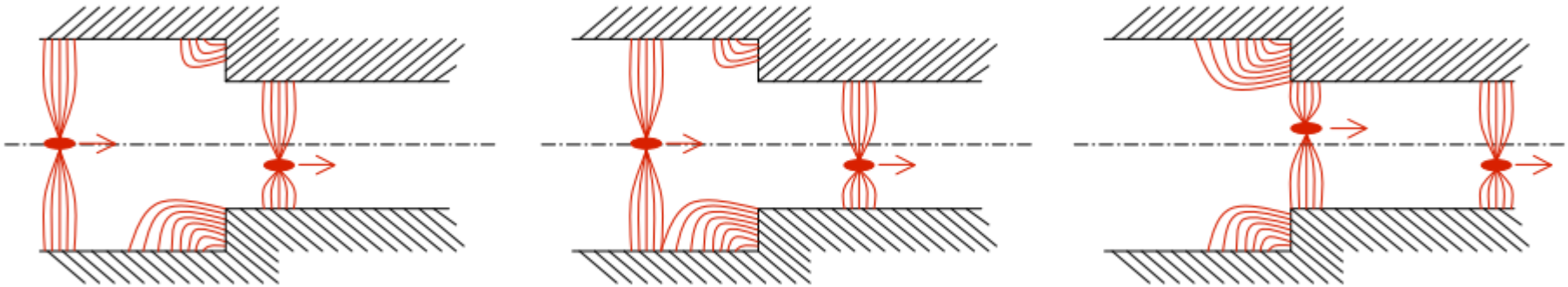
LCLS-II post-BC2



See: G. Stupakov, Effect of Coulomb collisions on Echo-Enabled Harmonic Generation, FEL 2011 or LCLS-II-TN-15-37 (2015).

Wakefields

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



W. Barletta

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

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

Wakefields – Modal Representation

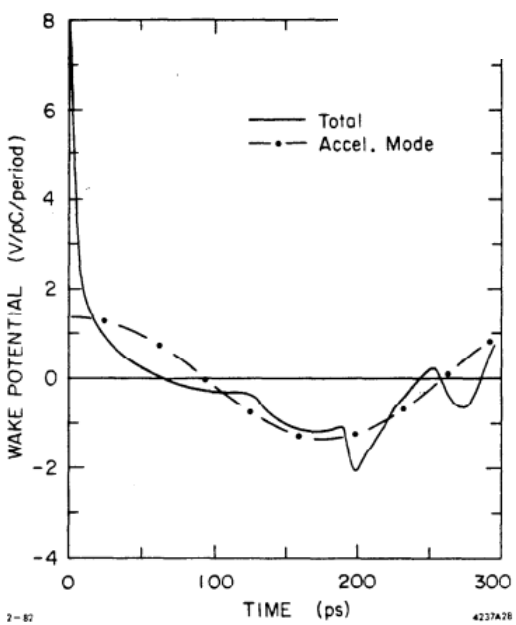
Beam is traveling near speed of light but beam will excite fundemental and higher-order modes in the cavity

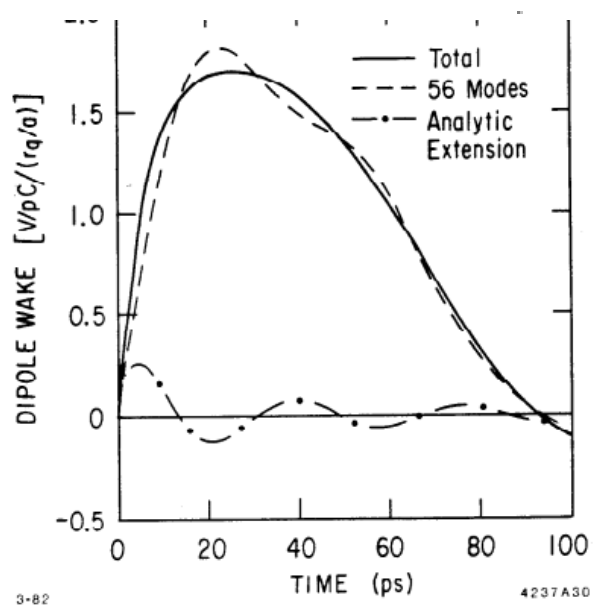
$$W_z \simeq \sum_n 2k_{0n}(a)\cos\frac{\omega_{0n}s}{c} \qquad s > 0$$

Monopole modes

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

Dipole modes





A leading particle leaves a field that impacts trailing particles

Suggestion: look up the Panofsky-Wenzel Theorem

P.B. Wilson, SLAC-PUB-2884 (1982)

Short Range Wakes

Longitudinal and transverse short-range wakes can be approximated as:

$$W_{\parallel}(z) \approx \frac{Z_0 c}{\pi a^2} \exp\left(-\sqrt{\frac{z}{s_0}}\right) \quad \text{and} \quad W_{\perp}(z) \approx \frac{2 Z_0 c}{\pi a^4} s$$

where s_0 depends on detailed accelerator structure parameters but scales as a^2 / p where a is the iris radius and p is the iris spacing. In the SLAC S-band structure s_0 is ~1.4 mm and is ~2.3 mm in the TESLA 1.3 GHz cavities.

The longitudinal wake falls rapidly with distance while the transverse increases roughly linearly.

Many papers through 90's an 2000's.
For example: K.L.F. Bane, et al,EPAC'98 (1998);
F. Zimmermann, Phys. Rev. E 57, 7146 (1998);
G. Stupakov, et al, Phys. Rev. ST Accel. Beams **18**, 034402

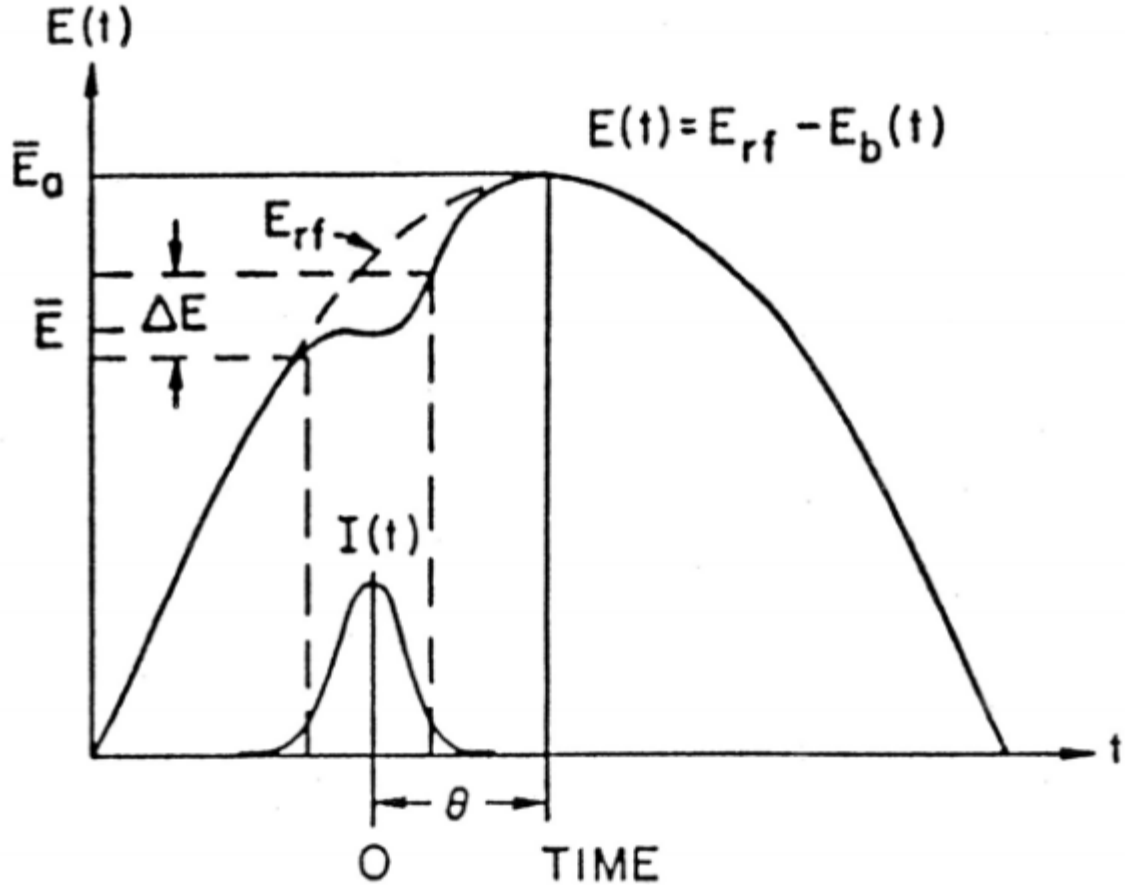
Longitudual Wakefield Compensation

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

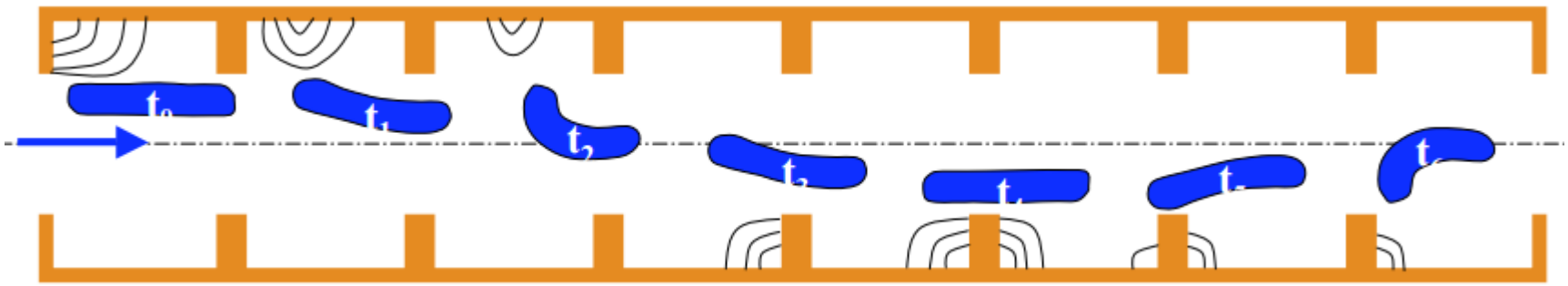
Homework



Transverse Wakefields

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

A. W. Chao, B. Richter, C. Y. Yao, SLAC-PUB-2561 (1980).



W. Barletta

There is no 6D emittance dilution but a strong nonlinear coupling between x and z that increases the projected emittance. Fortunately, this is less of a challenge for short bunches. Tolerances start to become challenging at high rf frequency (X-band-based) FEL's.

Y. Sun, et al, PRSTAB, 17,110703 (2014).

Resistive Wall Wakefield

Resistive wall wakefield is important due to non-linearity: where s0 depends on the conductivity: $s_0 = (2a^2/Z_0\sigma_c)^{1/3}$ assuming constant conductivity.

$$W_\delta(s) = \frac{Z_0 c}{\pi a^2}\left(\frac{1}{3}e^{-s/s_0}\cos\frac{\sqrt{3}s}{s_0} - \frac{\sqrt{2}}{\pi}\int_0^\infty dx\frac{x^2 e^{-sx^2/s_0}}{x^6+8}\right)$$

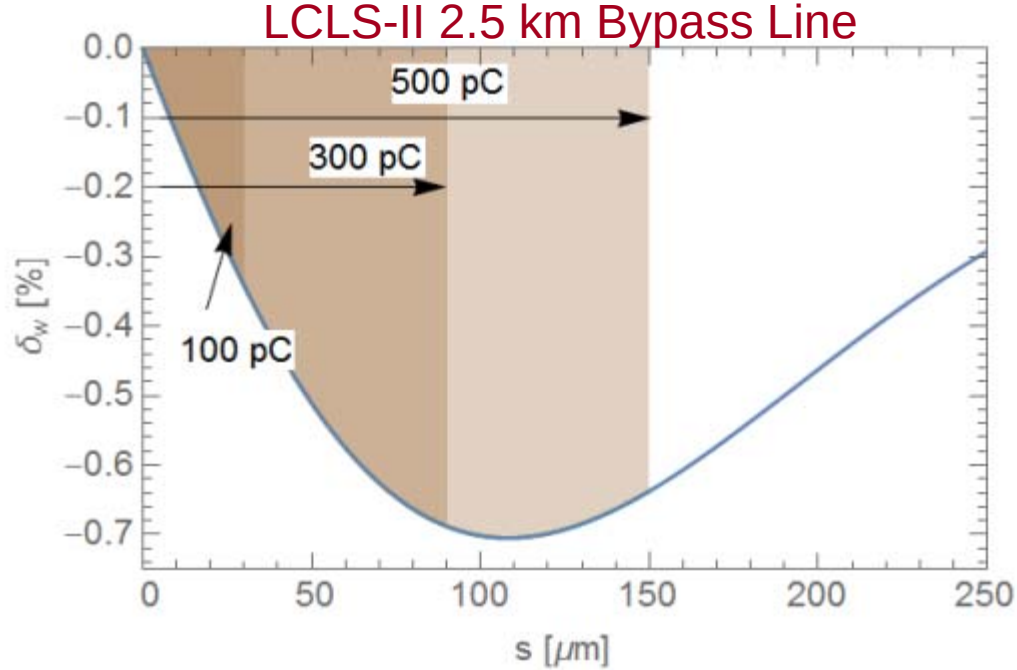
K. Bane, et al, LCLS-II-TN-15-09 (2015).

AC conductivity will change the result slightly. Anomalous skin effect is an impact at low T.

Transverse effects scale as $Z_0 cs/\pi a^4$.

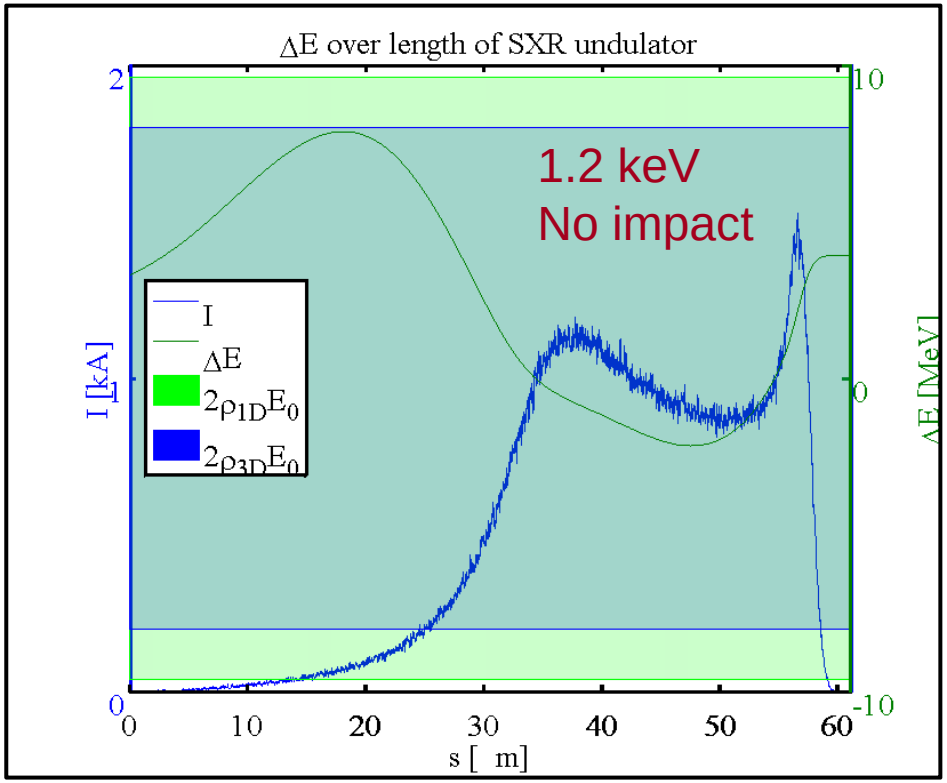
Homework

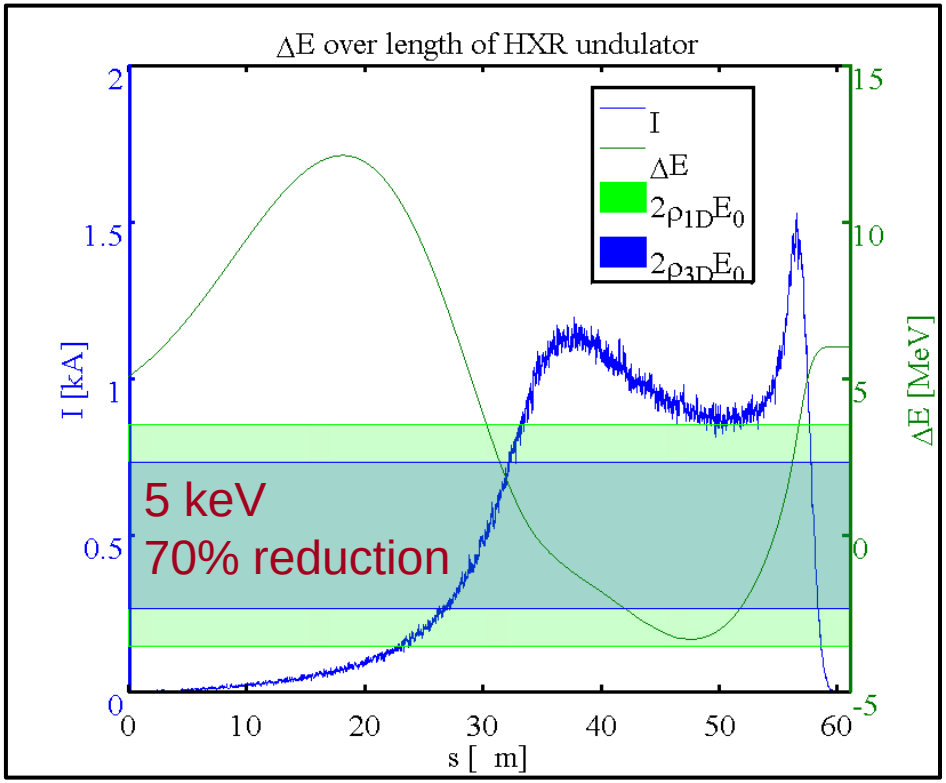
LCLS-II 2.5 km Bypass Line



Undulator Wakefield

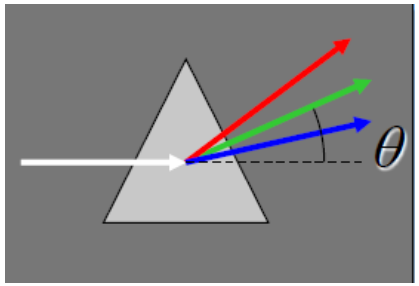
The undulator tends to have small gaps and long chambers. RW wake is a significant limitation. Two examples from LCLS-II with 100+meter undulators with Al chamber having 5 mm vertical gap.





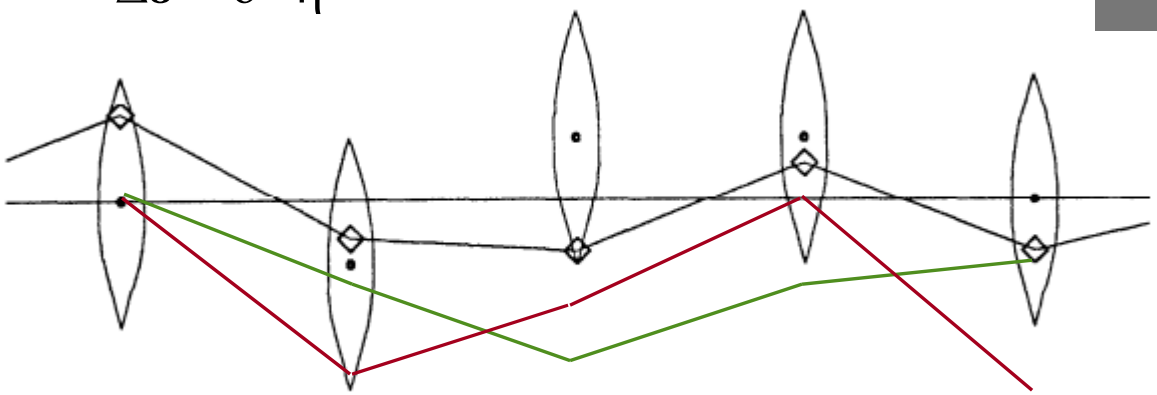
Dispersive Emittance Dilution

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



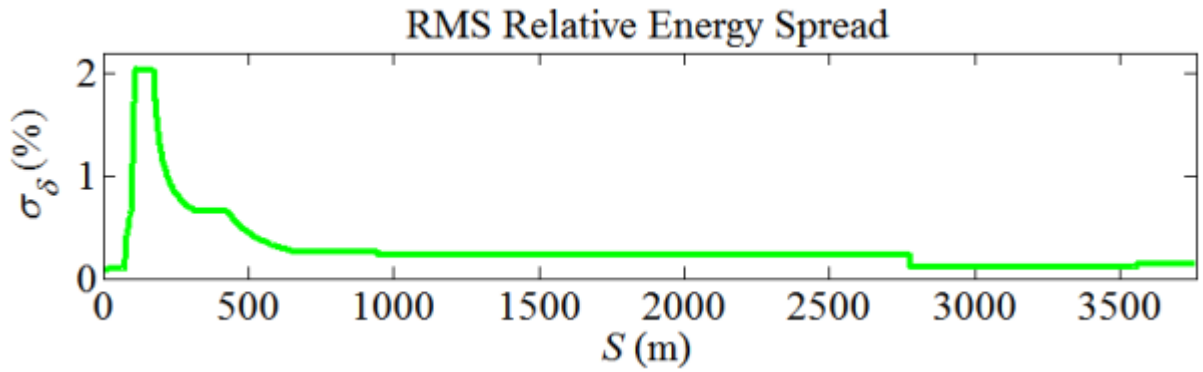
→ energy dependent trajectory as if residual dispersion

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



Residual dispersion arises from trajectory offsets in quadrupoles and grows as a random walk due to random offsets of a corrected trajectory

Example: LCLS-II Tolerances



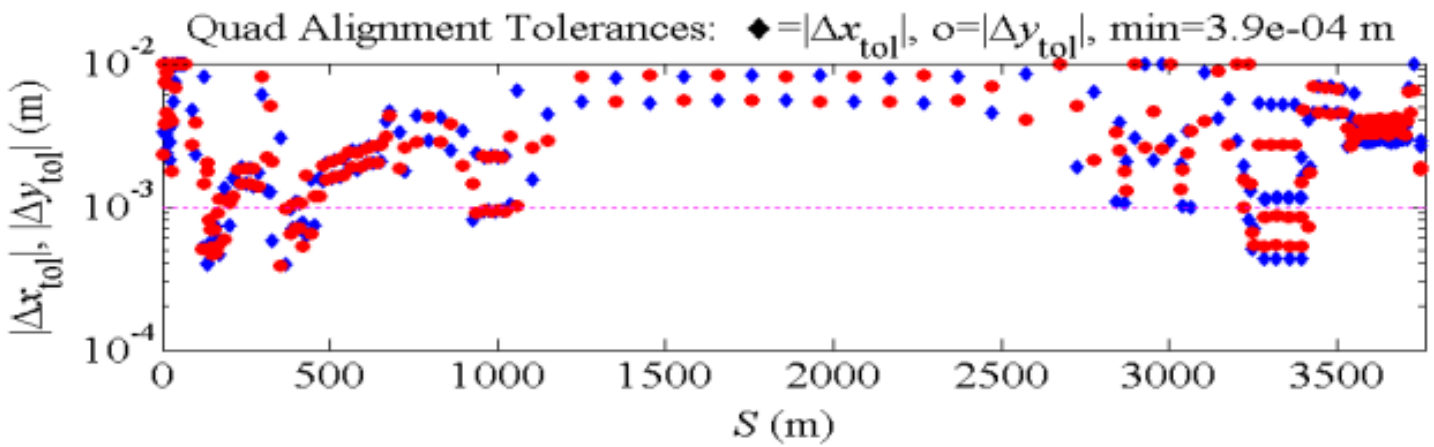


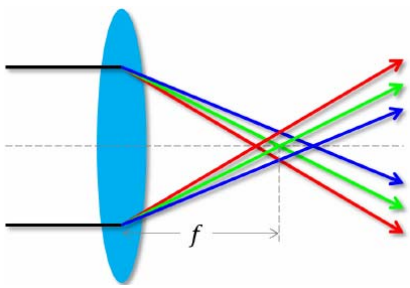
Figure 5: Horizontal and vertical position tolerances for *quadrupole* magnets. The maximum tolerance is limited to 10 mm here. The tightest position tolerance is 0.39 mm. The undulator quadrupole tolerances (dense group of points at far right, from $S \approx$ 3570-3710 m) should be ignored here. The final quadrupole magnet alignment in the undulators (~10 μm) is accomplished with a beam-based procedure, requiring ~0.1 mm initial survey alignment.

Emma, LCLSII-PR-2.4-0496

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!



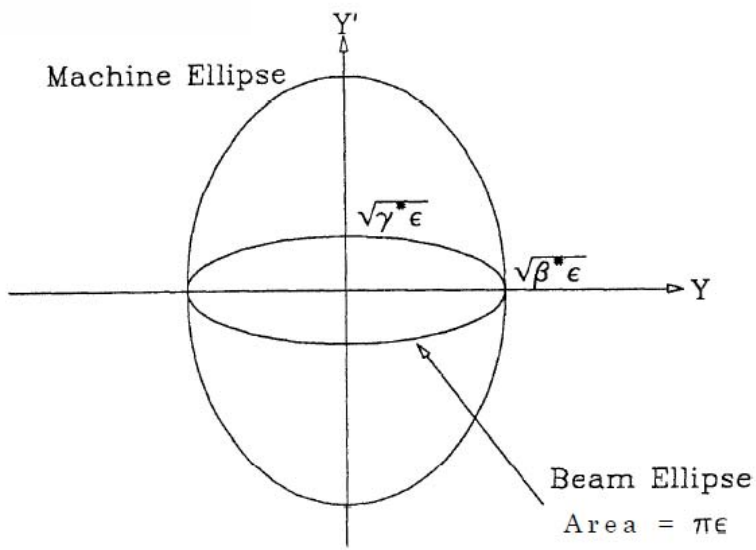


Fig. 48. Beam and machine ellipses for an unmatched beam.

What happens when the beam is mismatched?

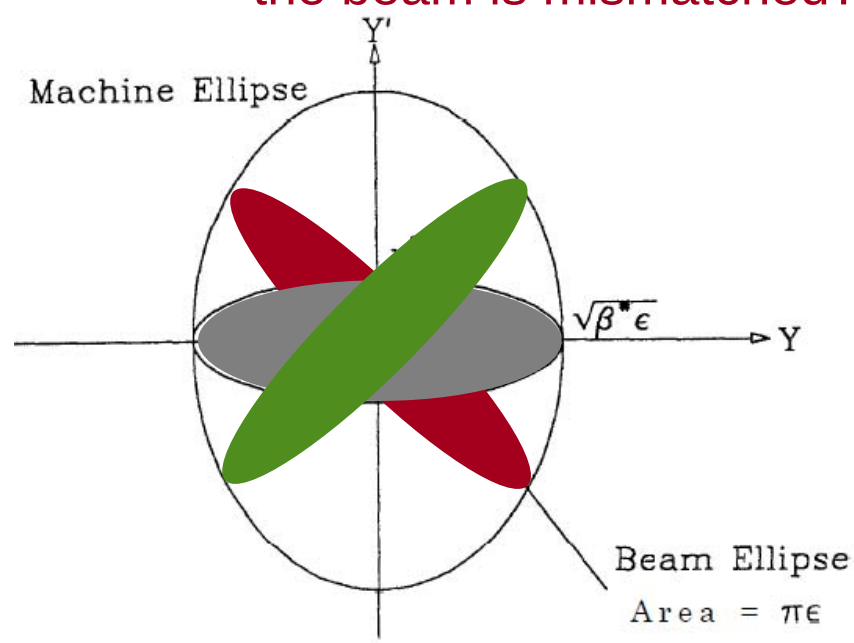


Fig. 48. Beam and machine ellipses for an unmatched beam.

Dispersive and Chromatic Dilution – p 2.

FEL beam slice energy spread tends to be small but chirp can be many times larger – typically % for compression.

Assuming a roughly linear chirp along the beam, the dispersion can be used to compensate transverse wakefields or vise versa. Partial bunch compression will tend to leave correlations largely correctable.

Chromatic dilution is hard to correct (without sextupoles). Mismatch is usually quantified with:

$$B_{mag} = \frac{1}{2}\left(\beta_0\gamma - 2\alpha_0\alpha + \gamma_0\beta\right) \geq 1$$

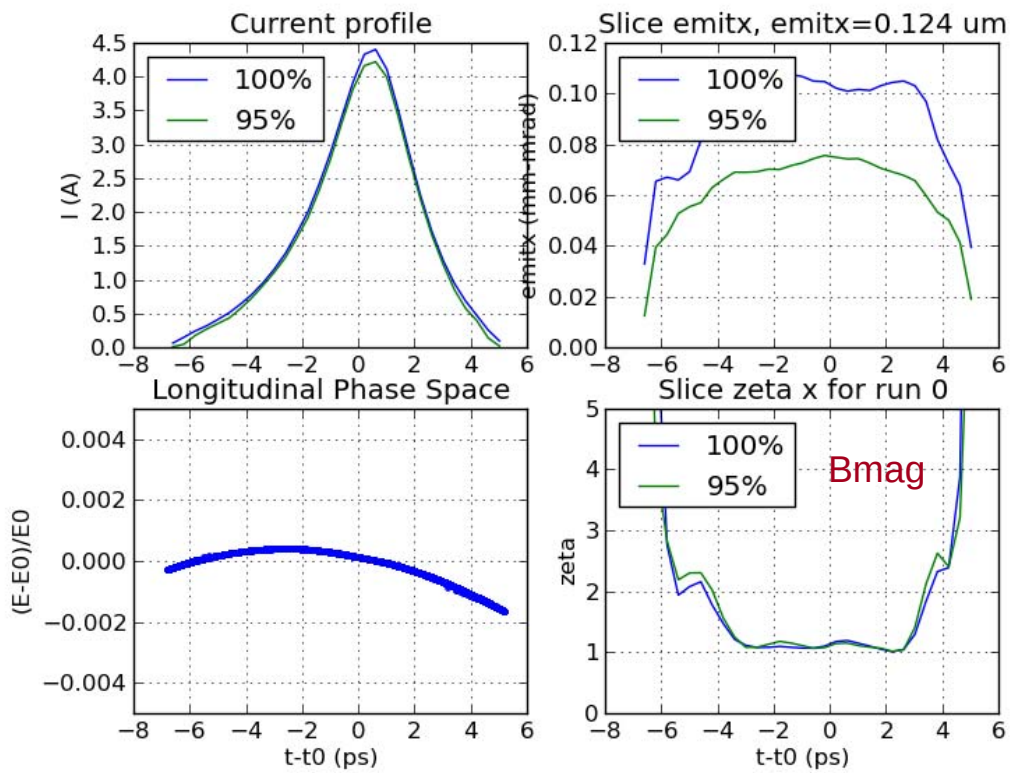
LCLS seems impacted with Bmag > 1.2

P. Baxevanis, et al., PRSTAB.16.010705 (2015).

Variation of match from Injector

Injector is designed to compensate space charge aberrations but variation of transverse force with position along bunch leads to focusing variation along bunch.

Mismatches will partially filament and effect at undulator probably less severe that implied at injector



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

Space Charge Fields

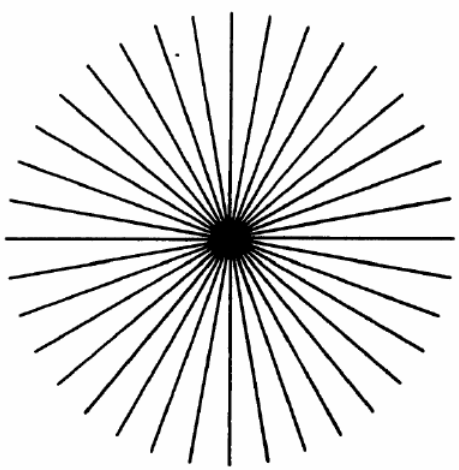
Fields of a uniformly moving particle, extend through space as given by the Lorentz transform of the Coulomb field

$$E_x = \frac{1}{4\pi\epsilon_0}\frac{e\gamma x}{[x^2+y^2+\gamma^2(z-vt)^2]^{3/2}}$$

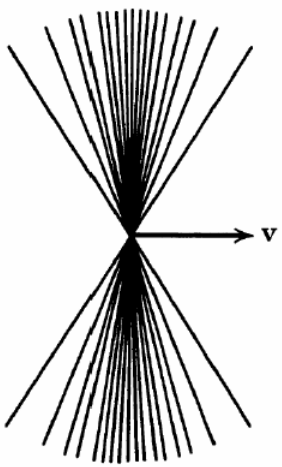
$$E_y = \frac{1}{4\pi\epsilon_0}\frac{e\gamma y}{[x^2+y^2+\gamma^2(z-vt)^2]^{3/2}}$$

$$E_z = \frac{1}{4\pi\epsilon_0}\frac{e\gamma (z-vt)}{[x^2+y^2+\gamma^2(z-vt)^2]^{3/2}}$$

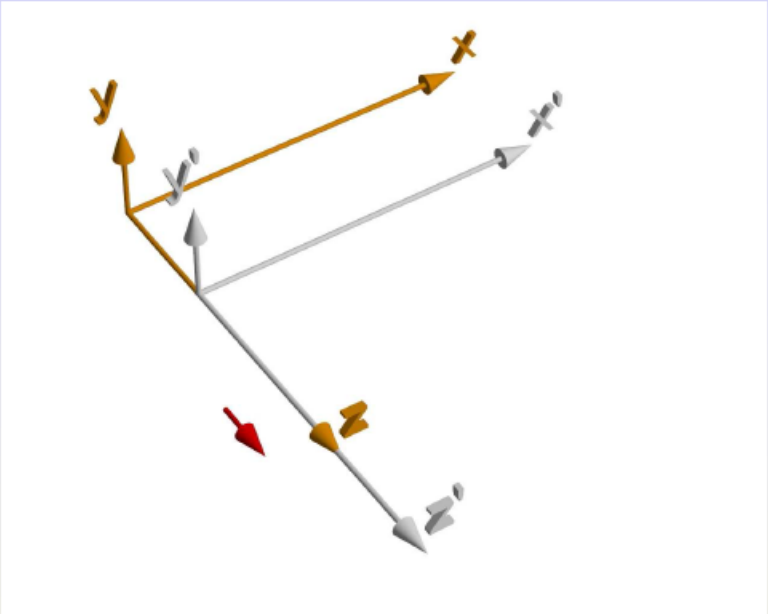
β = 0



β > 0



Transformation of EM Fields



A frame of reference K' is moving relative to the frame K with velocity v along z

$$
\begin{aligned}
x' &= x\,, \\
y' &= y\,, \\
z' &= \gamma(z - \beta ct)\,, \\
t' &= \gamma(t - \beta z/c)\,,
\end{aligned}
\qquad (2.2)
$$

where $\beta = v/c$, and $\gamma = 1/\sqrt{1-\beta^2}$.

$$
\begin{aligned}
E_z &= E'_z\,, \qquad & \mathbf{E}_\perp &= \gamma\left(\mathbf{E}'_\perp - \mathbf{v}\times\mathbf{B}'\right)\,, \\
B_z &= B'_z\,, \qquad & \mathbf{B}_\perp &= \gamma\left(\mathbf{B}'_\perp + \frac{1}{c^2}\mathbf{v}\times\mathbf{E}'\right)\,,
\end{aligned}
\qquad (2.3)
$$

Gennady Stupakov

Transverse Space Charge

Transverse space charge generates a current dependent defocusing along the bunch

- Space charge force scales as $K_1 \sim 2\, I(z) / 2\pi\, \gamma^3\, I_A\, \sigma^2$ where $I_A = 17$ kA
- Obviously important in injectors where γ is small
- But can be important after bunch compression where current get large

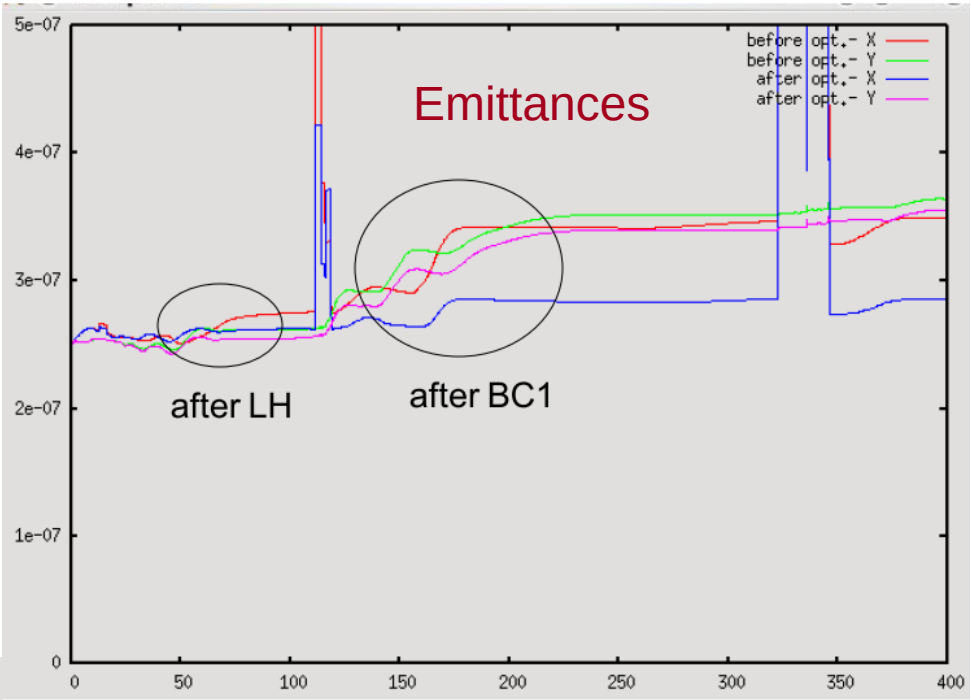
Scale of space charge / external focusing:

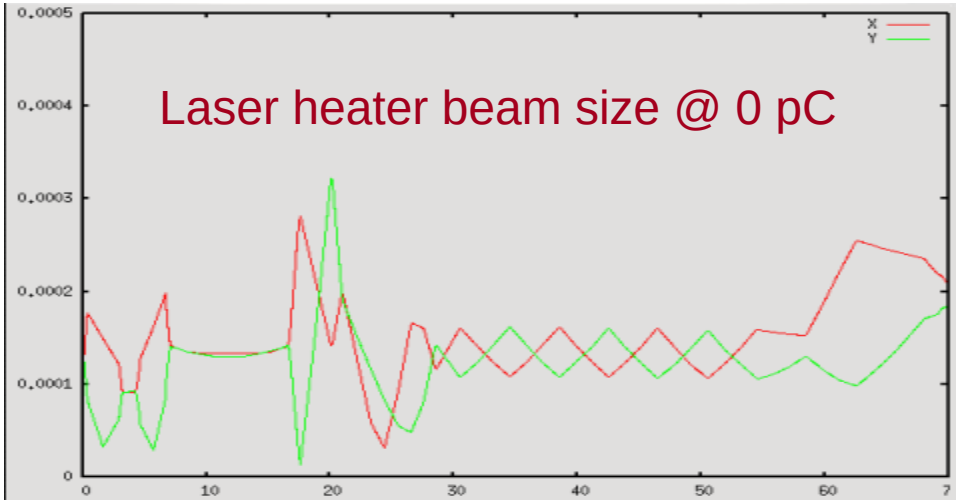
$$\frac{2I(z)\,\bar{\beta}}{2\pi I_A \gamma^2 \gamma \varepsilon} \ll 1$$

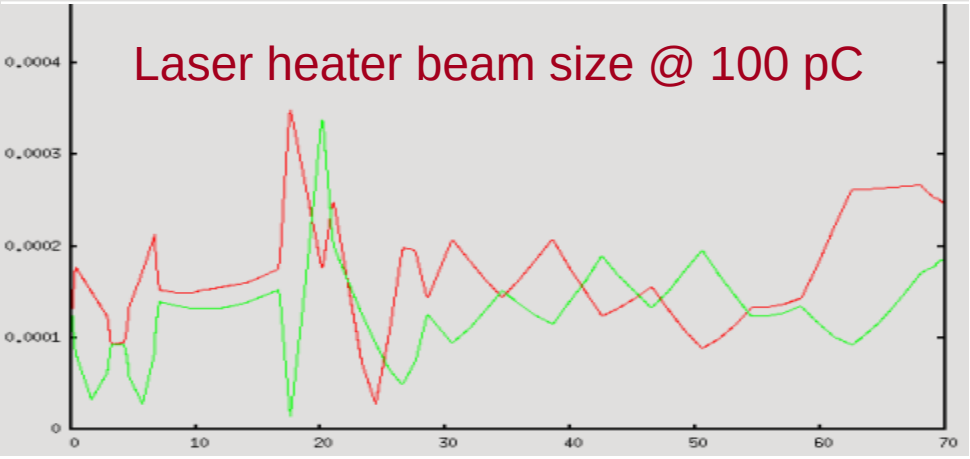
Example: LCLS-II after BC1 (250 MeV) with 150 A, 0.3um, and $\beta \sim 50$ m → space charge is important

Transverse Mismatch in LCLS-II

Tracking with IMPACT using 3D space charge fields







Longitudinal Space Charge (LSC)

In free space, the longitudinal space charge field of a uniform beam can be calculated in the beam frame:

$$Z(k) = \frac{4i}{ka^2}\left[1 - \frac{ka}{\gamma}K_1\left(\frac{ka}{\gamma}\right)\right]$$

$$\approx \frac{ik}{\gamma^2}\left(1 + 2ln\left(\frac{\gamma}{ka}\right)\right) \quad \text{when} \quad ka \ll \gamma$$

$$\approx \frac{4i}{ka^2} \quad \text{when} \quad ka \gg \gamma \quad \text{(short wavelength)}$$

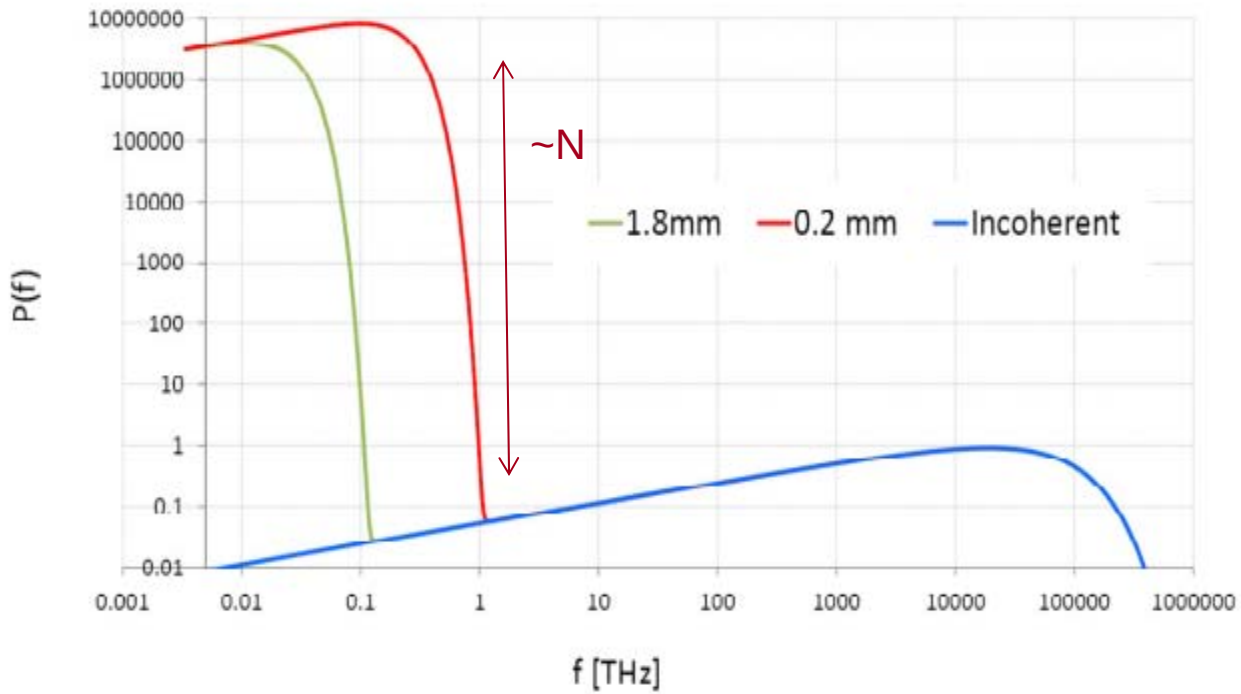
Lack of γ^2 cancellation means LSC can have significant impact even at high energies

Homework

Coherent Synchrotron Radiation

Radiation from Gaussian bunches

Bunch radiates coherently at wavelengths longer than the density modulation



A. Novokhatski, slac-pub-14893.pdf (2012)

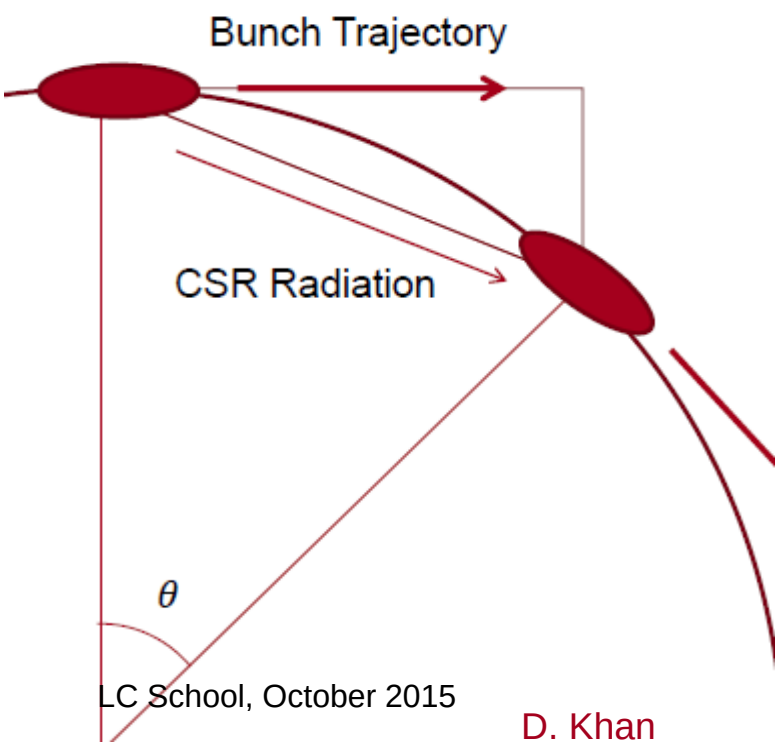
$$I_b(\omega) = I(\omega)\left|j(\omega)\right|^2 = I(\omega)N\left[1 + N\exp\left(-\left(\frac{\omega\sigma}{c}\right)^2\right)\right]$$

CSR In Dipoles

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

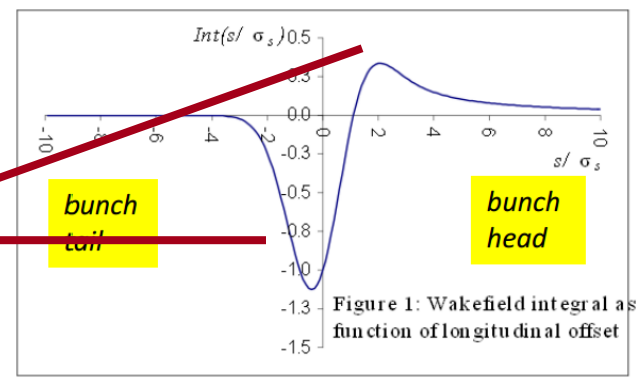
Uniform Bend Approx

$$\sigma_{\Delta E/E} \approx 0.2 \frac{N r_e}{\gamma R^{2/3} {\sigma_z}^{4/3}} L$$



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

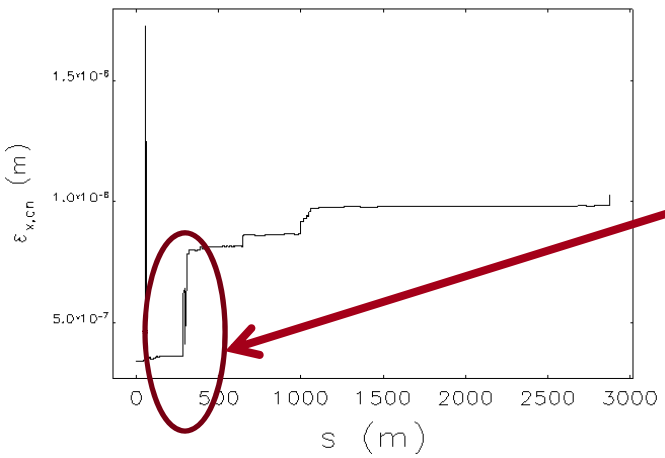
Peaks intensify as σ_z gets smaller!



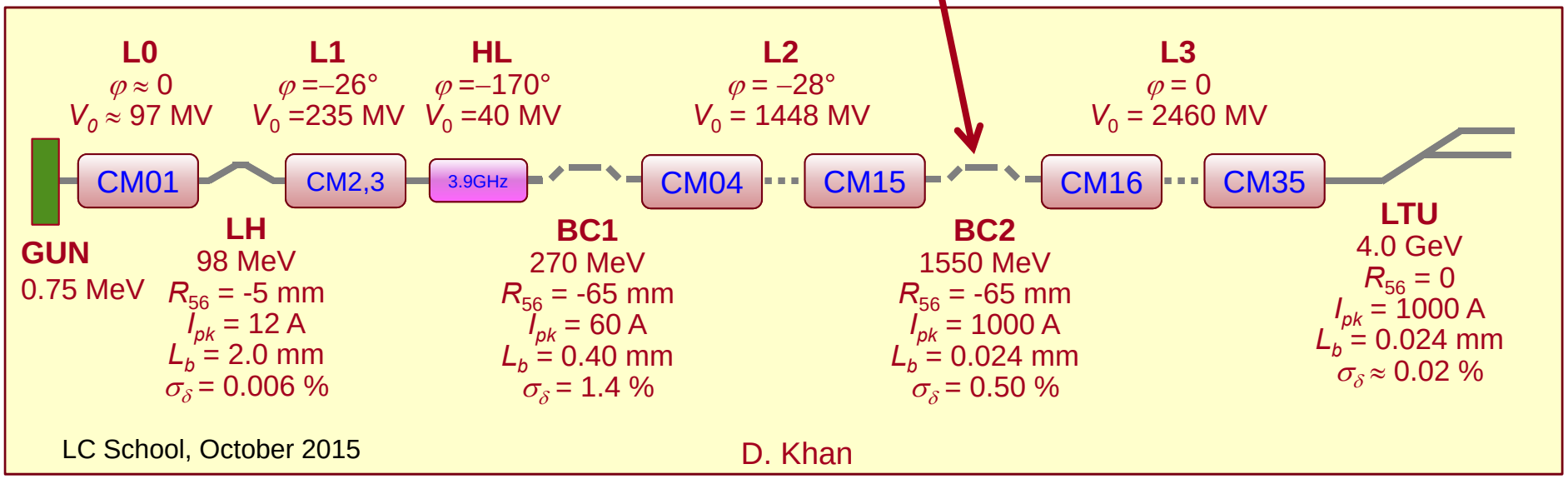
Ya. S. Derbenev, et al., TESLA FEL-Report 1995-05 (1995).

LCLS II Beamline: Area of Interest

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

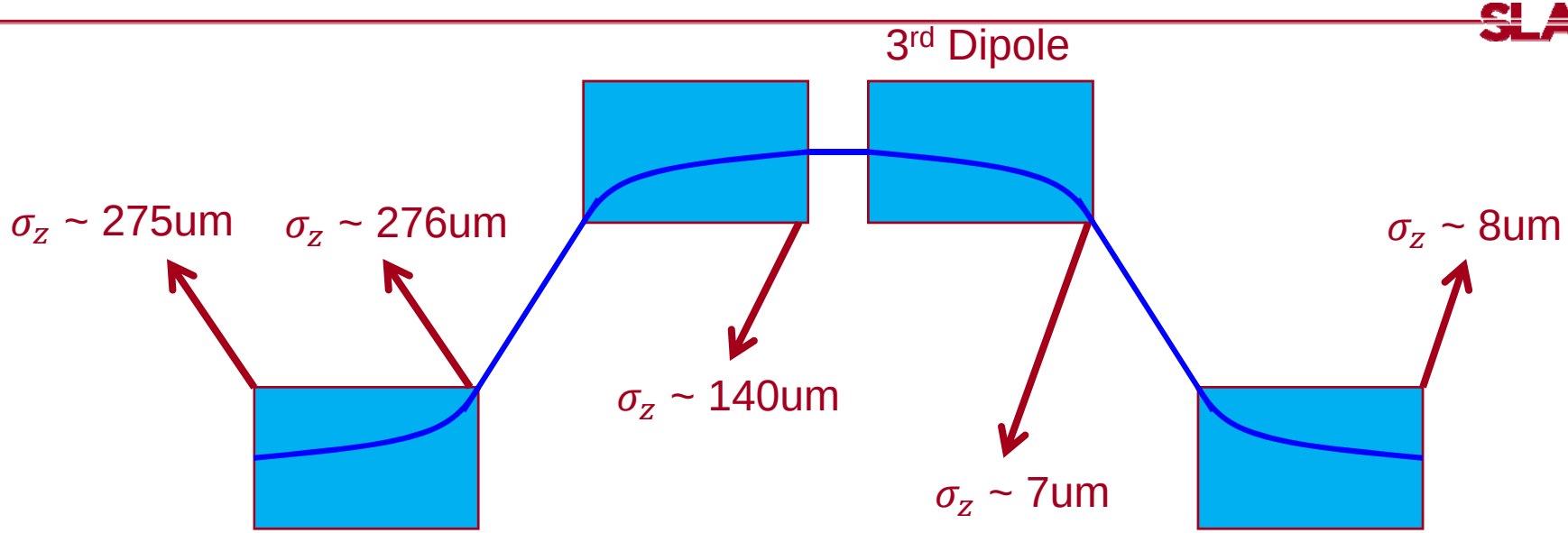


CSR

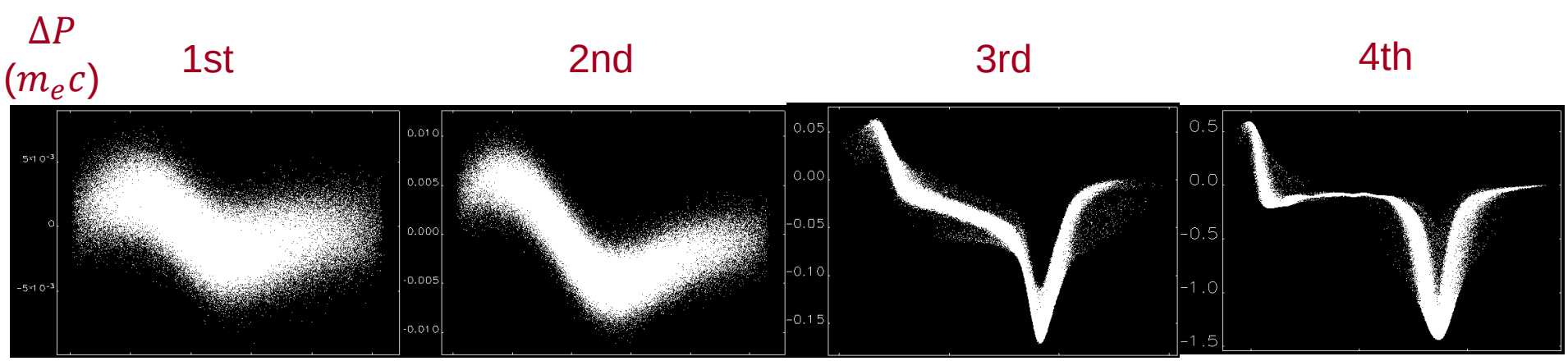


D. Khan

A Closer Look At BC2 From Current LCLS2



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

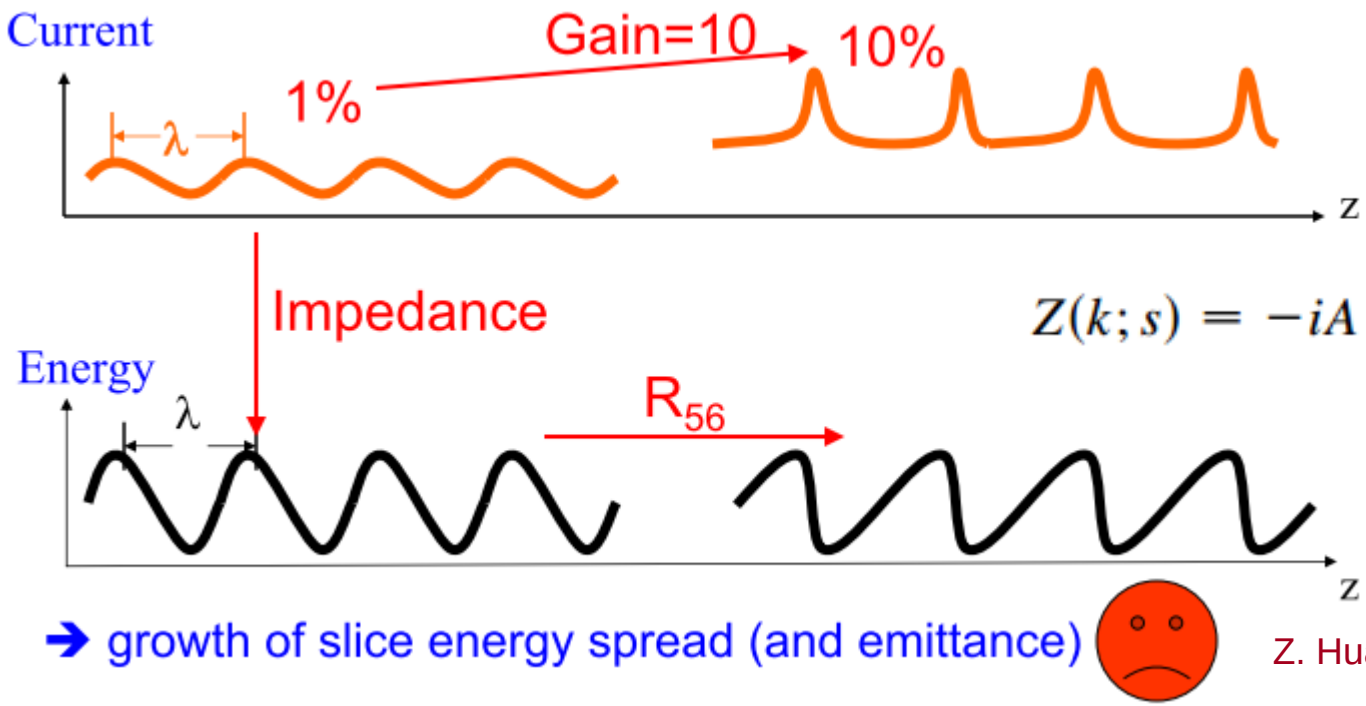


σ_z ~ 276um σ_z ~ 140um σ_z ~ 7um σ_z ~ 8um

Density Variations → Microbunching

CSR will also radiate due to density variation along the bunch

→ Leads to energy variation along with density perturbation



$$Z(k;s) = -iA\,\frac{k^{1/3}}{\rho(s)^{2/3}}$$

CSR

$$A = 1.63i - 0.94$$

→ growth of slice energy spread (and emittance)

Z. Huang

Lots of papers in early 2000's: E. Saldin, et al, NIM A 490, 1 (2002)
Z. Huang, et al, PhysRevSTAB.5.074401 (2002).

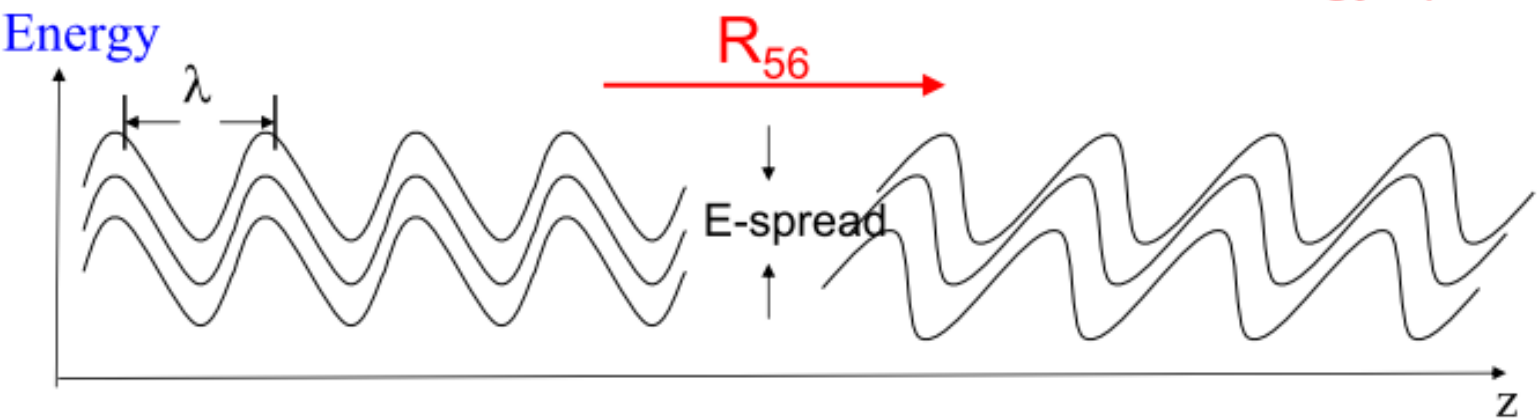
Microbunching Gain

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

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

local energy spread

- No emittance damping!

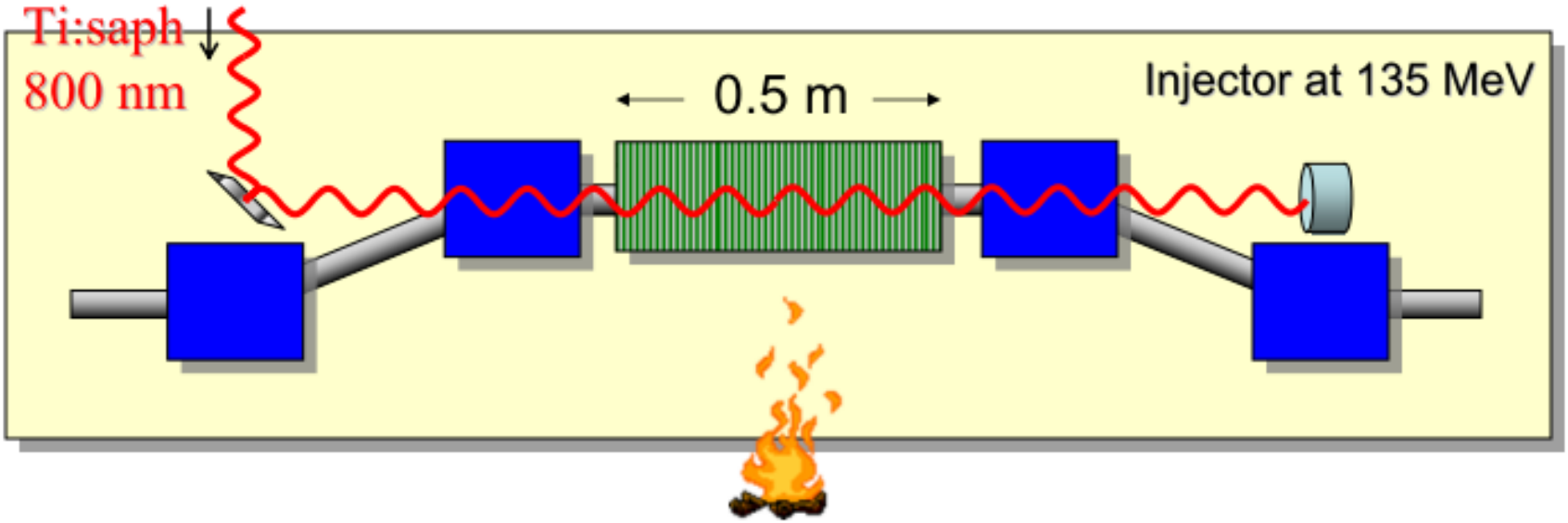


- All beams have finite incoherent (uncorrelated) energy spread, smearing of microbunching occurs if

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

Laser Heater: 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

Energy exchange between Laser and Electron

Go back to the pendulum equations for interaction in an undulator

$$\frac{dW}{dt} = -\mathrm{e}E_0 \cos(ks - \omega t + \varphi) \cdot \frac{cK}{\gamma} \sin(k_u s) = -\frac{ecE_0 K}{2\gamma}[sin\Psi_+ - sin\Psi_-]$$

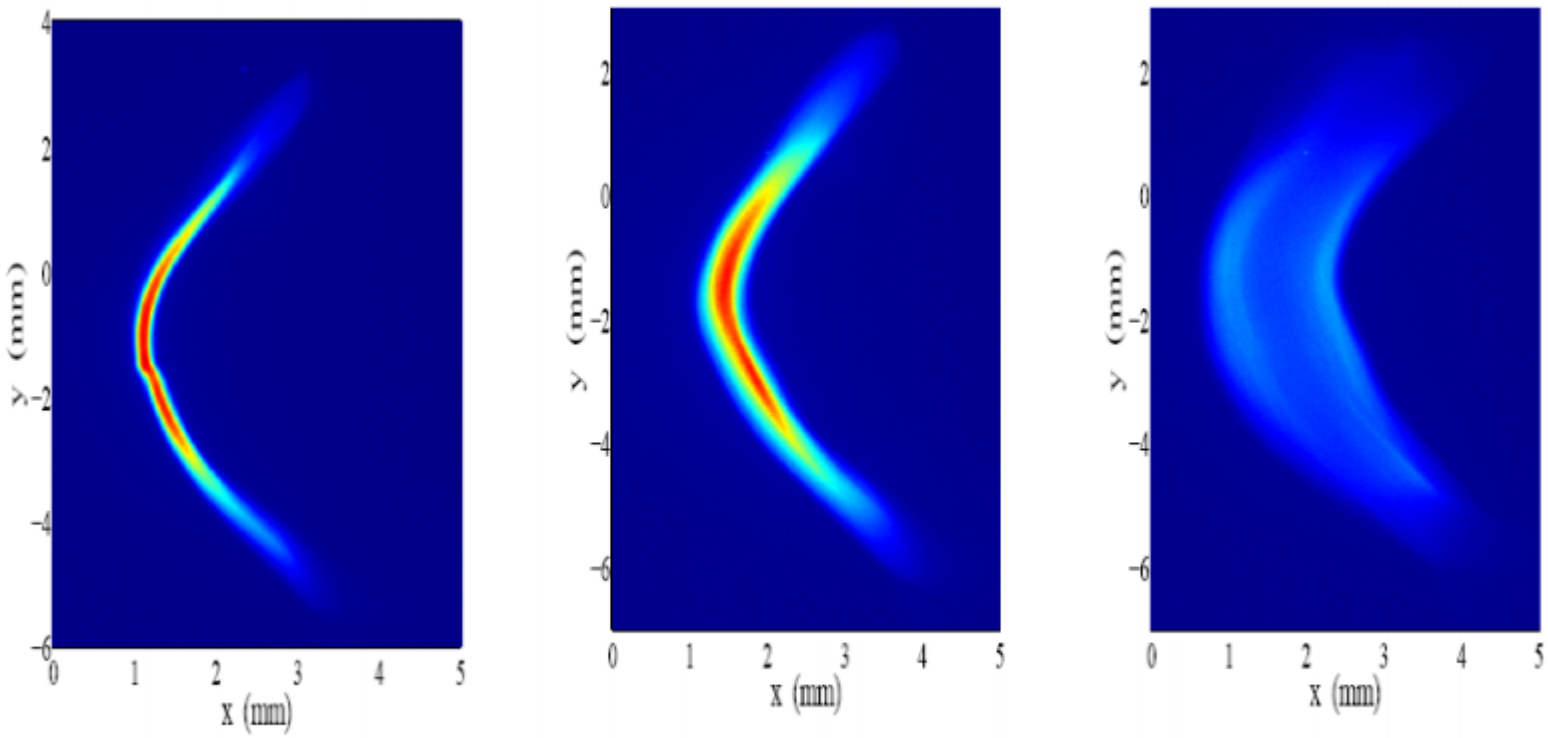
In a laser beam (at a waist), the field is: $E^2 = Z_0 P / \pi\sigma_r^2$ or about 1GV/m from a 100 MW laser into a 100 um spot size.

Laser generates z-δ sinusoidal variation. Half chicane smears this out due to R52 (R52 = R16 = η). Introducing the energy variation with η generates some emittance growth with a residual x-δ after chicane.

Homework

LCLS Laser Heater Measurement

Measurement of z (vertical) versus E (horizontal) at 135 MeV



(a)no heating (b)nominal heating (c)maximum heating

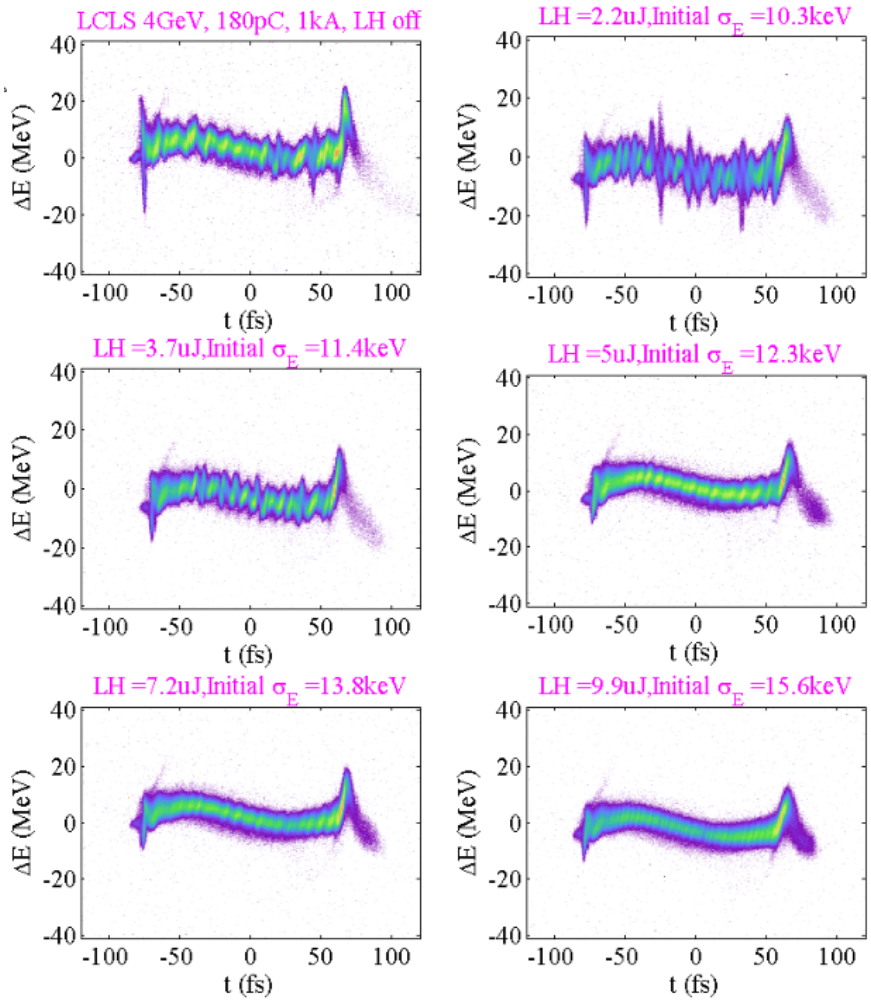
10 uJ 220 uJ

Z. Huang et al., PRSTAB, 13, 020703 (2010).

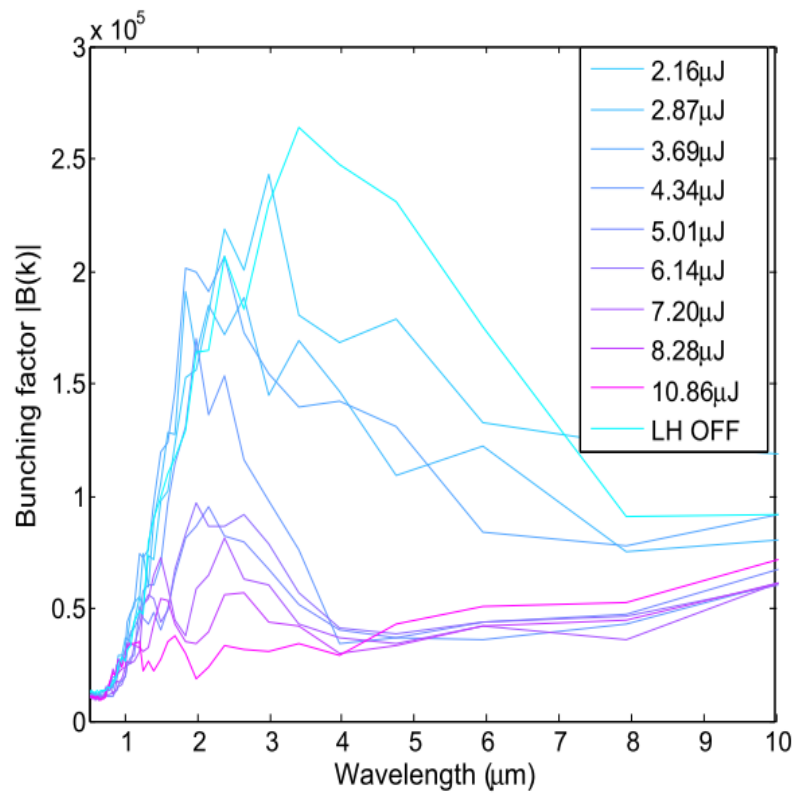
Microbunch Effects in LCLS

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

Measured final t-δ phase space vs laser heater



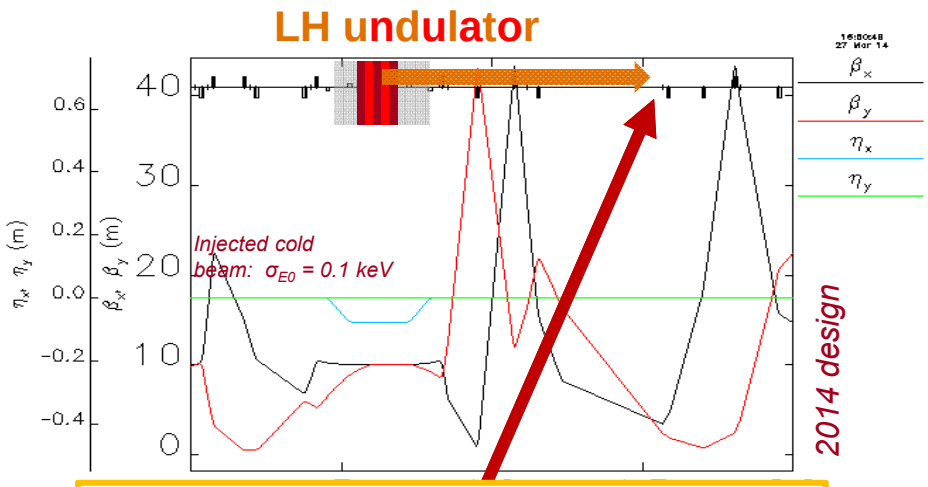
preliminary analysis of bunching factor



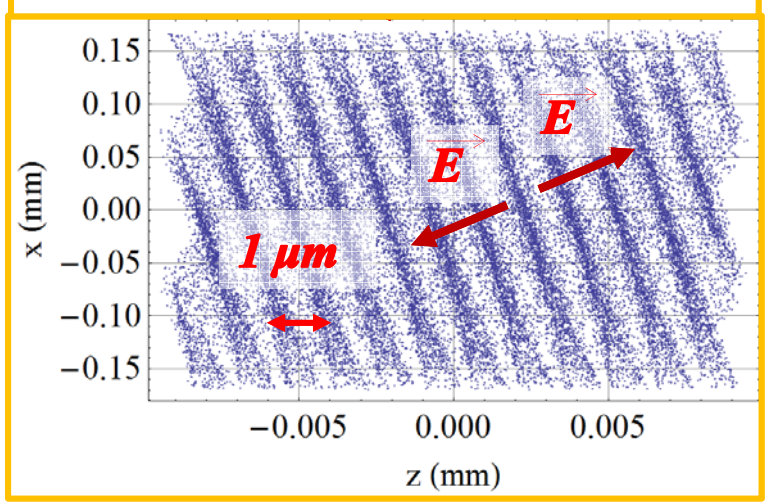
D. Ratner, et al., Phys. Rev. ST Accel. Beams **18**, 030704 (2015).

The 'trickle' heating effect induced by laser-beam interaction

M. Venturni
SLAC

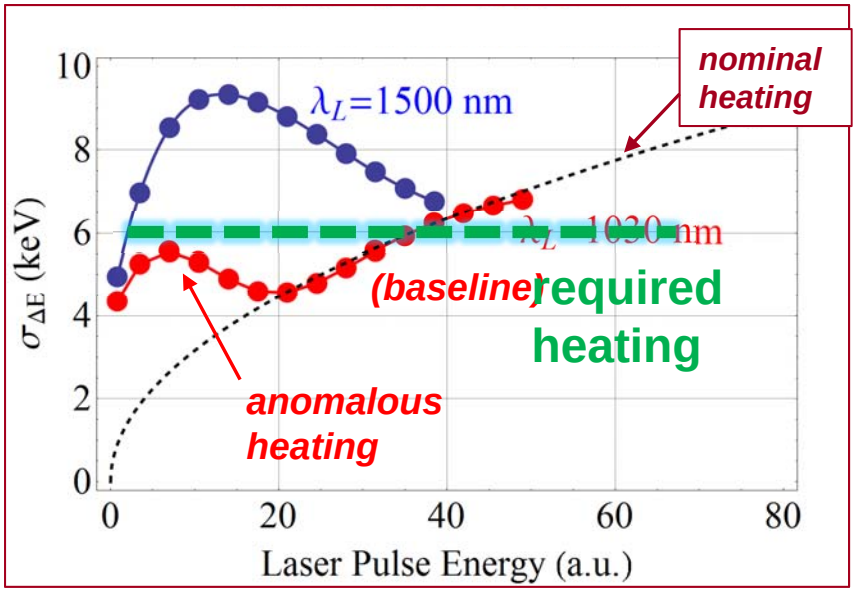


μ-structure appears downstream of LH



- Longitudinal component of electric field due to 2D structure heats the beam

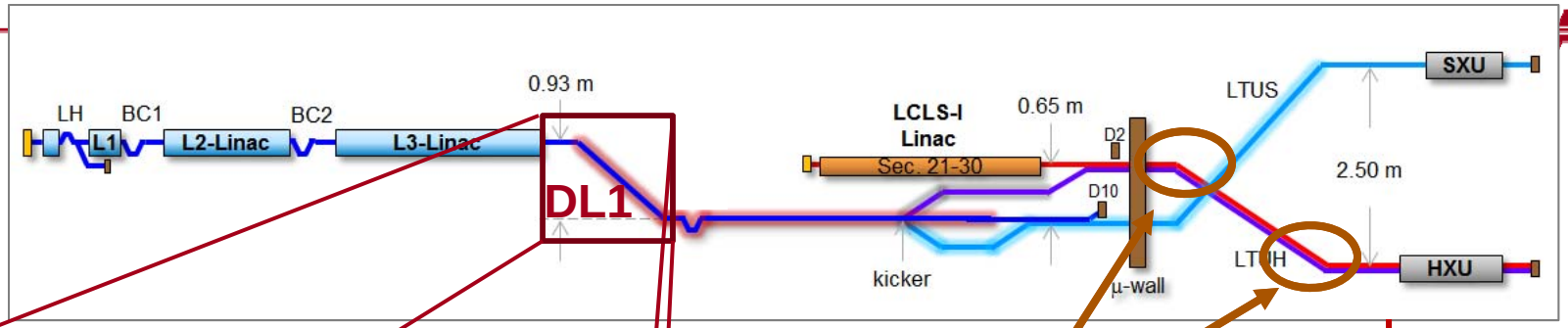
Trickle heating effect for two choices of laser wavelengths ($Q = 100\ pC$)

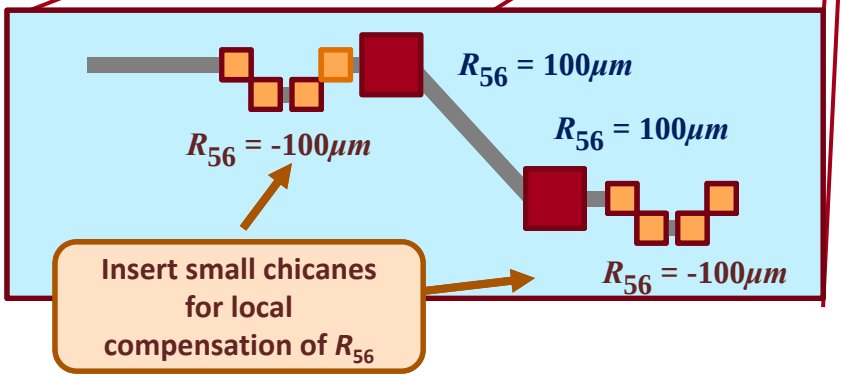


- **IMPACT** simulation. **Idealized flat-top** beam with $I_0 = 12$ A (100 pC bunch). Gaussian energy and transverse beam distribution.
- Excessive anomalous heating would **limit tuning range** of heater.

Z. Huang, et al., PRST-AB 11, 020703 (2010)

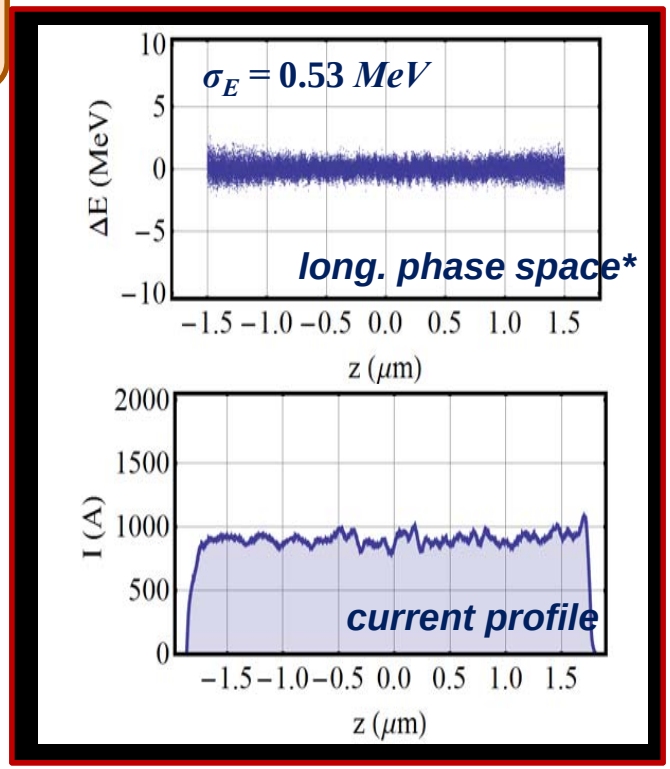
What to do about uBI?
Introduce local cancellation of R_{56}





Insert small chicanes for local compensation of R_{56} here as well

Beam as observed at HXU FEL shows little microbunching

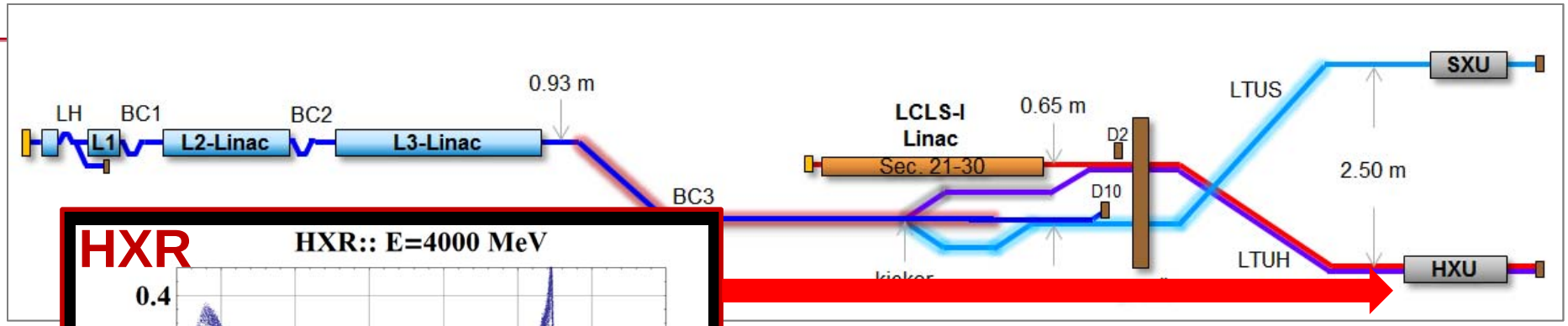


- Method appears to be highly effective
  - *Delaying compression to exit of bypass could also be a way to reduce microbunching, may have drawbacks*

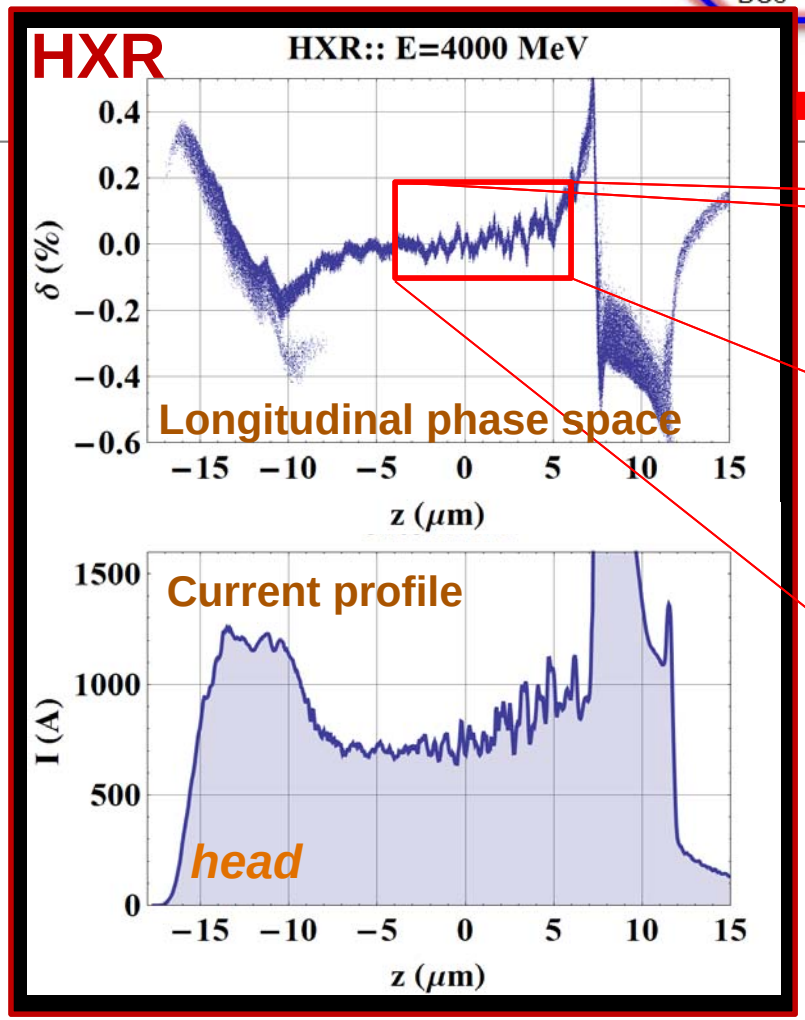
** Correlated energy chirp removed*

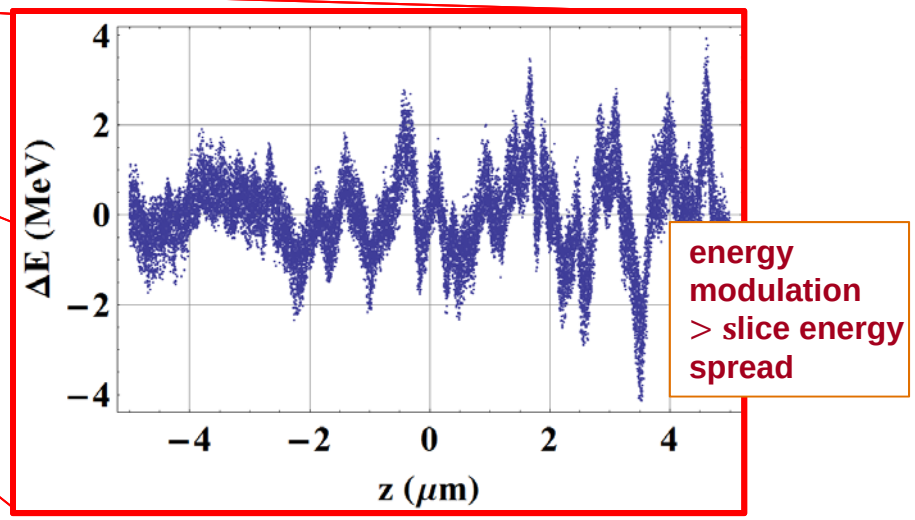
C. Mitchell

S2E simulations: 100 pC, LCLS-II HXR



M. Venturni





- Current baseline lattice with Compensating Chicanes in doglegs
- Observed μBI is mostly due to T_{566} and Transverse SC within the doglegs

M. Venturini, et al, Phys. Rev. ST Accel. Beams **18**, 054401

Take-Away

Detailed beam dynamics of compressed beam is challenging

Many factors come into play: CSR, LSC, normal wakefields, …

Micro-bunching instability leads to an increase of the longitudinal emittance either due to the instability or by the need to suppress it.

Ongoing research to understand how to model and control effects