VUV and X-ray Free-Electron Lasers

Electron Bunch Compression, CSR, μBi, Laser Heater & Machine Layout

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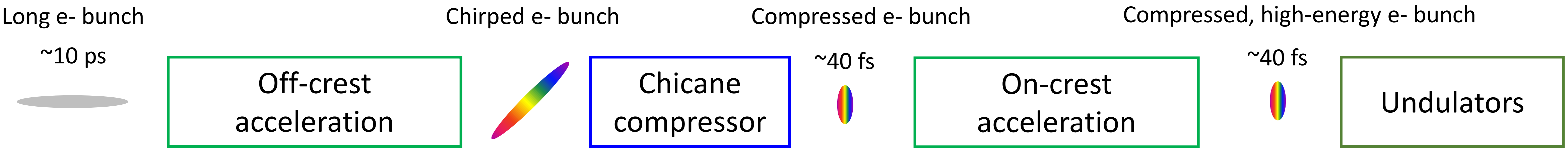
Thursday (February 4) Lecture Outline

	Time
• Electron Bunch Compression	10:00 – 10:40
• Coherent Synchrotron Radiation (CSR)	10:40 – 11:00
• Break	11:00 – 11:10
• Microbunching Instabilities & Laser Heaters	11:10 – 11:30
• Machine Layout	11:30 – Noon

Bunch Compression Overview

Photoinjectors produce electron bunches with ~10 ps bunch length and ~10 A peak current. To obtain kA peak current at the undulators, we compress the bunch by imposing a “chirp” (a linear energy-z correlation) via off-crest acceleration, followed by a chicane compressor to rotate the “chirped” bunch into an upright ellipse, i.e., a compressed bunch.



Long e- bunch

~10 ps

Off-crest acceleration

Chirped e- bunch

Chicane compressor

Compressed e- bunch

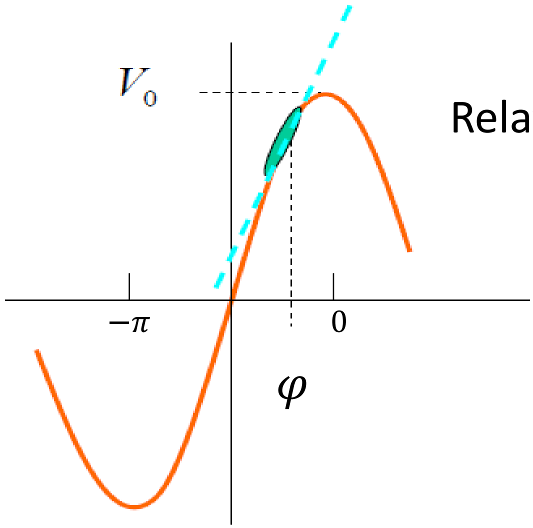
~40 fs

On-crest acceleration

Compressed, high-energy e- bunch

~40 fs

Undulators



Relative energy deviation vs. z

$$\delta(z) = \kappa z + O(z^2)$$

First-order pathlength change in chicane

$$\Delta z \approx R_{56}\delta$$

First-order momentum compaction of chicane

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

Creating an Energy Chirp in RF Cavities

Energy versus z , coordinate along the bunch

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

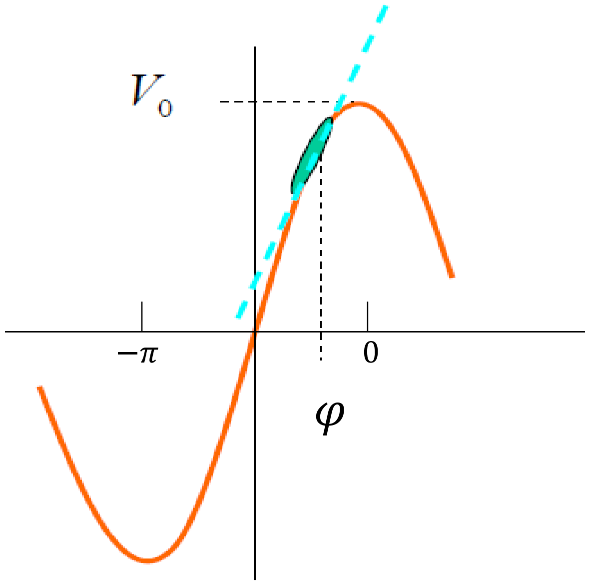
Relative energy deviation, δ versus z

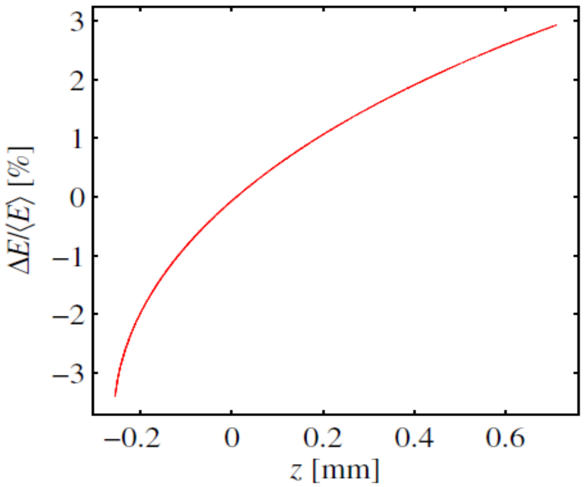
$$\delta(z) = \frac{eV_0(cos(kz + \varphi) - cos\varphi)}{E_0 + eV_0 cos\varphi}$$

$$\delta(z) = \kappa z + O(z^2)$$

Energy chirp

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





Chirper Cavity *R* Matrix

$$\begin{bmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \end{bmatrix}_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ R_{21} & R_{22} & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & R_{43} & R_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & R_{65} & R_{66} \end{bmatrix} \begin{bmatrix} x \\ x' \\ y \\ y' \\ z \\ \delta \end{bmatrix}_0$$

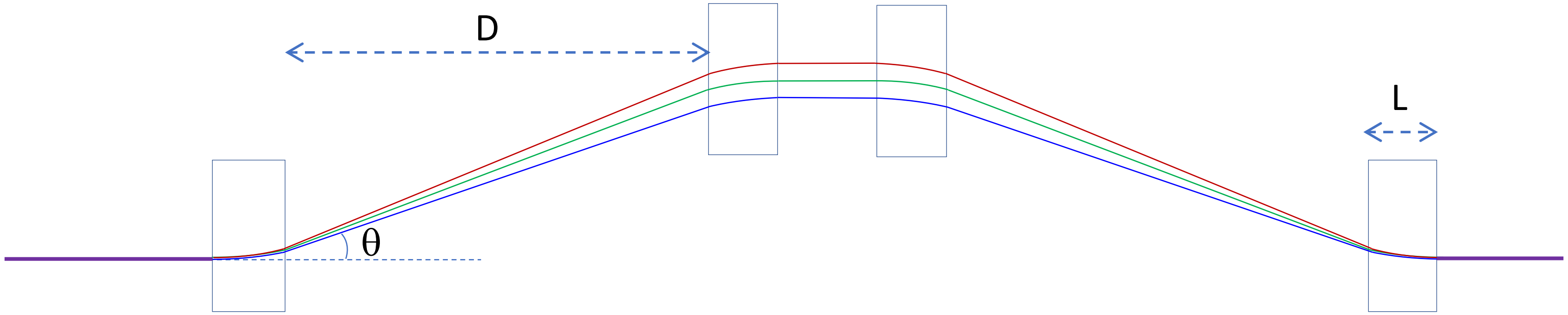
Exit centroid energy

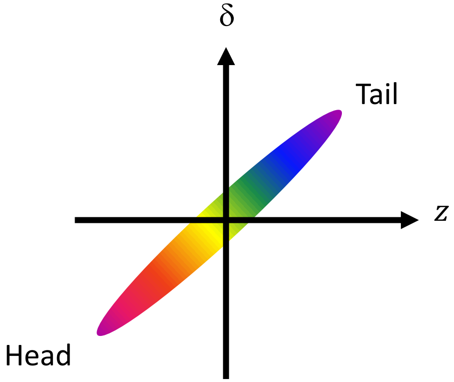
$$E_{1c} = E_0 + eV_0 cos\varphi$$

$$R_{65} = \kappa = -\frac{eV_0 k}{E_{1c}} sin\varphi$$

$$R_{66} = \frac{E_0}{E_{1c}}$$

Chicane as a Non-linear Bunch Compressor





Chirped electron bunch

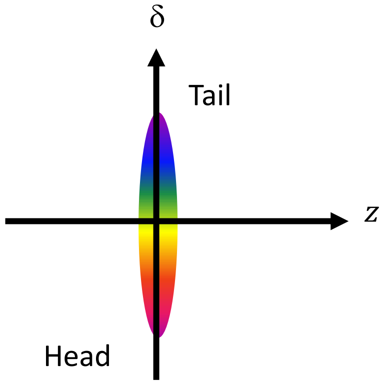
$$\Delta z = R_{56}\delta + T_{566}\delta^2 + O(\delta^3)\dots$$

First-order momentum compaction

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

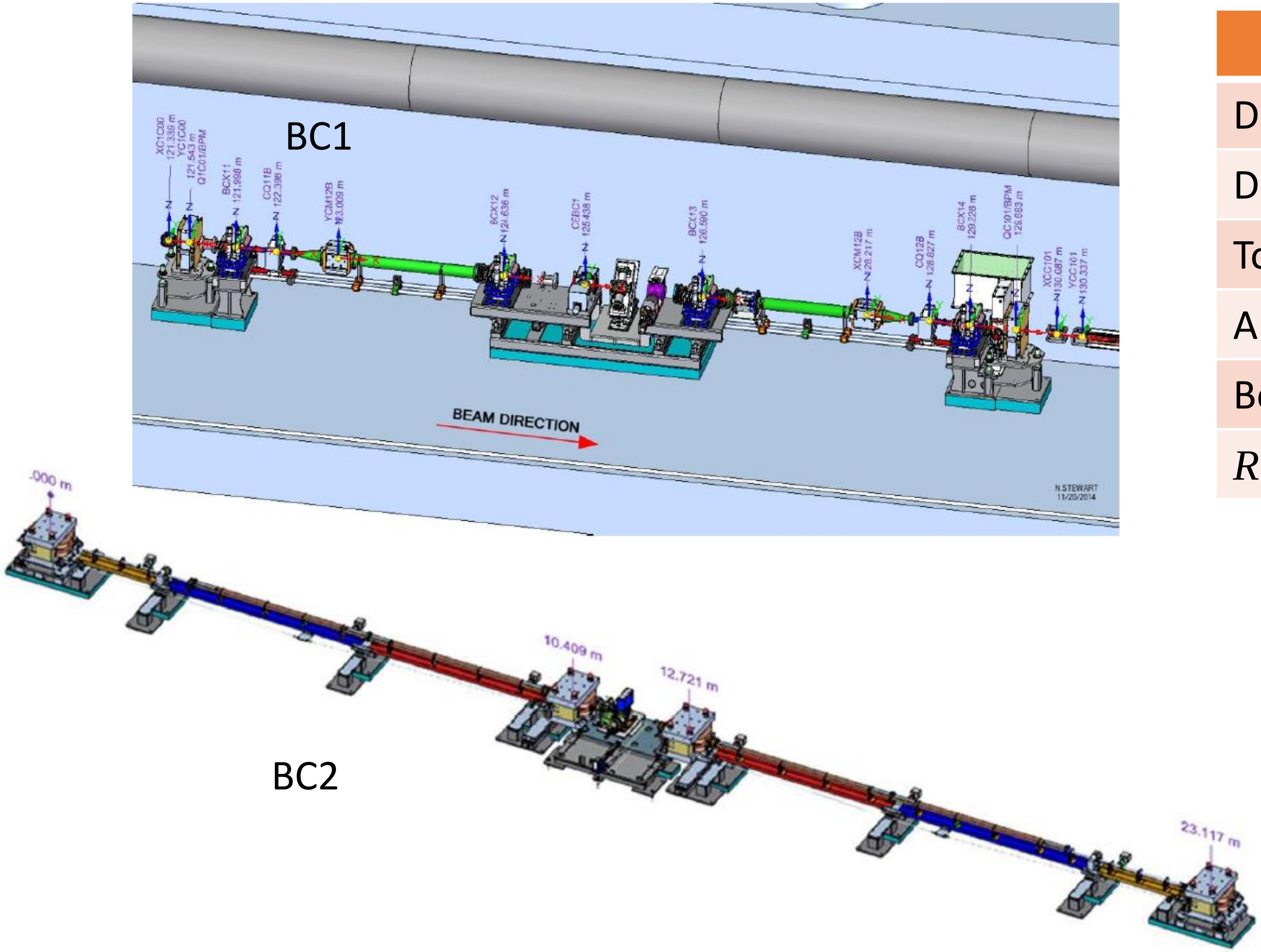
Second-order momentum compaction

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



Compressed electron bunch

Physical Dimensions of LCLS-II Chicanes



	BC1	BC2
Dipole L	0.2 m	0.54 m
Distance D	3 m	10.41 m
Total length	6.3 m	23.7 m
Angle θ	0.087 rad	0.05 rad
Beam energy E_b	250 MeV	1.6 GeV
R_{56}	-39 mm	-54 mm

Approximate value of R_{56} for $D >> L$

$$R_{56} \approx -2\theta^2 D$$

Vary R_{56} by adjusting the dipole magnetic field, thus changing θ

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

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

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

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

Final Compressed Bunch Length

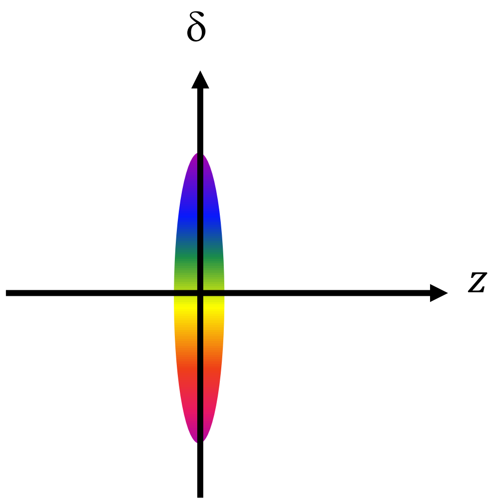
Final rms bunch length

$$\sigma_{z,f} = \sqrt{(1+\kappa R_{56})^2\sigma_{z,i}^2 + \left(\frac{E_{ic}}{E_{fc}}\right)^2 R_{56}^2\sigma_{\delta,i}^2}$$

Minimum compressed bunch length is achieved with the final ellipse in upright position

$$R_{56} = -\frac{1}{\kappa} = -\frac{1}{R_{65}}$$

$$\boxed{\sigma_{z,f} = \left(\frac{E_{ic}}{E_{fc}}\right) R_{56}\sigma_{\delta,i}}$$



Compressed electron bunch

Nonlinear Bunch Compression

Particle energy as a function of bunch coordinate

$$\delta(z) = \kappa z + \mu z^2 + \ldots$$

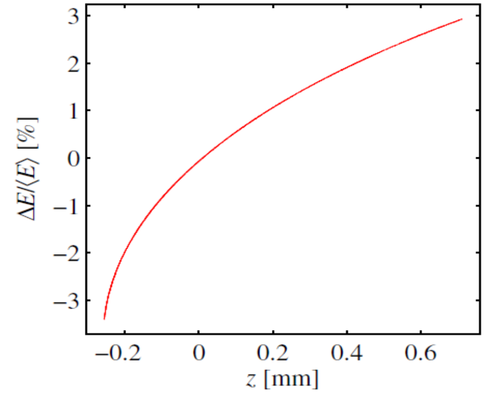
Linear chirp

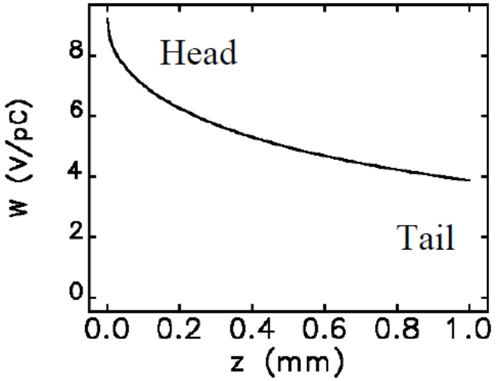
Second order curvature

$$\mu = -\frac{k^2 eV_0}{2E_{c,f}} cos\varphi$$

Position change in the chicane with first and second-order momentum compactions

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





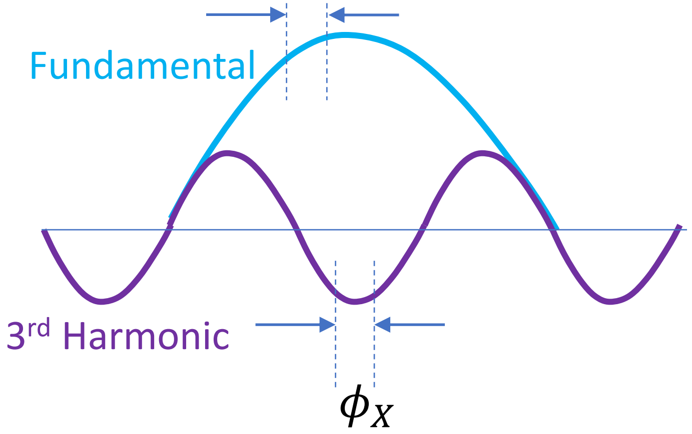
Short-range wake field in LCLS S-band linac is used to “dechirp” the final compressed bunch, i.e. remove both the linear energy chirp and 2nd order curvature.

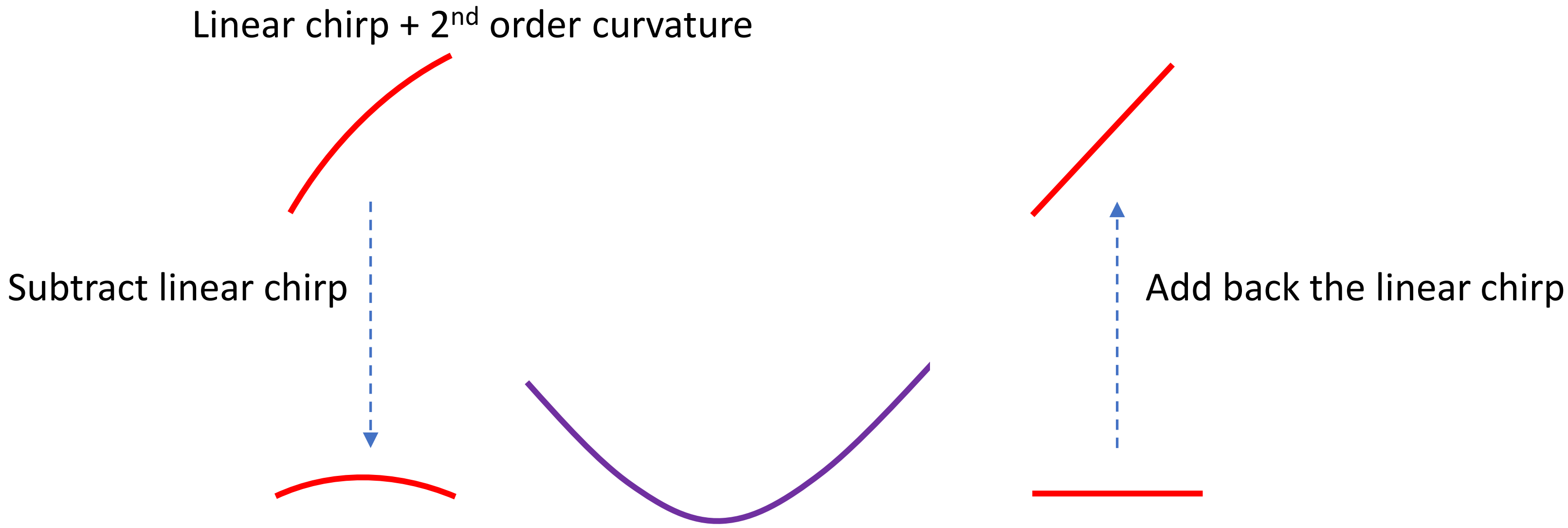
Harmonic Linearizer

Harmonic linearizer curvature

$$E_X = -k_X e V_X \cos\phi_X$$

$$\phi_X \approx -\pi$$

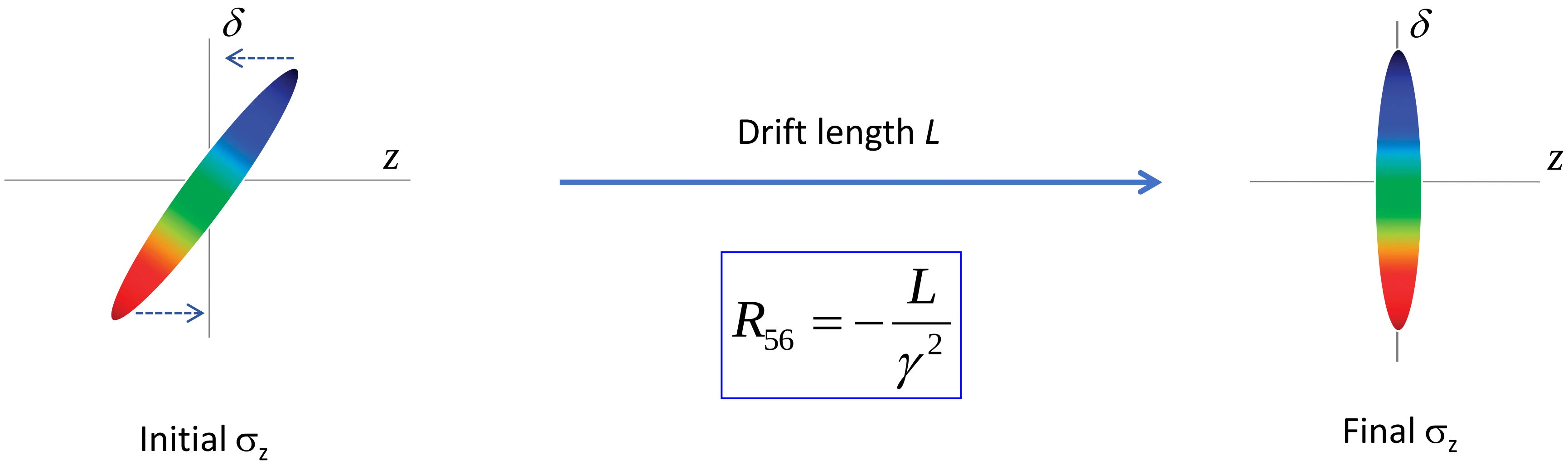




Second order curvature is corrected by the harmonic linearizer

Ballistic Compression

Ballistic compression is usually applied to electron beams at relatively low energy (<2 MeV). As the chirped electron bunch propagates in the drift, the slow electrons at the head move back with respect to the center and fast electrons at the tail catch up with the center.



Drift length *L*

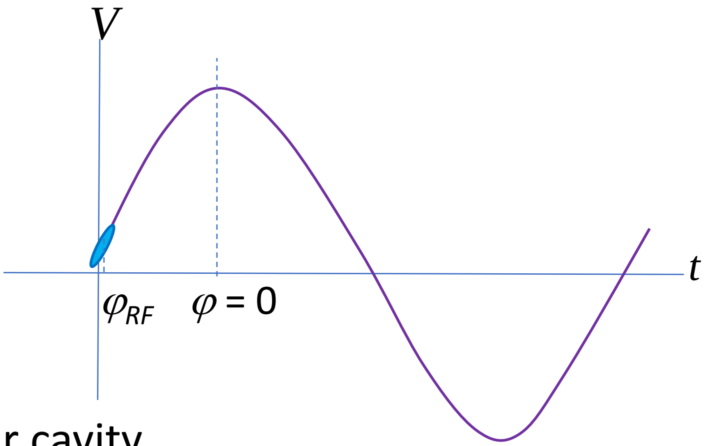
$$R_{56} = -\frac{L}{\gamma^2}$$

Initial σ_z

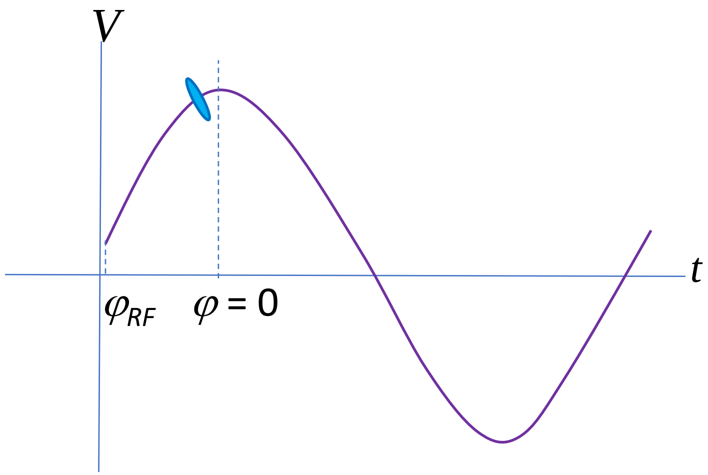
Final σ_z

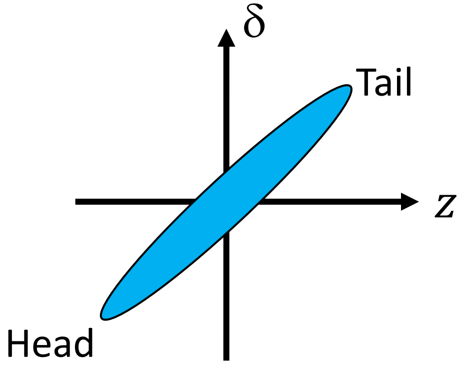
Ballistic compression is negligible at high energy as the magnitude of R_{56} of the drift decreases with the electron beam energy ($1/\gamma^2$).

Longitudinal Phase-space Manipulation

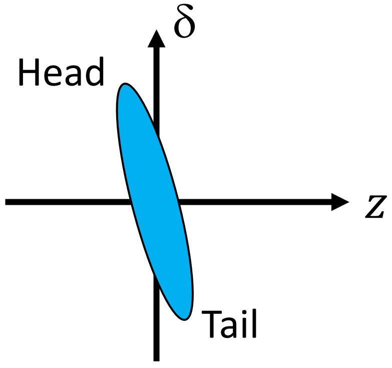


Chirper cavity

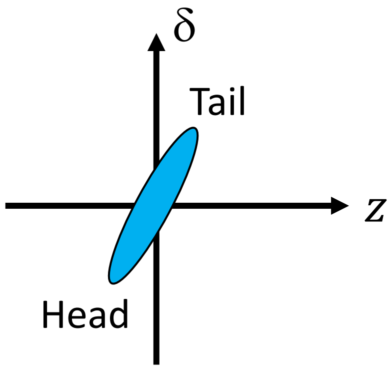




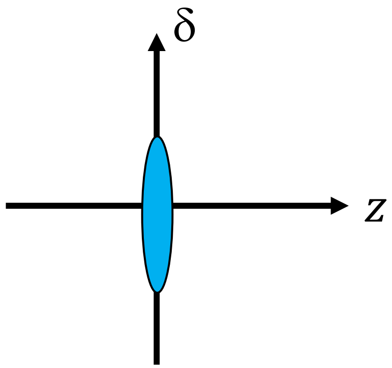
Exit of buncher cavity



Over-compression



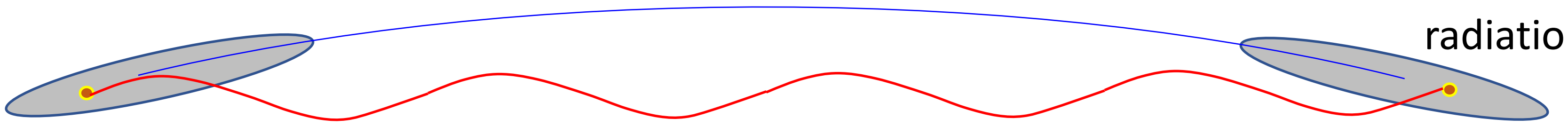
Exit of linac



After compression

Coherent Synchrotron Radiation

Coherent Synchrotron Radiation

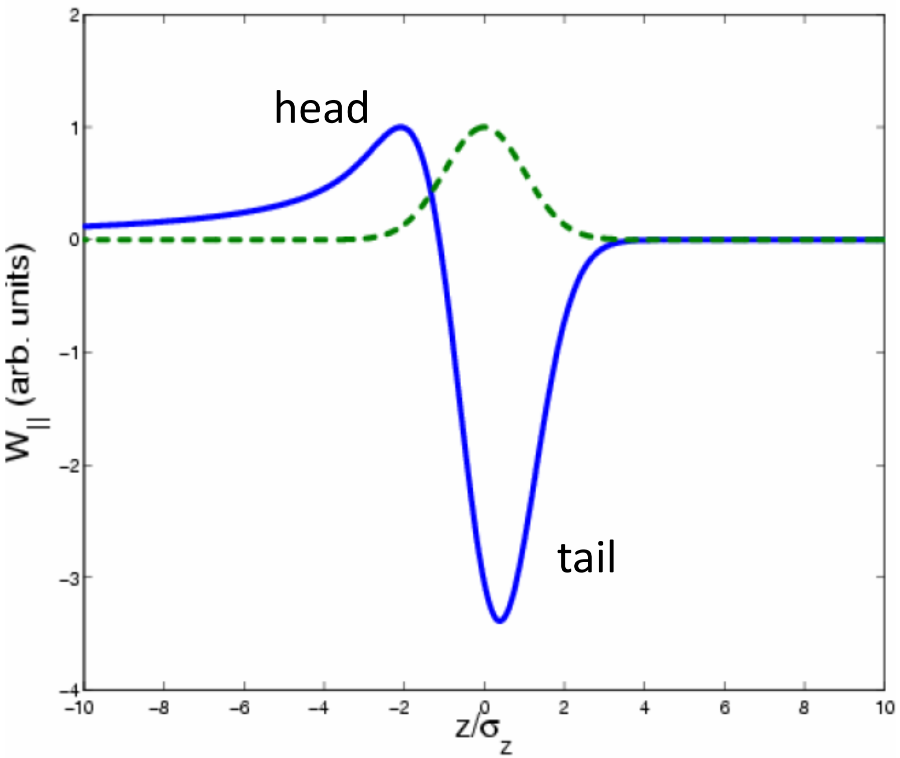


Electrons at the head absorb radiation and gain energy

Electrons in the back of the bunch emit radiation and lose energy

For electron bunches with Gaussian distribution and bunch length longer than the critical wavelength of the synchrotron radiation, the total energy loss can be expressed as

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

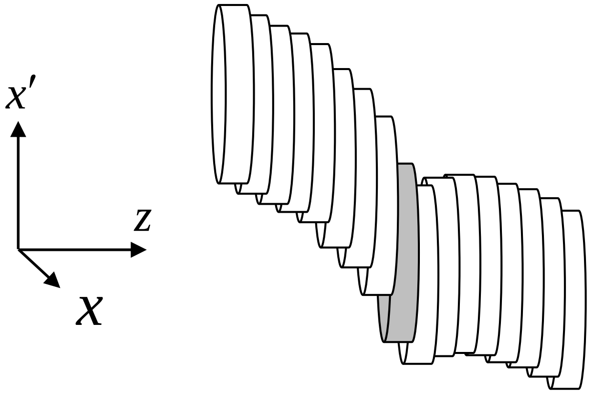


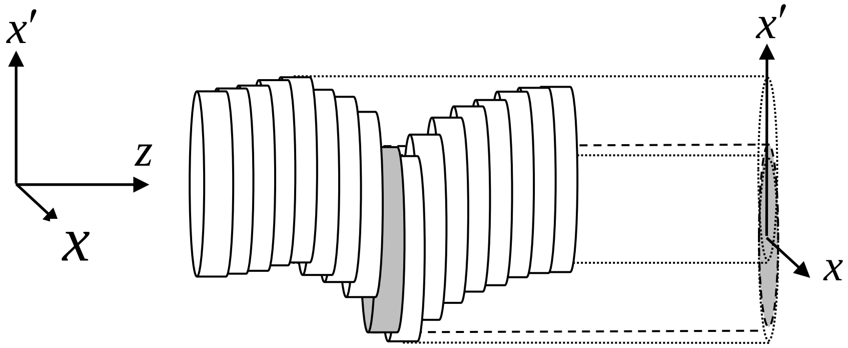
Emittance Growth

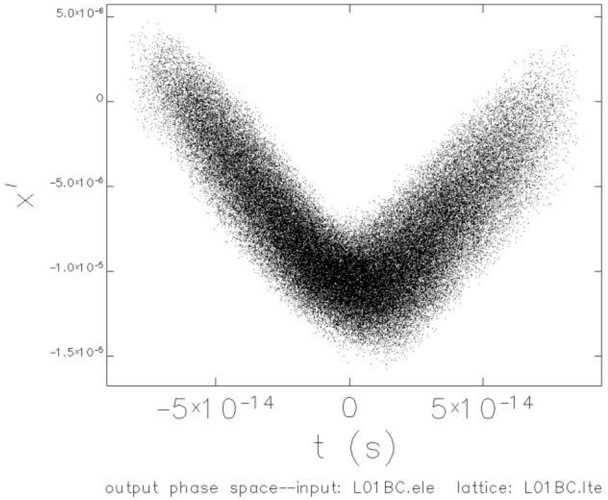
CSR wake and dispersion cause the trace space of different slices to spread out in x’- x space

$$\Delta x = R_{16}\left(\frac{\Delta\gamma}{\gamma}\right)_{CSR}$$

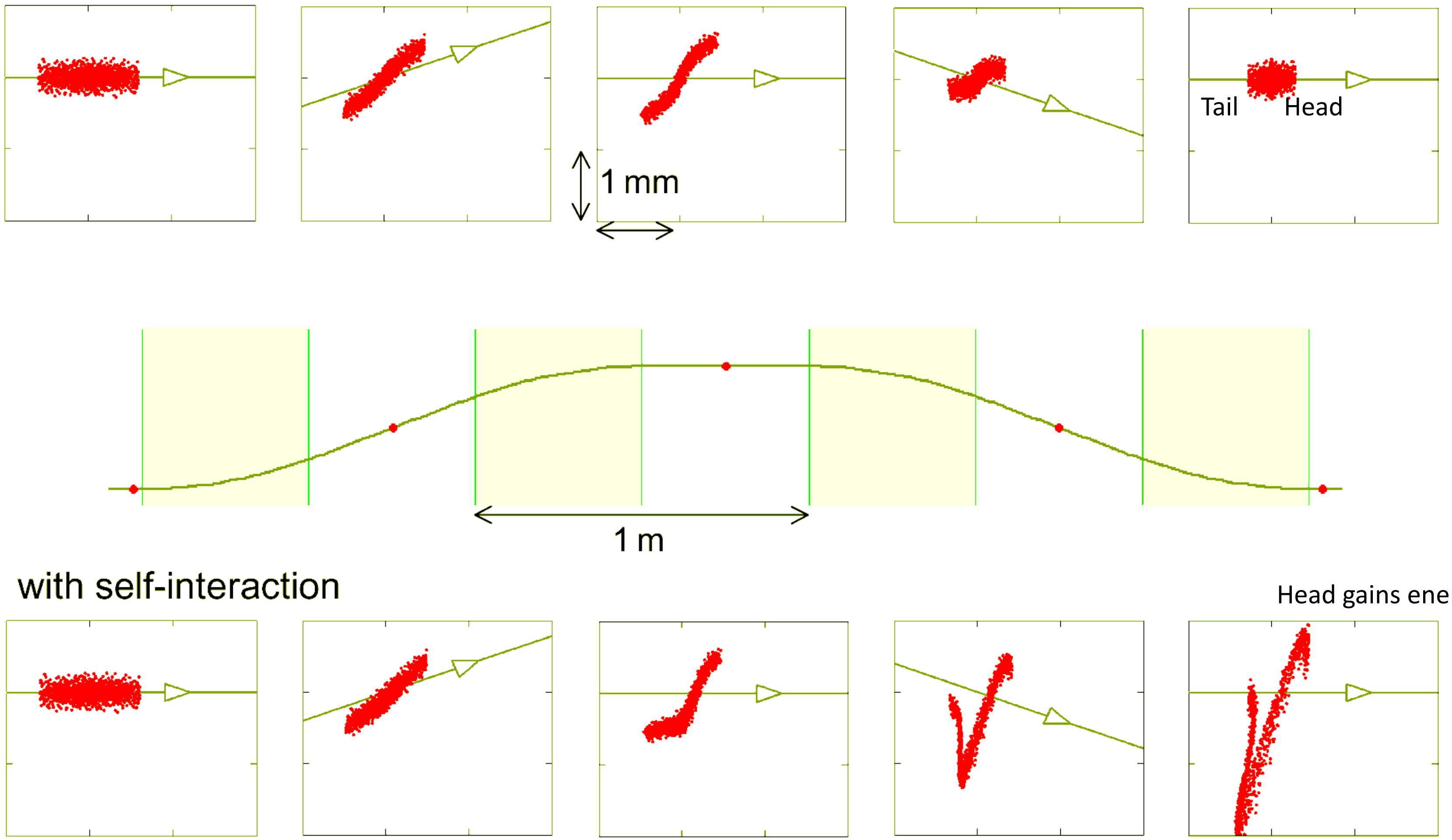
$$\Delta x' = R_{26}\left(\frac{\Delta\gamma}{\gamma}\right)_{CSR}$$







Compression with no CSR and with CSR



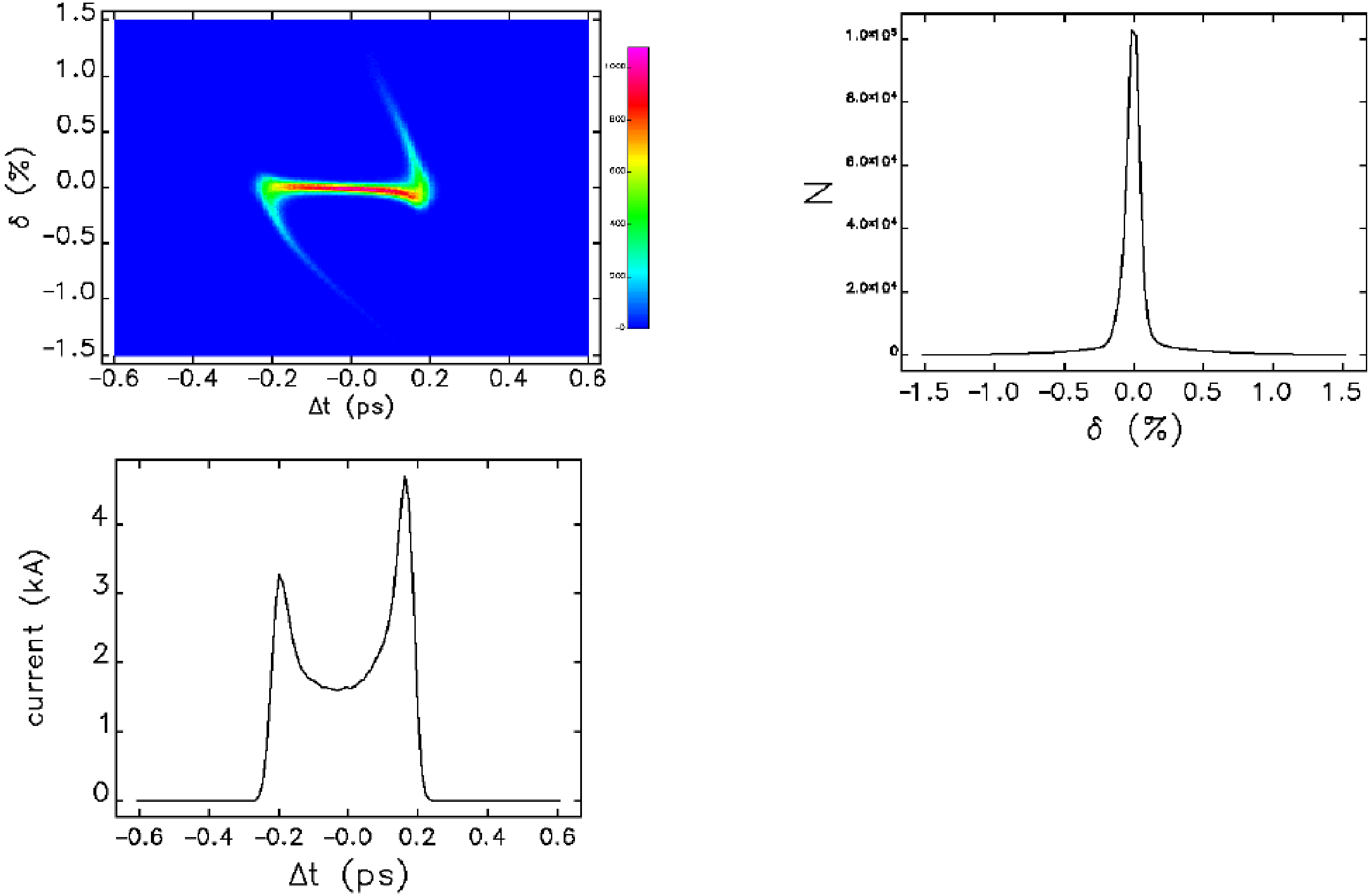
without self-interaction

with self-interaction

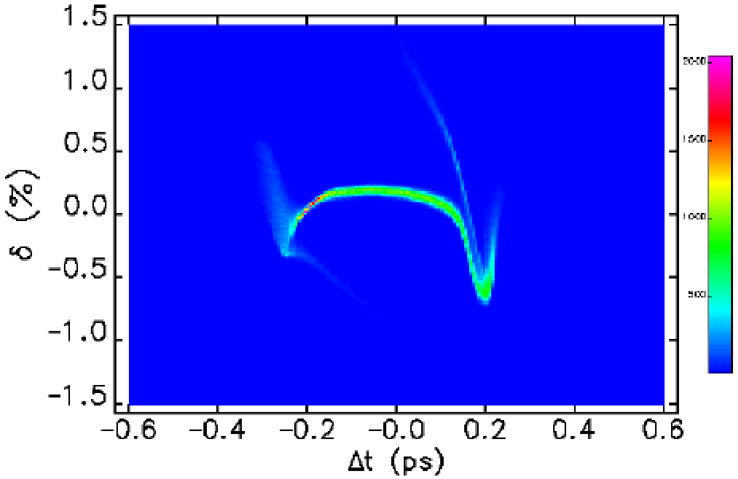
Head gains energy

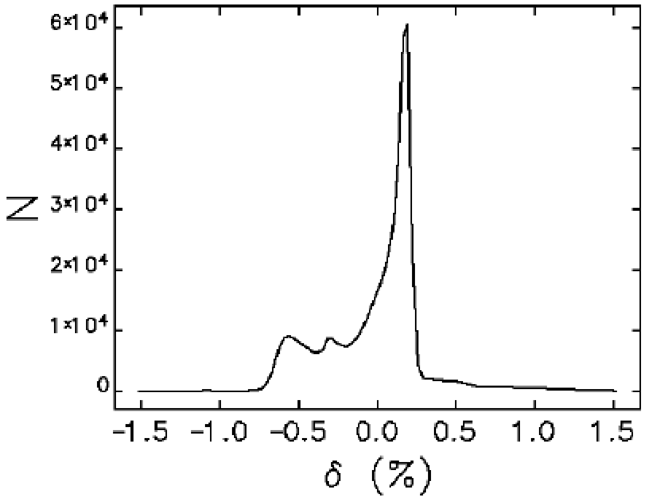
Center & tail lose energy

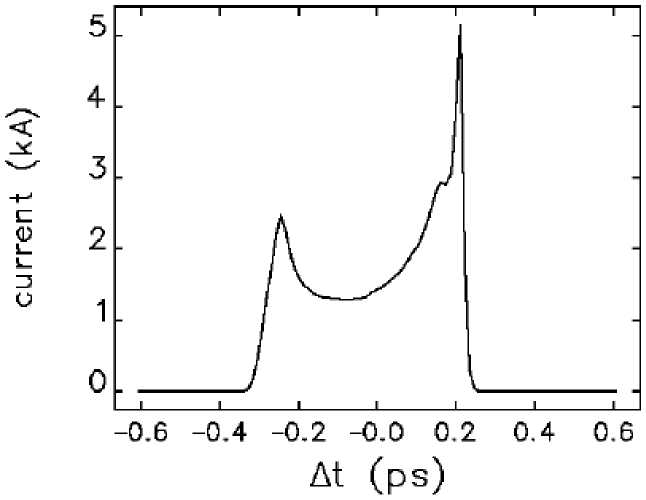
Bunch Compression without CSR



Bunch Compression with CSR

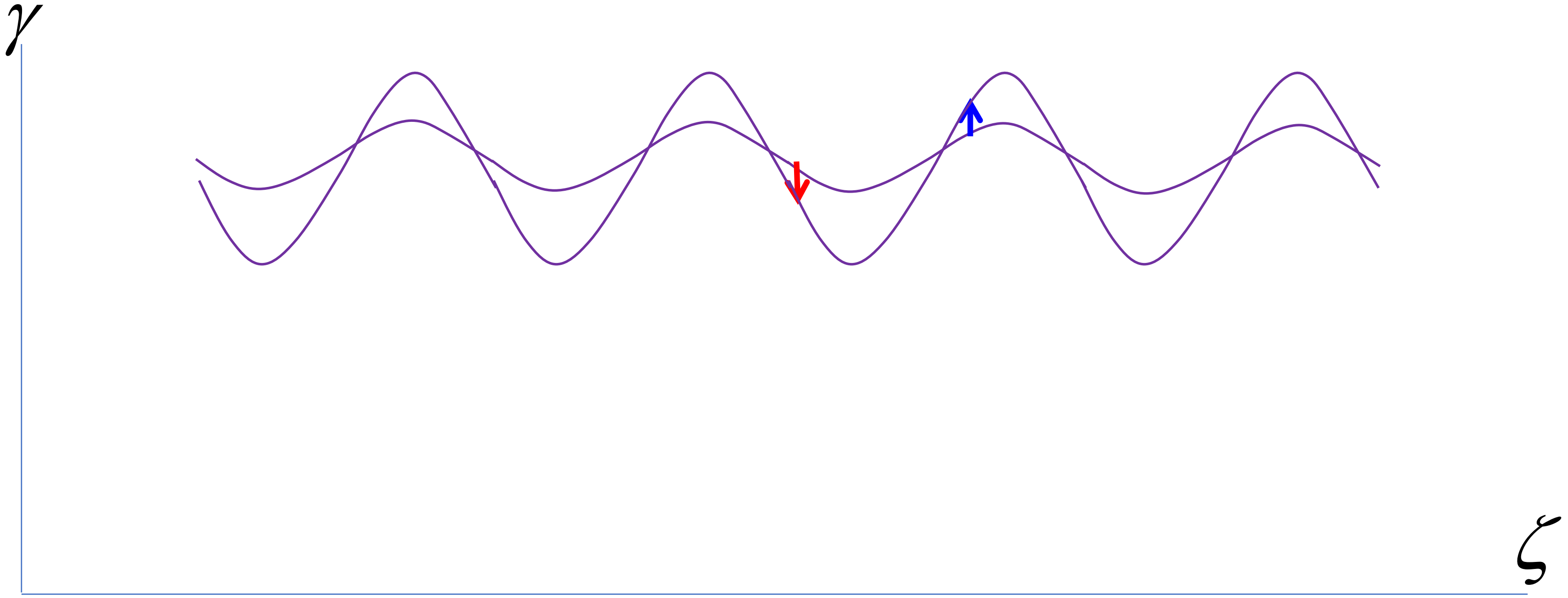






Microbunching Instabilities & Laser Heaters

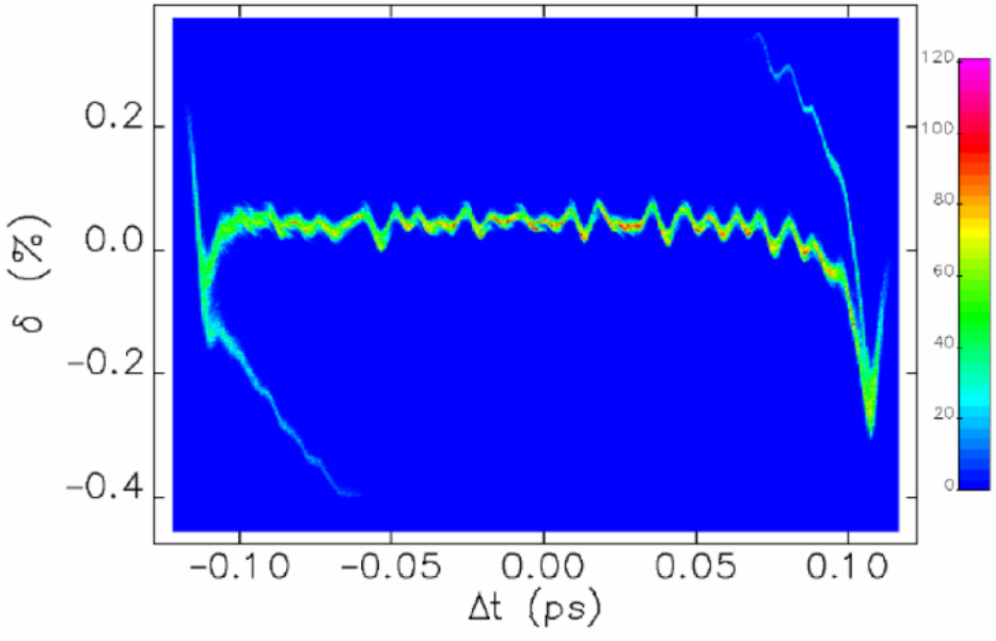
Longitudinal Space Charge

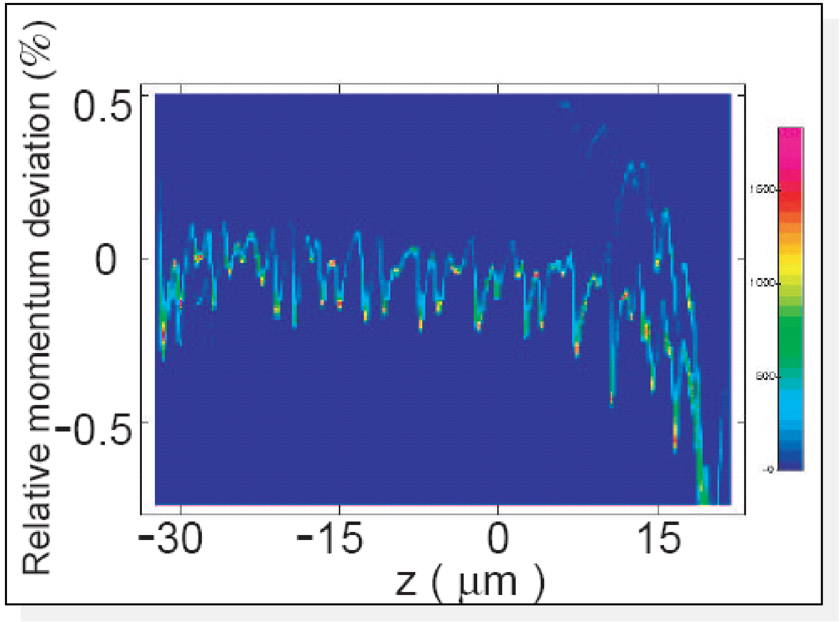


Longitudinal space charge increases the initial small energy modulations which grow with time.

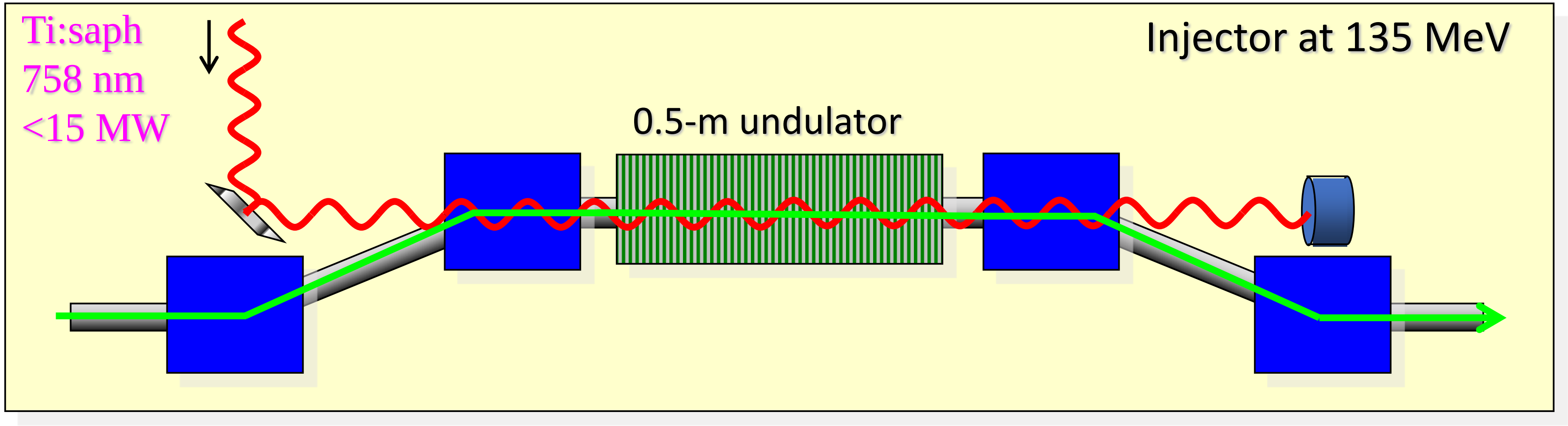
Chicanes convert energy modulations into density modulations and thus magnify the microbunching instabilities.

Microbunching Instabilities



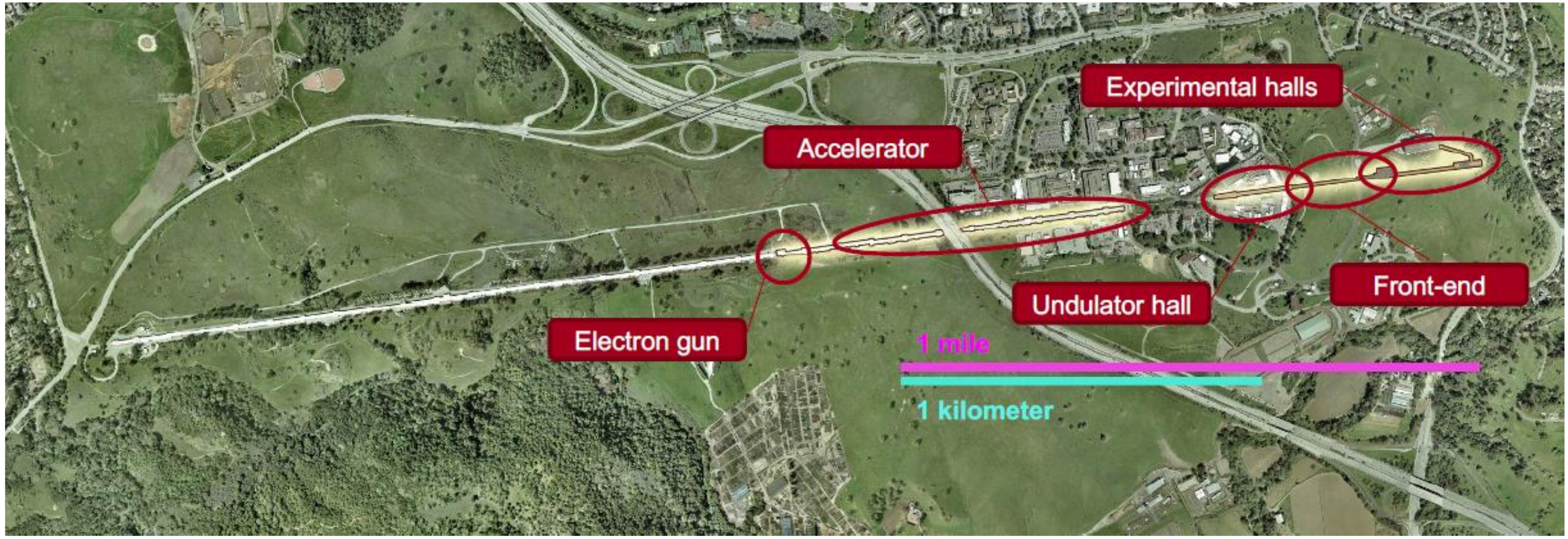


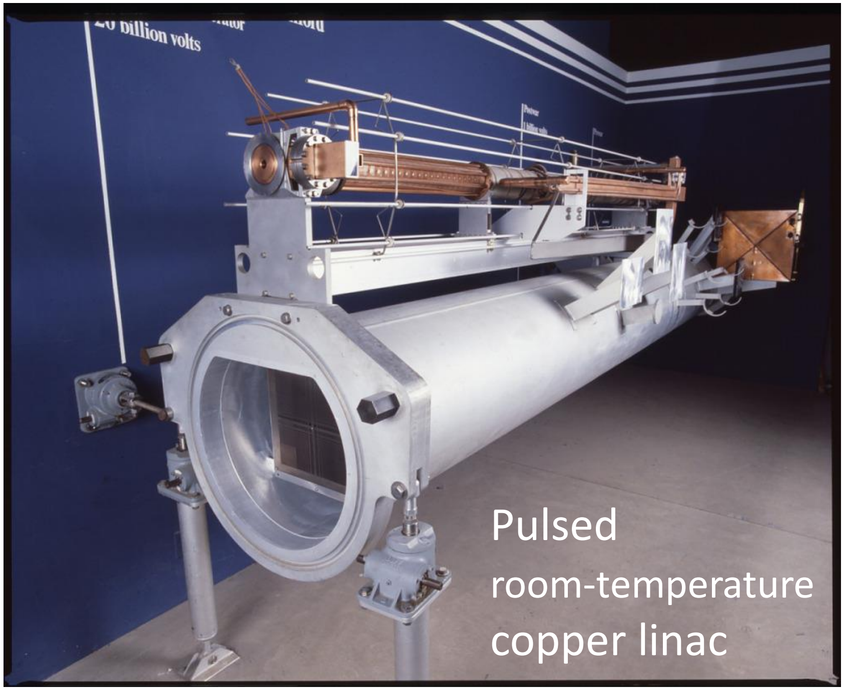
LCLS Laser Heater

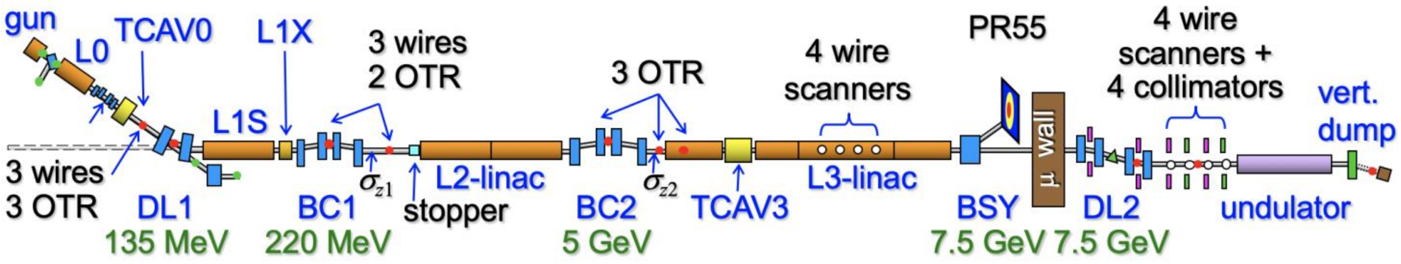


Machine Layout

LCLS Copper Linac X-ray FEL at SLAC



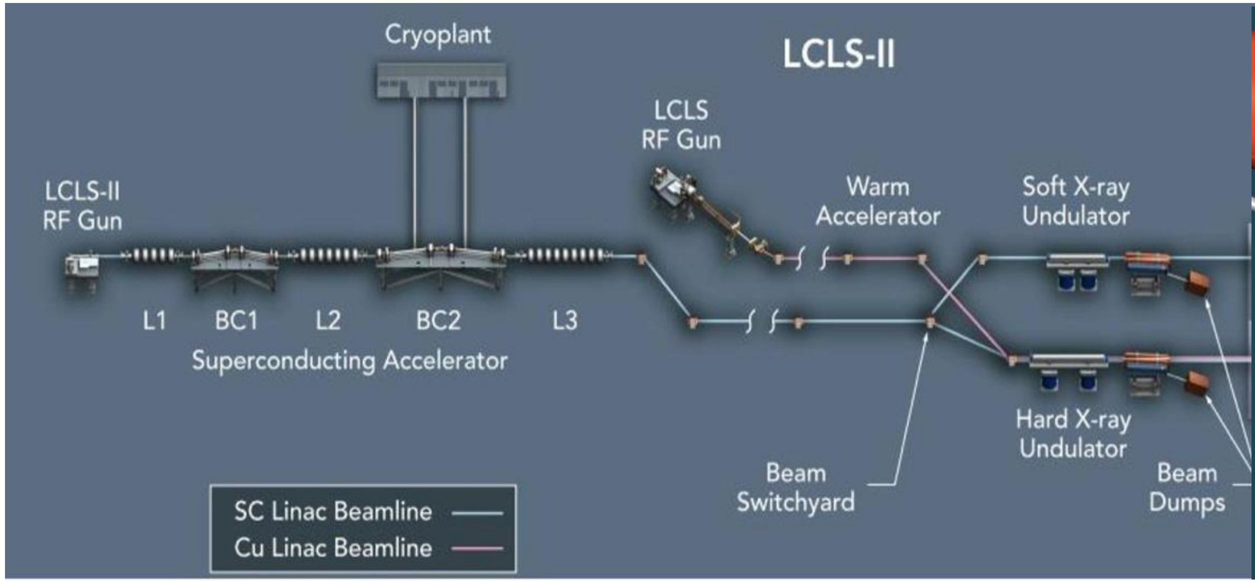

Pulsed room-temperature copper linac

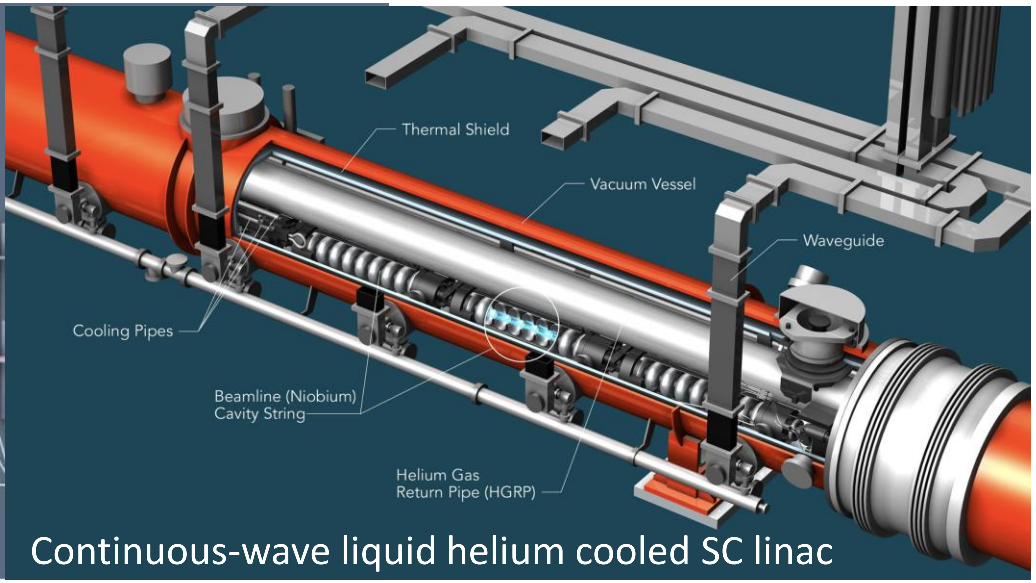


120-Hz X-ray pulse repetition rate

Photoinjector	Injector Linac	Laser Heater	Linac 1	BC1	Linac 2	BC2	Linac 3	Undulators
1.6-cell NC Cu 2.856 GHz	NC Cu S-band 2.856 GHz	760 nm	NC Cu S-band X-band linearizer	R_{56} = -45.5mm	NC Cu 2.856 GHz	R_{56} = -24.7mm	NC Cu 2.856 GHz	Hybrid PMU HXR (v) SXR (h)
6 MeV	135 MeV	135 MeV	250 MeV	250 MeV	5 GeV	5 GeV	15 GeV	25 keV

LCLS-II and LCLS-II-HE at SLAC





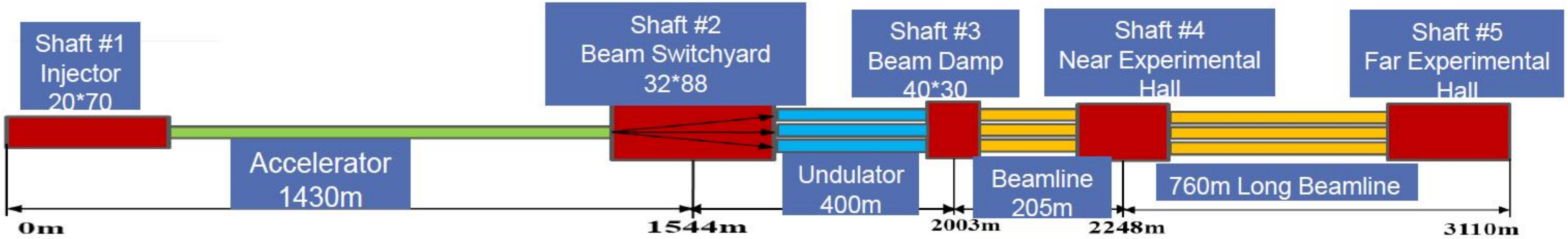
Continuous-wave liquid helium cooled SC linac

	SC Linac	Beam energy
LCLS-II	Injector, L1, L2, L3	4 GeV
LCLS-II-HE	Additional CM in L3, L4	8 GeV

High-repetition-rate (<1 MHz) X-ray pulses

Photoinjector	Injector Linac	Laser Heater	Linac 1	BC1	Linac 2	BC2	Linac 3 & Linac 4	Undulators
186-MHz gun + NC 1.3-GHz bunchers	SC Linac 1.3 GHz	R_{56} = -3.5mm	SC 1.3 GHz 3.9-GHz linearizer	R_{56} = -55mm	SC 1.3 GHz	R_{56} = -37mm	SC 1.3 GHz	Hybrid PMU HXR (v) SXR (h)
0.75 MeV	100 MeV	100 MeV	250 MeV	250 MeV	1.6 GeV	1.6 GeV	8 GeV	0.2 - 20 keV

SHINE XFEL at SINAP



Shaft #1
Injector
20*70

Shaft #2
Beam Switchyard
32*88

Shaft #3
Beam Damp
40*30

Shaft #4
Near Experimental Hall

Shaft #5
Far Experimental Hall

Accelerator
1430m

Undulator
400m

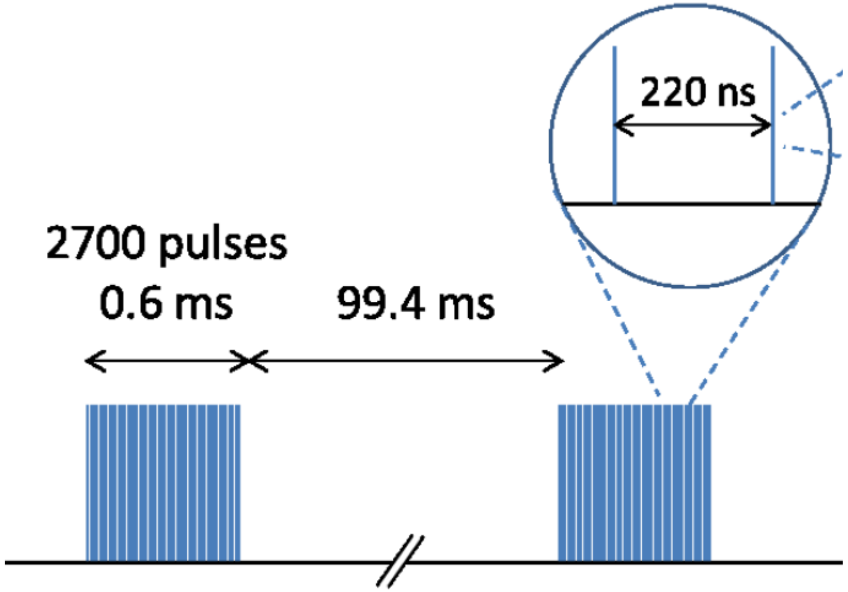
Beamline
205m

760m Long Beamline

0m
1544m
2003m
2248m
3110m

Photoinjector	Injector Linac	Laser Heater	Linac 1	BC1	Linac 2	BC2	Linac 3 & Linac 4	Undulators
217-MHz gun + NC 1.3-GHz bunchers	SC Linac 1.3 GHz	1030 nm	SC 1.3 GHz 3.9-GHz linearizer	R_{56} = -55mm	SC 1.3 GHz	R_{56} = -37mm	SC 1.3 GHz	2 PMU lines 1 SCU line
0.75 MeV/2.4 MeV	100 MeV	100 MeV	270 MeV	270 MeV	1.5 GeV	1.5 GeV	8.6 GeV	0.4 - 25 keV

European X-ray FEL at DESY



SASE 1 has the XFEL highest photon energy

10-Hz macropulse repetition rate

4.5-MHz micropulse repetition rate

Photoinjector	Injector Linac	Laser Heater	BC0	Linac 1	BC1	Linac 2	BC2	Linac 3 & 4	Undulators
1.5-cell NC Cu 1.3 GHz	SC 1.3 GHz 3.9-GHz linearizer	1030 nm	R_{56} = -150 to -30mm	SC 1.3 GHz	R_{56} = -120 to -50mm	SC 1.3 GHz	R_{56} = -80 to -20mm	SC 1.3 GHz	SASE 1-3 HPMU
6 MeV	130 MeV	130 MeV	130 MeV	600 MeV	600 MeV	2.4 GeV	2.4 GeV	17.5 GeV	30 keV

Summary

- X-ray FELs use multi-stage compression to shorten the ps electron bunches from the photoinjector to produce femtosecond bunches with kA peak current.

- Bunch compression is routinely performed with a chirper cavity and a chicane, sometimes in multiple stages through the linac, with counteracting effects of the non-linearities in the cavity (RF curvature), wake field and harmonic linearizer.

- CSR introduces emittance growth and energy spread in the compressed bunch.

- Microbunching instabilities can be mitigated by using a laser heater to increase the energy spread of the low-energy beam to reduce longitudinal space charge.