RF Linac for High-Gain FEL

Bunch Compression

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VI. Bunch Compression

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Overview

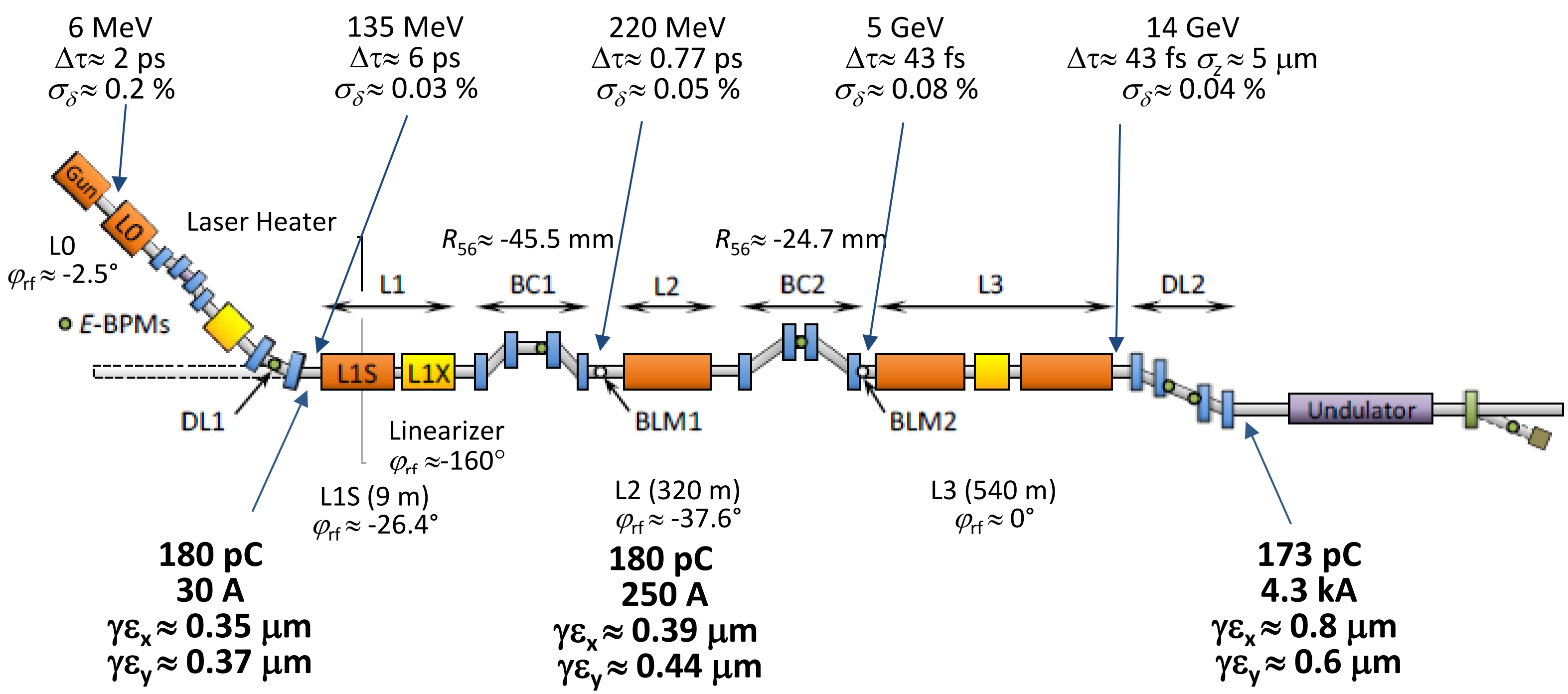
Picosecond electron bunches are produced in RF guns with peak current less than 100 A. Bunch compressors are used to compress the bunches to tens of femtoseconds to produce kA peak current at higher beam energy.

Modern RF linac use highly optimized compression techniques to correct for energy chirp and non-linearities due to RF curvature and wakefields, as well as mitigating collective effects such as CSR and microbunching instability.

The final compressed bunches have peak currents in excess of 3 kA which makes SASE possible at x-ray wavelengths. Emittance growth is minimized with the use of multi-stage chicane compressors. Energy spread is reduced by dechirping the electron bunches after compression. Microbunching instability which can increase both emittance and energy spread is mitigated by “warming” the beam before the bunch compressor with a “laser heater.”

Example: LCLS Bunch Compressor

The LCLS bunch compressor is an example of the multi-stage compressor with post-compression “dechirping” using wake fields in the NCRF linac. The bunches are shortened from 2 ps at the gun to ~40 fs at the undulator (50X compression).



LCLS two-stage bunch compressor

Courtesy of SLAC LCLS Team

Chirper Cavity Transfer Matrix

R_{65} matrix element converts a particle's initial z_0 position (with respect to the initial bunch centroid) to its final energy deviation δ_1 from the central final energy E_{1c}. R_{66} reduces the initial δ_0 by the ratio of the final to initial energy.

$$\begin{pmatrix} z_1 \\ \delta_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ R_{65} & R_{66} \end{pmatrix} \cdot \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix}$$

$$\begin{pmatrix} z_1 \\ \delta_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ h_1 & \dfrac{E_{0c}}{E_{1c}} \end{pmatrix} \cdot \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix}$$

*h*1 is the linear chirp induced by the chirper cavity

$$\boxed{h_1 = -\frac{eV_{RF} k_{RF}}{E_{1c}} \sin \varphi_{RF}}$$

$$z_1 = z_0$$

$$\delta_1 = h_1 z_0 + \frac{E_{0c}}{E_{1c}} \delta_0$$

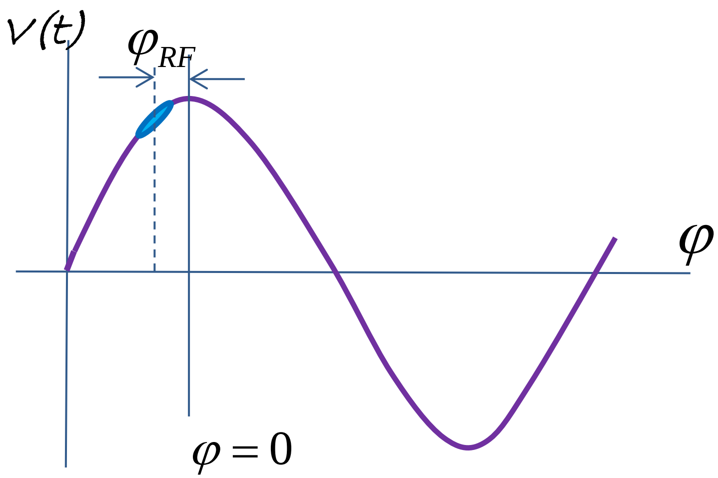
Imposing an Energy Chirp on e- Bunch

Consider a single electron with initial position z_0 and energy deviation δ_0

$$E_0(\delta_0) = E_{0c}(1+\delta_0)$$

Accelerating voltage

$$V(t) = V_{RF}\cos(\varphi_{RF} + k_{RF} z)$$



Final energy after traversing the chirper cavity

$$E_1 = E_0(\delta_0) + eV_{RF}\cos(\varphi_{RF} + k_{RF} z_0)$$

$$E_1 = E_{1c}(1+\delta_1) = [E_{0c} + eV_{RF}\cos(\varphi_{RF})](1+\delta_1)$$

$$\delta_1 = \frac{E_{0c}(1+\delta_0) + eV_{RF}\cos(\varphi_{RF} + k_{RF} z_0)}{E_{1c}} - 1$$

$$\delta_1 = \frac{eV_{RF}}{E_{1c}}\left[\cos(\varphi_{RF} + k_{RF} z_0) - \cos\varphi_{RF}\right] + \delta_0\left(\frac{E_{0c}}{E_{1c}}\right)$$

$$\delta_1 \approx -\frac{eV_{RF} k_{RF} z_0}{E_{1c}}\sin(\varphi_{RF}) + \delta_0\left(\frac{E_{0c}}{E_{1c}}\right)$$

$$\boxed{R_{65} = \frac{\delta_1}{z_0} = -\frac{eV_{RF} k_{RF}}{E_{1c}}\sin\varphi_{RF}}$$

$$\boxed{R_{66} = \frac{\delta_1}{\delta_0} = \frac{E_{0c}}{E_{1c}}}$$

Harmonic Linearizer

- Non-linear chirp

$$\boxed{\delta(z) = \delta_0 + h_1 z + h_2 z^2 + h_3 z^3 + \ldots}$$

- RF curvature

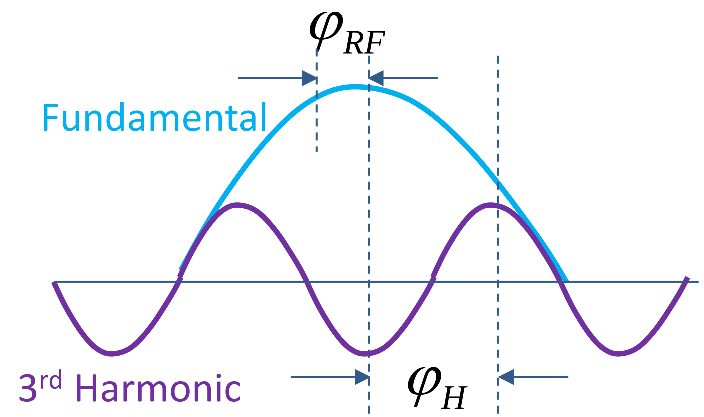
$$h_2 = -\frac{k^2 e V_0 \cos\varphi_{RF}}{2E_{fc}}$$

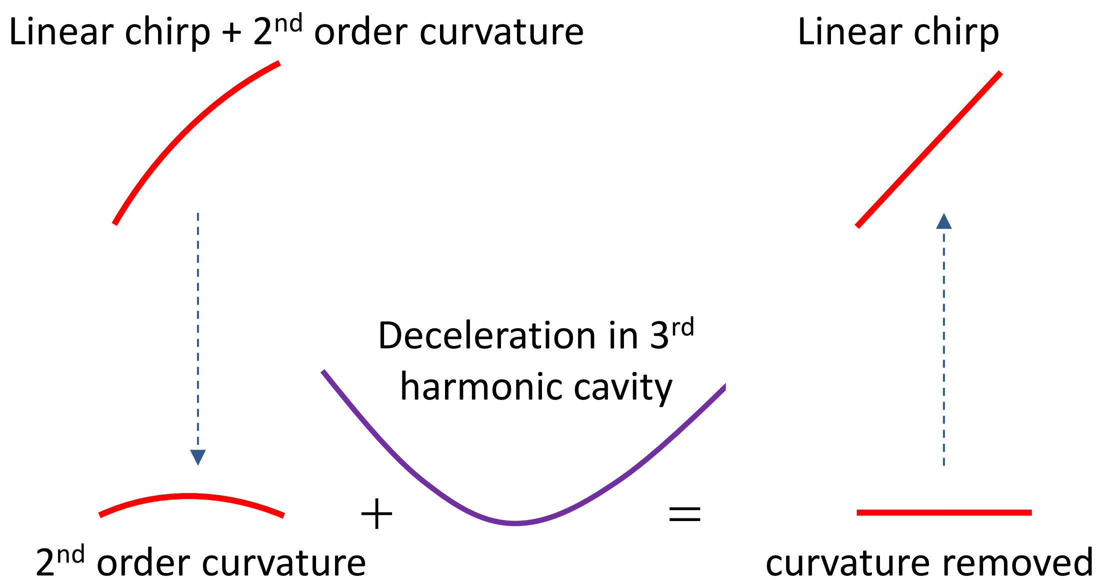
- Harmonic linearization

$$E_H = -k_H e V_H \cos\varphi_H$$

$$\varphi_H \approx -\pi$$

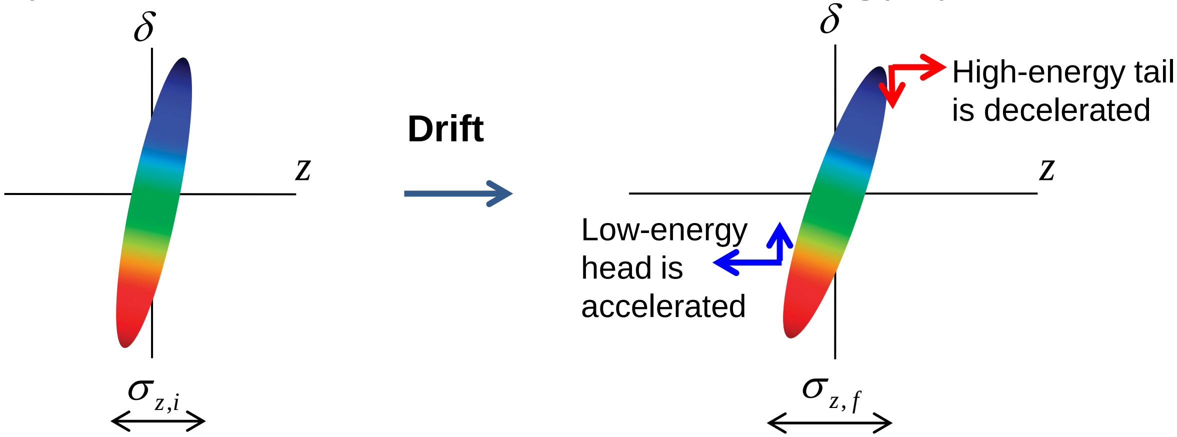
- Deceleration in a harmonic cavity reduces RF curvature caused by the fundamental





Space Charge Effects

Space charge stretches the bunch length, reduces the energy slew of a positively chirped bunch and increases the rms energy spread

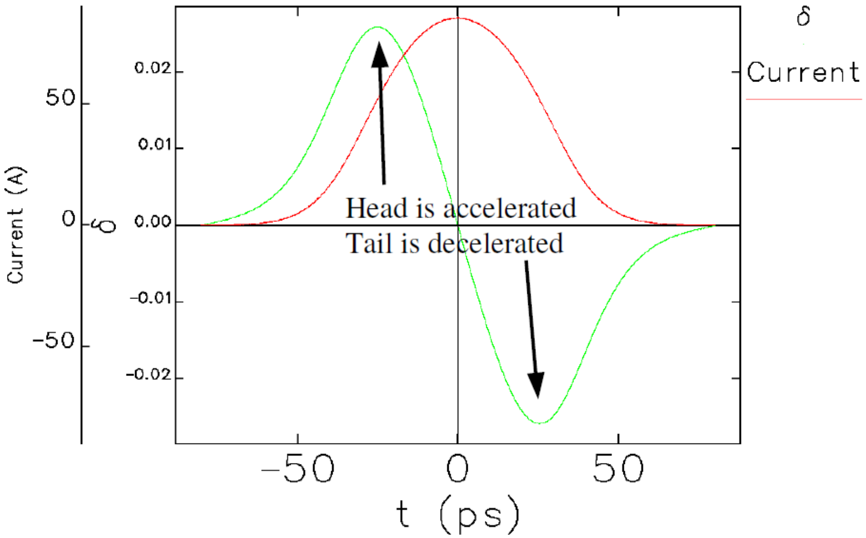


Space charge effect on bunch length

$$F_z = \frac{dp_z}{dt} = m\frac{dv_z}{dt} + v_z\frac{dm}{dt}$$

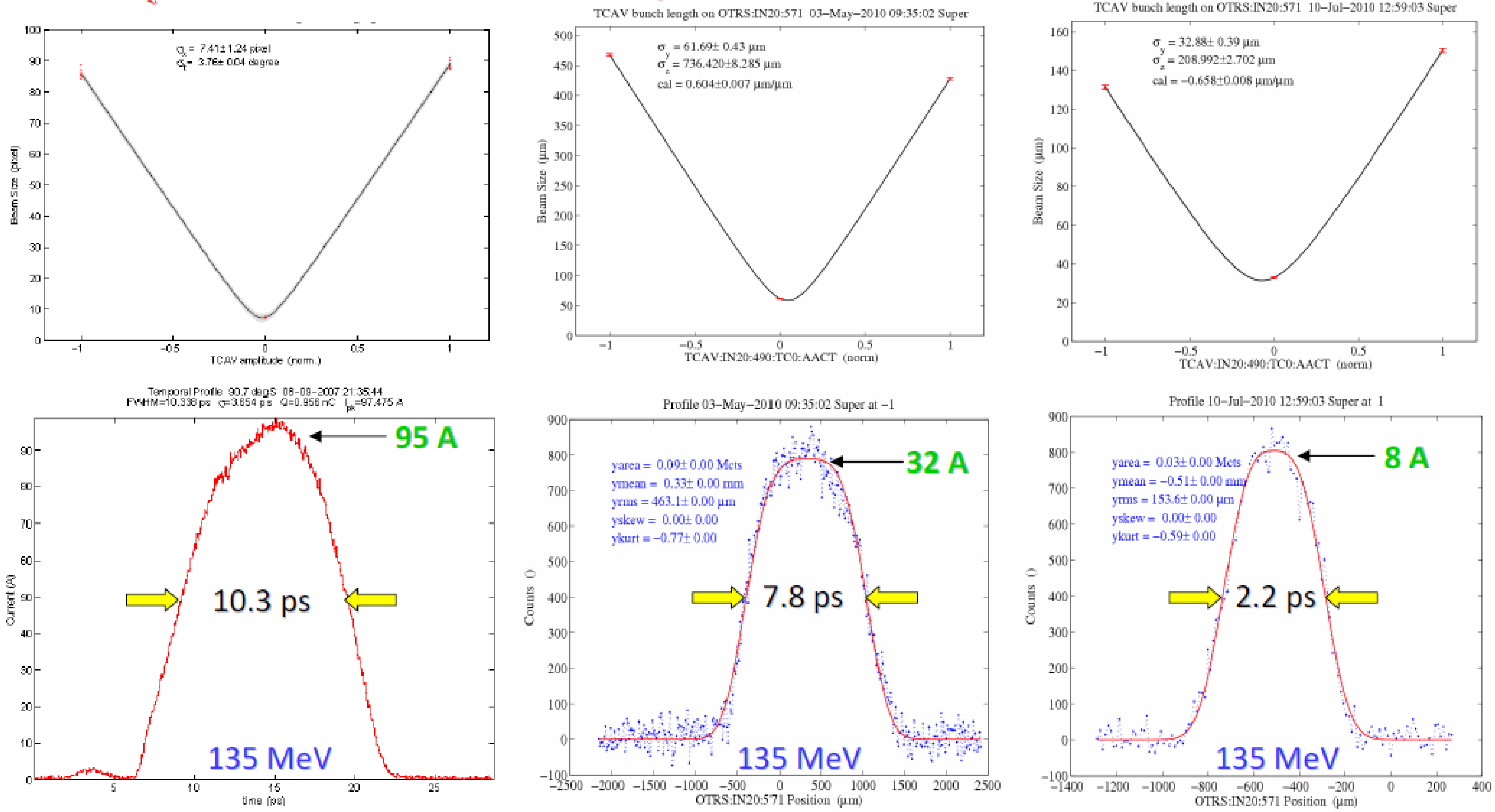
$$F_z = m_0 c\left[\gamma\frac{d\beta}{dt} + \beta\frac{d\gamma}{dt}\right] = m_0 c\gamma^3\frac{d\beta}{dt}$$

$$\frac{d^2 z}{dt^2} = \frac{F_z}{m_0\gamma^3} = k_{SC}^2 z$$



Space charge increases both bunch length and longitudinal emittance

1 nC	0.25 nC	0.020 nC
$\sigma_z = 1.10$ mm rms	$\sigma_z = 0.74$ mm rms	$\sigma_z = 0.21$ mm rms



$\gamma\varepsilon_z \approx \sigma_z(3\ \mathrm{keV})/mc^2 = 6.5\ \mu\mathrm{m}$

$\gamma\varepsilon_z \approx \sigma_z(1\ \mathrm{keV})/mc^2 = 0.4\ \mu\mathrm{m}$

Compressor Transfer Matrix

R_{56} matrix element converts a particle's initial energy deviation (with respect to the central energy) to its final z position with respect to the centroid position.

$$\begin{pmatrix} z_f \\ \delta_f \end{pmatrix} = \begin{pmatrix} 1 & R_{56} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} z_i \\ \delta_i \end{pmatrix}$$

Since z is in unit of length and d is dimensionless, R_{56} matrix element is also in unit of length. Typical value of R_{56} is a few cm.

Final position of an electron

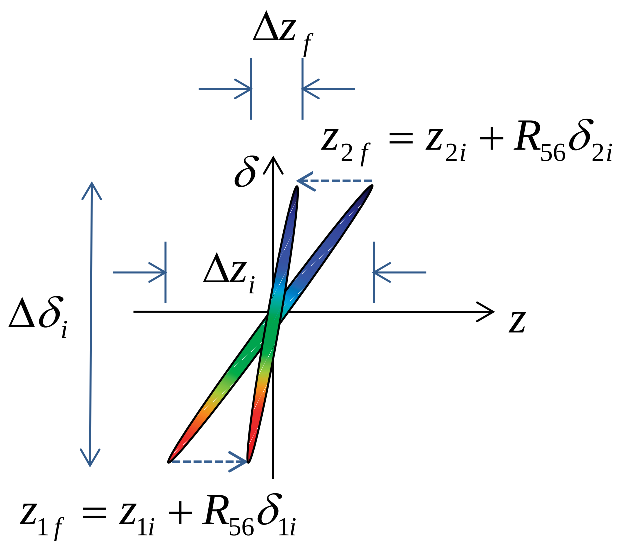
$$z_f = z_i + R_{56}\delta_i$$

Change in bunch length

$$\Delta z_f = \Delta z_i + R_{56}\Delta\delta_i$$

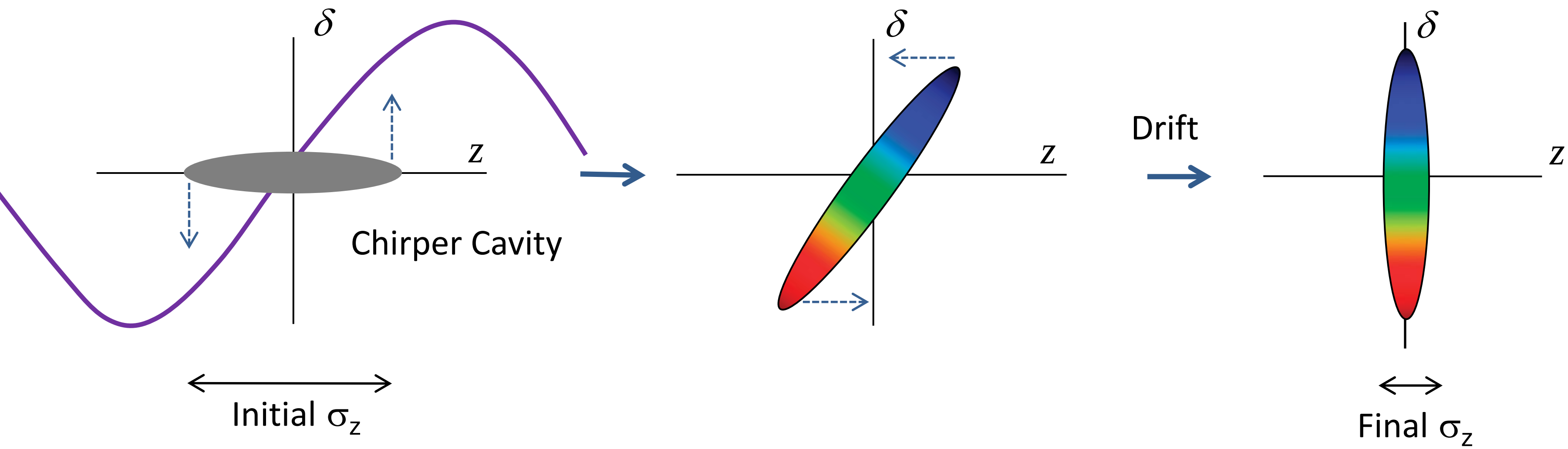
Ratio of final to initial length

$$\frac{\Delta z_f}{\Delta z_i} = 1 + R_{56} h_1$$



Ballistic Compression

Ballistic compression is carried out by chirping an electron bunch in a chirper cavity at zero crossing, followed by a drift where slow electrons at the head move back with respect to the centroid and fast electrons at the tail catch up with the centroid.

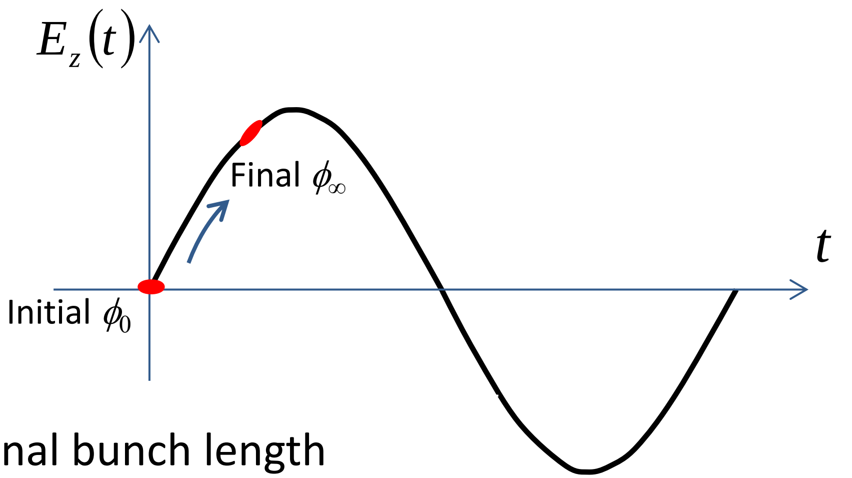


Ballistic compression is typically done at low beam energy (<2 MeV) because the magnitude of R_{56} decreases quadratically with beam energy ($1/\gamma^2$).

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

Velocity Compression

Sub-relativistic electrons ($\beta_c < 1$) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave ($\beta_{RF} \sim 1$). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed.



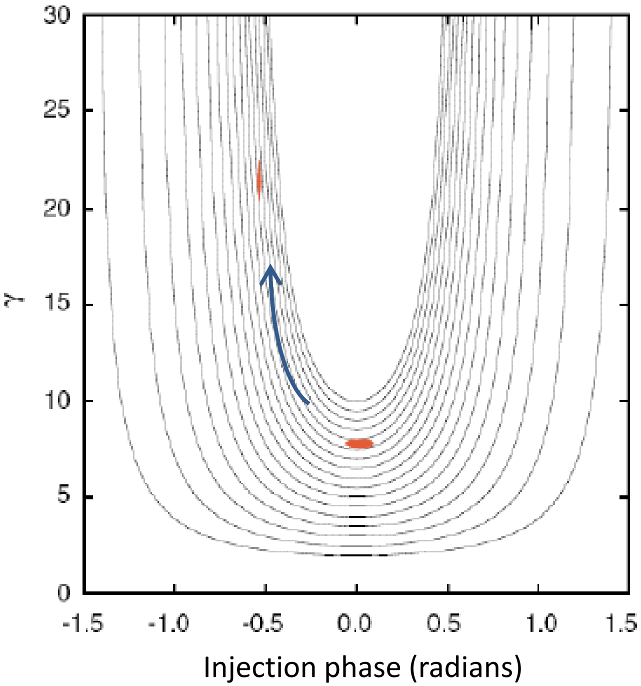
Final bunch length

$$\boxed{\sigma_{z_f} = \frac{\sin\phi_0}{\sin\phi_\infty}\sigma_{z_i} + \frac{1}{2\alpha\gamma_0^2\sin\phi_\infty}\sigma_{\gamma_i}}$$

Dimensionless gradient $\alpha = \dfrac{eE_0}{k_{RF} m_e c^2}$

1st term = injection phase slippage

2nd term = contribution from initial energy spread

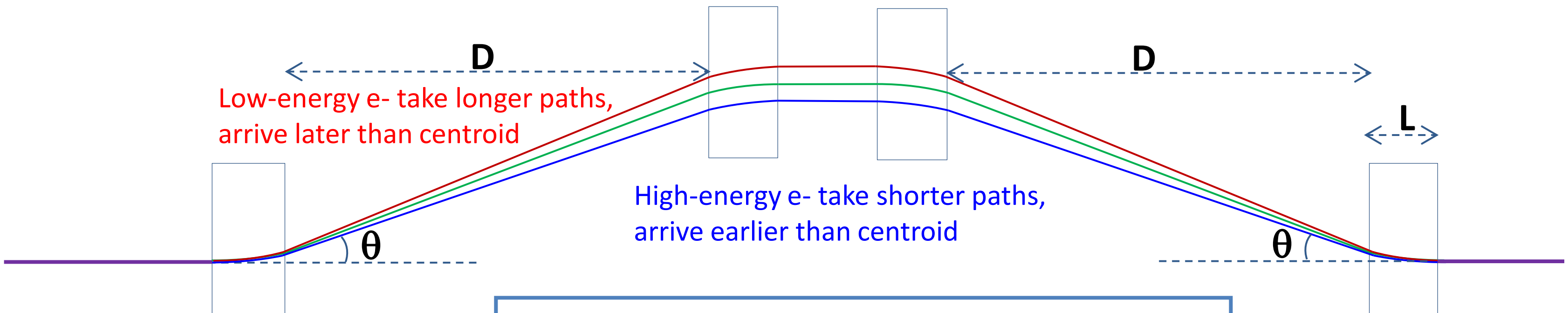


Initial β_c = 0.994 (4 MeV)

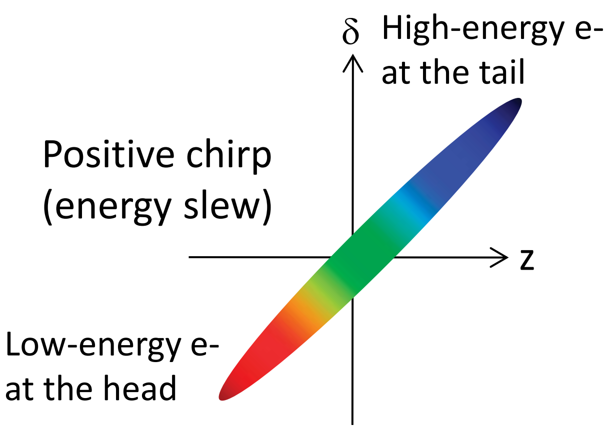
See Wangler, Chapter 6 (6.10)

Chicane Compressor

A chicane consists of four rectangular dipoles length L with the 1st and 2nd (also 3rd and 4th) separated by distance D. The distance between 2nd and 3rd does not contribute to R_{56}.



$$\boxed{\Delta z = R_{56}\delta_1 + T_{566}\delta_1^2 + U_{5666}\delta_1^3 + \dots}$$

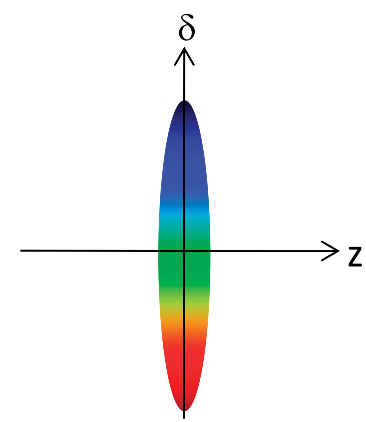


Chirped, uncompressed bunch

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

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

$$U_{5666} \approx 2R_{56}$$



Compressed bunch

Chirper-Chicane Transfer Matrix

Transfer matrix of the RF chirper cavity (*h_1* denotes the linear chirp)

$$\begin{pmatrix} z_1 \\ \delta_1 \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ h_1 & \dfrac{E_{0c}}{E_{1c}} \end{pmatrix} \cdot \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix}$$

Transfer matrix of the chicane

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

initial beam

Multiply the two matrices together

final beam

$$\begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix} = \begin{pmatrix} 1 + h_1 R_{56} & R_{56} \dfrac{E_{0c}}{E_{1c}} \\ h_1 & \dfrac{E_{0c}}{E_{1c}} \end{pmatrix} \cdot \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix}$$

Minimum Compressed Bunch Length

rms bunch length at end of the chicane

$$z_2 = (1 + h_1 R_{56}) z_0 + \left(\frac{E_{0c}}{E_{1c}} \right) R_{56} \delta_0$$

For an upright ellipse

$$\sigma_{z,f} = \sqrt{(1 + h_1 R_{56})^2 \sigma_{z,i}^2 + \left(\frac{E_{ic}}{E_{fc}} \right)^2 R_{56}^2 \sigma_{\delta,i}^2}$$

Minimum bunch length is achieved when the chicane undoes the chirp

$$R_{56} = -\frac{1}{h_1} = -\frac{1}{R_{65}} \longrightarrow 1 + h_1 R_{56} = 0$$

Minimum bunch length depends on R_{56} and initial "slice" energy spread

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

Correcting Non-linear Chirp using Longitudinal Short-range Wake Fields

Relative energy chirp

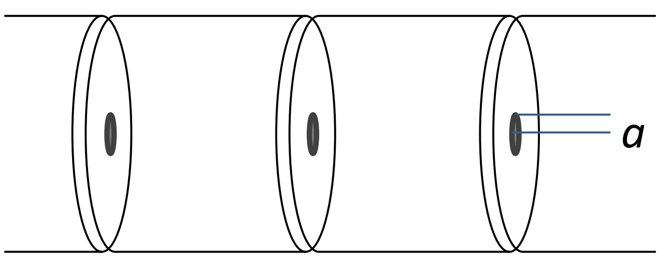
$$\boxed{\delta(z) = \delta_0 + h_1 z + h_2 z^2 + h_3 z^3 + \ldots}$$

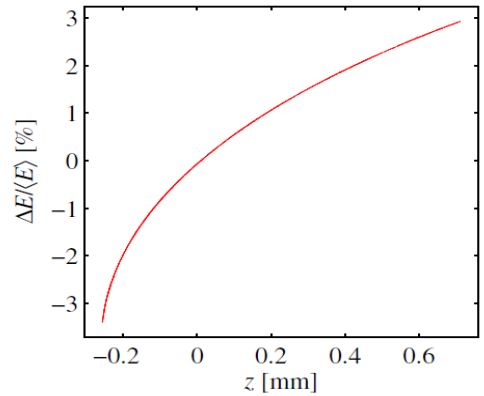
Non-linear chirp due to RF curvature

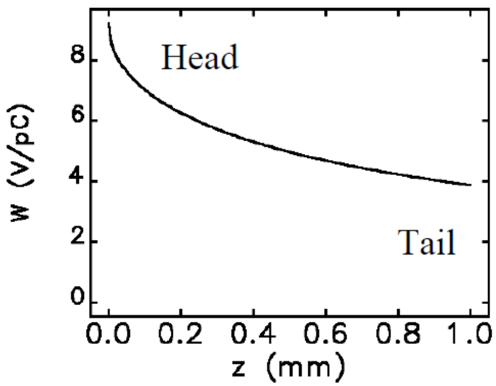
$$h_2 \approx -\frac{k^2 \cos\varphi_c}{2}$$

Longitudinal wake field, in unit of V/(pC-m)

$$\kappa \approx \frac{Z_0 c}{\pi a^2} \qquad \Delta E \approx -q\kappa L$$

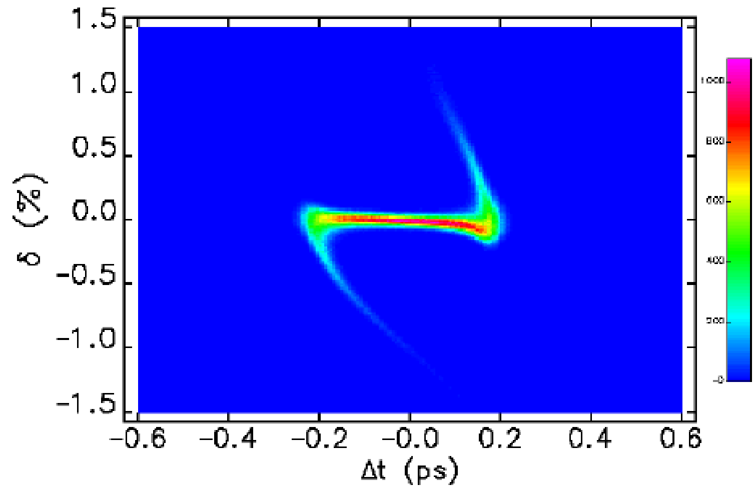


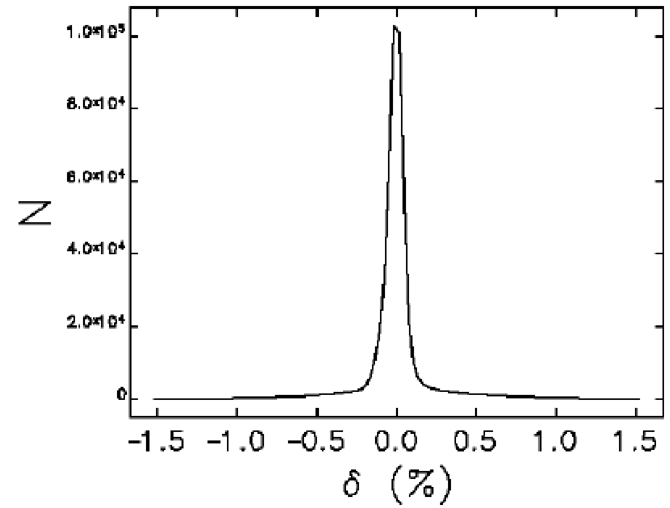


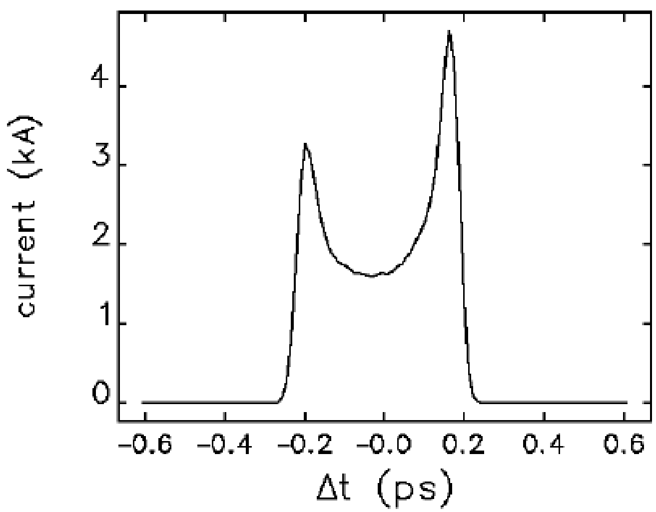


Short-range wake field in NCRF linac is often used to “dechirp”, i.e. remove both the linear energy chirp and 2nd order curvature, in the final compressed bunch.

Chicane Compression without CSR



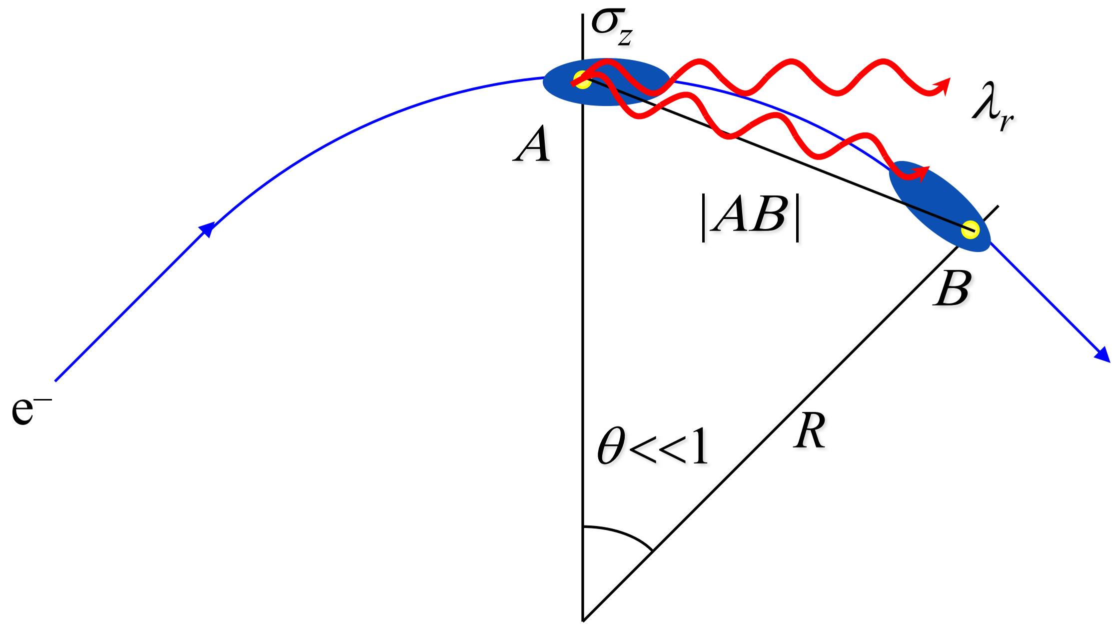




Simulated output from a chicane compressor with post-compression wake field to dechirp the bunch without CSR. Note that the core has negligible energy slew (horizontal line) with small energy spread but the two “horns” at the ends have large energy swings. Only the core electrons contribute to FEL “lasing.”

Courtesy of M. Borland

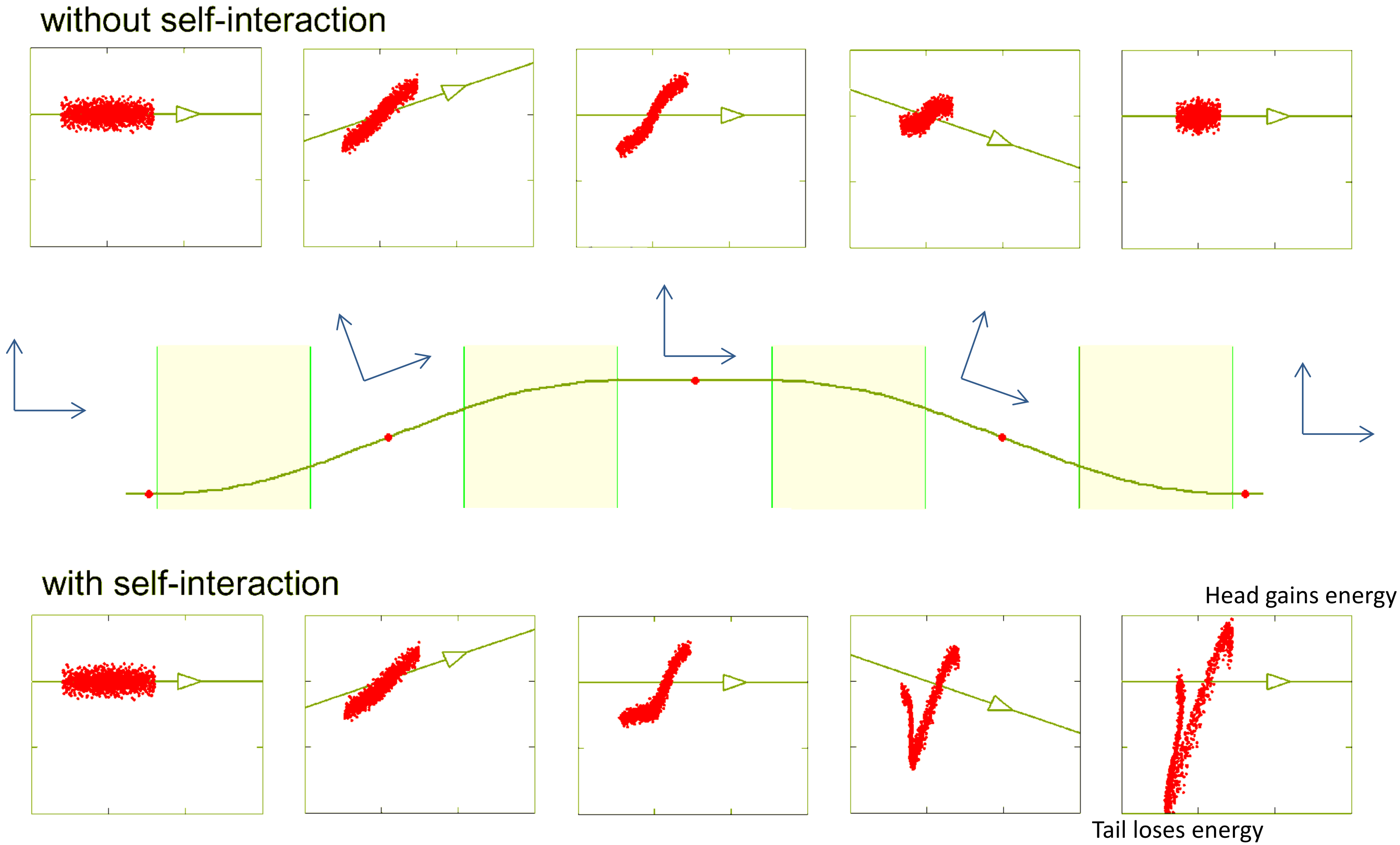
Coherent Synchrotron Radiation



Radiation from the tail at point A travels in a straight line and catches up with the head of the electron bunch at point B. The overtaking distance, |AB|, is

$$L_0 = |AB| \approx \left(24\sigma_z R^2\right)^{\frac{1}{3}}$$

Coherent Synchrotron Radiation



Courtesy of M. Dohlus

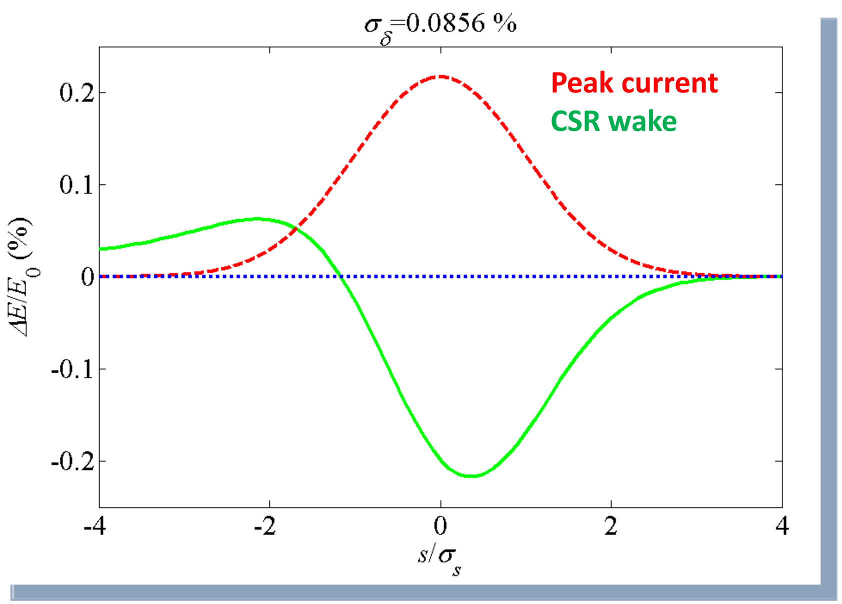
Effect of CSR on Electron Energy

CSR energy wake

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

Q	bunch charge (coulomb)
R	bend radius (m)
θ	bend angle (mrad)
σ_z	compressed length (m)
E_c	centroid beam energy (MeV)

CSR wake is approximately the mirror image of peak current profile



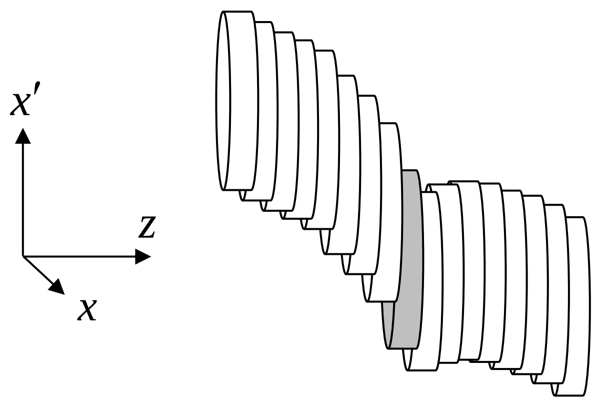
CSR causes an energy slew similar to the short-range wakefield. CSR is minimized by operating at low charge, increasing the bend radius and reducing the bend angle.

Effect of CSR on x'-x Trace Space

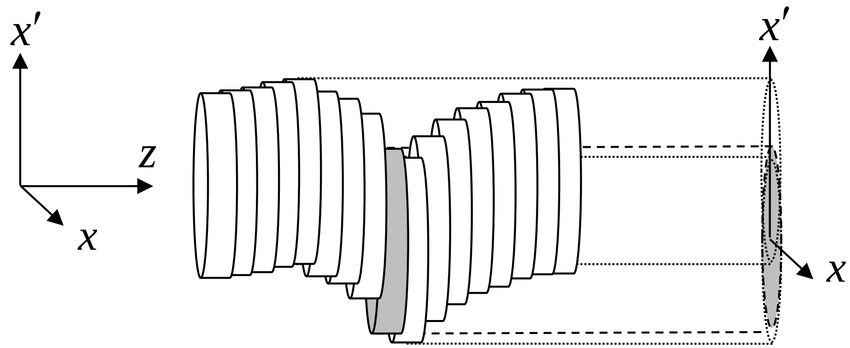
CSR wake and dispersion cause the trace space of different slices to spread out in x'- x space

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

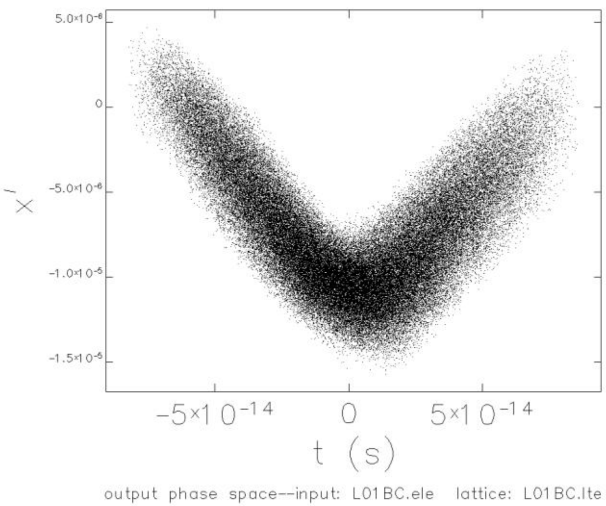
$$\Delta x' = R_{26}\left(\frac{\Delta\gamma}{\gamma}\right)_{CSR}$$



x' – x trace space of different slices (chirped)



x' – x trace space of different slices (chirp removed)



Courtesy of D. Douglas

Effect of CSR on Energy Spread and Projected Emittance

In the regime of short electron bunches ($\sigma_z < s$), long magnets and Gaussian linear charge distribution, the CSR-induced rms energy spread is given by

$$\sigma_\delta = 0.2459 \frac{r_e N_e}{R^{2/3} \sigma_z^{4/3}} \left(\frac{R\theta}{\gamma} \right)$$

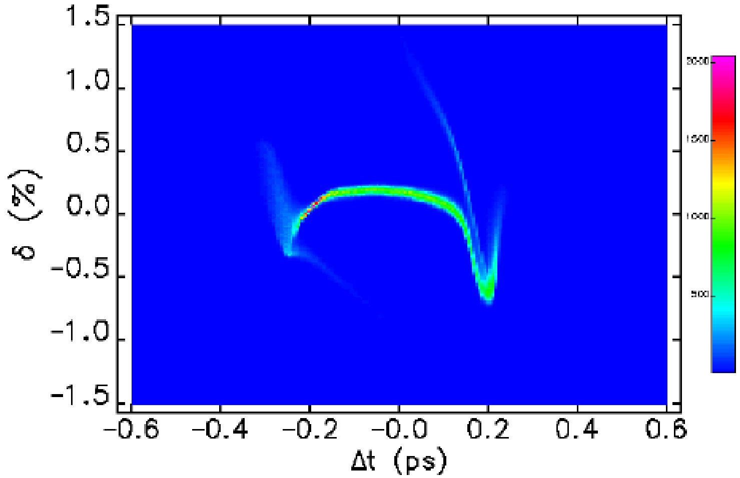
Due to dispersion in the chicane matrix, both R_{16} and R_{26} terms, the CSR-induced energy spread results in an emittance growth, relative to the initial emittance, as

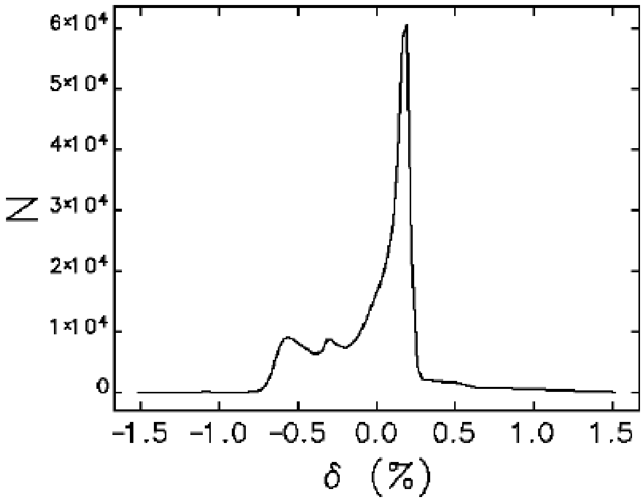
$$\boxed{\frac{\Delta\varepsilon}{\varepsilon} \approx \frac{1}{2} \frac{\beta}{\varepsilon} \theta^2 \sigma_\delta^2}$$

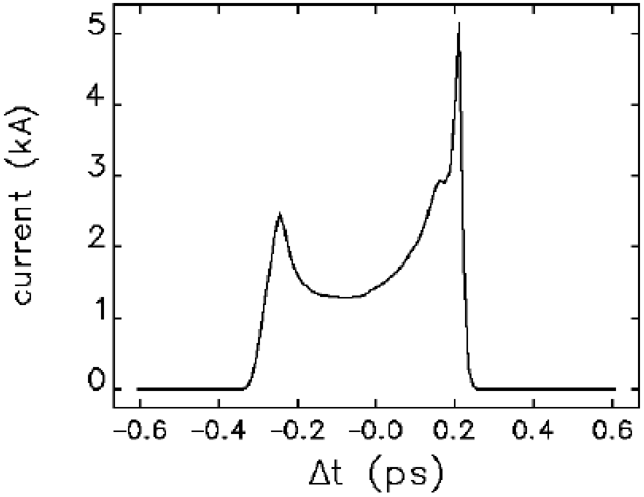
Choose a small β-function or small bend angle, basically to reduce the relative effect of CSR on the electrons' bend angle compared to the beam divergence angle, in the latter half of the chicane to minimize CSR-induced emittance growth.

Reference: S. Di Mitri, "Design and Simulation Challenges of a Linac-Based Free Electron Laser in the Presence of Collective Effects," Free Electron Lasers, Dr. Sandor Varro (Ed.), ISBN: 978-953-51-0279-3, InTech, available at: www.intechopen.com/books/free-electron-lasers

Chicane Compression with CSR



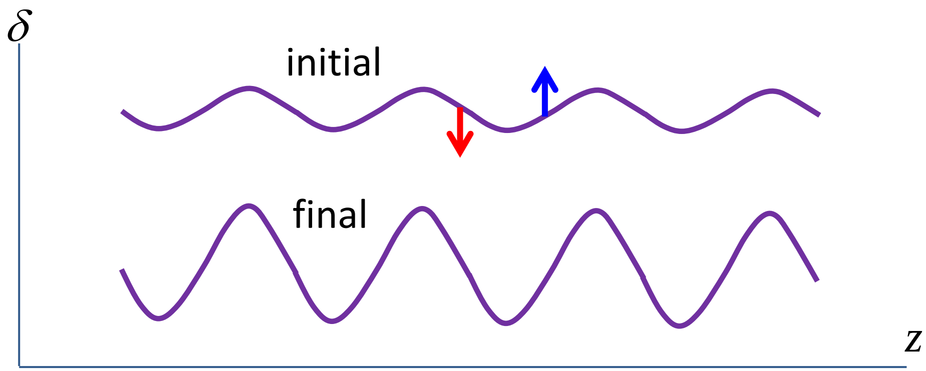




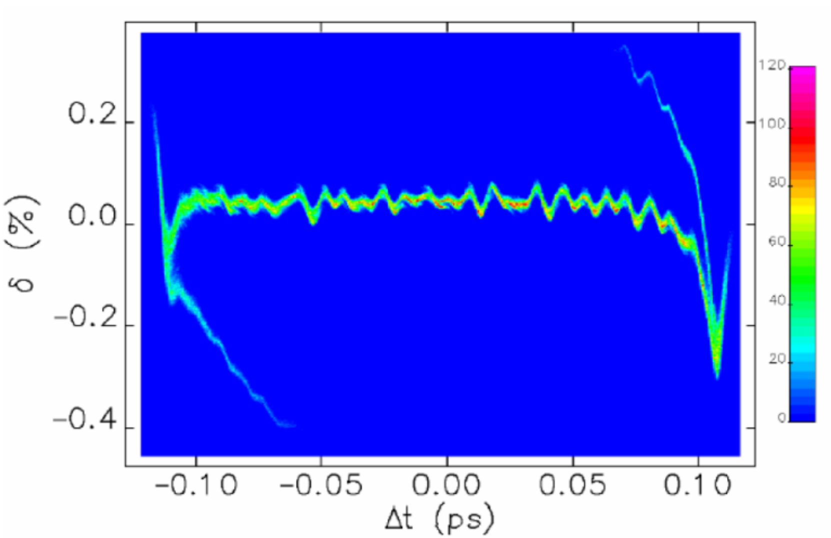
CSR causes an increase in the slice emittance, imposes an energy slew on the "core" and thus reduces the number of FEL usable electrons, as well as increasing the energy spread in the two "horns" at the ends. The width of the electron energy spectrum is the CSR wake.

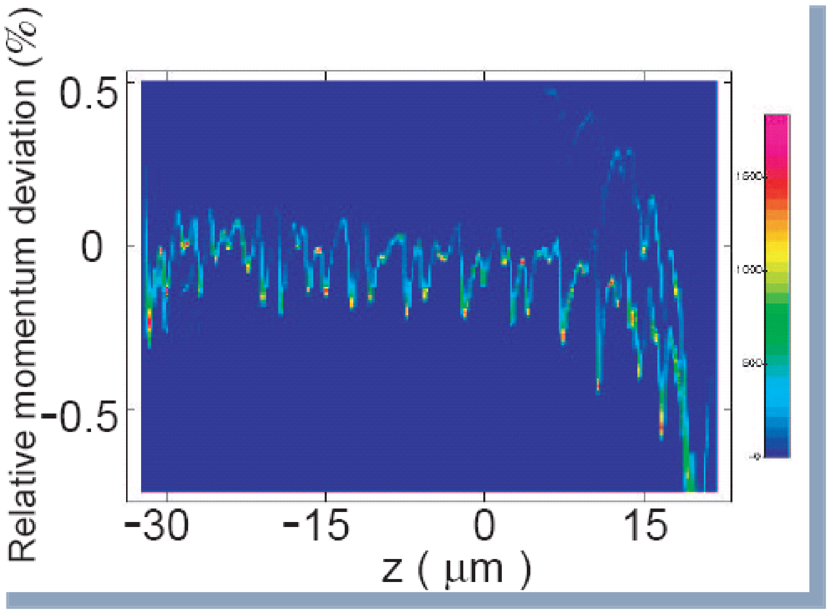
Courtesy of M. Borland

Microbunching Instability

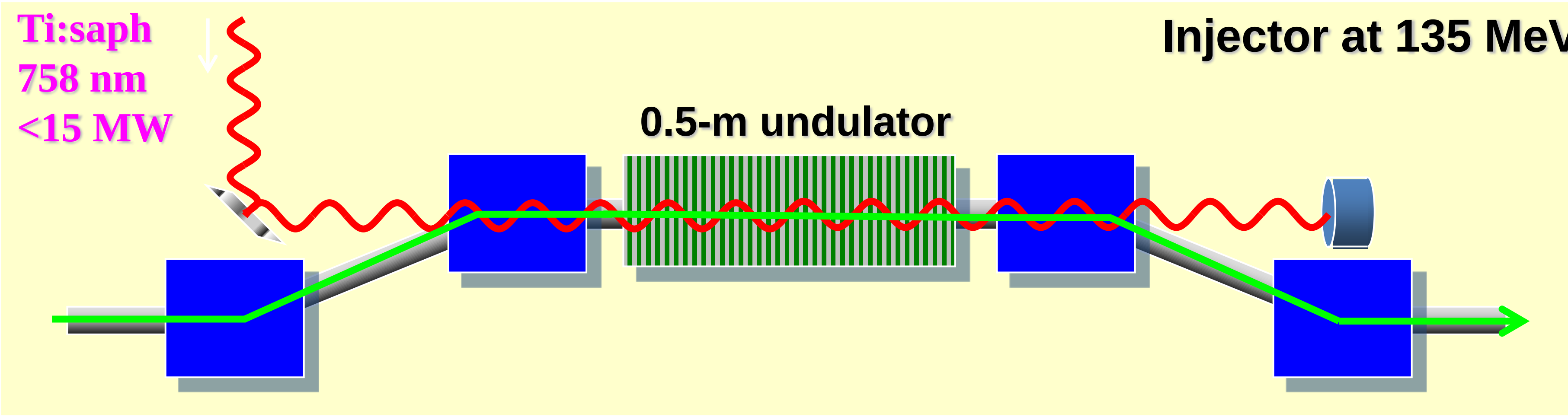


Collective effects (longitudinal space charge and CSR) magnify the initially small current and energy modulations as an electron bunch propagates along the linac and gets compressed in a chicane. This leads to the microbunching instability that increases the energy spread of the compressed bunch.

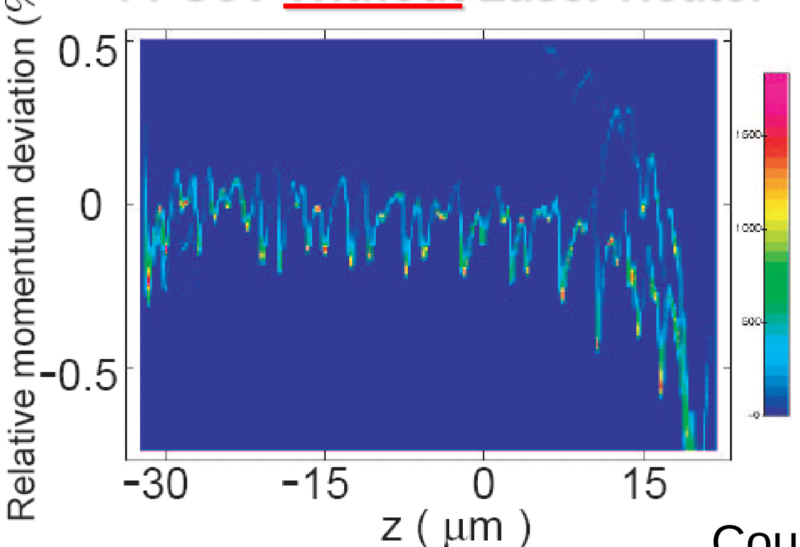




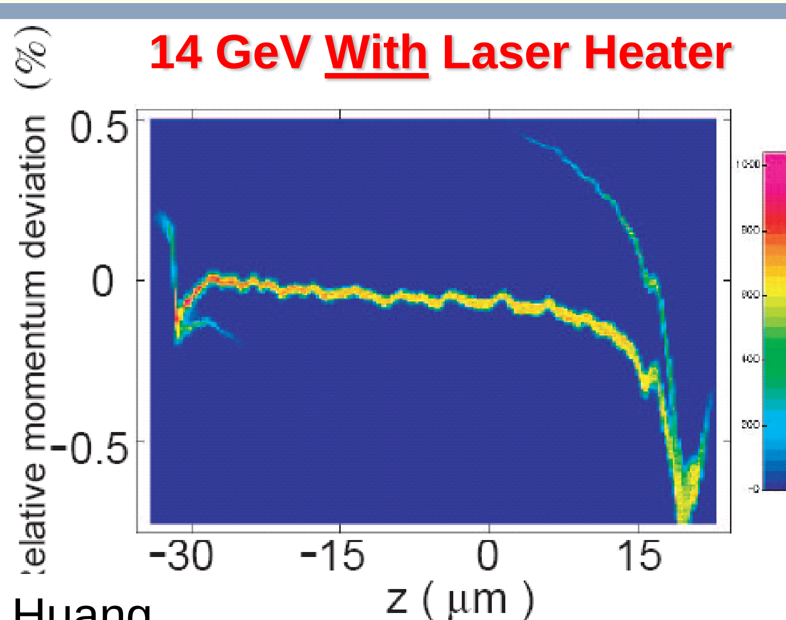
Laser Heater



14 GeV Without Laser Heater

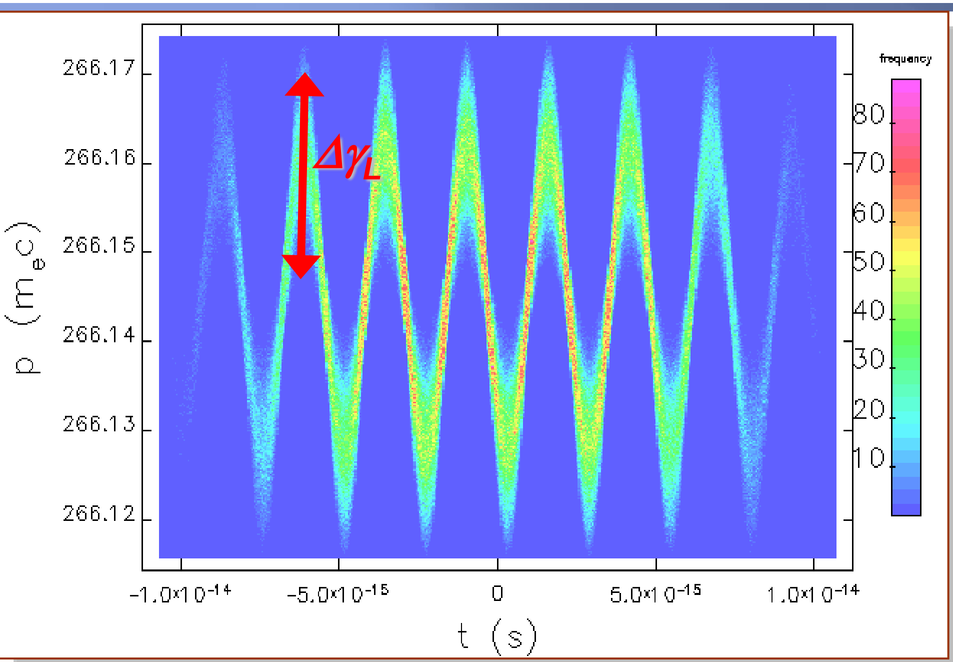


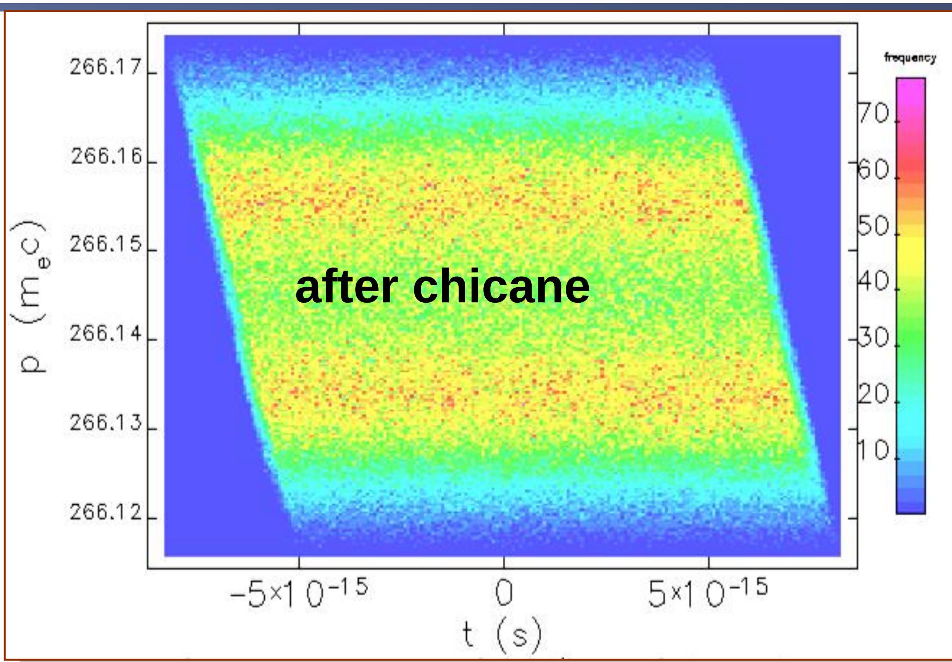
14 GeV With Laser Heater



Courtesy of Z. Huang

How Does the Laser Heater Work?





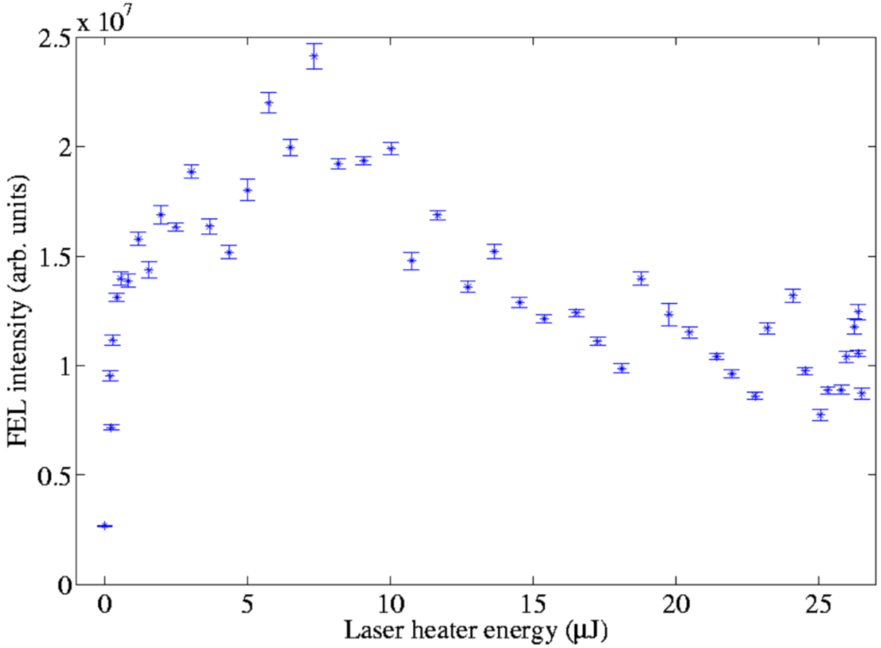
The FEL interaction gives rise to energy modulation in the electron bunch longitudinal profile as a Gaussian function of radius r.

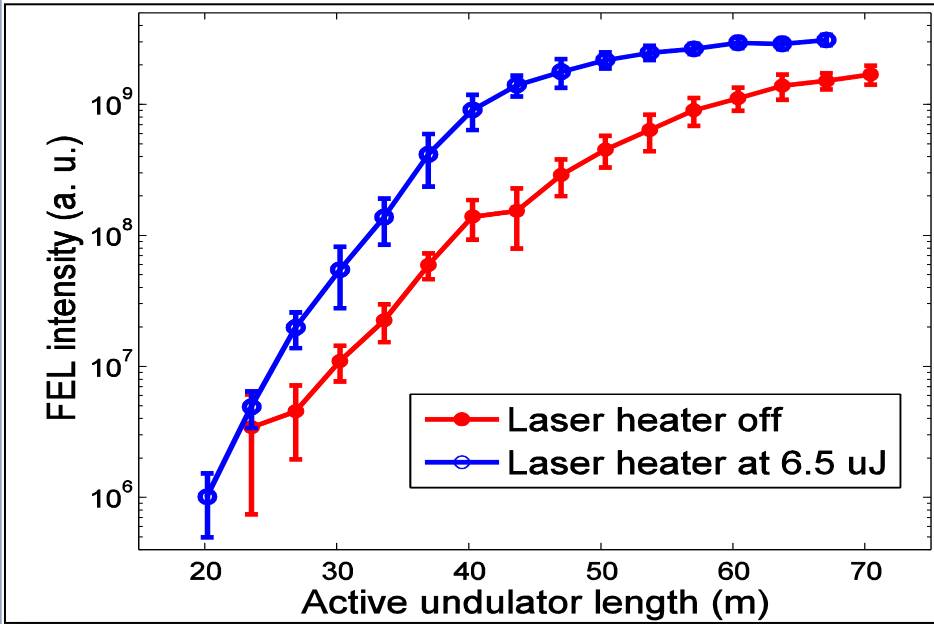
$$\Delta\gamma(r) = \sqrt{\frac{P_L}{P_0}}\frac{K \cdot JJ \cdot L_u}{\gamma_0 \sigma_r}\exp\left(-\frac{r^2}{4\sigma_r^2}\right)$$

where P_0 = 8.7 GW. The last half of the laser heater chicane smears the momentum slices together, giving rise to an increase in thermal energy spread.

Courtesy of Z. Huang

FEL Performance with Laser Heater





The optimal heating is achieved with 6.5 μJ of laser pulse energy, which corresponds to a slice energy spread of 20 keV. The final relative energy spread is 1.1×10^{-4}

$$\sigma_\delta = \left(\frac{\sigma_{z,initial}}{\sigma_{z,final}} \right) \frac{\Delta E_{slice}}{E_{final}}$$

which is less than the MBI-induced energy spread of ~1×10^{-3}.

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Summary

- Bunch compression has been used successfully to compress electron bunches down to a few fs and create peak current > 3 kA.

- The success of 4GLS depends on bunch compression techniques that preserve the beam brightness (minimize emittance growth).

- Ballistic and velocity bunching are practical with low-energy electron beams, but have limited use for high-energy beams.

- Chicane compression is the most commonly used technique, but requires sophisticated balancing of non-linear phenomena such as CSR and MBI.

- Laser heater has been used successfully to “warm” the electron beams, reduce the microbunching instability induced energy spread and improve FEL performance.