# Linear Collider Bunch Compressors

Andy Wolski
*Lawrence Berkeley National Laboratory*

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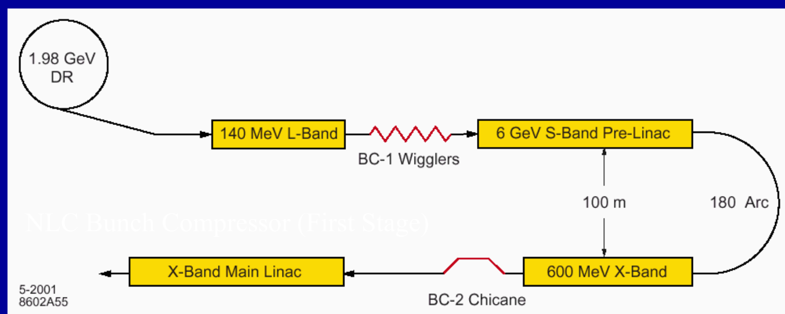
## Outline

- Damping Rings produce "long" bunches
  - quantum excitation in a storage ring produces longitudinal emittance that is relatively large compared to some modern particle sources
  - long bunches tend to reduce the impact of collective effects
    - large momentum compaction rapidly decoheres modes
    - the longer the bunch, the lower the charge density
  - bunch lengths in damping rings are ~ 5 mm
- Main Linacs and Interaction Point require "short" bunches
  - of the order 100 μm in NLC, 300 μm in TESLA
- Main issues are:
  - How can we achieve bunch compression?
  - How can we compensate for the effects of nonlinear dynamics?
  - What are the effects of (incoherent and coherent) synchrotron radiation?

2

## Schematic Layout (NLC)

- Essential components of a bunch compression system include:
  - RF power
  - "Phase Slip": variation of path length with energy

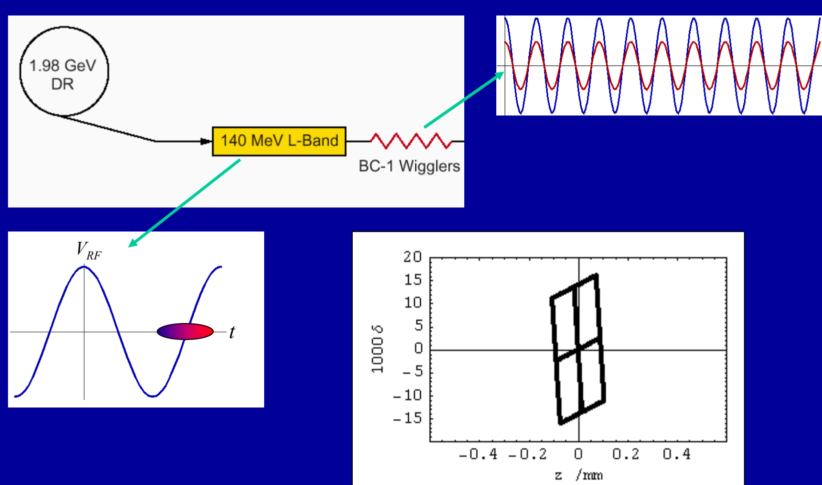



NLC Bunch Compressor (First and Second Stages)

3

## Basic Principles

- A "rotation" of longitudinal phase space…




4

## Lets do some maths…

- We would like to know
  - how much RF power
  - how much wiggler (or chicane, or arc)

  are needed to achieve a given compression
- We consider the changes in the longitudinal phase space variables of a chosen particle in each part of the compressor
- The RF section changes only the energy deviation:

$$z_1 = z_0$$
$$\delta_1 = \delta_0 + \frac{eV_{RF}}{E_0}\cos\left(\frac{\pi}{2} - k_{RF} z_0\right)$$

- In a linear approximation, we can write:

$$\begin{pmatrix} z_1 \\ \delta_1 \end{pmatrix} \approx \begin{pmatrix} 1 & 0 \\ R_{65} & 1 \end{pmatrix} \cdot \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix} \qquad R_{65} = \frac{eV_{RF}}{E_0}\sin(\phi_{RF}) k_{RF}$$

5

## Lets do some maths…

- The wiggler (or arc) changes only the longitudinal co-ordinate:

$$z_2 = z_1 + R_{56}\delta_1 + T_{566}\delta_1^2 + U_{5666}\delta_1^3 \ldots$$
$$\delta_2 = \delta_1$$

- Again in a linear approximation:

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

- The full transformation can be written:

$$\begin{pmatrix} z_2 \\ \delta_2 \end{pmatrix} \approx \mathbf{M} \cdot \begin{pmatrix} z_0 \\ \delta_0 \end{pmatrix} \qquad \mathbf{M} = \begin{pmatrix} 1 + R_{65}R_{56} & R_{56} \\ R_{65} & 1 \end{pmatrix}$$

6

## Optimum Compression

- Since the transformation is symplectic (in the case of no acceleration from the RF) the longitudinal emittance is conserved

$$\varepsilon = \sqrt{\sigma_z^2 \sigma_\delta^2 - \sigma_{z\delta}^2}$$

- For a given value of $R_{65}$, the best compression that can be achieved is:

$$\left( \frac{\sigma_{zf}}{\sigma_{zi}} \right)_{\min} = \frac{1}{\sqrt{1+a^2}} \qquad a = \frac{\sigma_{zi}}{\sigma_{\delta i}} R_{65}$$

- This optimum compression is obtained with:

$$R_{56} = -\frac{a^2}{1+a^2} \cdot \frac{1}{R_{65}}$$

7

## Limitations on Compression

- For final bunch length << initial bunch length, we can make the approximations:

$$\left( \frac{\sigma_{zf}}{\sigma_{zi}} \right)_{\min} \approx \frac{1}{a} \qquad R_{56} \approx -\frac{1}{R_{65}}$$

$$a = \frac{\sigma_{zi}}{\sigma_{\delta i}} R_{65} \gg 1 \qquad R_{65} = \frac{eV_{RF}}{E_0} \frac{\omega_{RF}}{c}$$

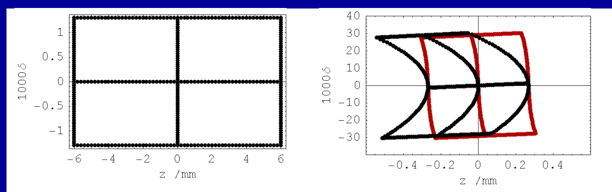
- Clearly, we can make the final bunch length shorter simply by
  - increasing the RF voltage, and/or
  - increasing the RF frequency

  and adjusting $R_{56}$ appropriately.
- In practice, the compression that can be achieved is limited by:
  - available RF power
  - increase in energy spread of the bunch (emittance is conserved)
  - nonlinear dynamics, CSR etc.

8

# Nonlinear Effects

- So far, we have made linear approximations for
  - the energy change variation with position in bunch (in the RF section)
  - the path length variation with energy (in the wiggler or arc), also known as nonlinear phase slip
- The nonlinear phase slip is dependent on the linear slip
  - for an arc, $T_{566} \approx 1.9R_{56}$
  - for a chicane or wiggler, $T_{566} \approx -1.5R_{56}$




*Bunch compression in TESLA. The pictures show the initial (left) and final (right) longitudinal phase space, excluding (red) and including (black) the nonlinear phase slip terms.*



# Nonlinear Effects

- The nonlinear phase slip introduces a strong correlation between $z$ and $\delta^2$
- Since the phase space is rotated by ~ π/2, we can compensate this with a correlation between $\delta$ and $z^2$ at the start of the compressor
- Note that the energy map (for a general RF phase) looks like:

$$\delta_1 \approx \delta_0\left(1-\frac{eV_{RF}}{E_0}\cos(\phi_{RF})\right)+\frac{eV_{RF}}{E_0}\left[\cos(\phi_{RF}-k_{RF}z_0)-\cos(\phi_{RF})\right]$$

- Choosing an appropriate value for the RF phase introduces the required correlation between $\delta$ and $z^2$ to compensate the nonlinear phase slip

## Compensation of Nonlinear Phase Slip

- An expression for the RF phase required to compensate the nonlinear phase slip can be found as follows:
  - calculate the complete map for the bunch compressor up to second order in the phase space variables
  - select the coefficient of $\delta^2$ in the expression for $z$, and set this to zero
- We find that the required RF phase is given by:

$$\cos(\phi_{RF}) = \frac{\sqrt{1+8(1+2r)r\theta^2}-1}{2(1+2r)\theta} \approx 2\theta r$$

$$\theta = \frac{eV_{RF}}{E_0} \qquad r = \frac{T_{566}}{R_{56}}$$

- The optimum (linear) phase slip is now given by:

$$R_{56} = -\frac{a^2}{1+a^2}\cdot\frac{1}{R_{66}R_{65}}$$

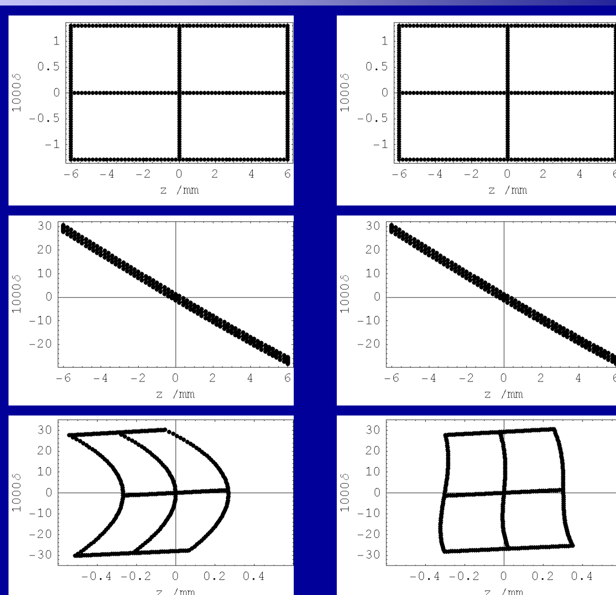


## Compensation of Nonlinear Phase Slip - TESLA

*Entrance of Bunch Compressor*

*After RF*

*After RF and chicane*



## Two-Stage Compression

- The NLC uses a two-stage bunch compressor:
  - Stage 1 at low energy (1.98 GeV), bunch length reduced from ~ 5 mm to 500 μm
  - Stage 2 at higher energy (8 GeV), bunch length reduced to ~ 110 μm
- Advantages:
  - Acceleration provides adiabatic damping of energy spread, so the maximum energy spread anywhere in the system is less than 2%
  - High frequency RF can be used in Stage 2, where the bunch length is already short
- Disadvantage:
  - More complex, longer system

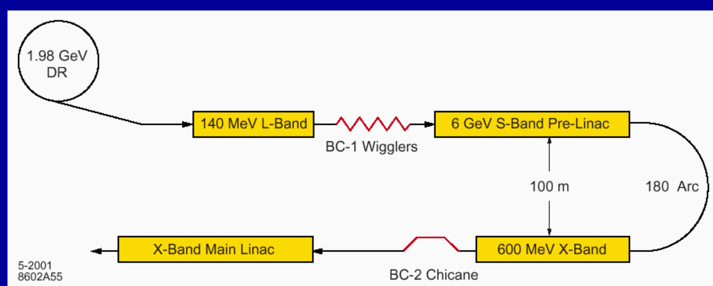


## Two-Stage Compression in NLC

- Phase errors at the entrance to the main linac are worse than energy errors
  - Energy error becomes adiabatically damped in the linac
  - Phase error at the entrance leads to large energy error at the exit
- First stage rotates longitudinal phase space ~ $\pi/2$
  - Energy of beam extracted from Damping Rings is very stable
  - Phase errors from beam loading in the damping ring become energy errors at the exit of the first stage of bunch compression
- Second stage rotates phase space by $2\pi$
  - Energy errors from imperfect beam loading compensation in the prelinac stay as energy errors

# Two-Stage Compression in NLC

- How do we achieve compression with a rotation through 2π?
- NLC Stage 2 compressor uses a sequence of systems:
  - RF
  - arc
  - RF
  - chicane




15

# Longitudinal Phase Space Telescope

- The linear map for the NLC Stage 2 compressor is as follows:

$$\mathbf{M} = \begin{pmatrix} 1 + R_{65}^{(2)} R_{56}^{(2)} + R_{65}^{(1)} \left( R_{65}^{(2)} R_{56}^{(1)} R_{56}^{(2)} + R_{56}^{(1)} + R_{56}^{(2)} \right) & R_{65}^{(2)} R_{56}^{(1)} R_{56}^{(2)} + R_{56}^{(1)} + R_{56}^{(2)} \\ R_{65}^{(1)} + R_{65}^{(2)} + R_{65}^{(1)} R_{65}^{(2)} R_{56}^{(1)} & \dots \end{pmatrix}$$

- With appropriate choices for the parameters:

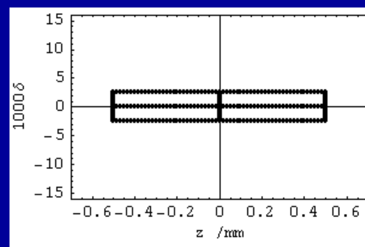
$$1 + R_{65}^{(2)} R_{56}^{(2)} = \pm 1/m \qquad R_{56}^{(1)} = \mp m R_{56}^{(2)}$$

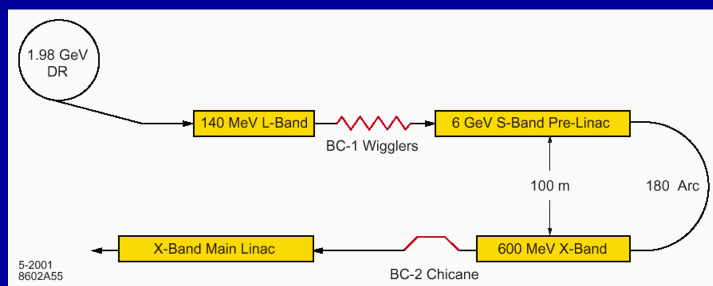
this can be written:

$$\mathbf{M} = \begin{pmatrix} \pm 1/m & 0 \\ R_{65}^{(1)} + R_{65}^{(2)} + R_{65}^{(1)} R_{65}^{(2)} R_{56}^{(1)} & \pm m \end{pmatrix}$$

16

## NLC Stage 2 Compressor




17

## Effects of Synchrotron Radiation

- Synchrotron radiation is emitted in the arcs or wiggler/chicane used to provide the phase slip in a bunch compressor
- Effects are:
  - Transverse emittance growth
  - Increase in energy spread
- For very short bunches at low energy, coherent synchrotron radiation (CSR) may be more of a problem than incoherent synchrotron radiation
- Weaker bending fields produce less radiation, and therefore have less severe effects
- CSR may also be limited by “shielding” the radiation using a narrow aperture beam pipe

18

## Incoherent Synchrotron Radiation

- Transverse and longitudinal emittance growth is analogous to quantum excitation in storage rings
- Transverse emittance growth is given by:

$$\Delta(\gamma\varepsilon) = \tfrac{2}{3} C_q r_e \gamma^6 I_5 \qquad I_5 = \int \frac{\mathcal{H}}{|\rho|^3} \mathrm{d}s$$

- The energy loss from incoherent synchrotron radiation is:

$$U_0 = \frac{C_\gamma}{2\pi} E_0^4 I_2 \qquad I_2 = \int \frac{1}{\rho^2} \mathrm{d}s$$

- The increase in energy spread is given by:

$$\Delta\sigma_\delta^2 = \tfrac{4}{3} C_q r_e \gamma^5 I_3 \qquad I_3 = \int \frac{1}{|\rho|^3} \mathrm{d}s$$



## Coherent Synchrotron Radiation

- A bunch of particles emits radiation over a wide spectrum
- For regions of the spectrum where the radiation wavelength is much less than the bunch length, the emission is incoherent
  - for a bunch of $N$ particles, radiation power $\propto N$
- Where the radiation wavelength is of the order of or longer than the bunch length, the bunch emits as a single particle
  - radiation power $\propto N^2$
- Since $N$ is of the order $10^{10}$, the coherence of the radiation represents a significant enhancement
- The radiation acts back on the beam, leading to a correlated energy spread within the bunch

# Coherent Synchrotron Radiation