Bunch Compressor for Linear Colliders

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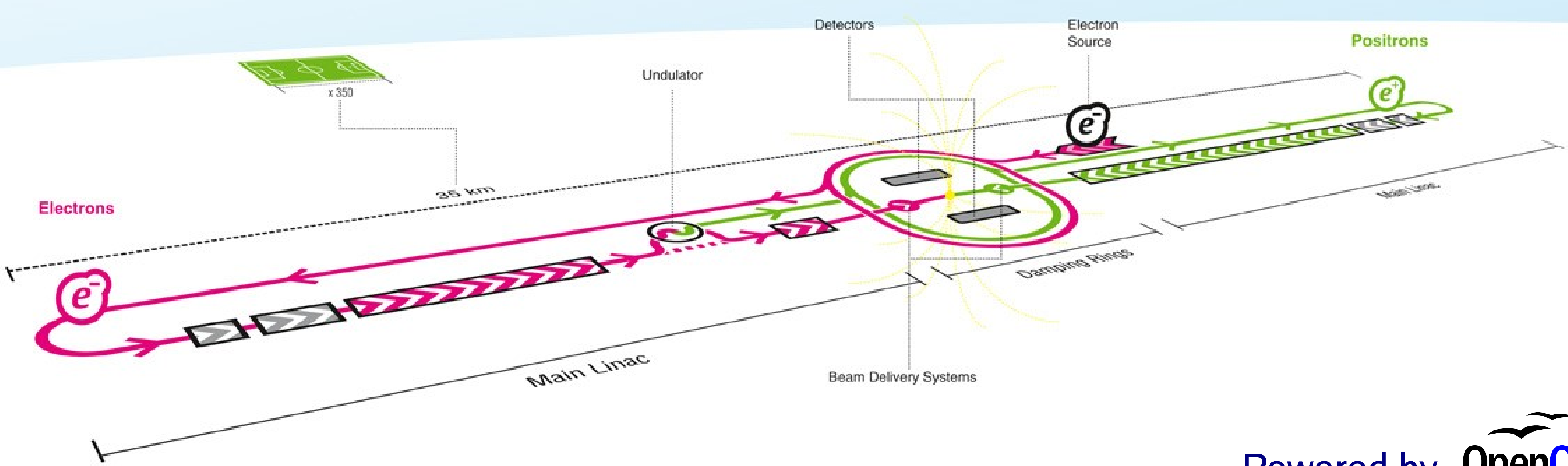

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Outlines

Introduction

Fundamen-tals

ILC Bunch Compressor

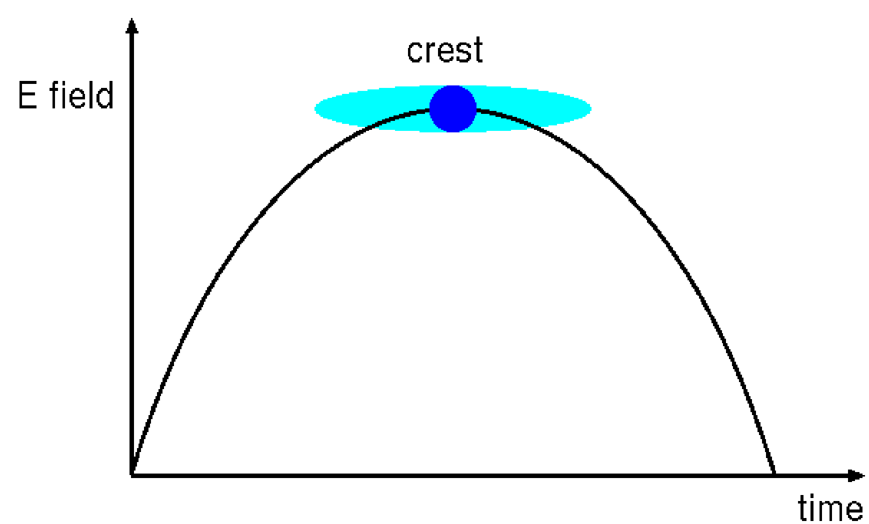
Summary

- Introduction.
- Fundamentals.
- ILC bunch compressor design.
- Summary.

Introduction (1)

- Introduction
- Fundamentals
- ILC Bunch Compressor
- Summary

- In any accelerator with RF field, the beam should be concentrated in a short period of longitudinal space for small energy spread;
  - $E = E_0 \cos(\omega t - ks)$
- Bunch compressor and buncher shorten the bunch length down to an adequate size for acceleration.



Introduction (2)

Introduction

Fundamen-tals

ILC Bunch Compressor

Summary

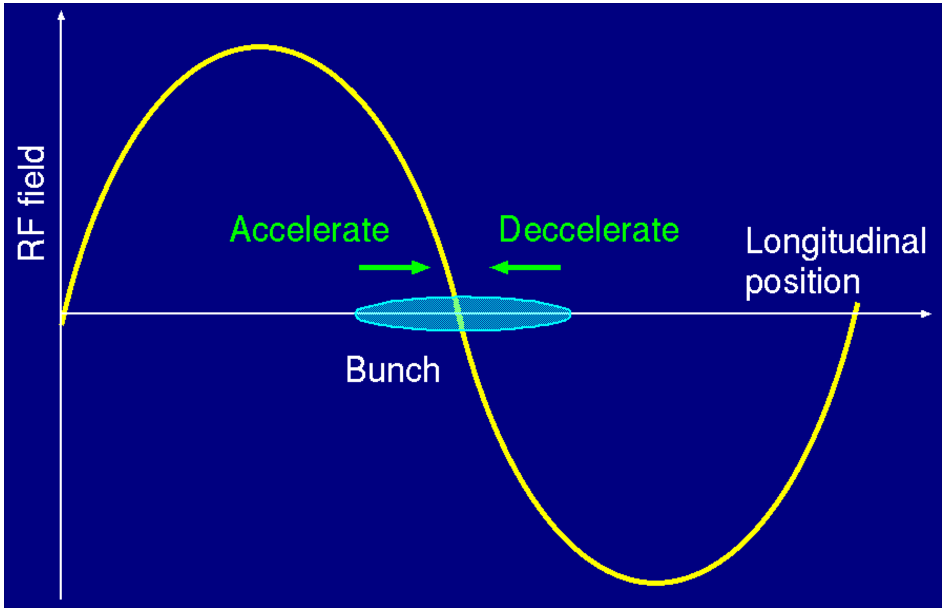
- Bunching after the source (See Source part)
  - Particle source can generate only long bunch or continuous beam.
- Bunching after the storage ring (Main issue in this part)
  - In a storage ring, the bunch length is determined by RF and its amplitude; It is sometimes too long to accelerate in Linac.
- There are two ways for bunch compression:
  - Velocity Bunching
  - Magnetic Bunching

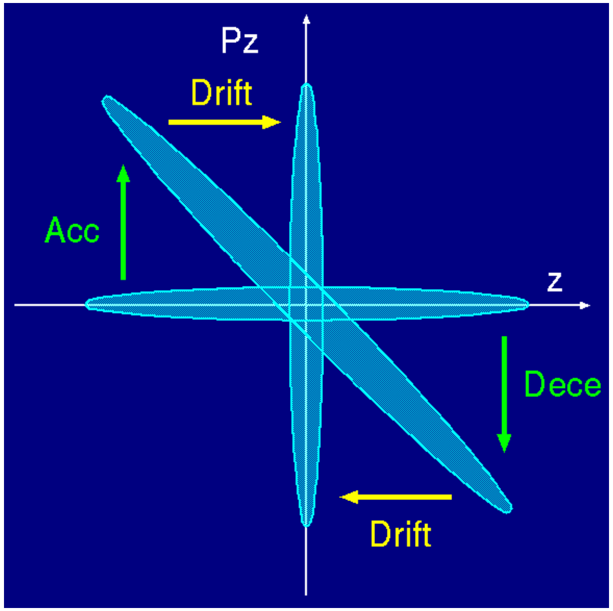
Velocity Bunching (1)

- Bunch compression is performed by velocity modulation within a bunch;
  - Bunch head is decelerated.
  - Bunch tail is accelerated.
- Beta is saturated as $\beta=1-1/\gamma^2\sim 1$ if $\gamma >>1$.
- Then, it works only for low energy particle.
  - Bunch compression at the injector.

Velocity Bunching (2)

- Lower RF accelerating cavities employed.
- Bunch sits where the head is decelerated and the tail is accelerated.
- By drifting, bunch length is minimized at some point. The whole bunch is then accelerated to suppress the relative energy spread.





Magnetic Bunching (1)

- Bunch compression is performed by energy modulation with dispersive path length difference.
  - Chicane, Wiggler, Arc, etc.
- A path length difference by a dispersive section, Δz is

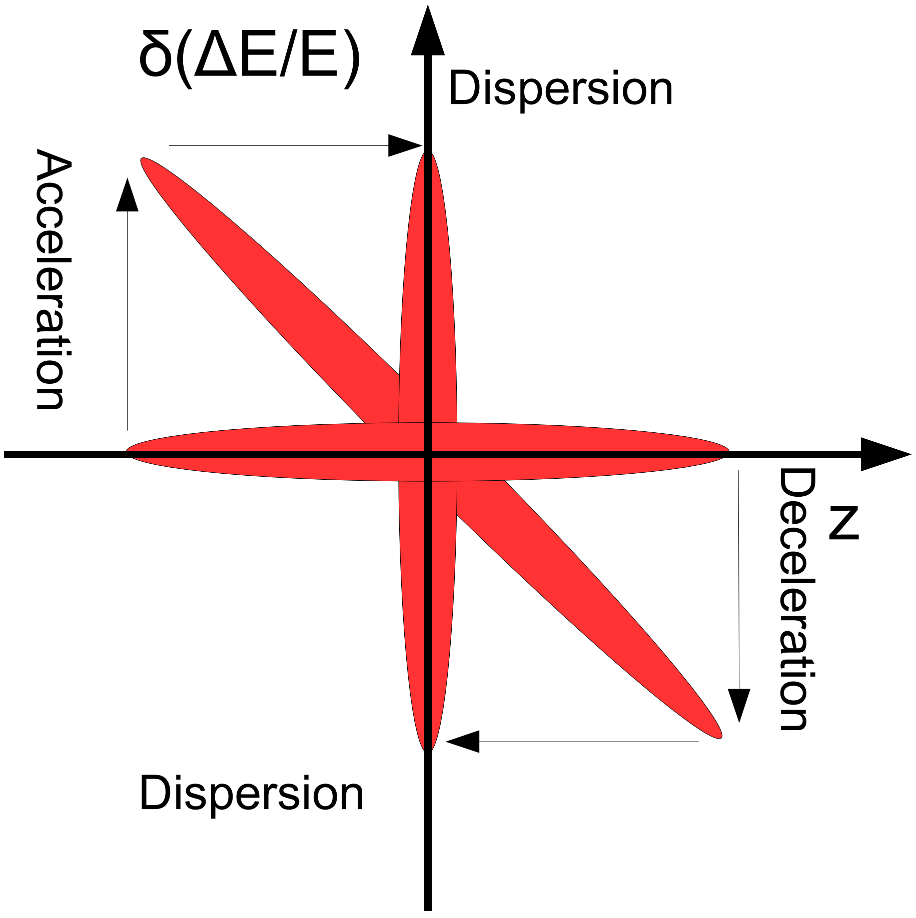
$$\Delta z = \eta \frac{\Delta E}{E}$$

where η is (longitudinal) dispersion and $\Delta E/E$ is relative energy deviation.

- It works well for any energy particle because the measure is the relative energy deviation.

Magnetic Bunching (2)

- Energy modulation by RF (acc- and deceleration).
- Drift through a dispersive section rotates the beam in the phase space.
- By appropriate modulation and drift, the bunch length is compressed.



Formalism : R Matrix (1)

- In the linear dynamics regime, particle motion in 6 dimensional phase space are expressed by R matrix

$$\vec{X}(s)=R\,\vec{X}(0)$$

$$\begin{bmatrix} x(s) \\ x'(s) \\ y(s) \\ y'(s) \\ z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} & R_{12} & R_{13} & R_{14} & R_{15} & R_{16} \\ R_{21} & R_{22} & R_{22} & R_{23} & R_{24} & R_{25} & R_{26} \\ R_{31} & R_{32} & R_{32} & R_{33} & R_{34} & R_{35} & R_{36} \\ R_{41} & R_{42} & R_{42} & R_{43} & R_{44} & R_{45} & R_{46} \\ R_{51} & R_{52} & R_{52} & R_{53} & R_{54} & R_{55} & R_{56} \\ R_{61} & R_{62} & R_{62} & R_{63} & R_{64} & R_{65} & R_{66} \end{bmatrix} \begin{bmatrix} x(0) \\ x'(0) \\ y(0) \\ y'(0) \\ z(0) \\ \delta(0) \end{bmatrix}$$

- It is reduced if there is no mixing to other DOF.

$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} R_{55} & R_{56} \\ R_{65} & R_{66} \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$

Example of R-matrices

– Drift space

$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$

– Dispersive area

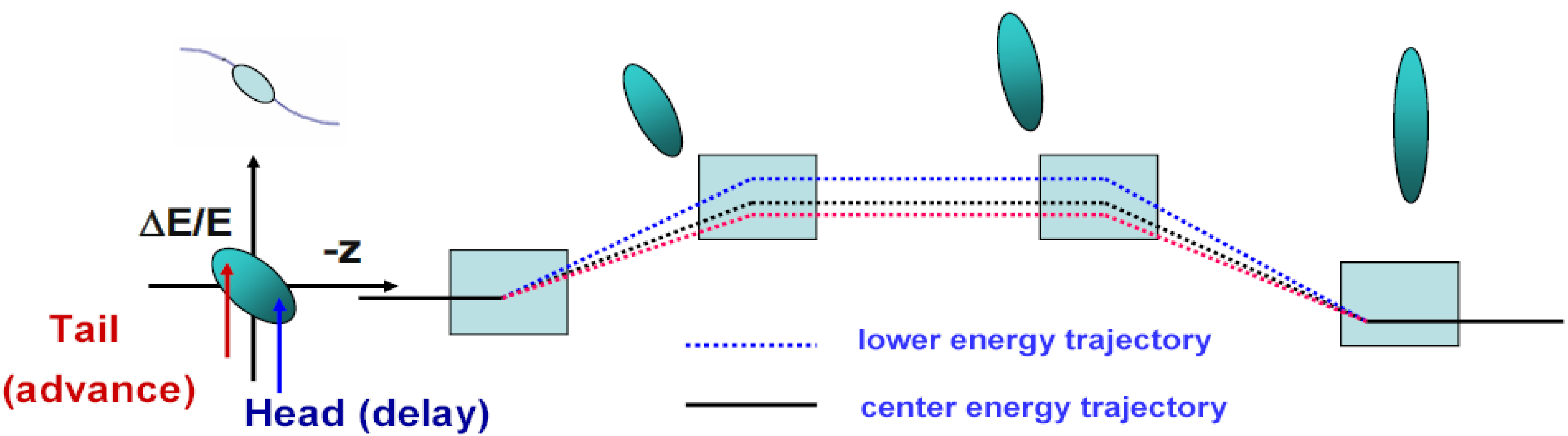
$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$

– Energy modulation

$$\begin{bmatrix} z(s) \\ \delta(s) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$

Concept of Bunch Compressor

- Energy Modulation : RF cavity.
  - R_{65} at zero crossing …
- Dispersive section : Chicane, Wiggler, Bend,..
  - For example, four bending magnets compose a chicane

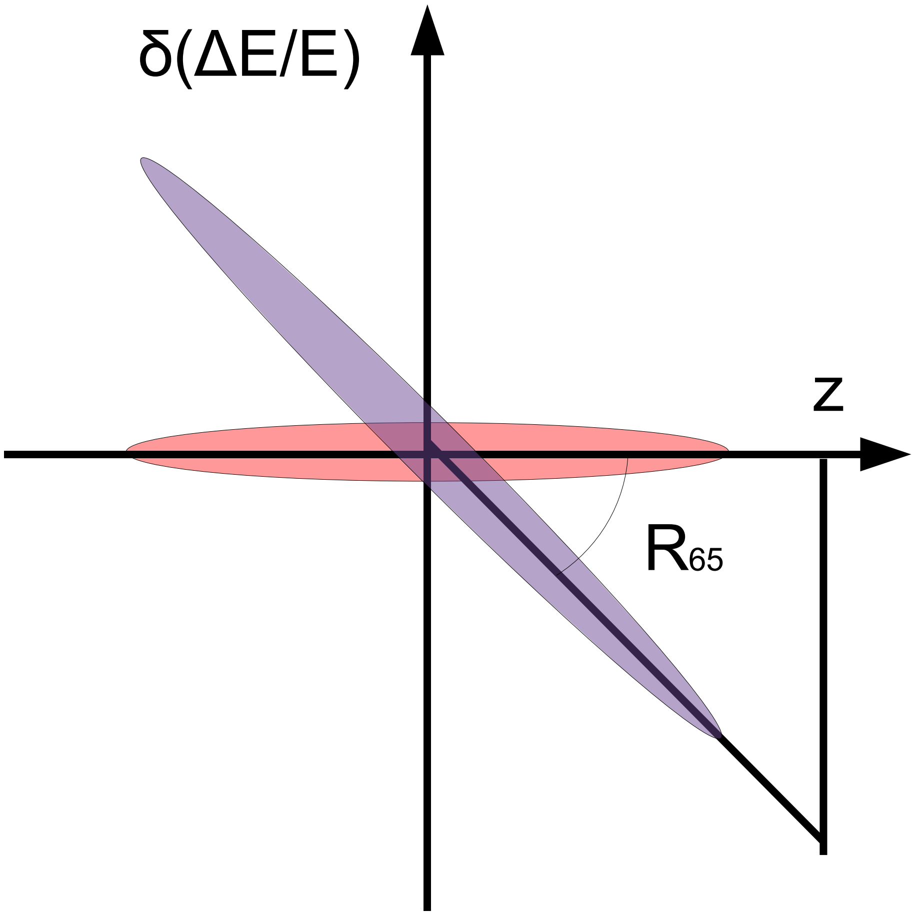


By E.S. Kim

Energy Modulation

- Energy modulation by RF (acc- and deceleration).

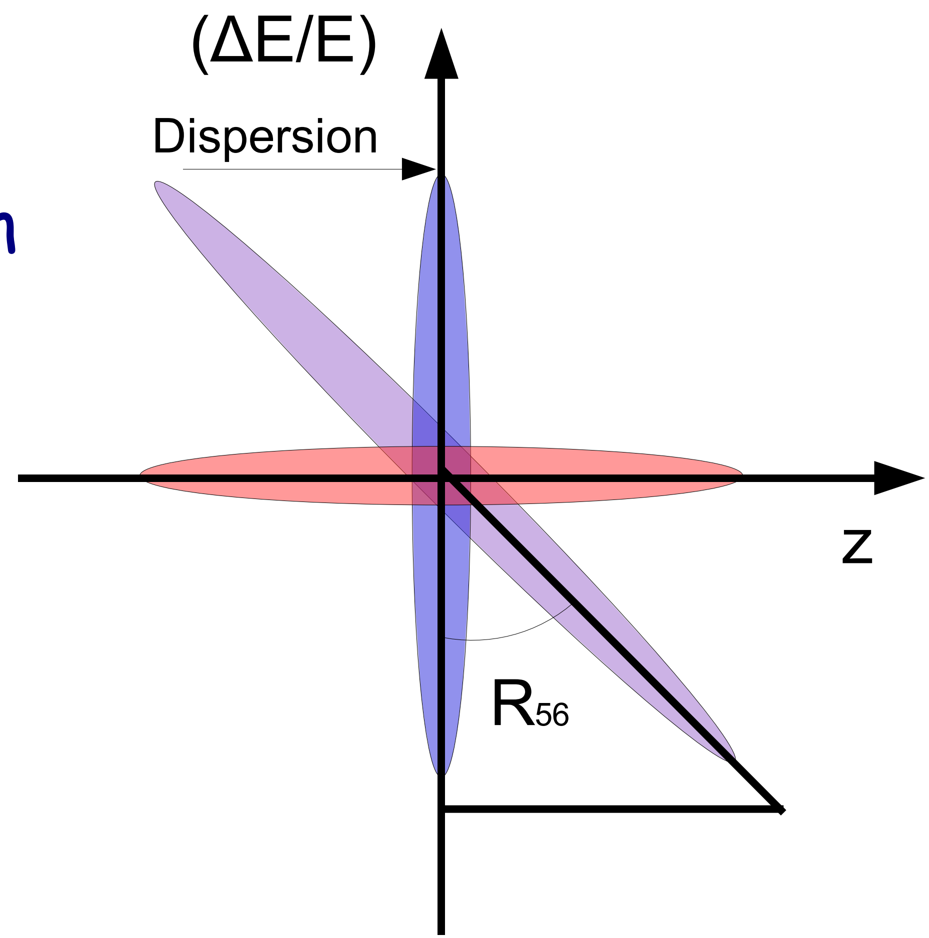
$$\begin{bmatrix} z(s_1) \\ \delta(s_1) \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(0) \\ \delta(0) \end{bmatrix}$$



Dispersive Section

- Drift through a dispersive section rotates the beam in the phase space.

$$\begin{bmatrix} z(s_2) \\ \delta(s_2) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} z(s_1) \\ \delta(s_1) \end{bmatrix}$$



Total Transfer

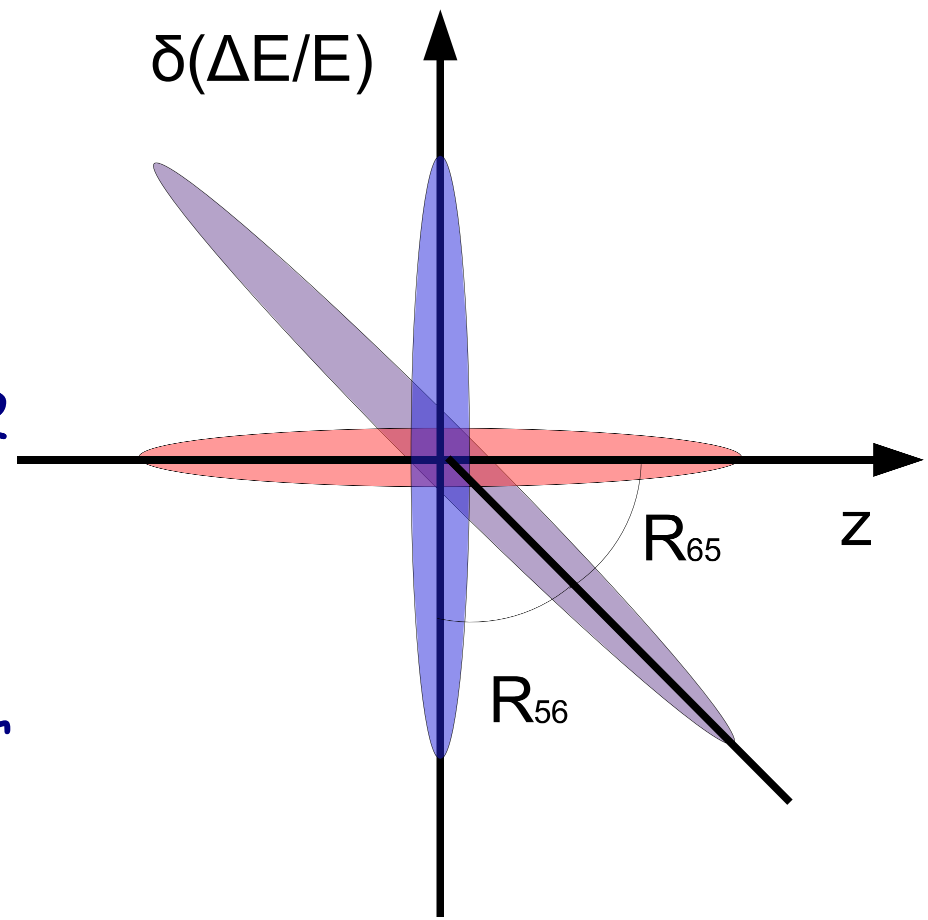
- Total Transfer Matrix of BC section.

$$\begin{bmatrix} z(s_2) \\ \delta(s_2) \end{bmatrix} = \begin{bmatrix} 1 & R_{56} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix}$$

$$= \begin{bmatrix} 1+R_{56}R_{65} & R_{56} \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix}$$

- If $1+R_{56}R_{65}=0$, the phase space distribution rotate $\pi/2$ and the bunch length is minimized.
- The phase in the linac is insensitive to phase errors or bunch lengthening in the DR.

$$\begin{bmatrix} z(s_2) \\ \delta(s_2) \end{bmatrix} = \begin{bmatrix} 0 & R_{56} \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix}$$



Final Bunch Length

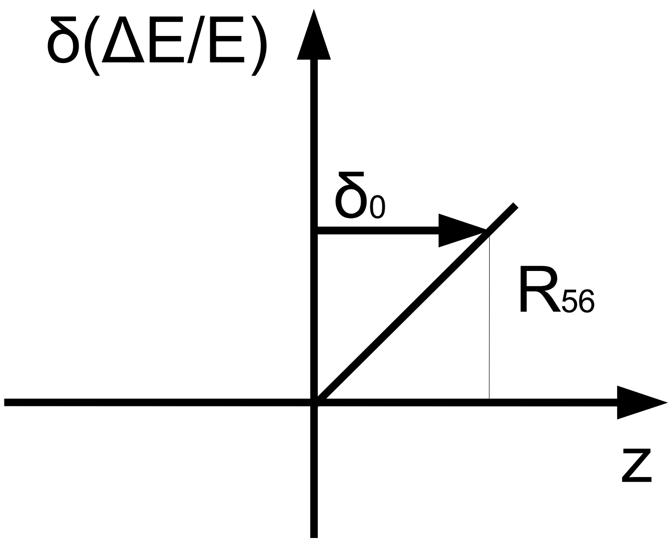
- Final bunch length after an optimized BC section ($1+R_{56}R_{65}=0$) is determined by the initial energy spread as;

$$\delta_2 = R_{56}\delta_0$$

- It can be understood by considering the transport of a reference point.

$$\begin{bmatrix} 0 \\ R_{65} z_0 \end{bmatrix} = \begin{bmatrix} 0 & R_{56} \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z_0 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} R_{56}\delta_0 \\ \delta_0 \end{bmatrix} = \begin{bmatrix} 0 & R_{56} \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} 0 \\ \delta_0 \end{bmatrix}$$



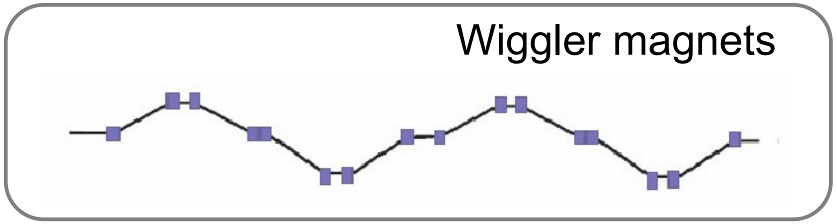
Beam Parameters

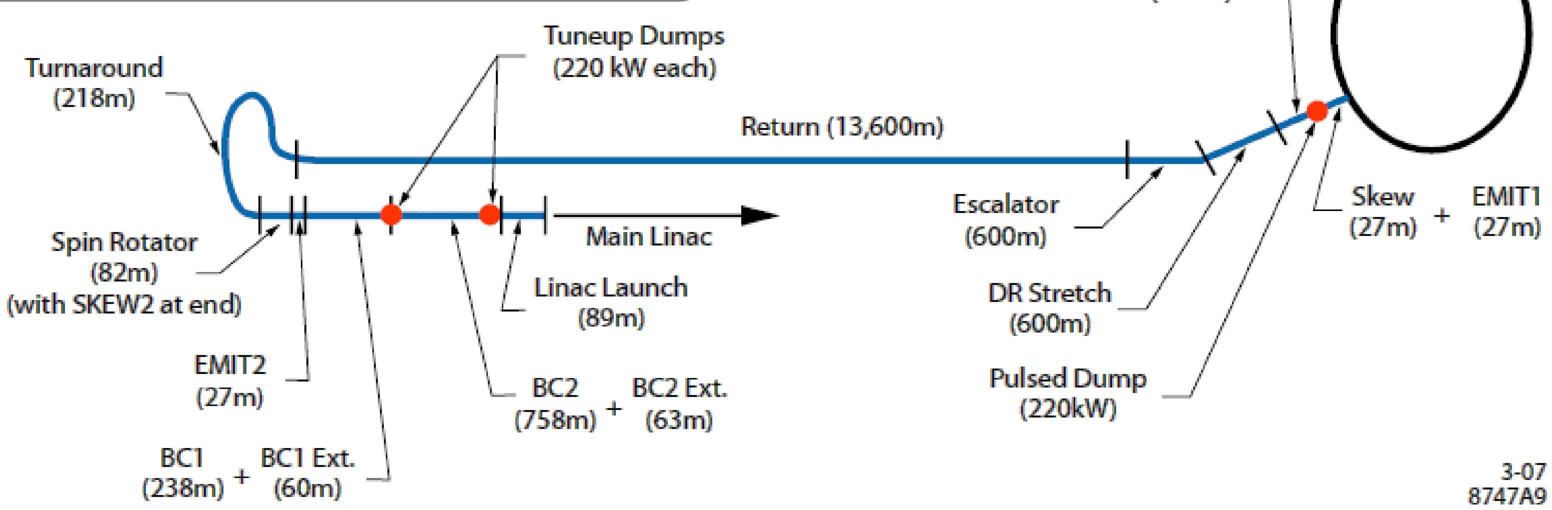
Parameter	Initial Value	Final Value	Unit
Energy	5.0	15.0	GeV
Energy Spread	0.15	1.5	%
Emittance	8.0 / 20	< 9.0 / 24	μm/nm
Horizontal beam jitter	1	0.1	σ
Bunch length	9.0	0.3	mm

- Bunch length should be shorten down to 0.3 mm for acceleration in ML.
- Energy spread is increased in the process of the bunch compression, but it should be within an acceptable size.
- Emittance growth should be within a budget.

ILC Bunch Compressor

- ILC Bunch Compressor is placed before ML.
- ILC Bunch Compressor is 2 stages based on wiggler.
  - Gives a large flexibility on the tuning.
  - Gives a large tolerance on system errors.





ILC Bunch Compressor

Parameter	BC1	BC2	Unit
Initial Energy	5.0	4.88	GeV
Initial Energy Spread	0.15	2.5	%
Initial Bunch Length	9.0	1.0	mm
RF Voltage	0.448	11.4	GV
RF Phase	-105	-27.6	Deg
R_{56}	-376	-54	mm
Final Energy	4.88	15.0	GeV
Final Energy Spread	2.5	1.5	%
Final Bunch Length	1.0	0.3	mm
Total Section Length	238	758	m

- BC1: Almost zero cross, large BC factor, relatively large energy spread.
- BC2: Small BC factor, simultaneous acceleration to suppress the relative energy spread.

Summary

- There are two ways for bunch compression:
  - Velocity bunching (for low energy beam)
  - Magnetic bunching (for high energy beam)
- Bunch compression after DR is for preparation of accelerator in main linac based on magnetic bunching.
- The final bunch length after the BC section was determined by the initial energy spread and R_{56}.
- ILC BC has been designed and satisfied basic requirements.

Reference

- E.S. Kim, "Bunch Compressors", 1st Accelerator School for Linear Colliders" (May 2006)
- Chap. 2. "Handbook of Accelerator Physics and Engineering", edited by A. Chao and M. Tigner, World Scientific (September 1998)
- Reference Design Report of ILC, August,2007.

Homework

- Calculate the expected final bunch length after BC section assuming
  - δ_0=0.15%
  - R_{56}=-0.2 (m)
- How much voltage (V_{RF}) is required to compose this BC section?
  - Initial energy is 5 GeV.
  - Initial Bunch length 9mm.
  - RF is 1.3 Ghz.
  - RF Phase is -90 deg (zero cross).