Bunch Compressor for Linear Colliders

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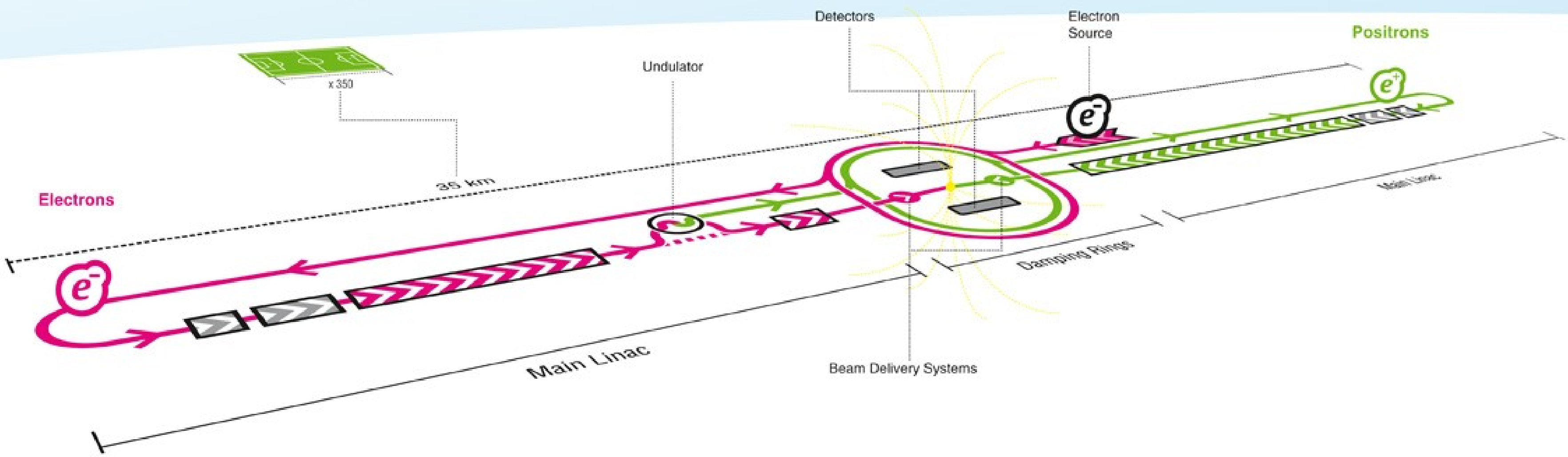


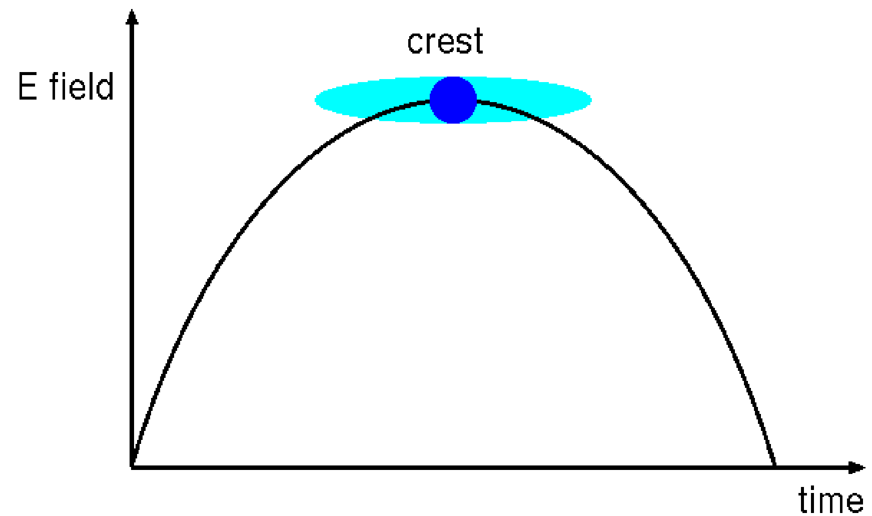
Outlines

Introduction
Fundamen-tals
Effects on beam
ILC BC design
Summary

- Introduction.
- Fundamentals.
- Effects on beam.
- ILC bunch compressor design.
- Summary.

Introduction (1)

- 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

Effects on beam

ILC BC design

Summary

- Bunching after the source (See also Source part)
  - **Particle source can generate only long bunch or continuous beam.**
- Bunching after the storage ring (Main issue in this part)
  - **Long bunch length tend to reduce beam instabilities in DR.**
  - **Thus, the bunch length is compressed after DR.**
- There are two ways for bunch compression:
  - **Velocity Bunching (at the injector)**
  - **Magnetic Bunching (at RTML)**

Velocity Bunching (1)

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- Bunch compression is performed by velocity modulation within a bunch;
  - **Bunch head is decelerated.**
  - **Bunch tail is accelerated.**
- Velocity is modulated by this energy modulation according to

$$c\beta = c\sqrt{1-\frac{1}{\gamma^2}}$$

- Velocity is saturated to c at γ>>1. Then, it works only for low energy particle (β<1).
  - **Bunch compression at the injector.**

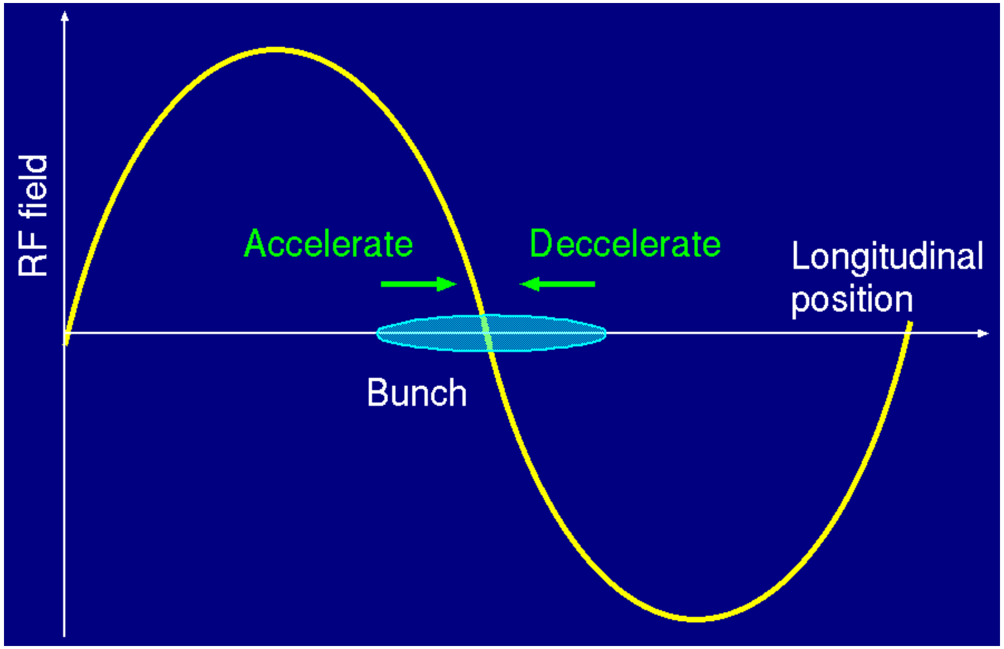
Velocity Bunching (2)

- RF cavity voltage varies as a function of relative position (t) in a bunch

$$V = -V_0 \sin(\omega t)$$

- Generate energy modulation depends on t as

$$\frac{dE}{E_0} \sim \frac{-eV_0}{E_0} \omega t$$



Velocity Bunching (3)

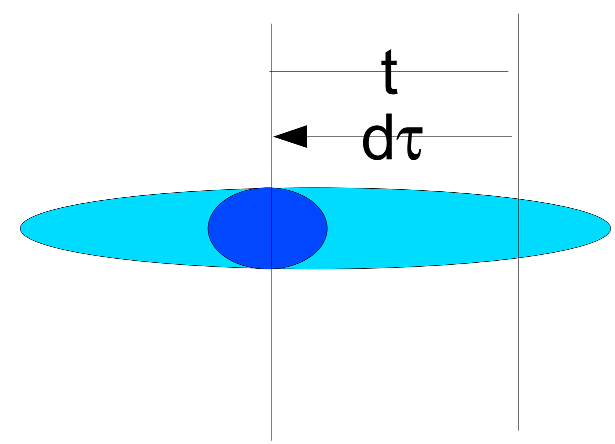
- Time to travel distance L is

$$\tau = \frac{L}{c\beta}$$

- Relative particle position in a bunch to the bunch center is modulated as

$$d\tau = -\frac{L}{c\gamma^2\beta^3}\frac{dE}{E} \sim -\frac{L}{c\gamma^2\beta^3}\frac{eV_0\omega}{E}t$$

- If dτ equals to -t, all particles are gathered at the bunch center - bunched.
- The bunch compressor has a sub effect, that the bunch timing is less sensitive to it before the bunch compression, because all electrons concentrate at t=0 position.



Magnetic Bunching (1)

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- 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)

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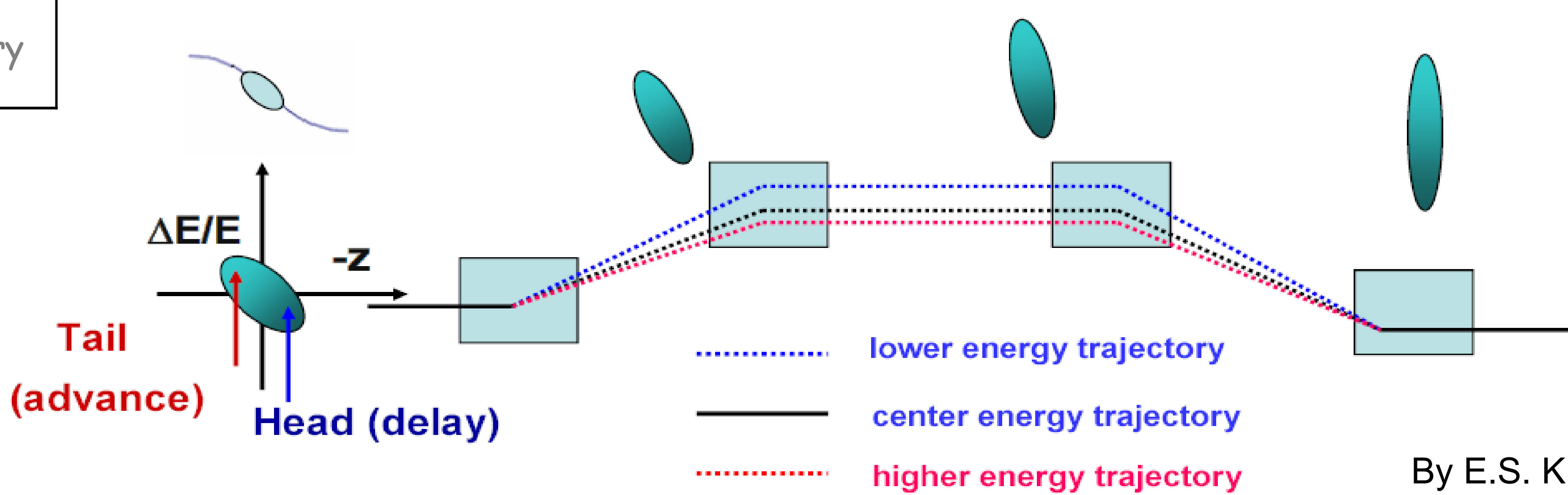
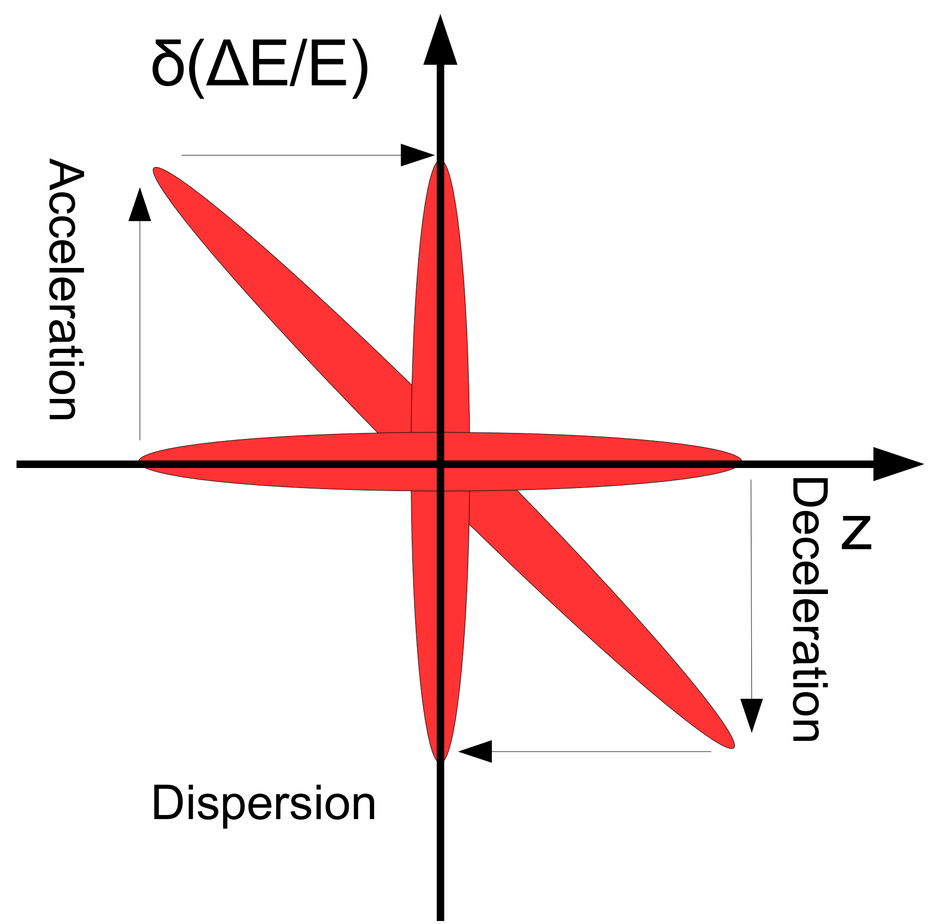
- Energy Modulation : RF cavity.
- Dispersive section : Chicane, Wiggler, Bend,..
  - E.g. four bending magnets compose a chicane
- Bunch head (tail) travels longer (shorter) path and bunch length becomes shorter.



By E.S. Kim

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.

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

Formalism : R Matrix (2)

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- 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

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

Energy Modulation

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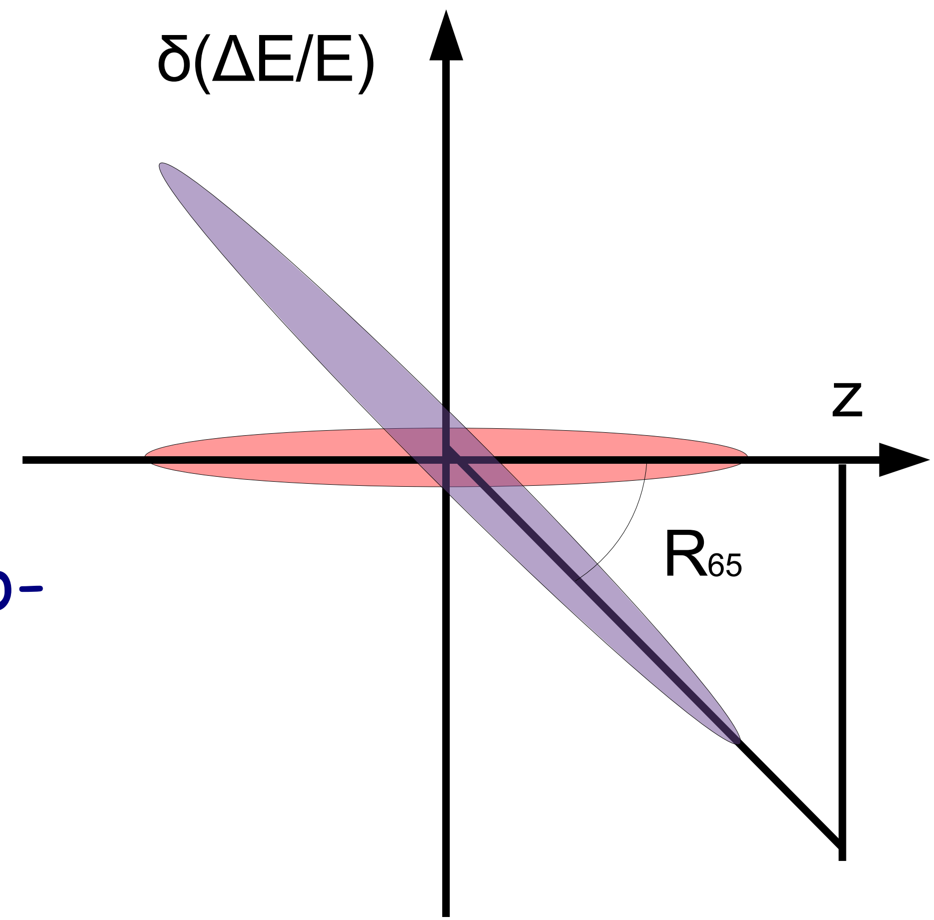
Energy modulation by RF (acc- and deceleration)

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

If the beam is on zero-cross

$$R_{65} = \frac{\sigma}{z} = \frac{1}{z} \frac{\Delta E}{E}$$

$$\sim \frac{eV_0}{E} \frac{\omega}{\beta c}$$



Total Transfer

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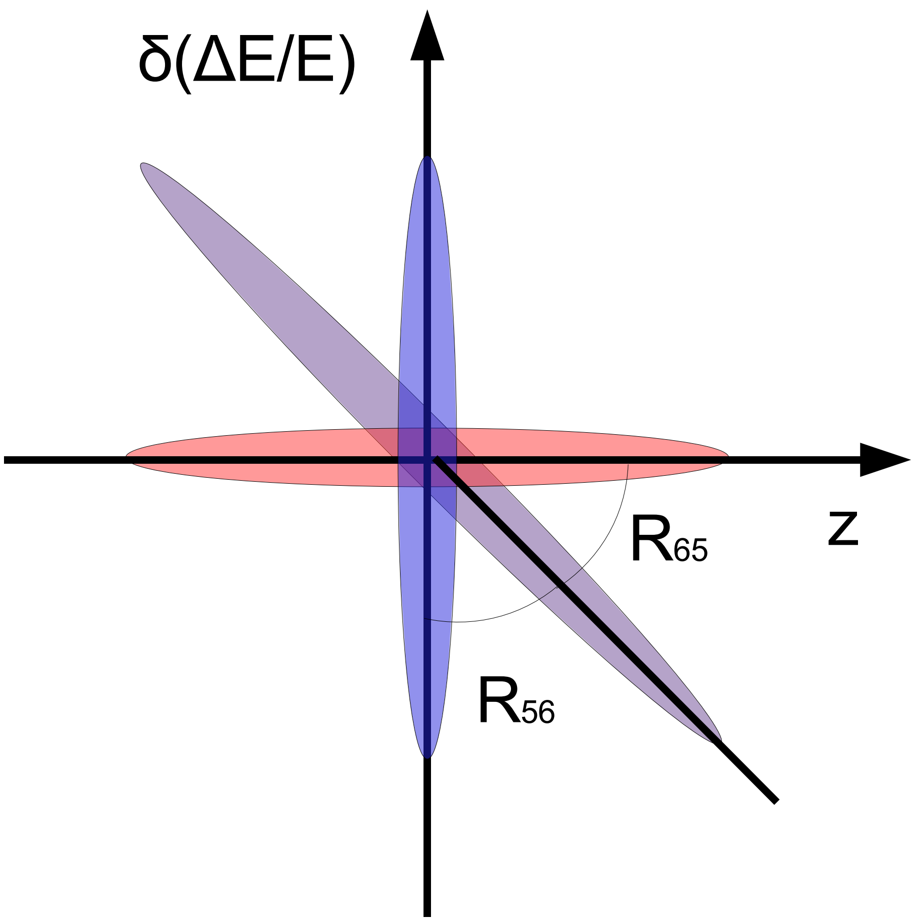
- Total Transfer Matrix of BC section.

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

- If $1+R_{56}R_{65}=0$, the phase space distribution rotate π/2 and the bunch length is minimized.



Phase Stability

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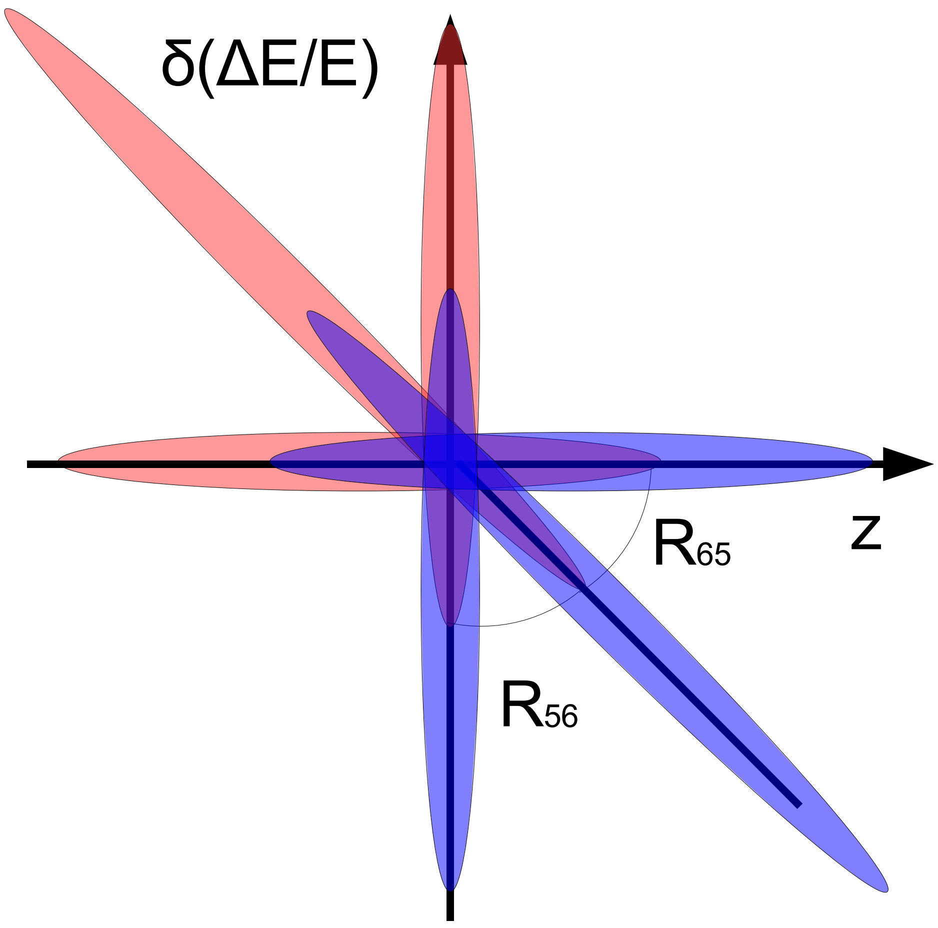
$$\begin{bmatrix} z(s_2) \\ \delta(s_2) \end{bmatrix} = \begin{bmatrix} 0 & R_{56} \\ R_{65} & 1 \end{bmatrix} \begin{bmatrix} z(s_0) \\ \delta(s_0) \end{bmatrix}$$

- The phase in the linac, $z(s_2)$, depends only on $\delta(s_0)$; It is insensitive to the phase fluctuation or drift in DR.
- This is a good mechanism to stabilize the bunch phase prior to acceleration in Main Linac.



Final Bunch Length

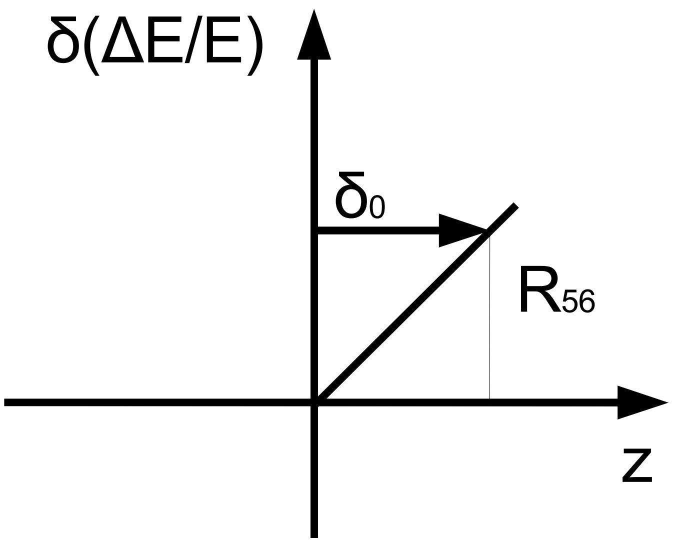
- Final bunch length after an optimized BC section ($1+R_{56}R_{65}=0$) is determined by the initial energy spread as;

$$z_2 = R_{56}\delta_0$$

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

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

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



Effects on the beam

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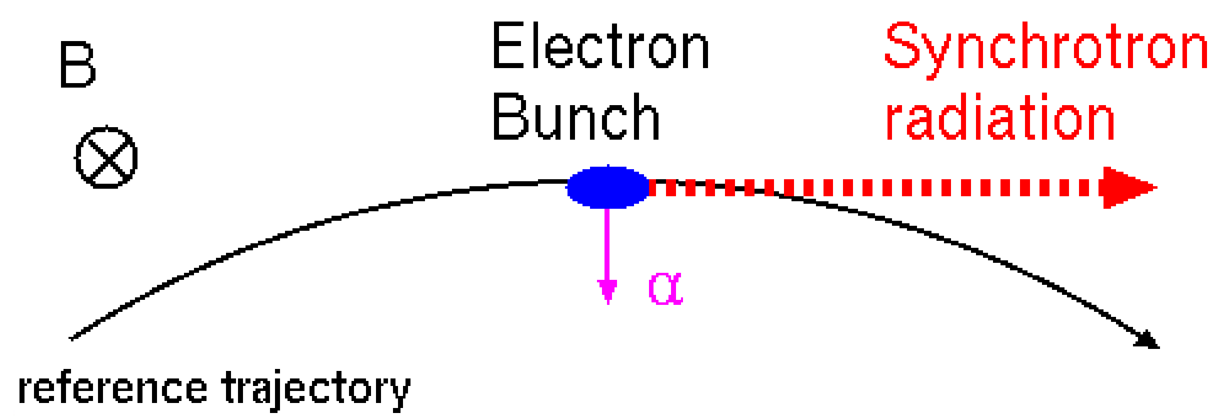
- During the beam transport and bunch compression, electrons emit photon by synchrotron radiation in bending magnets.
- SR causes effects on the electron beam
  - Energy loss
  - Increment of energy spread
  - Increment of emittance
- During the beam transport, these effects should be in tolerance.



Energy Loss

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Summary

- Energy loss can be recovered by additional accelerating section, but lower energy enhances other beam effects.
- Synchrotron Radiation power in bending magnets (transverse acceleration) is

$$P_\gamma(GeV/s) = \frac{c\,C_\gamma}{2\pi}\frac{\beta^4 E^4}{\rho^2}$$

$$C_\gamma = \frac{4\pi}{3}\frac{r_c}{(mc^2)^3} = 8.86\text{E-5}\left[\frac{m}{GeV^3}\right]$$

Taking integral along the beam line gives

$$\Delta E = \int P_\gamma dt = \frac{C_\gamma}{2\pi}\beta^3 E^4 I_2$$

$$I_2 = \int \frac{ds}{\rho^2}$$

Energy Spread

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- Synchrotron radiation is a quantum and statistical process.
- The energy spread is increased in unit of time as

$$\dot{N}_{ph}\langle\epsilon^2\rangle = C_q \frac{4}{3} r_c c (mc^2)^2 \beta^4 \frac{\gamma^7}{\rho^3}, \qquad C_q = \frac{55}{32\sqrt{3}} \frac{\hbar c}{mc^2}$$

$$C_q = 3.84\text{E-}13\,(m), \quad r_c = 2.82\text{E-}15\,(m)$$

- By taking integral along the beam trajectory, relative energy spread is

$$\Delta\sigma^2 = \int \frac{\dot{N}_{ph}\langle\epsilon^2\rangle}{E^2} dt = \frac{4}{3} C_q r_c \beta^3 \gamma^5 I_3, \qquad I_3 = \int \frac{ds}{|\rho^3|}$$

Transverse Emittance (1)

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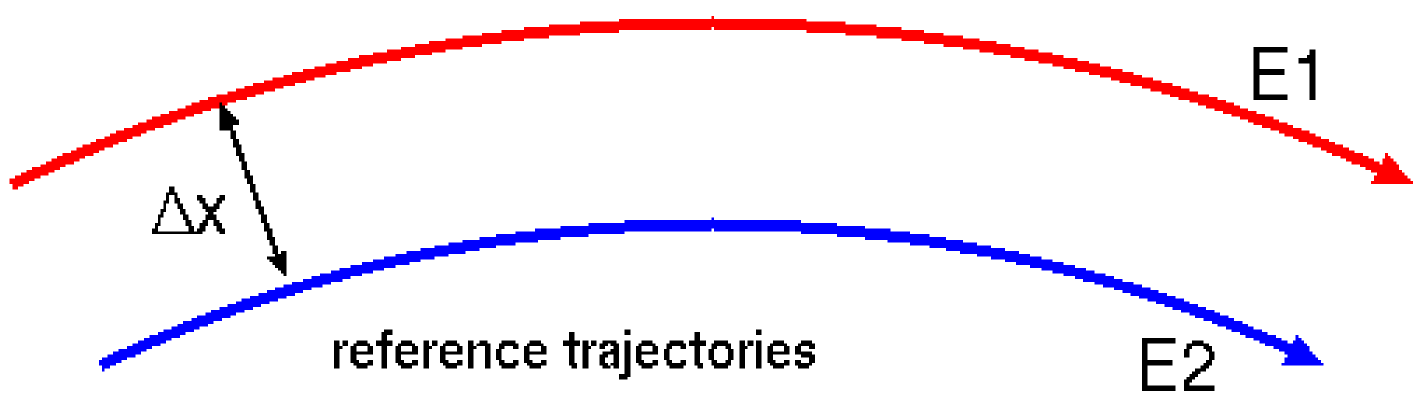
- Beam particle performs betatron motion around the reference path.
- Two particles with different energy follow two different reference trajectories (η(s): dispersion, E_0: reference energy)

$$\Delta x = \eta(s) \frac{E_1 - E_2}{E_0}$$



Transverse Emittance (2)

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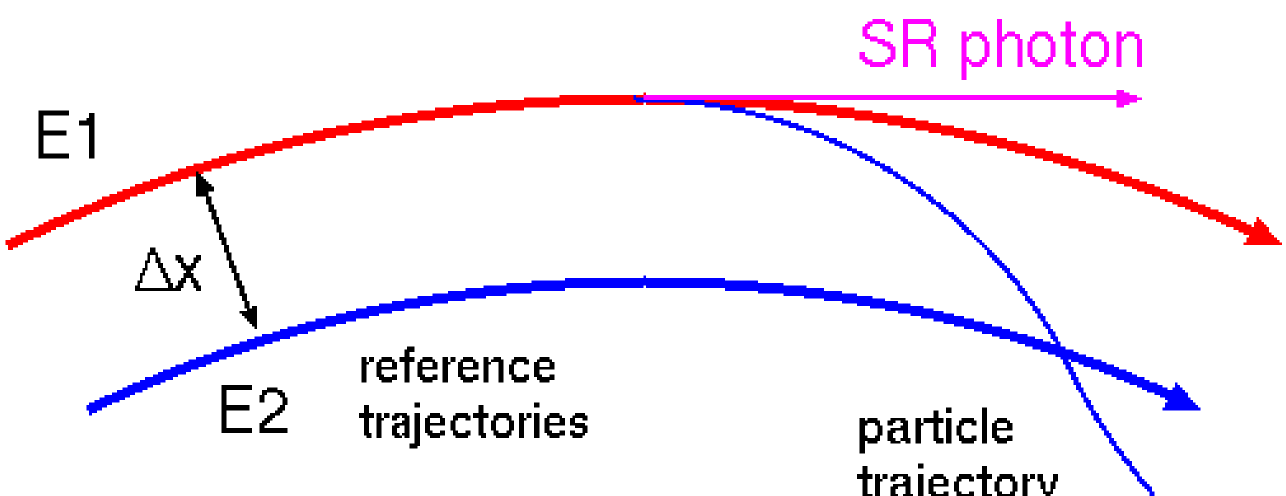
Summary

- If a particle emits SR photon(E_1->E_2), there is no change on the position x and direction x'.
- But, betatron motion is induced because of the change of the reference path.

$$\Delta x = \eta(s) \frac{E_1 - E_2}{E_0}$$



Transverse Emittance (3)

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- The change of the particle motion in the phase space (betatron motion) is

$$\Delta x = \eta(s)\frac{\epsilon}{E_0}, \qquad \Delta x' = \eta'(s)\frac{\epsilon}{E_0},$$

- The change in the betatron action is

$$\Delta J = \left(\frac{\epsilon}{E_0}\right)^2 H, \qquad H = \gamma\eta^2 + 2\alpha\eta\eta' + \beta\eta'^2$$

- Integrating over the phase space and path length, the emittance growth by SR is

$$\Delta\epsilon = \frac{\gamma\beta}{2\beta c E^2}\int \dot{N}_{ph}\langle\varepsilon^2\rangle H ds$$

$$= \frac{2}{3}C_q r_c \beta^4 \gamma^6 I_5, \qquad I_5 = \int \frac{H}{|\rho^3|} ds$$

Beam Parameters

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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 (1)

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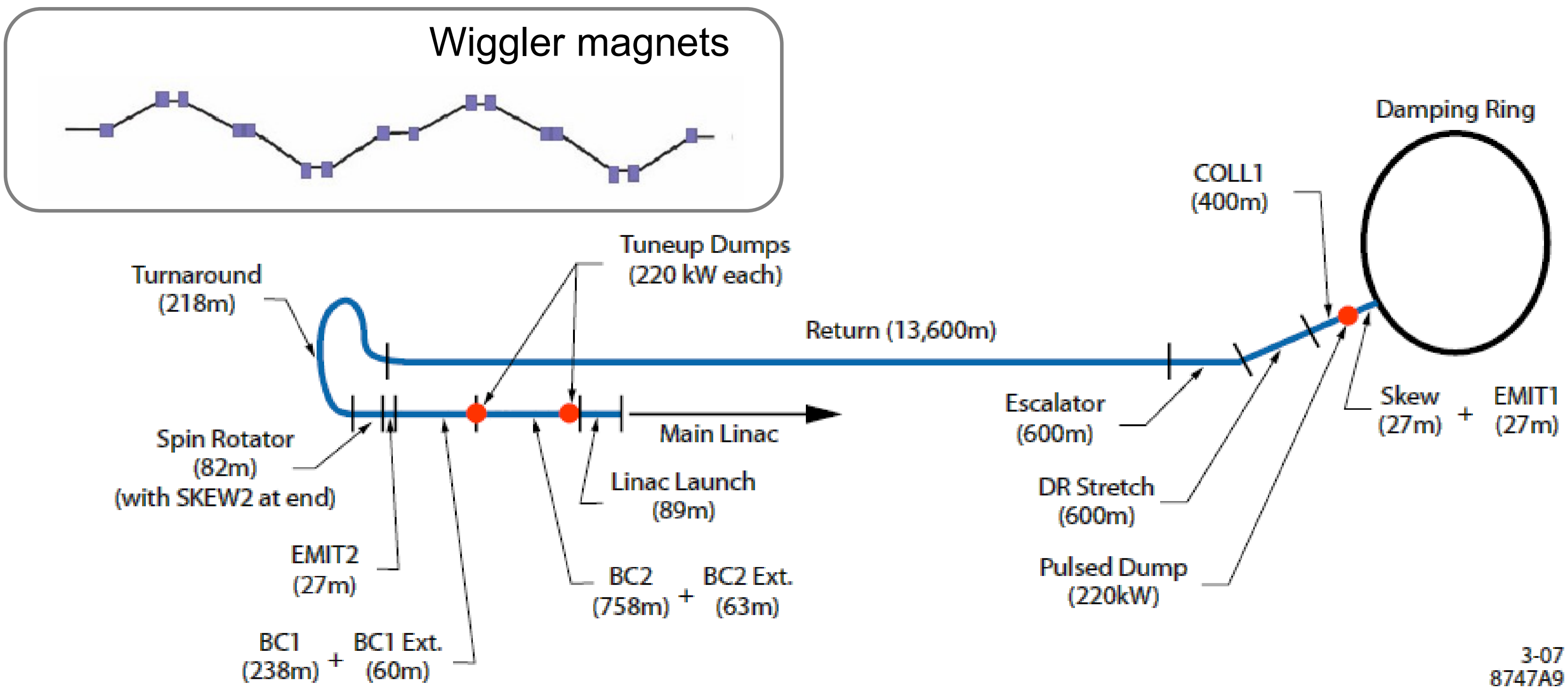
- ILC Bunch Compressor is placed before ML.
- ILC Bunch Compressor is 2 stages based on wiggler.
  - **Gives a large flexibility on the tuning.**
  - **Gives a large tolerance on system errors.**



ILC Bunch Compressor (3)

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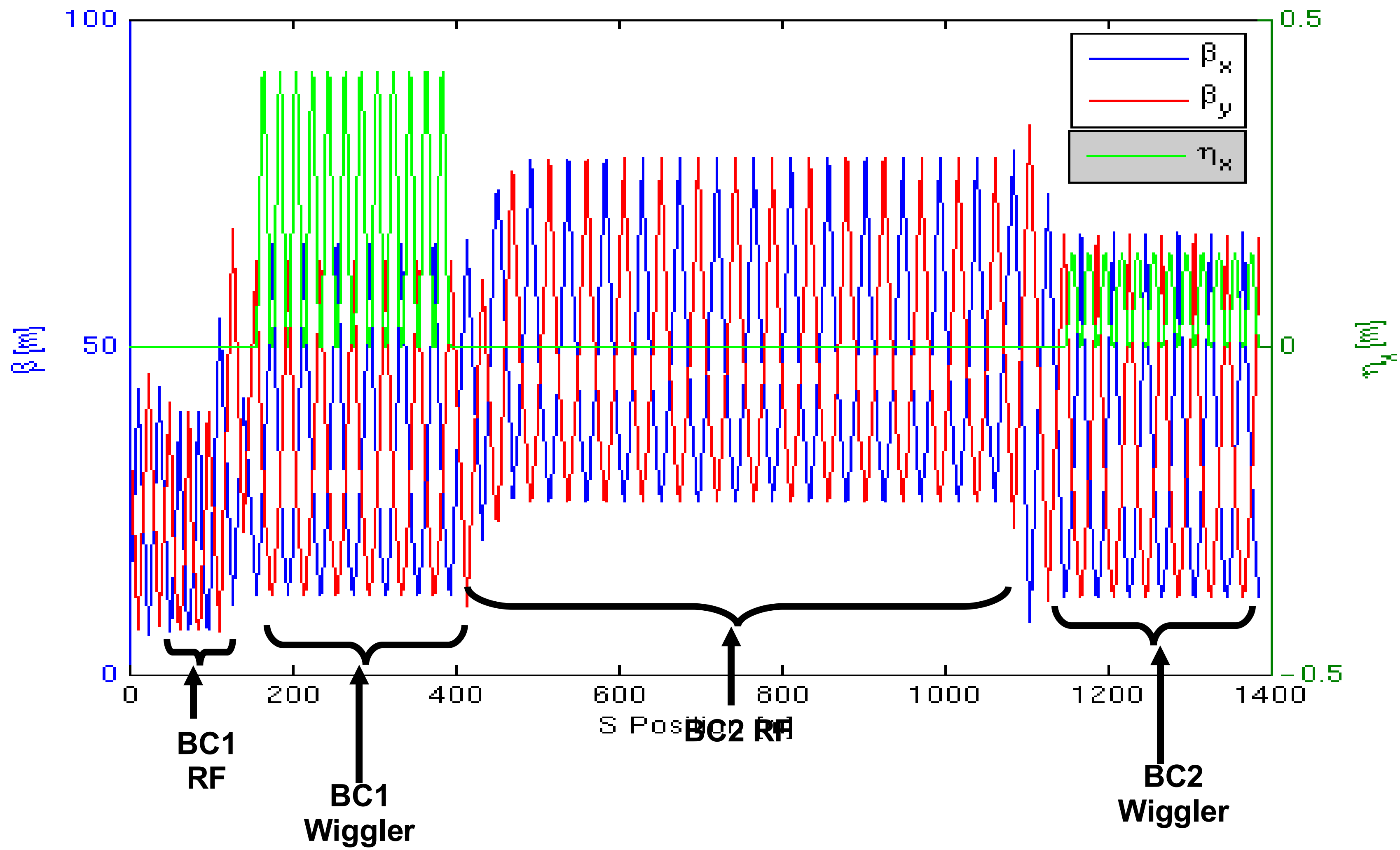
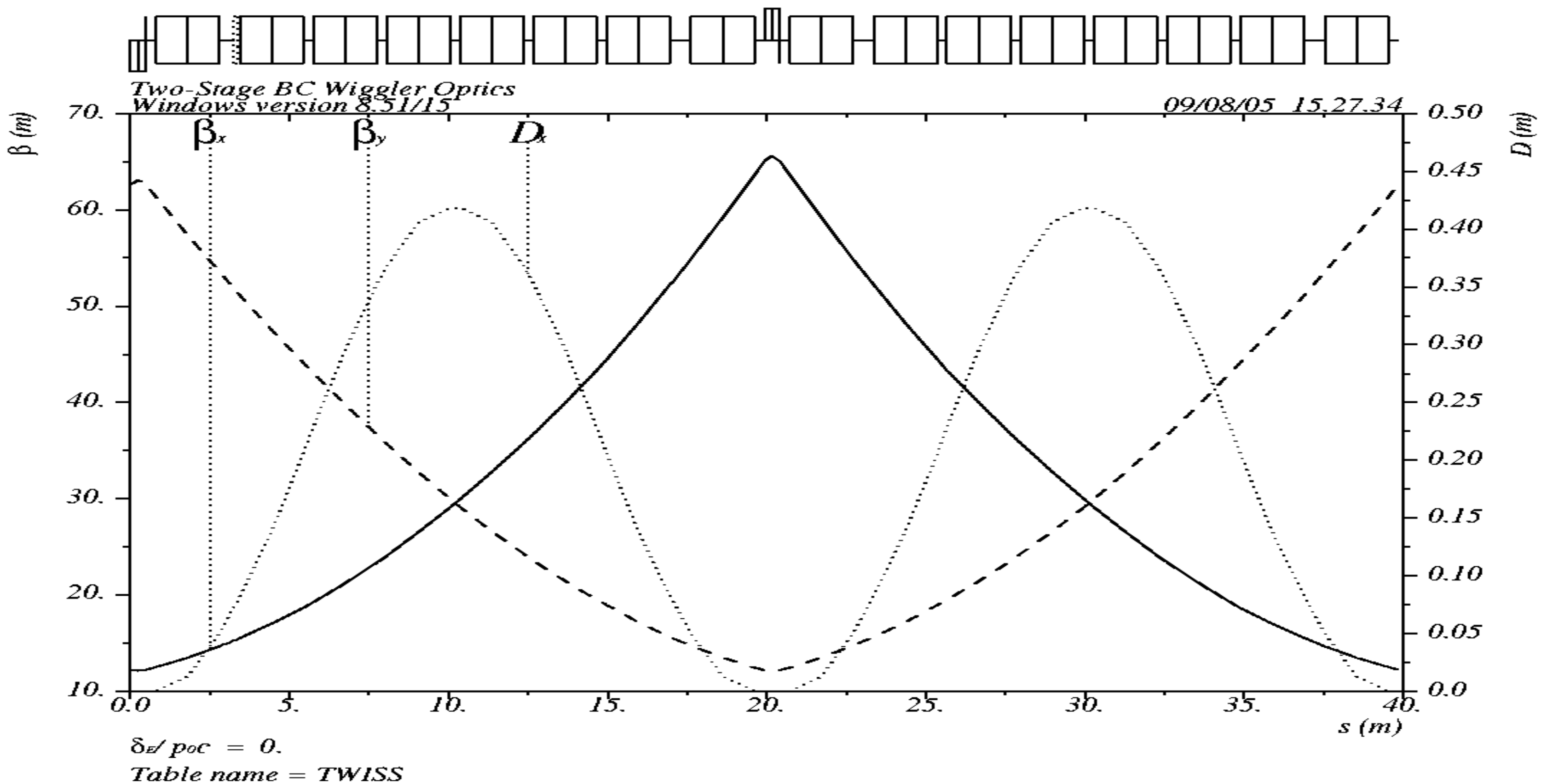


Wiggler Section

- 16 bendings and 2 quadrupoles compose a wiggler section
- 6 periods (FODO cells) for each BC stages



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ILC Bunch Compressor: BC1

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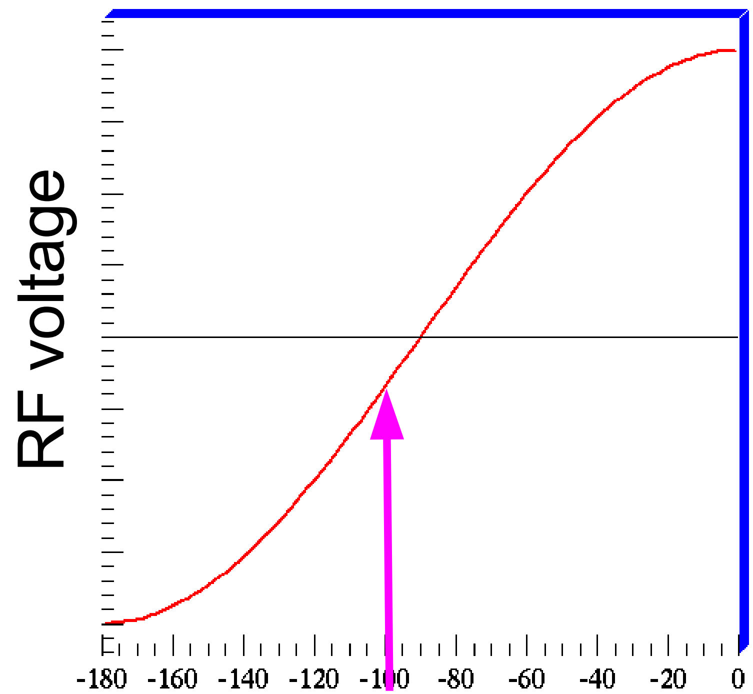
- Almost zero cross (-100deg)
- large BC factor 9 (9mm to 1mm)
- Large energy spread (0.1% to 2.5%).
  - 24x9 cell RF cavities arranged in 3 cryomodules.
  - 6 Periods of wiggler section, which is composed from 16 bendings and 2 quadrupoles.



ILC Bunch Compressor: BC2

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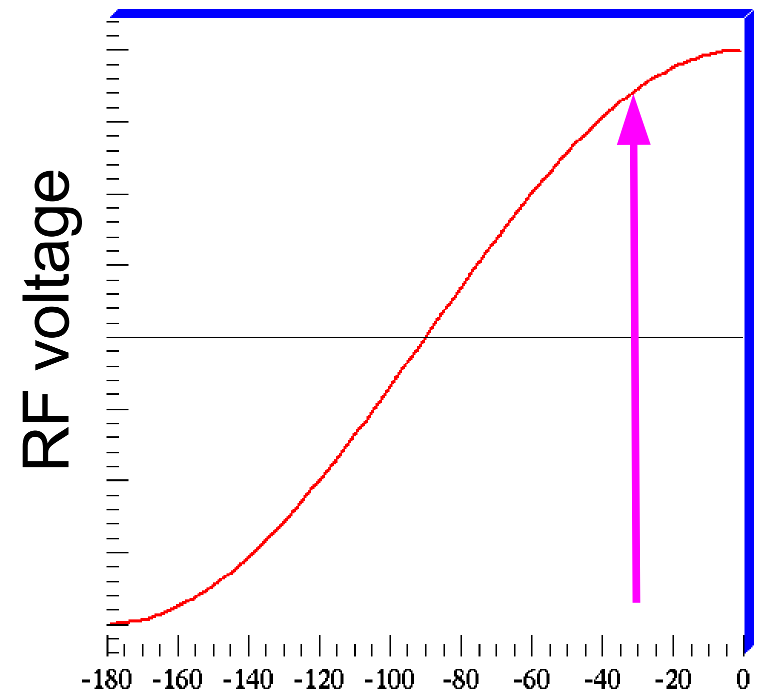
- Simultaneous acceleration (-27.6deg) to compensate the energy spread.
- Small BC factor 3.3 (1mm to 0.3mm)
- Energy spread is suppressed by acceleration (2.5% to 1.5%).
  - 456 9 cell RF cavities arranged in 57 cryomodules.
  - 6 Periods of wiggler section, which is composed from 16 bendings and 2 quadrupoles.



ILC Bunch Compressor (2)

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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

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- 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

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