Alternative Bunch Compressors for ILC

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Why we need BC in ILC Project?

To supply e+e- colliding beams with high luminosity of a few $10^{38}$ m$^{-2}$s$^{-1}$

- **Luminosity $L$ (TESLA TDR 2001):**

  $$ L = \frac{n_b N_b^2 f_{rep}}{4\pi \sigma_x \sigma_y} \times H_D \approx 5.74 \cdot 10^{20} \text{ m}^{-3/2} \times \frac{P_b}{E_{cm}} \times \left( \frac{\delta_{BS}}{\varepsilon_{n,y}} \right)^{1/2} \times H_D \quad \text{for } \beta_y^* = \sigma_z $$

For given center of mass energy $E_{cm}$ and fractional beamstrahlung loss $\delta_{BS}$
- higher average beam power $P_b$
- smaller vertical emittance $\varepsilon_{n,y}$
- smaller vertical beam size at IP $\sigma_y^*$
- shorter bunch length $\sigma_z = \text{smaller } \beta_{n,y}^*$ (hourglass effect, $\beta_y^* \geq \sigma_z$)

give higher higher luminosity $L$.

According to Tor Raubenheimer’s new suggested ILC beam parameters range, we should compress bunch length from 6.0 mm to 0.15 mm for high luminosity mode operation (compression factor = 40).

Recently, Andy Wolski suggested to use 9.0 mm length in damping ring. In this case, compression factor from 9.0 mm to 0.15 mm is 60.
Working Principle of Bunch Compressor (BC)

Bunch Compressor Layout for SCSS Project - Y. Kim et al, NIMA 528 (2004) 421

![Diagram of Bunch Compressor Layout](image)

\[ dz_f = dz_i + R_{56} (dE / E)_i + T_{566} (dE / E)_i^2 + O((dE / E)_i^3) \]

where \( T_{566} = -\frac{3}{2} R_{56} \) for the rectangular bend chicane.

\[ R_{56} \approx 2\theta_B^2 \left( \Delta L + \frac{2}{3} L_B \right) \]
Considerations - ISR in Dipole

Incoherent Synchrotron Radiation (ISR) is generated when relativistic long beam goes through dipole magnet. Since ISR is a random quantum process, it generates incoherent (= slice, or uncorrelated) energy spread, hence slice emittance growth in the bending plane. For one dipole magnet, the relative uncorrelated energy spread due to ISR is given by

\[ \sigma_{\delta,ISR,1\text{dipole}} \approx \frac{1}{L_B} \sqrt{(4.13 \times 10^{-11} \text{ m}^2 \cdot \text{GeV}^{-5})E^5|\theta_B^3|}. \]

Slice emittance growth due to ISR is given by

\[ \Delta \gamma \varepsilon_x \approx 8 \times 10^{-8} E^6 \frac{\theta_B^5}{L_B^2} \left[(\Delta L + L_B) + \frac{\beta_{\max} + \beta_{\min}}{3}\right] \quad \text{for chicane.} \]

\[ P_{ISR} \propto N_b \]

- lower energy
- longer dipole
- smaller bending angle
are good against ISR effects
Considerations - CSR in BC

In BC where dispersion is nonzero, bunch length becomes smaller. Short electron bunches in dipole can radiate coherently (CSR) at wavelength $\lambda \geq c/\gamma z$. CSR from tail electrons can overtakes head electrons after the overtaking length.

$$L_{OT} \approx \left(24\sigma_z R^2\right)^{1/3}$$ where $\sigma_z$ is rms bunch length, $R$ is bending radius.

Electrons are transversely kicked at the nonzero dispersion region or in BC. Hence, projected emittance is increased in BC due to CSR.
Considerations - CSR in BC

Without CSR self-interaction

With CSR self-interaction

Head with lower energy

Projected emittance growth due to CSR

\[ \eta_x \neq 0 \text{ in BC} \]

\[ x = x_0 + \eta_x \frac{dE}{E} \]

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
Considerations – CSR for None Uniform Beams

If there is a nonuniformity in current distribution, the local charge concentration or spike is generated during the bunch compression process. In this case, CSR is enhanced due to the local charge concentration. (R. Li, LINAC2000)

![Graph showing longitudinal charge distribution and CSR force for a compressed bunch](image)

[Longitudinal Charge Distribution and CSR force for a compressed bunch]
Without higher harmonic compensation cavity, nonlinearity in \( dz-dE \) chirping becomes stronger after BC, and there is some local charge concentration in very small local region. This nonlinearity by RF curvature makes femtosecond spike at TTF2.
Considerations – Nonlinearities

- Linearization of longitudinal phase space with a higher harmonic cavity

\[
\frac{d}{d(dz_2)} \left( \frac{d(dE_1 + dE_2)}{d(dz_2)} \right) = 0 \quad \therefore \quad GL_2 = -\left( GL_1 / n^2 \right) \cos \phi_{s1}
\]

where \( GL_2 \) is the energy gain of the higher harmonic cavity, \( GL_1 \) is energy gain of the low frequency linac, and \( n \) is the harmonic number.

Linear range ~ 60 degree
- 60 deg in 2856 MHz ~ 60 ps (18 mm)
- 60 deg in 1300 MHz ~ 126 ps (37.8 mm)
- 60 deg in 650 MHz ~ 252 ps (75.6 mm)
Good for 9.0 mm (rms) ILC bunch

Nonlinearities in the longitudinal phase space due to RF curvature, short-range wakefields, T566, and space charge force can be compensated by harmonic cavity.
Considerations – Twiss Parameters around BCs

- Strong focusing lattice around BCs to reduce CSR induced emittance growth

Strong focusing against CSR

$\alpha$-functions $\approx 0$

$\beta$-functions $\approx 3$

Lattice optimization to minimize this term

Before BC1

After BC1

$\varepsilon \approx \sqrt{1 + \frac{(0.22)^2 r_e^2 N^2}{36 \gamma_e \theta_N \beta} \left( \frac{L_B}{\sigma_z^4} \right)^2 \left( L_B^2 \left( 1 + \alpha^2 \right) + 9 \beta^2 + 6 \alpha \beta L_B \right)}$
Considerations – Compression Ratio in BCs

- Longer bunch length at BC1 ➔ Weaker CSR at BC1
  ➔ Stronger compression at BC1

- Shorter bunch length at BC2 ➔ Stronger CSR at BC2
  ➔ Weaker compression at BC2

European XFEL (10AUG04 Version)

BC1: 1.76 µm → 94 µm
Compression factor = 18.7

BC2: 94 µm → 21.5 µm
Compression factor = 4.4
Considerations – Linac Length & Wakefields

- Shorter linac with a lower frequency between BC1 and BC2 to control over-compression and CSR at BC2 due to the short-range longitudinal wake fields.

**BC2 for LCLS**

Over-compression after BC2 due to longitudinal wakefields in the long L2 linac generates large project emittance growth at BC2.

**TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider**
BCs for European XFEL (13JAN04 Version)

With TESLA XFEL Injector, $\varepsilon_n = 0.9 \, \mu m$

$Q = 1.0 \, nC$

e-beam

$\sigma_z = 1.76 \, mm \rightarrow 113 \, \mu m \rightarrow 23 \, \mu m$

$\epsilon_n = 0.9 \, \mu m$

$Q = 1.0 \, nC$

e-beam

$\sigma_z = 20.5 \, \mu m$

$E = 510 \, MeV$

$\sigma_\delta \sim 1.89\%$

$R_{56} = 87 \, mm$

$\theta = 3.95 \, deg$

$E = 510 \, MeV$

$\sigma_\delta \sim 1.88\%$

$R_{56} = 4.8 \, mm$

$\theta = 0.93 \, deg$

To the end of Linac: ELEGANT with CSR

with geometric wakefields

without space charge

$E = 20.0 \, GeV$

$\sigma_\delta = 0.008\%$

$\sigma_x = 37.3 \, \mu m$, $\sigma_y = 31.6 \, \mu m$, $\sigma_z = 20.5 \, \mu m$

$\varepsilon_{nx} = 1.15 \, \mu m$, $\varepsilon_{ny} = 0.94 \, \mu m$

All projected parameters!
New BCs for XFEL (10AUG04 Version)

With New European XFEL Injector, $\varepsilon_n = 0.88 \mu m$

$Q = 1.0 \text{ nC}$

e-beam

$\sigma_z = 1.72 \text{ mm} \rightarrow 94 \mu m \rightarrow 21.6 \mu m$

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To the end of Linac: ELEGANT with CSR

with geometric wakefields without space charge

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$E = 518 - 760 - 1100 \text{ MeV}$

$\sigma_\delta \sim 1.87 - 1.33 - 0.9\%$

$R_{56} \sim 5.3 \text{ mm}$

$\theta \sim 0.93 \text{ deg}$

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All are projected parameters!
Considerations – S2E Simulations on RF Jitter

change in bunch length $\sigma_s$ within +10%
change in beam energy within 0.005%
change in bunch arrival time within 50 fs

p2p phase error = $3\times0.05\ \text{deg}$
p2p amplitude error = $3\times0.02\%$

p2p current error = $3\times0.02\%$

After applying random error set (p2p = $3 \times$ tolerance) to each component, I have performed about 400 times S2E simulations from gun to the end of linac to compare two linac layouts under same jitter tolerance set.
Considerations – Jitter under Random Errors

400 Times Tracking with (13JAN04)

most sensitive jitter source on bunch length = ACC2 phase error

wider change in bunch length for (13JAN04 Version)
stronger correlation with errors in other components!

400 Times Tracking with (10AUG04)
Considerations – Jitter under Random Errors

400 Times Tracking with (13JAN04)  

most sensitive jitter source on arriving time = BC1 current error

wider change in bunch arriving time for (13JAN04 Version)  
stronger correlation with errors in other components!
ACC234 Phase is the most sensitive jitter source to saturation power and saturation length.

For ± 0.5 deg change in ACC2 phase

strong over-compression against ACC234 phase error
ACC234 Phase is the most sensitive jitter source to saturation power and saturation length.

For ± 0.5 deg change in ACC2 phase, weak over-compression against ACC234 phase error.

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TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
RF Jitter at TTF2

GUN and ACC1 with RF feedback
variation of energy ~ 0.054%

energy drift = 69.991keV

variation of energy spread ~ 1%

mean $\sigma_x$ = 168.856keV
mean $\sigma_y$ = 12.235pixel
$\text{s}_{\text{dd}} \sigma_x$ = 6.908keV
$\text{s}_{\text{dd}} \sigma_y$ = 0.319pixel
Drift of Bunch Length at TTF2

Drifting pyroelectric detector signal indicates status of drifting bunch length

RF jitter is the most important thing for the proper BC operation !!!

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
Current ILC Bunch Compressor in TDR

**BC Parameters**
- Energy ~ 5.0 GeV
- Charge = 3.2 nC
- Initial energy spread at DR exit = 0.13%
- Initial rms bunch length = 6 mm
- Final rms bunch length = 0.3 mm
- Momentum compaction $R_{56} = 215$ mm
- Compression factor = 20
- Initial horizontal emittance = 8.0 µm
- Initial vertical emittance = 0.02 µm

Periodically dispersion: emittance compensation

- One stage: sensitive to RF jitter
- Many dipoles: twelve dipoles with 3.23 deg bending angle & six dipoles with 6.46 deg
- Large energy spread due to ISR and CSR from many dipole, hence emittance growth
- No consideration of short-range wakefields in TESLA modules (under estimation)
- No effective nonlinearity compensation
- Many dipoles and QMs, which induce chromatic effects
1st Alternative BC for ILC (10NOV04 Version)

**Initial parameters**

- \( E = 5.0 \text{ GeV} \)
- \( \sigma_\delta = 0.13\% \) (small !)
- \( \sigma_z = 6.0 \text{ mm} \)
- \( \varepsilon_{nx} = 8.0 \mu\text{m}, \varepsilon_{ny} = 0.02 \mu\text{m} \)

- \( Q = 3.2 \text{ nC} \)
- e-beam

**Damping Ring**

- 23.4 MV/m
- -45 deg
- 24.8 MV/m
- 170.0 deg

**ACC1 ACC2 ACC3 ACC4 ACC39 BC1 ACC5 ACC6 BC2**

- \( E = 6.0 \text{ GeV} \)
- \( \sigma_\delta \approx 2.174\% \)
- \( R_{56} \approx 17 \text{ mm} \)
- \( \theta \approx 1.4 \text{ deg} \)

- \( E = 5.689 \text{ GeV} \)
- \( \sigma_\delta \approx 2.4\% \)
- \( R_{56} = 236 \text{ mm} \)
- \( \theta = 5.3 \text{ deg} \)

- \( E = 6.0 \text{ GeV} \)
- \( \sigma_\delta \approx 2.174\% \)
- \( R_{56} \approx 17 \text{ mm} \)
- \( \theta \approx 1.4 \text{ deg} \)

Up to **main linac** : ELEGANT with CSR, ISR, and geometric short-range wakefields. but without space charge

**Final parameters**

- \( E = 6.0 \text{ GeV} \)
- \( \sigma_\delta = 2.173\% \)
- \( \sigma_z = 300 \mu\text{m} \)
- \( \varepsilon_{nx} = 8.7 \mu\text{m}, \varepsilon_{ny} = 0.02 \mu\text{m} \)
From various experiences in **Start-To-End simulations** and **BC designs** for TTF2, European XFEL, SCSS, PAL XFEL, we have chosen **two BC stages**

Two ACC398 3.9 GHz TESLA 3rd harmonic modules, $-114$ MeV

ACC4 1.3 GHz TESLA module, 5809 MeV

**BC2 has same layout**
1st Alternative ILC BC – Long. Phase Space

10NOV04 Version

strong nonlinearity due to RF curvature

![Graph showing strong nonlinearity due to RF curvature](image)

Before ACC1

After ACC234
1st Alternative ILC BC – Long. Phase Space

Linearization with two ACC39 modules (3.9 GHz) is not enough!

\[ \sigma_z = 6.00 \text{ mm} \]
\[ \mu m \]

\[ \sigma_z = 673 \]
1st Alternative ILC BC – Long. phase space

10NOV04 Version

Edges: over (or under)-compression by the nonlinearity due to wakefields, T566, RF curvature

\[ \sigma_z = 673 \, \mu m \]

\[ \sigma_z = 300 \, \mu m \]
1\textsuperscript{st} Alternative ILC BC – Compression Ratio

10NOV04 Version

\[ \sigma_\delta = 2.173\% \]

8.9 times compression at BC1

2.2 times compression at BC2
even rms horizontal emittance is increased to 8.7 µm due to ISR and CSR but vertical emittance is almost const (0.02 µm).

final horizontal emittance = 8.7 µm

with consideration of CSR and ISR

final vertical emittance = 0.02 µm
1st Alternative ILC BC – Zoomed after BC2

10NOV04 Version

Edges: over (or under) -compression due to the nonlinearity

It seems that 3rd harmonic cavity is not enough to compensate the nonlinearity
Linear range of current compensation layout (1300 MHz + 3900 MHz) is very close to the initial bunch length of 6.0 mm (RMS). With this layout, we can not compensate the nonlinearity well if the initial bunch length is 9.0 mm (RMS).

60 deg (FW) in 1300 MHz Linac
- corresponding to 126 ps (FW)
- corresponding to 37.8 mm (FW)
- corresponding to 6.3 mm (RMS)
  (close to current $\sigma_z = 6.0$ mm)

60 deg (FW) in 650 MHz Linac
- corresponding to 252 ps (FW)
- corresponding to 75.6 mm (FW)
- corresponding to 12.6 mm (RMS)
  (wider than $\sigma_z = 9.0$ mm)
- corresponding 3rd harmonic = 1950 MHz

Here Full Width (FW)
~ six times of RMS
Nonlinearity Compensation with 2nd Harmonic

Linear range of a new compensation layout (650 MHz + 1300 MHz) is a wide range of 85 deg. With this layout, we can compensate the nonlinearity properly even though the initial bunch length is 9.0 mm (RMS).

85 deg (FW) in 1300 MHz Linac
- corresponding to 178.5 ps (FW)
- corresponding to 53.55 mm (FW)
- corresponding to 8.93 mm (RMS)
  (not enough for $\sigma_z = 9.0$ mm)

85 deg (FW) in 650 MHz Linac
- corresponding to 357 ps (FW)
- corresponding to 107.1 mm (FW)
- corresponding to 17.9 mm (RMS)
  (much wider than $\sigma_z = 9.0$ mm)
- corresponding $2^{nd}$ harmonic = 1300 MHz

Here Full Width (FW) ~ six times of RMS
2nd Alternative ILC BC - (04APR05 Version)

- Frequency of precompressor linac (before BC1) = 650 MHz
  - helpful in reducing tight RF jitter tolerance, wakefield effects, and misalignment effects
- Frequency of compensation cavity = 1300 MHz (2nd harmonic of 650 MHz)
- Frequency of main linac from down stream of the 2nd bunch compressor = 1300 MHz
- Chicane type = S-type to control dispersion within about 1.0 m
  and to compensate the projected emittance growth due to CSR
- Initial bunch length = 9.0 mm (rms)
- Final bunch length = 100 µm (rms) with 1.4 deg bending angle at BC2
  138 µm (rms) with 1.35 deg bending angle at BC2

1300 MHz TESLA module can replace 650 MHz SACC56

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
2nd Alternative ILC BC – (04APR05 Version)

Initial parameters

- \( E = 5.0 \text{ GeV} \)
- \( \sigma_\delta = 0.13\% \) (small !)
- \( \sigma_z = 9.0 \text{ mm} \)
- \( \varepsilon_{nx} = 8.0 \mu\text{m}, \varepsilon_{ny} = 0.02 \mu\text{m} \)

Q=3.2 nC

e-beam

Final parameters

- \( E = 6.0 \text{ GeV} \)
- \( \sigma_\delta = 2.0491\% \)
- \( \sigma_z = 138 \mu\text{m} \)
- \( \varepsilon_{nx} = 9.2 \mu\text{m}, \varepsilon_{ny} = 0.02 \mu\text{m} \)

Here from SACC12 to SACC56 are two 650 MHz subharmonic modules with 12 cavities, and ACC1 is the 1300 MHz TESLA module with 12 cavities. From the downstream of SBC2, we will use the 1300 MHz TESLA module for the main linac.

Up to main Linac with ELEGANT under CSR, ISR, and geometric short-range wakefields. but without space charge
To avoid chromatic effect with high beta function, we chose doublet in modules.

S-type BC1 chicane = 6 dipoles

S-type BC2 chicane = 6 dipoles

Too small modules for FODO cells

Dispersion is within ±1.0 m

Emittance growth due to CSR is compensated by reversed dispersion.
edge-to-edge ~ 42 mm for 2σ cutting in initial beam distribution

reduced nonlinearity due to weaker wakefield and weaker RF curvature in 650 MHz linac!
Nonlinearity was compensated by a 1300 MHz TESLA module (ACC1)

\[ \sigma_z = 9.00 \text{ mm} \]

\[ \sigma_z = 624 \mu\text{m} \]
$\sigma_z = 624 \, \mu m$ 
SBC2

$\sigma_z = 138 \, \mu m$  for 1.35 deg at SBC2

$\sigma_z = 100 \, \mu m$  for 1.40 deg at SBC2
2\textsuperscript{nd} Alternative ILC BC – Energy Spread

04APR05 Version

\[ \sigma_z = 9 \text{ mm} \]
\[ \sigma_\delta = 2.0491\% \]
\[ \sigma_z = 138 \mu\text{m} \]
2\textsuperscript{nd} Alternative ILC BC – Projected Emittance

04APR05 Version

final horizontal emittance = 9.2 μm

final vertical emittance = 0.02 μm
Action of CSR and ISR when we compress $\sigma_z = 9.0$ mm to $138$ $\mu$m

- Final horizontal emittance with consideration of CSR and ISR = $9.2$ $\mu$m
- Final horizontal emittance with consideration of only ISR = $8.68$ $\mu$m
- Final horizontal emittance without consideration of CSR and ISR = $8.04$ $\mu$m

We never ignore CSR and ISR!

Horizontal emittance = $8.68$ $\mu$m

Vertical emittance = $0.02$ $\mu$m
2nd Alternative ILC BC – Peak Current

04APR05 Version

good compensation by ACC1
good symmetric peak current

\[ \sigma_z = 9.0 \text{ mm with 3.2 nC} \]

\[ \sigma_z = 138 \text{ \mu m with 3.2 nC} \]

Before BC1 with 70 slices

After BC2 with 70 slices
3rd Alternative ILC BC - (09JUL05 Version)

- Frequency of precompressor linac = 650 MHz
  - helpful in reducing tight RF jitter tolerance, wakefield effects, and misalignment effects

- Frequency of compensation cavity = 1300 MHz (2nd harmonic of 650 MHz)

- 1300 MHz normal TESLA modules can be usable for linac betweens BC1 and BC2

- A short linac between BCs to reduce construction cost

- Frequency of main linac from down stream of the 2nd bunch compressor = 1300 MHz

- Chicane type = S-type to control dispersion within about 1.0 m and to compensate the projected emittance growth due to CSR

- Initial bunch length = 6.0 mm (rms)

- Final bunch length = 150 µm (rms) or shorter

- Final relative rms energy spread = 1.44% (reduced !)
**3rd Alternative ILC BC – (09JUL05 Version)**

**Initial parameters**

\[-\begin{align*}
E &= 5.0 \text{ GeV} \\
\sigma_\delta &= 0.13\% \text{ (small !)} \\
\sigma_z &= 6.0 \text{ mm} \\
\varepsilon_{nx} &= 8.0 \mu\text{m}, \varepsilon_{ny} = 0.02 \mu\text{m}
\end{align*}\]

Q=3.2 nC

e-beam

\[\begin{align*}
\text{SACC12} & & \text{SACC34} & & \text{ACC1} & & \text{SBC1} & & \text{SACC56} & & \text{SBC2} & & \text{ACC2} & & \text{ACC3}
\end{align*}\]

[Damping Ring]

13.3 MV/m

\[-61\text{ deg}\]

25.1 MV/m

\[160.5\text{ deg}\]

\[E = 5.345 \text{ GeV} \]

\[\sigma_\delta \sim 1.57\%\]

\[R_{56} \sim 351 \text{ mm}\]

\[\theta = 5.15\text{ deg}\]

\[13.35 \text{ MV/m} \]

\[-26.0\text{ deg}\]

\[E = 6.00 \text{ GeV} \]

\[\sigma_\delta \sim 1.44\%\]

\[R_{56} \sim 24 \text{ mm}\]

\[\theta = 1.35\text{ deg}\]

**Final parameters**

\[-\begin{align*}
E &= 6.0 \text{ GeV} \\
\sigma_\delta &= 1.44\% \\
\sigma_z &= 150 \mu\text{m} \\
\varepsilon_{nx} &= 8.8 \mu\text{m}, \varepsilon_{ny} = 0.02 \mu\text{m}
\end{align*}\]

Here from SACC12 to SACC56 are two 650 MHz subharmonic modules with 12 cavities, and ACC1 is the 1300 MHz TESLA module with 12 cavities. From the downstream of SBC2, we will use the 1300 MHz TESLA module for the main linac.

Up to main Linac with ELEGANT under CSR, ISR, and geometric short-range wakefields. but without space charge

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
Nonlinearity was compensated by 1300 MHz TESLA module (ACC1)

\[ \sigma_z = 6.00 \text{ mm} \]

\[ \sigma_z = 150 \mu\text{m} \]
3rd Alternative ILC BC – Peak Current

σ_z = 6.00 mm with 3.2 nC

σ_z = 150 µm with 3.2 nC
$\sigma_z = 6 \text{ mm}$

$\sigma_\delta = 1.44\%$

$\sigma_z = 150 \mu\text{m}$
3rd Alternative ILC BC – Projected Emittance

09JUL05 Version

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider

- final horizontal emittance = 8.8 µm
- final vertical emittance = 0.02 µm
Still several 650 MHz modules against RF jitter and wakefields, and misalignment

Keep a low gradient in 650 MHz modules to reduce RF jitter sensitivity

2 m long four bends normal chicane in BC1 with 16 m long drifts
  • helpful in reducing ISR induced emittance growth at BC1

Four FODO cells with eight 650 MHz subharmonic modules between BCs
  • helpful in adjusting beam energy at BC2 and easy Twiss parameter matching between BCs

Still S-type BC in BC2 to compensate the projected emittance growth due to CSR

Still short length (total about 450 m)

Horizontal and vertical emittance after BC2 is 8.28 μm 0.020 μm with ISR and CSR

Horizontal and vertical emittance after BC2 is 8.04 μm 0.020 μm without ISR and CSR
4th Alternative ILC BC – (01AUG05 Version)

**Initial parameters**

- \( E = 5.0 \text{ GeV} \)
- \( \sigma_\delta = 0.13\% \) (small !)
- \( \sigma_z = 6.0 \text{ mm} \)
- \( \varepsilon_{nx} = 8.0 \text{ \(\mu\)m}, \varepsilon_{ny} = 0.020 \text{ \(\mu\)m} \)

Q = 3.2 \text{ nC e-beam}

- Damping Ring
- SACC12 (650 MHz)
- SACC34 (650 MHz)
- ACC1
- BC1
- SACC5-13 (1300 MHz)
- SBC2
- ACC2
- ACC3

14.0 MV/m -66.5 deg
26.3 MV/m 163.0 deg

**Final parameters**

- \( E = 6.4 (7.6) \text{ GeV} \)
- \( \sigma_\delta = 1.55\% \)
- \( \sigma_z = 150 \text{ \(\mu\)m} \)
- \( \varepsilon_{nx} = 8.28 \text{ \(\mu\)m}, \varepsilon_{ny} = 0.020 \text{ \(\mu\)m} \)

Here SACC5-13 are eight 650 MHz subharmonic modules with 12 cavities, and four 90 deg FODO cells is used in SACC5-13 modules. SACC5-13 can be replaceable with normal 1300 MHz TESLA modules.

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider

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4th Alternative ILC BC – Twiss Parameters

About 14 m long S-type chicane is under operating at TTF2!

Emittance growth due to CSR can be compensated by strong focusing Twiss parameters at BCs and by reversed dispersion at SBC2.
TTF2 Two Bunch Compressors

Q = 1.0 nC

\( \sigma_z = 1.821 \text{ mm} \)

\( E \sim 127 \text{ MeV} \)

\( R_{56} = 181.3 \text{ mm} \)

\( \sigma_\delta = 0.60\% \)

\( \Theta = 18.0355 \text{ deg} \)

(15 deg ~ 21 deg)

\( E = 380 \text{ MeV} \)

\( R_{56} = 43.1 \text{ mm} \)

\( \sigma_\delta = 0.18\% \)

\( \Theta = 3.577 \text{ deg} \)

(1.7 deg ~ 5.4 deg)

\( E = 445 \text{ MeV} \)

\( \sigma_\delta = 0.16\% \)

\( \sigma_z = 1.821 \text{ mm} \) 794 µm 728 µm (FWHM = 200 fs ~ 50 fs)

RF-GUN ACC1 ACC2 ACC3 ACC4 ACC5 COLLIMATOR 6 UNDULATORs DUMP

2nd Bunch Compressor (BC3)

12.95 MV/m 17.29 MV/m

16.84 MV/m 13.53 MV/m

-9.0 degree 0.0 degree

40.25 MV/m (peak)

38 degree from zero crossing

S-type chicane with 6 dipoles

bending angle ~ 3.577 deg

\( R_{56} ~ 43.1 \text{ mm} \)

dispersion ~ 0.192 m

total length ~ 14 m

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
Nonlinearity was compensated by 1300 MHz TESLA module (ACC1)

\[ \sigma_z = 6.00 \text{ mm} \]

At BC2, we can compress further because we have good linearity in \( dz \)-dE

\[ \sigma_z = 150 \mu \text{m} \]
RMS value through region A gives total (or projected) rms energy spread, $\sigma_E$ (or its relative RMS energy spread $\sigma_\delta$). In our case, initial total rms relative energy spread $\sigma_\delta = 0.13\%$.

RMS value through region B gives uncorrelated (or slice) rms energy spread $\sigma_{E,u}$. In our case, peak-to-peak momentum change in region B is about 30 ($=9800-9770$). If we change its unit to MeV, it is $30 \times 0.511 \sim 15.3$ MeV. Since RMS value is about six times smaller than peak-to-peak one, its RMS value $\sigma_{E,u}$ is about 2.55 MeV. Please note that $\sigma_{E,u} \times \sigma_z$ should be constant during bunch compression to conserve the longitudinal emittance. But unfortunately, many persons misunderstand that $\sigma_{\delta} \times \sigma_z$ (or $\sigma_{E} \times \sigma_z$) should be constant (wrong concept).
After BC2, longitudinal phase space is rotated about 90 deg such as shown in left plot. In this special case, total rms energy spread, $\sigma_E$ (or $\sigma_\delta$) is very close to uncorrelated (or slice) rms energy spread $\sigma_{E,u}$ (or $\sigma_{\delta,u}$). After BC2, peak-to-peak momentum change in region B is about 1155 (=13005-11850). If we change its unit to MeV, it is $1155*0.511 \sim 590.2$ MeV. Since RMS value is about six times smaller than peak-to-peak one, its RMS value $\sigma_{E,u}$ is about 98.4 MeV. Therefore is relative RMS uncorrelated energy spread $\sigma_{\delta,u} \sim 98.4 /6400 \sim 0.0154$ or 1.54%, which is slightly smaller than our total relative RMS energy spread $\sigma_\delta = 1.55\%$ after BC2.
At SACC1 (=before BC1), $\sigma_{E,u} \times \sigma_z = 6.0 \text{ mm} \times 2.55 \text{ MeV} \sim 15.3 \text{ mm.MeV}$

After BC2, $\sigma_{E,u} \times \sigma_z = 0.150 \text{ mm} \times 98.4 \text{ MeV} \sim 14.8 \text{ mm.MeV}$

Since $(\sigma_{E,u} \times \sigma_z)_{\text{SACC1}} \sim (\sigma_{E,u} \times \sigma_z)_{\text{BC2}}$, the longitudinal emittance is well conserved during bunch compression. Small difference is due to the short-range wakefield in modules, CSR and ISR effects in BC.

Therefore there is no special problem in the longitudinal emittance conservation in the 4th alternative ILC bunch compressor.
$\sigma_z = 6.00 \text{ mm with 3.2 nC}$

$\sigma_z = 150 \mu\text{m with 3.2 nC}$
Emittance around head and tail is slightly increased by chromatic effects and CSR.
4th Alternative ILC BC – Energy Spread

01AUG05 Version

\[ \sigma_z = 6 \text{ mm} \]

\[ \sigma_\delta = 1.55\% \]

\[ \sigma_z = 150 \text{ \(\mu\)m} \]
4th Alternative ILC BC – Projected Emittance

01AUG05 Version

final horizontal emittance = 8.28 µm
~ 3.5% growth under wakefields, ISR, and CSR

final vertical emittance = 0.020 µm
Action of CSR and ISR when we compress $\sigma_z = 6.0$ mm to 150 $\mu$m

- Final horizontal emittance with consideration of CSR and ISR = 8.28 $\mu$m
- Final horizontal emittance with consideration of only ISR = 8.218 $\mu$m
- Final horizontal emittance without consideration of CSR and ISR = 8.04 $\mu$m

By optimizing BC layout, by choosing ACC1 module for linearization, and by choosing short 650 MHz modules around BCs, CSR effect becomes weak, but there is still small ISR effect.
4th Alternative ILC BC – RF Jitter Sensitivity

Threshold of Jitter Sensitivity (just chosen conditions)

- ±15% p2p change (or 5% rms) in bunch length
- ±300 fs p2p change (or 20% in rms bunch length) in bunch arrival time
  (rms bunch length = 500 fs, hence 20% = 100 fs)

Much looser than European XFEL or other ILC design !!!

\[
\frac{\Delta \sigma_s}{\sigma_{so}} (\%) = 50 \times \sin(\pi \cdot \text{phase} / 180) \quad \text{for ACC1 phase (deg)}
\]

\[
\text{change in ACC1 phase (deg)}
\]

\[
\frac{\text{change in arriving time (fs)}}{\text{change in ACC1 phase (deg)}} = \frac{\text{p2p jitter sensitivity}}{\text{rms jitter sensitivity}}
\]

p2p jitter sensitivity = ±0.5 deg
rms jitter sensitivity = 0.17 deg (tightest)

p2p jitter sensitivity = ±1.0 deg
rms jitter sensitivity = 0.33 deg

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
Threshold of Jitter Sensitivity (just chosen conditions)

- $\pm 0.01\%$ p2p change in relative energy spread
- $\pm 0.02\%$ p2p change in beam average energy

p2p jitter sensitivity $= \pm 1.5$ deg
rms jitter sensitivity $= 0.5$ deg

p2p jitter sensitivity $= \pm 1.3$ deg
rms jitter sensitivity $= 0.43$ deg

TeV-Energy Superconducting Linear Accelerator Projects - TTF-2, TESLA X-ray FEL, TESLA Linear Collider
### For each Klystron

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity (p2p)</th>
<th>Tolerance (p2p)</th>
<th>Tolerance (rms)</th>
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<tr>
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<td>3.8 ps</td>
<td>1.26 ps</td>
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<td>dQ</td>
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<td>0.13 deg @ 650 MHz</td>
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<tr>
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<td>BC2 dI/I</td>
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</table>
To supply e+e- colliding beams with a high luminosity, we should compress bunch length down to 150 µm by bunch compressors.

To optimize BCs, we should consider various things such as ISR, CSR, nonlinearity, chicane type, compression ratio, energy spread at BCs, Twiss parameters around BCs, and chromatic effect.

We choose 2 BC stages to reduce jitter sensitivity and construction cost. 3 BC stages is expensive and it is not effective if nonlinearity in the longitudinal phase space is not compensated properly.

A shorter linac with a lower frequency BCs will be proper to avoid over-compression at BC2 due to longitudinal short-range wakefields and to reduce construction cost. Linac with a lower frequency also help in reducing RF jitter sensitivity.

From 2nd and 4th alternative bunch compressors, we choose subharmonic cavity with 650 MHz as a precompressor linac (before BC1) to compress a bunch with $\sigma_z = 9.0$ mm (rms) to 100 µm or more shorter.
The 4th alternative bunch compressor can compress a bunch with $\sigma_z = 6.0$ mm (rms) to 150 µm or more shorter with a lower final energy spread of 1.55% and about 3.5% (~ 0.0%) overall horizontal (vertical) emittance growth.

The most tight phase jitter tolerances in 4th alternative BC are about 0.14 deg @ 650 MHz and 0.17 deg @ 1300 Mz, which are much looser than other ILC BC design.

The 4th alternative BC layout are very promising in RF jitter tolerance and emittance. Even we can compress further with this layout.

To reduce horizontal emittance growth due to CSR and ISR effects at the ILC bunch compressor, we will optimize beam energy at BC2, optics around BCs, and chicane type and layout further.

Y. Kim sincerely thanks K. Flöttmann, and M. Dohlus for their encouragements of this work and many useful comments and discussions.