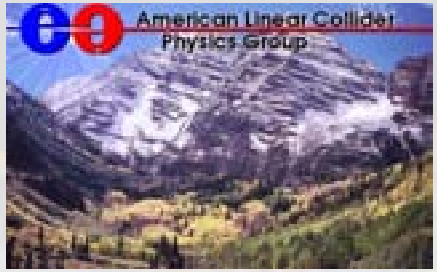

Alternative Bunch Compressors for ILC

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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):**

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

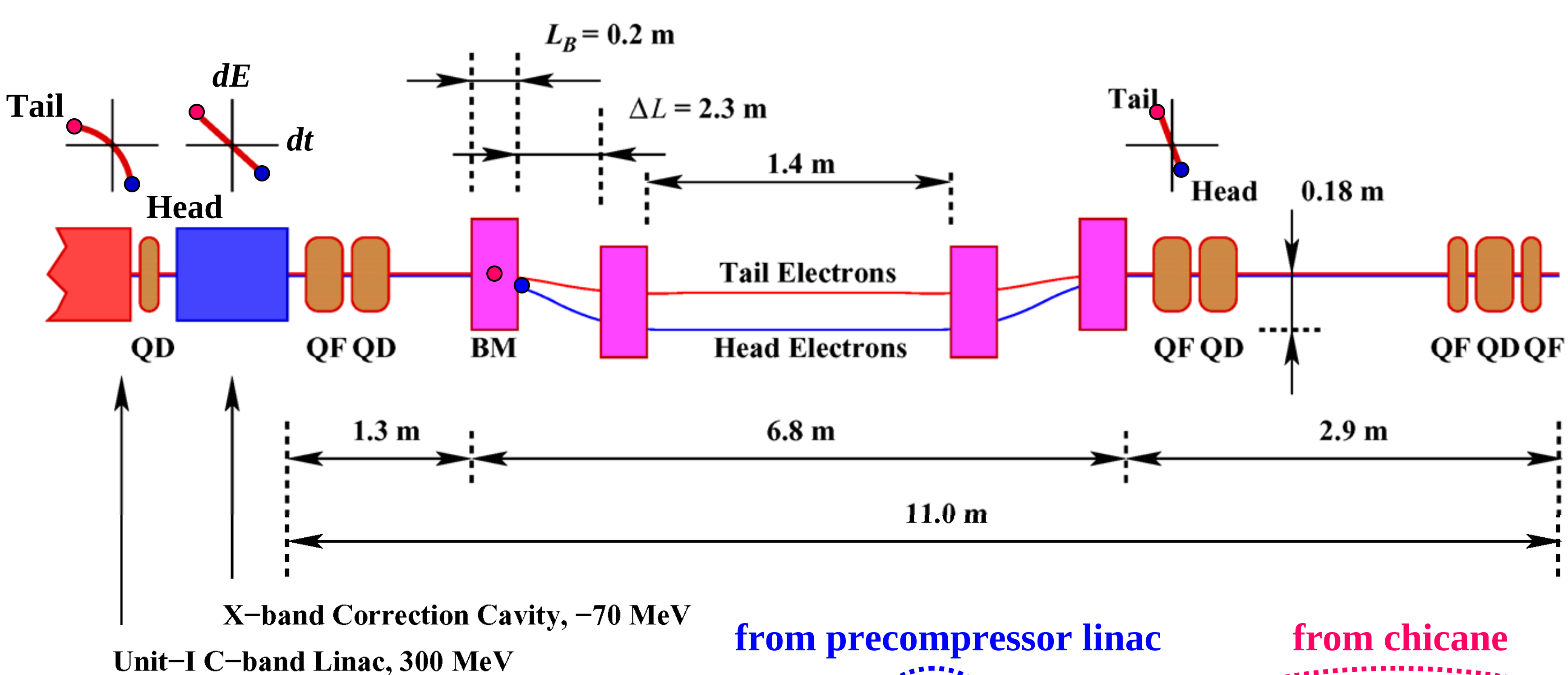
For given center of mass energy E_{cm} and fractional beamstrahlung loss δ_{BS}
- higher average beam power P_b
- smaller vertical emittance $\varepsilon_{n,y}$
- smaller vertical beam size at IP σ^*_y
- shorter bunch length σ_z = smaller $\beta^*_{n,y}$ (hourglass effect, $\beta_y^* \geq \sigma_z$)

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 Prinicple of Bunch Compressor (BC)

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



from precompressor linac

from chicane

$$dz_f = dz_i + R_{56}(dE/E)_i + T_{566}(dE/E)_i^2 + O((dE/E)_i^3) \qquad R_{56} \approx 2\theta_B^2(\Delta L + \frac{2}{3}L_B)$$

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

Considerations - ISR in Dipole

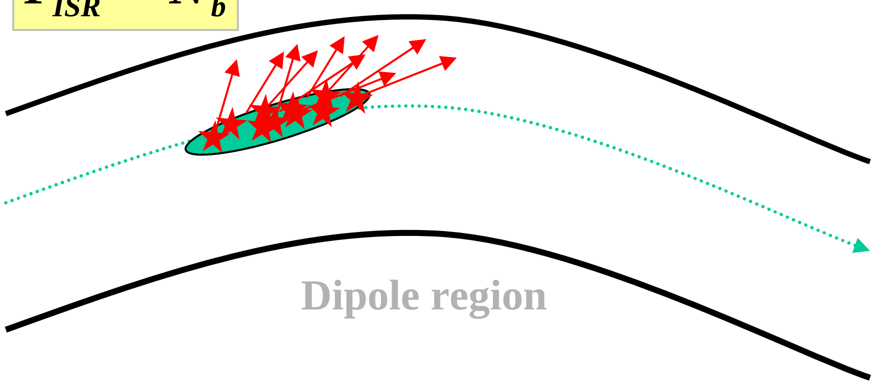
Incoherent Synchrotron Radiation (ISR) is generated when relativistic long beam goes through dipole magnet. Since ISR is a random quantum process, it generates incoherent (= slice, or uncorrelated) energy spread, hence slice emittance growth in the bending plane. For one dipole magnet, the relative uncorrelated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

$$\sigma_{\delta,ISR,1\mathrm{dipole}} \approx \frac{1}{L_B}\sqrt{(4.13\times10^{-11}\mathrm{m}^2\cdot\mathrm{GeV}^{-5})E^5\left|\theta_B^3\right|} \ .$$

Slice emittance growth due to ISR is given by

$$\Delta\gamma\varepsilon_x \approx 8\times10^{-8}E^6\frac{\theta_B^5}{L_B^2}\left[(\Delta L+L_B)+\frac{\beta_{\max}+\beta_{\min}}{3}\right] \quad \text{for chicane.}$$

$P_{ISR} \propto N_b$

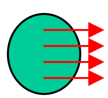


- lower energy
- longer dipole
- smaller bending angle
are good against ISR effects

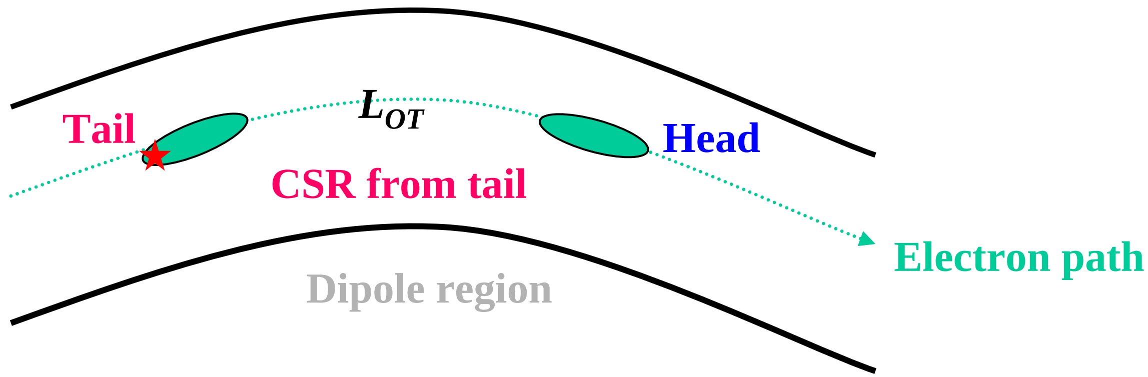
Considerations - CSR in BC

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

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



$$P_{CSR} \propto N_b^2$$



CSR generates correlated energy spread along whole bunch:

$$\sigma_{\delta,1\,\mathrm{dipole}} \approx 0.22\,\frac{r_e N L_B}{R^{2/3}\sigma_z^{4/3}\gamma}$$

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

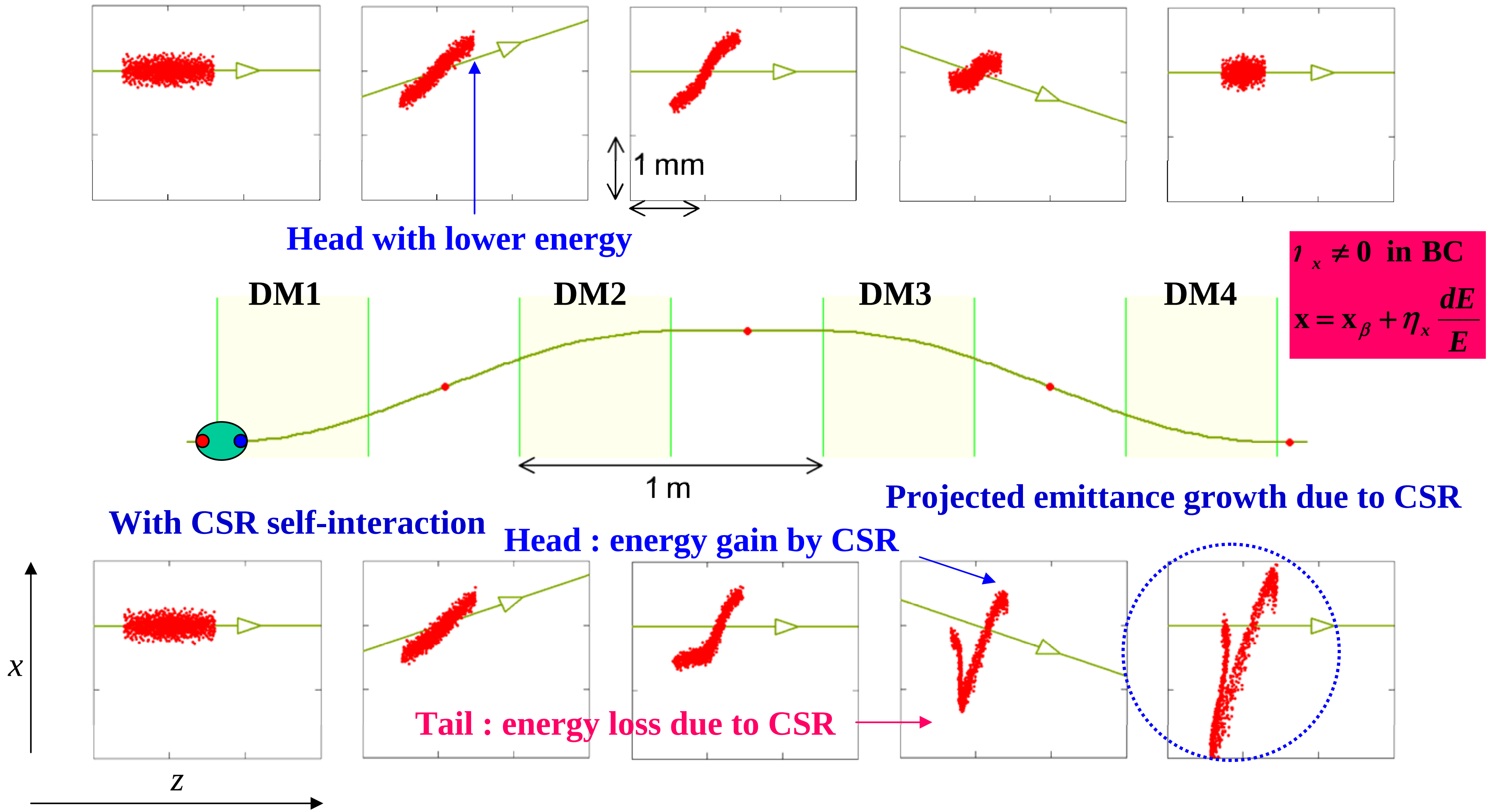
$\eta_x \neq 0$ in BC

$$\mathrm{x} = \mathrm{x}_\beta + \eta_x \frac{dE}{E}$$

Considerations - CSR in BC

Courtesy of M. Dohlus

Without CSR self-interaction



$\eta_x \neq 0$ in BC

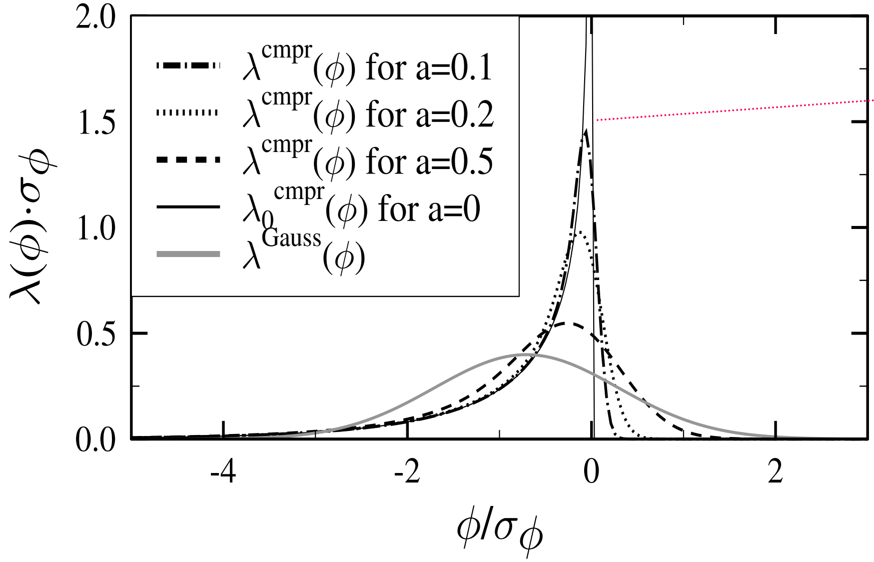
$$\mathbf{x} = \mathbf{x}_\beta + \eta_x \frac{dE}{E}$$

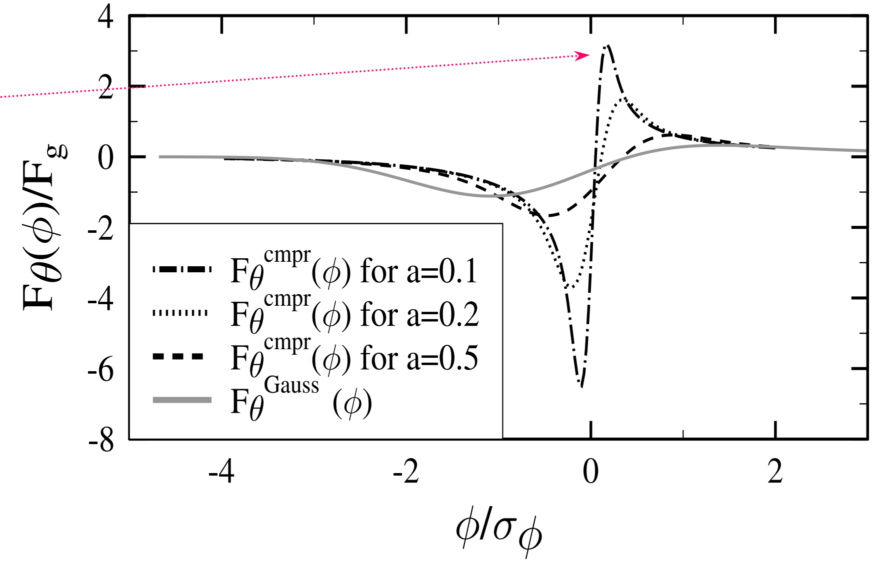
Considerations – CSR for None Uniform Beams

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)

Courtesy of Dr. R. Li

a $\propto \zeta_{un}$

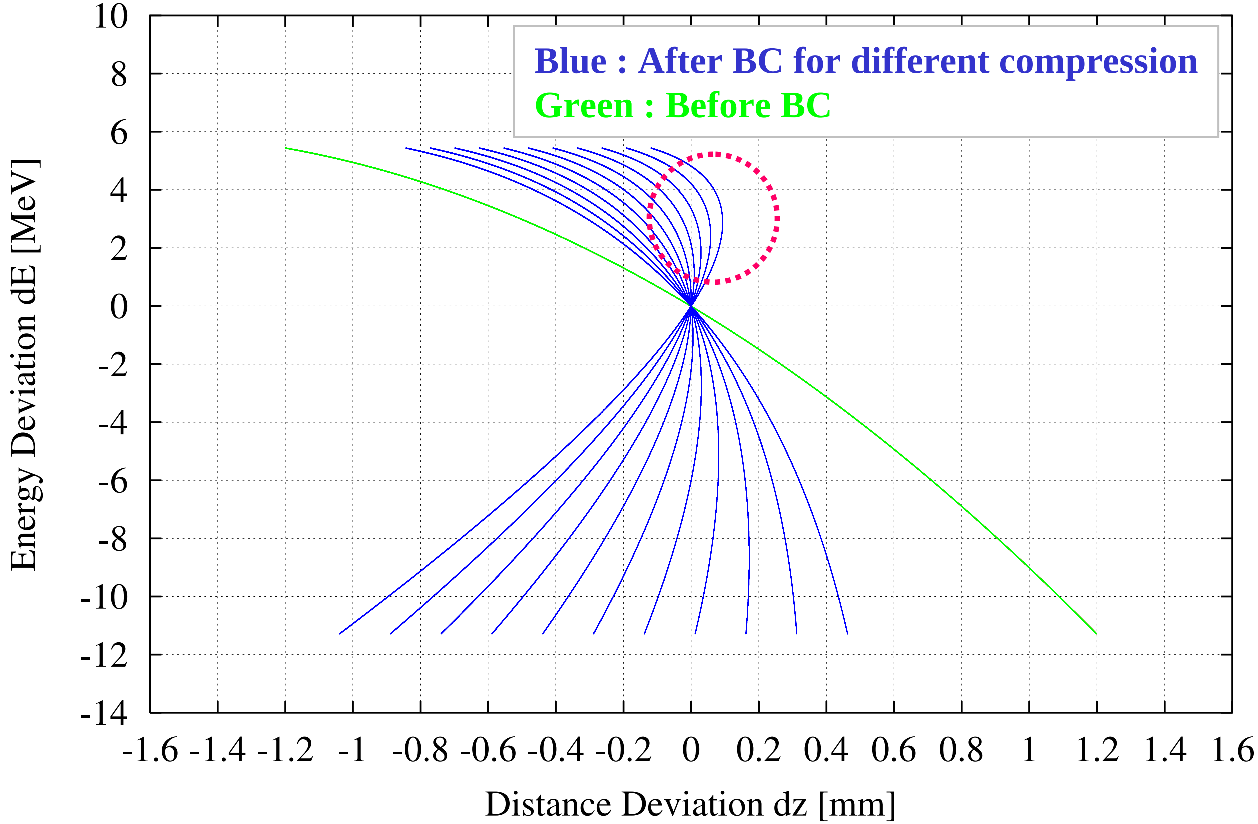




[Longitudinal Charge Distribution and CSR force for a compressed bunch]

Considerations - Nonlinearities

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



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.

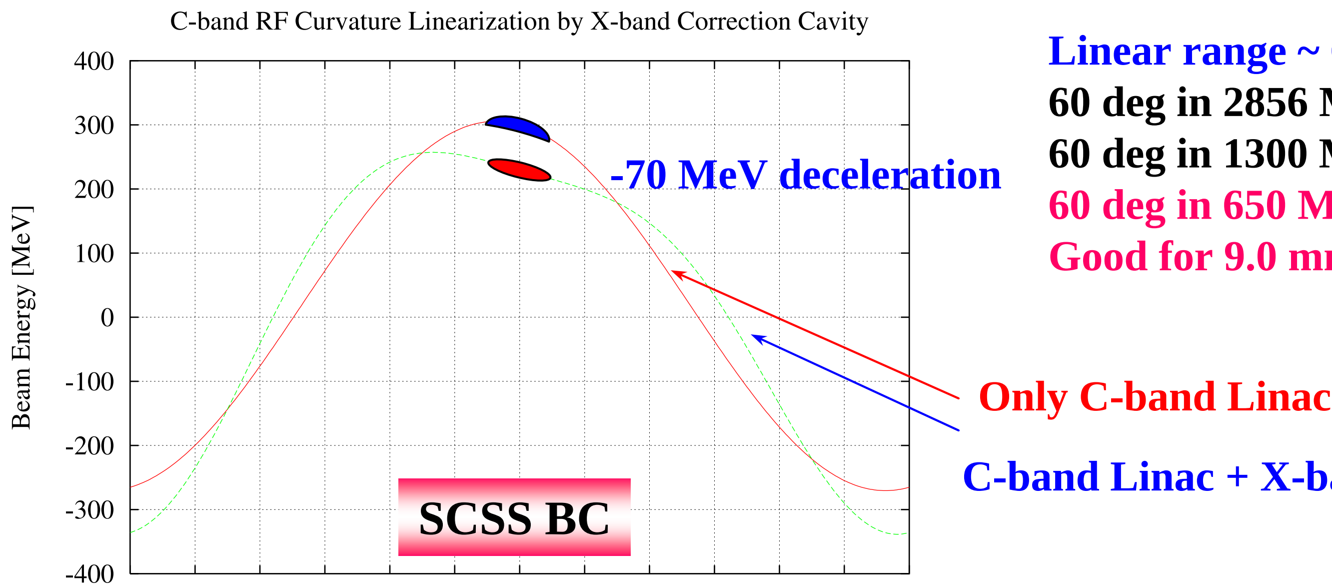
Considerations – Nonlinearities

□ Linearization of longitudinal phase space with a higher harmonic cavity

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

"-" means deceleration !

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.

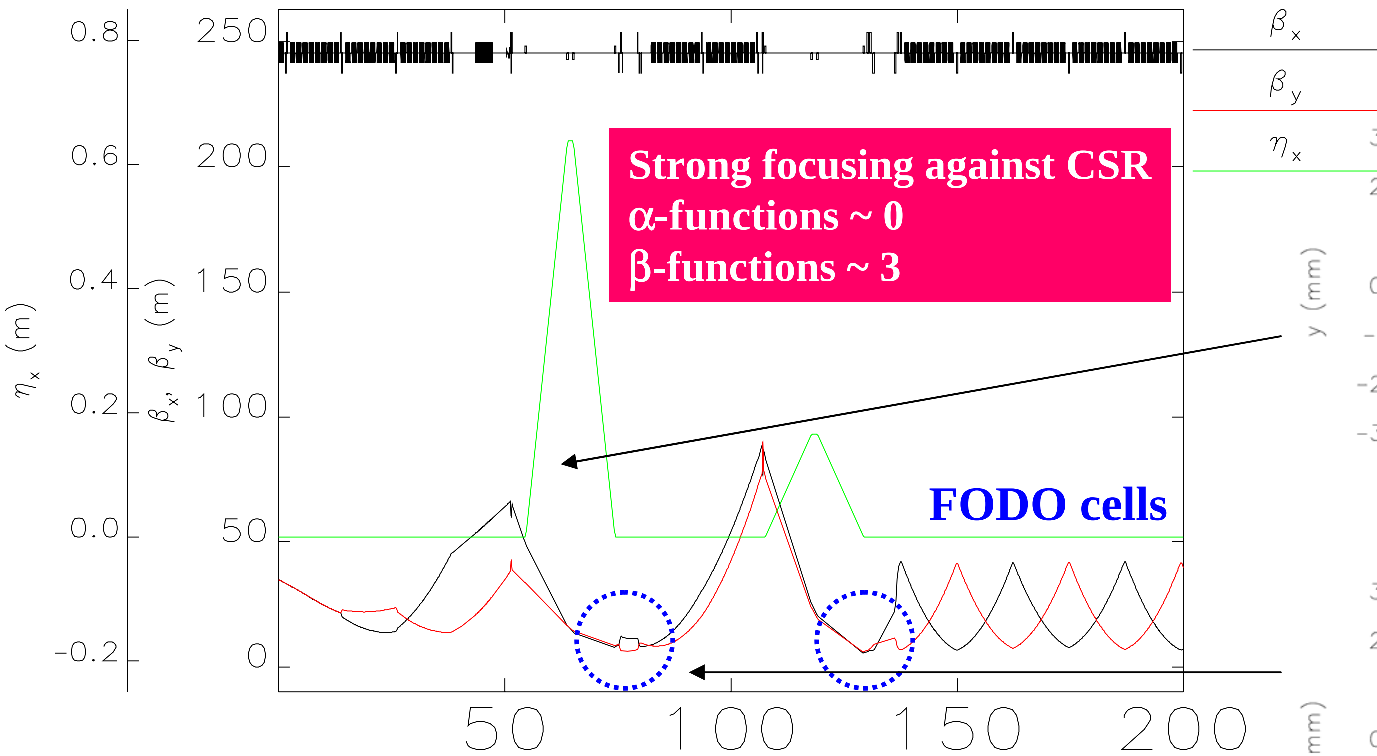


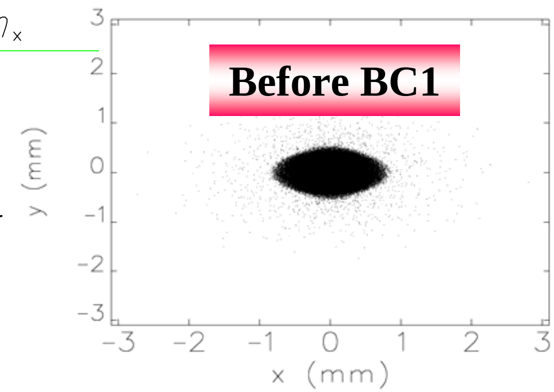
Linear range ~ 60 degree
60 deg in 2856 MHz ~ 60 ps (18 mm)
60 deg in 1300 MHz ~ 126 ps (37.8 mm)
60 deg in 650 MHz ~ 252 ps (75.6 mm)
Good for 9.0 mm (rms) ILC bunch

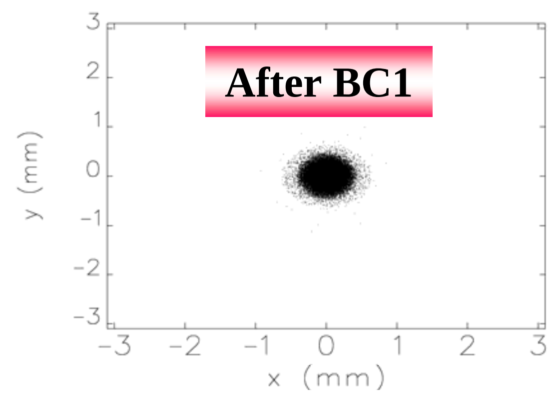
Nonlinearities in the longitudinal phase space due to RF curvature, short-range wakefields, T566, and space charge force can be compensated by harmonic cavity.

Considerations – Twiss Parameters around BCs

☐ **Strong focusing lattice around BCs to reduce CSR induced emittance growth**





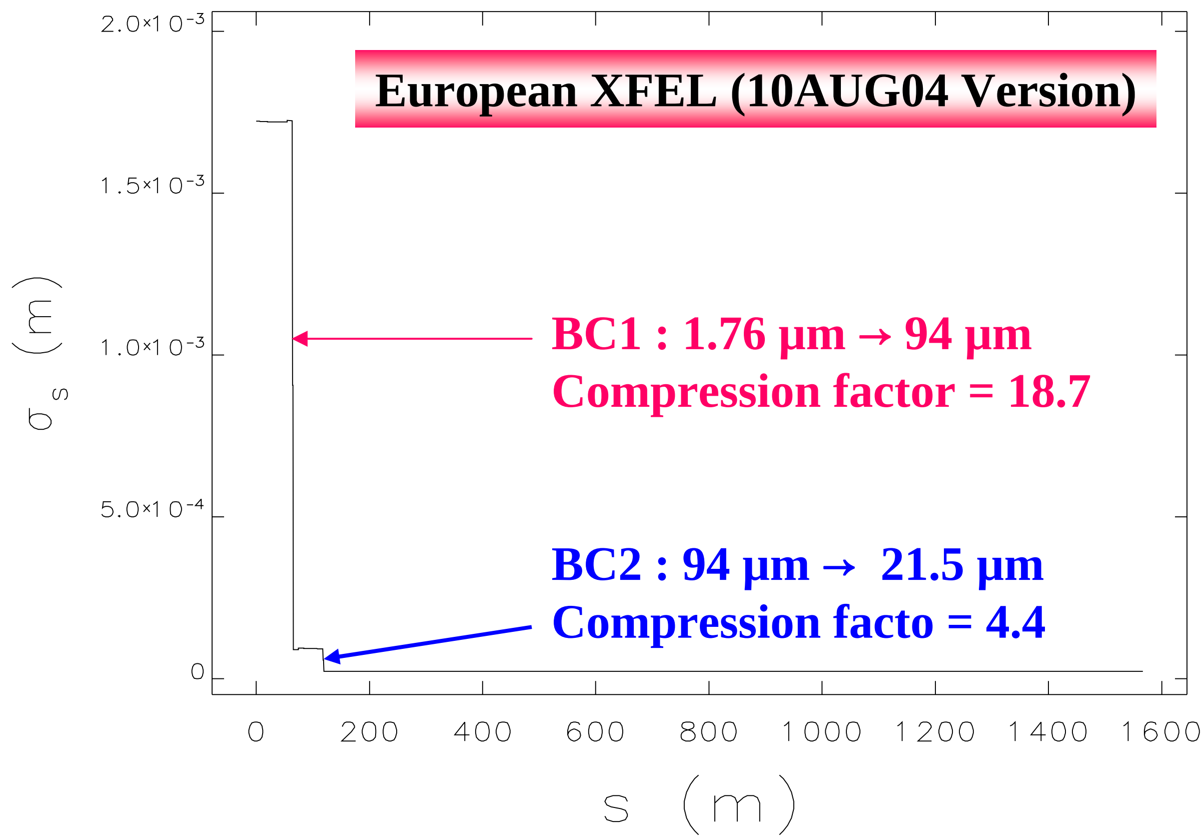


$$\frac{\varepsilon}{\varepsilon_0} \approx \sqrt{1+\frac{(0.22)^2}{36}\frac{r_e^2N^2}{\gamma\varepsilon_N\beta}\left(\frac{|\theta|^5 L_B}{\sigma_z^4}\right)^{2/3}\left[L_B^2\left(1+\alpha^2\right)+9\beta^2+6\alpha\beta L_B\right]}$$

Lattice optimization to minimize this term

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**

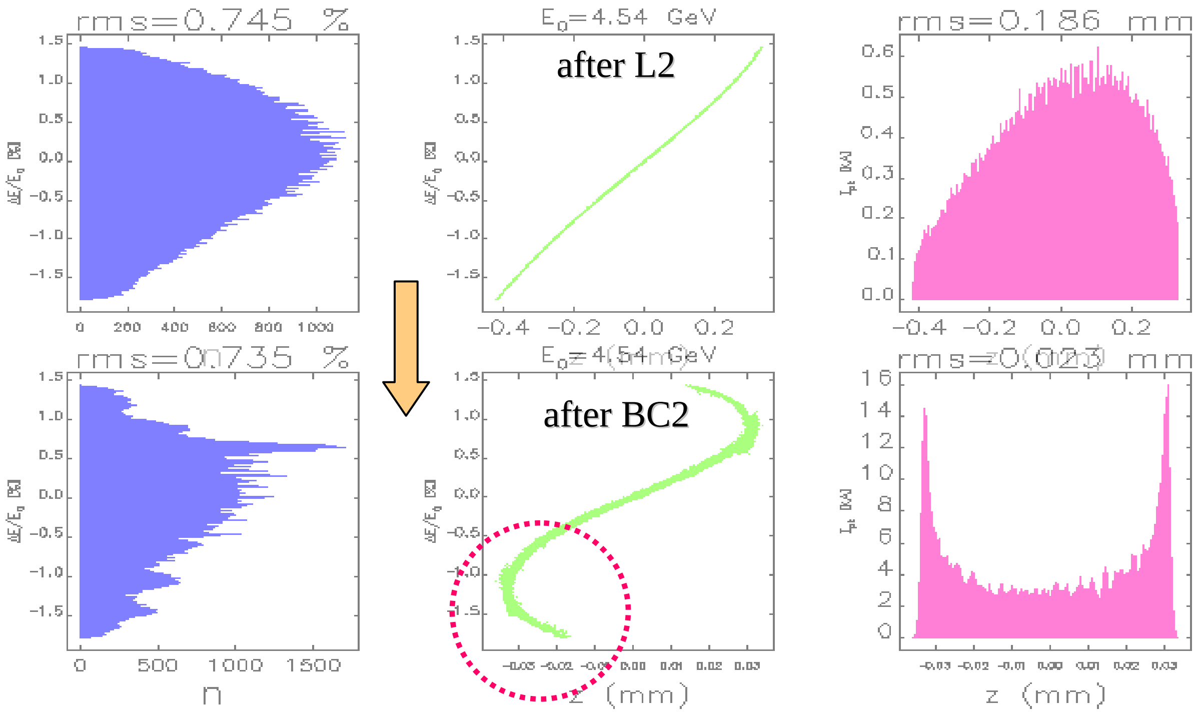


Considerations – Linac Length & Wakefields

☐ **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

Courtesy of P. Emma



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

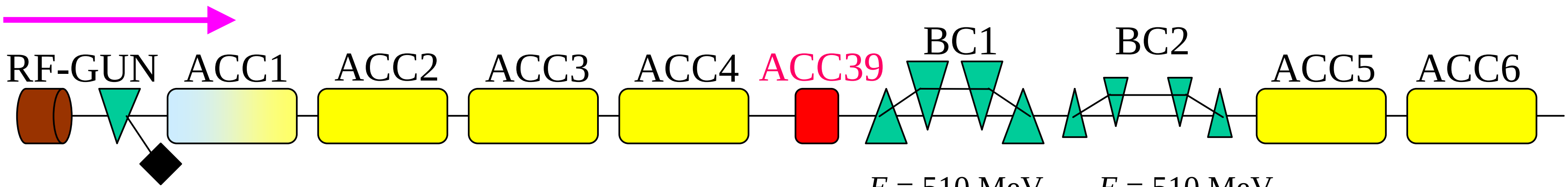
BCs for European XFEL (13JAN04 Version)

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

σ_z = 1.76 mm → 113 μm → 23 μm →

Q=1.0 nC

e-beam



60 MV/m
38 deg

11.5 MV/m
25.0 MV/m
-18.3 deg

20.5 MV/m
-29.6 deg

34.8 MV/m
160.6 deg

E = 510 MeV
$\sigma_\delta \sim$ 1.89%
R_{56} = 87 mm
θ = 3.95 deg

E = 510 MeV
$\sigma_\delta \sim$ 1.88%
R_{56} = 4.8 mm
θ = 0.93 deg

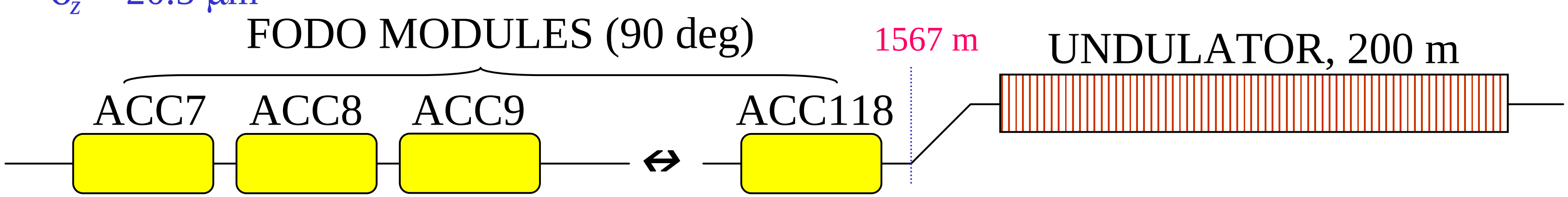
20.65 MV/m
0.0 deg

ASTRA with Space Charge

0.0 m — 12.0444 m

To the end of Linac : ELEGANT with CSR
with geometric wakefields
without space charge

σ_z = 20.5 μm →



20.65 MV/m
0.0 deg

E = 20.0 GeV
σ_δ = 0.008%
σ_x = 37.3 μm, σ_y = 31.6 μm, σ_z = 20.5 μm
ε_{nx} = 1.15 μm, ε_{ny} = 0.94 μm

All projected parameters !

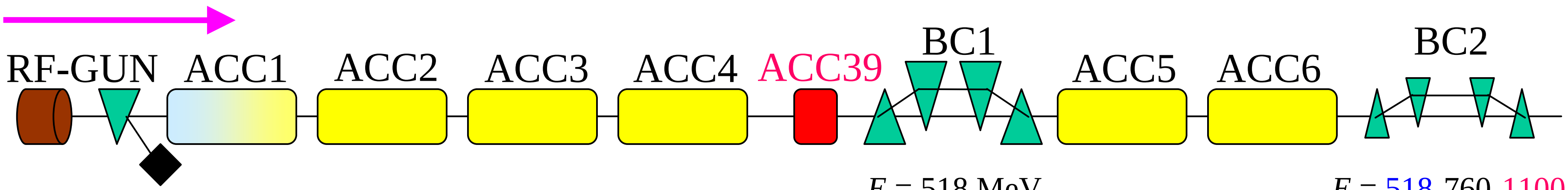
New BCs for XFEL (10AUG04 Version)

With New European XFEL Injector, ε_n= 0.88 μm

Q=1.0 nC

e-beam

σ_z = 1.72 mm → 94 μm → 21.6 μm



60 MV/m
40.0 deg

12.8 MV/m
24.84 MV/m
-25.0 deg

20.2 MV/m
-25.0 deg

34.5 MV/m
165.9 deg

E = 518 MeV
σ_δ ~ 1.87%
R_{56} = 87 mm
θ = 3.95 deg

0-20.5-35 MV/m
-44.5 deg

E = 518-760-1100 MeV
σ_δ ~ 1.87-1.33-0.9%
R_{56} ~ 5.3 mm
θ ~ 0.93 deg

ASTRA with Space Charge

0.0 m   12.9869 m

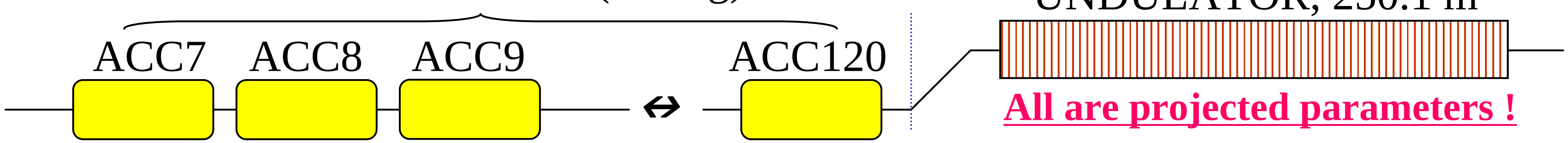
To the end of Linac : ELEGANT with CSR
with geometric wakefields
without space charge

σ_z = 21.6 μm

FODO MODULES (90 deg)

1579 m

UNDULATOR, 250.1 m



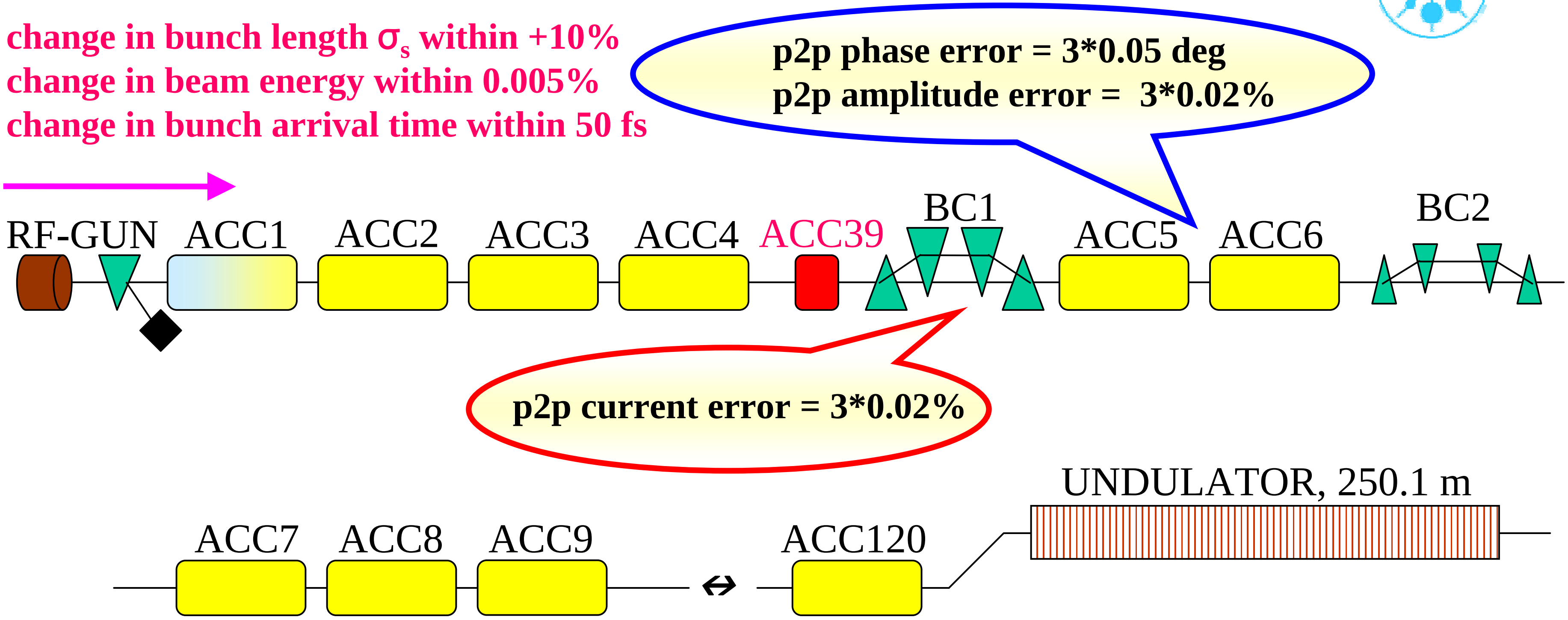
All are projected parameters !

20.38 MV/m
0.0 deg

***E* = 20.0 GeV**
σ_δ = 0.0088%
σ_x= 34.2 μm, σ_y= 29.5 μm, σ_z = 21.6 μm
ε_{nx}= 1.044 μm, ε_{ny}= 0.896 μm

Considerations – S2E Simulations on RF Jitter

change in bunch length σ_s within +10%
change in beam energy within 0.005%
change in bunch arrival time within 50 fs



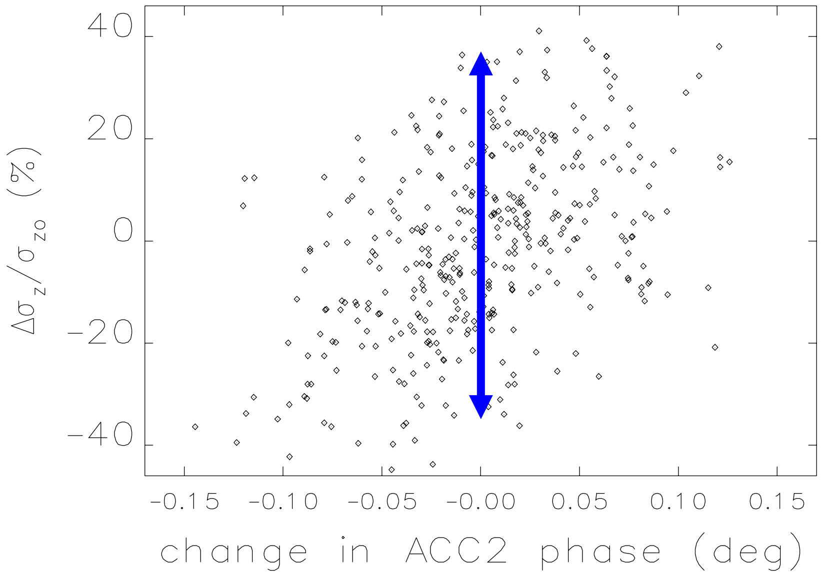
After applying random error set (p2p = 3 × tolerance) to each component, I have performed about 400 times S2E simulations from gun to the end of linac to compare two linac layouts under same jitter tolerance set.

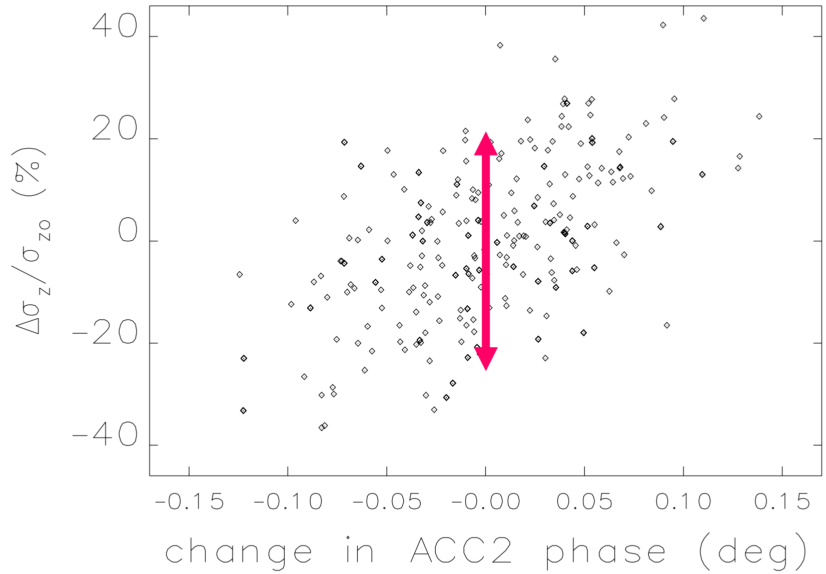
Considerations – Jitter under Random Errors

400 Times Tracking with (13JAN04)

400 Times Tracking with (10AUG04)

most sensitive jitter source on bunch length = ACC2 phase error



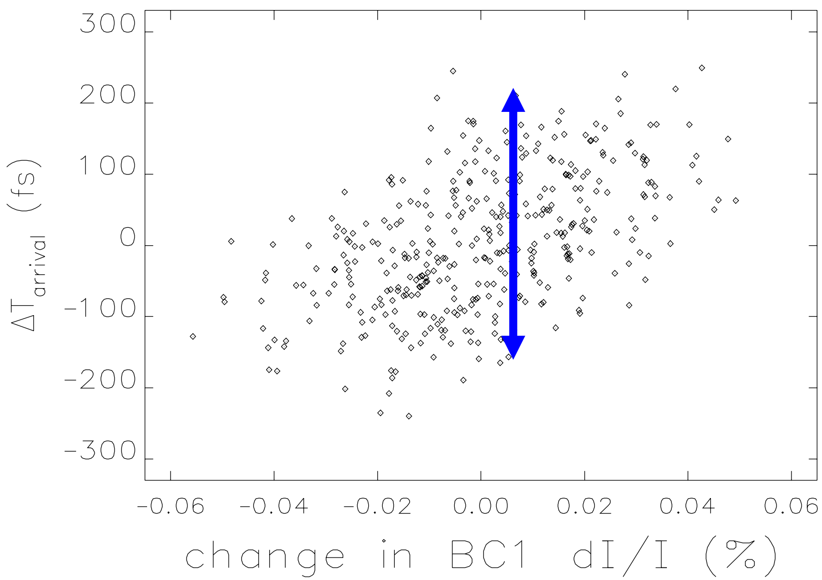


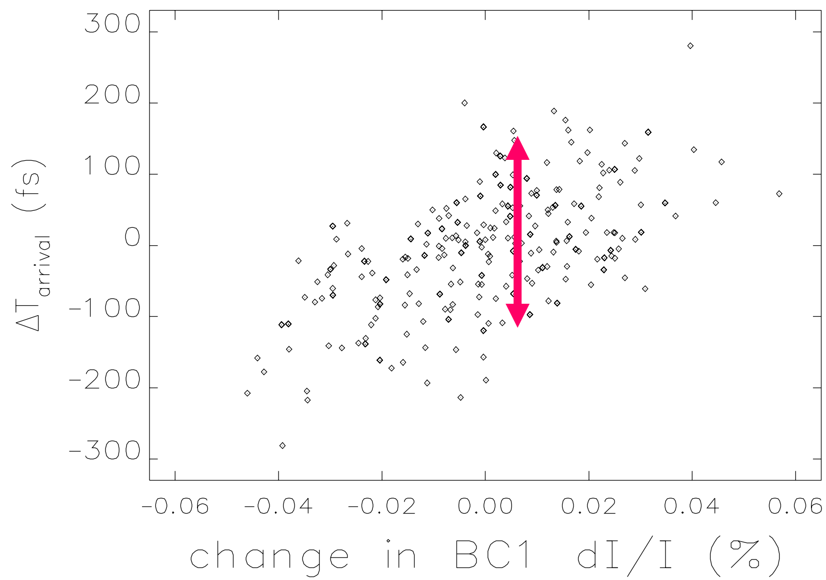
wider change in bunch length for (13JAN04 Version)
stronger correlation with errors in other components !

Considerations – Jitter under Random Errors

400 Times Tracking with (13JAN04) **400 Times Tracking with (10AUG04)**

most sensitive jitter source on arriving time = BC1 current error



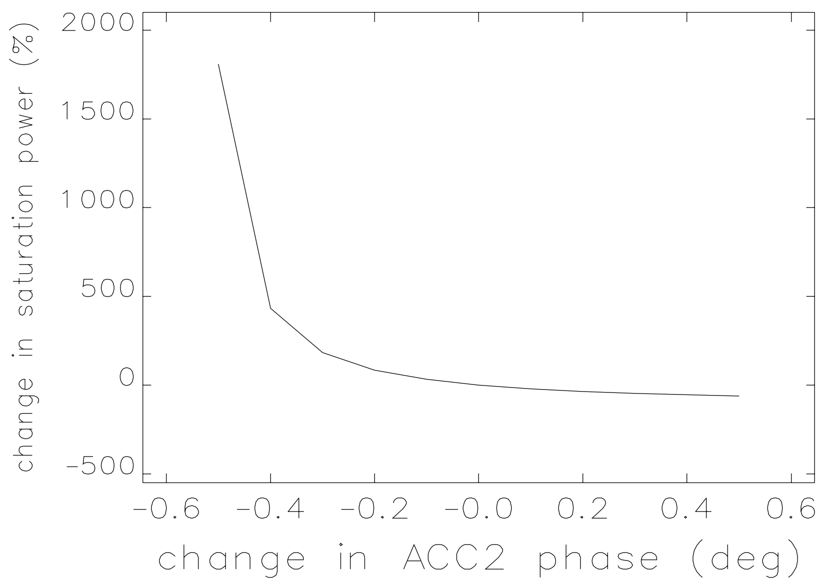


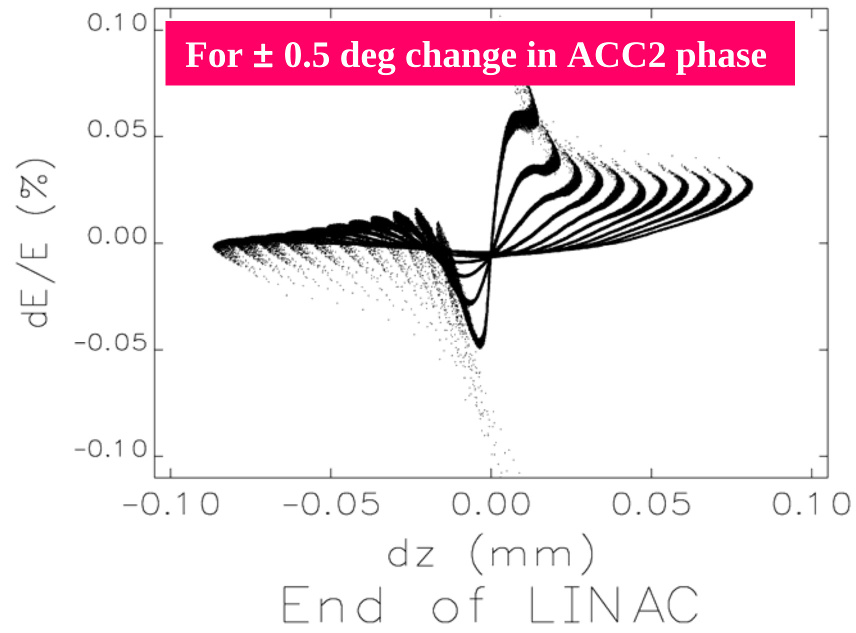
wider change in bunch arriving time for (13JAN04 Version)
stronger correlation with errors in other components !

Sensitive Jitter Sources to European XFEL

Layout with a Single BC Stage – Double Chicane (13JAN04)

ACC234 Phase is the most sensitive jitter source to saturation power and saturation length



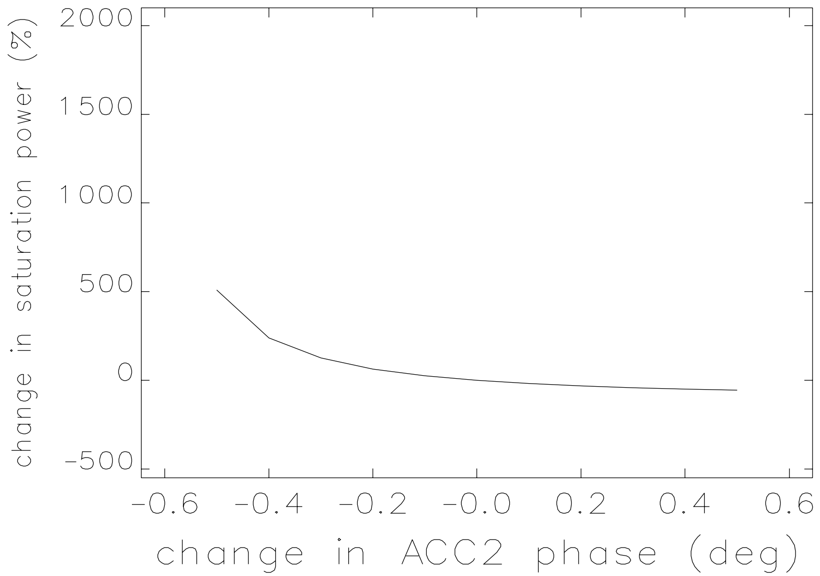


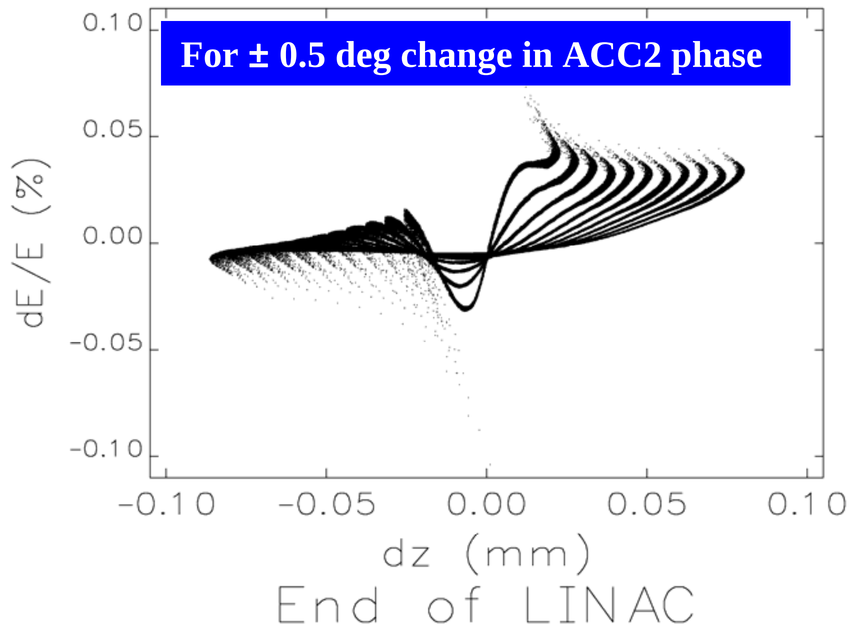
strong over-compression against ACC234 phase error

Sensitive Jitter Sources in European XFEL

Alternative Layout with 2BC Stages (10AUG04)

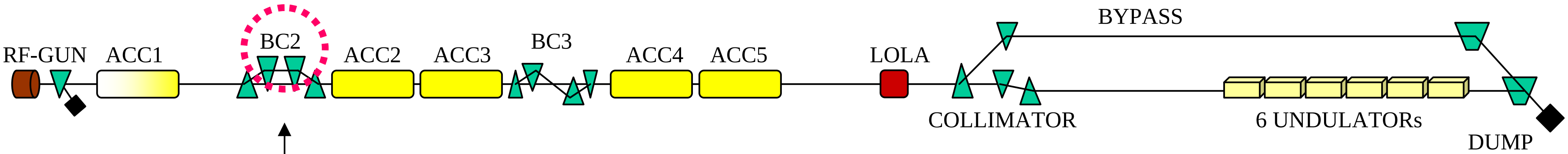
ACC234 Phase is the most sensitive jitter source to saturation power and saturation length

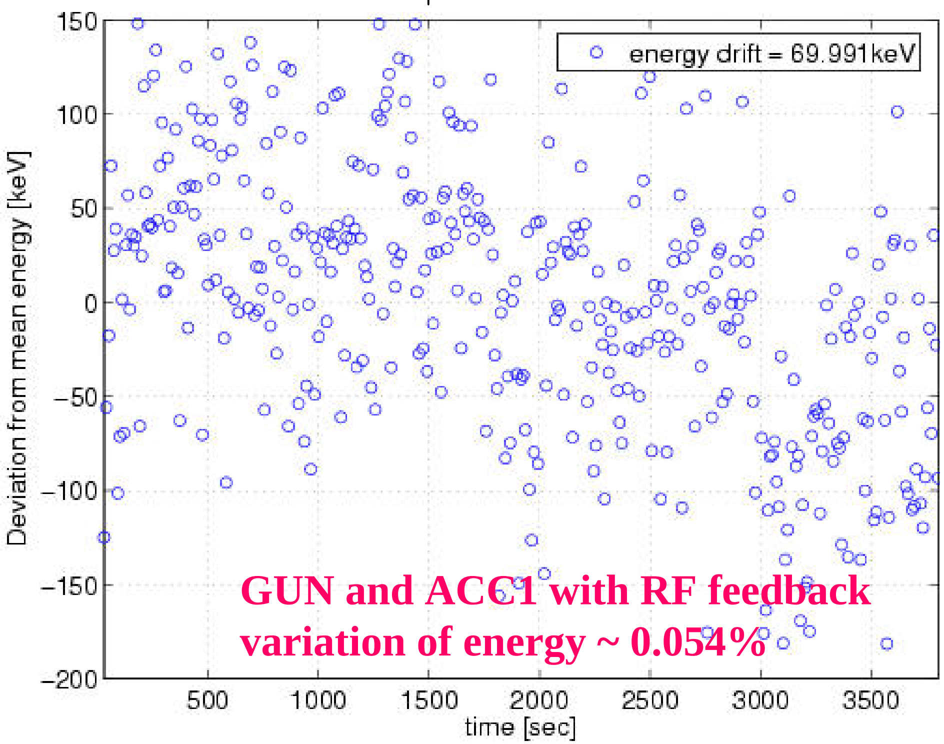


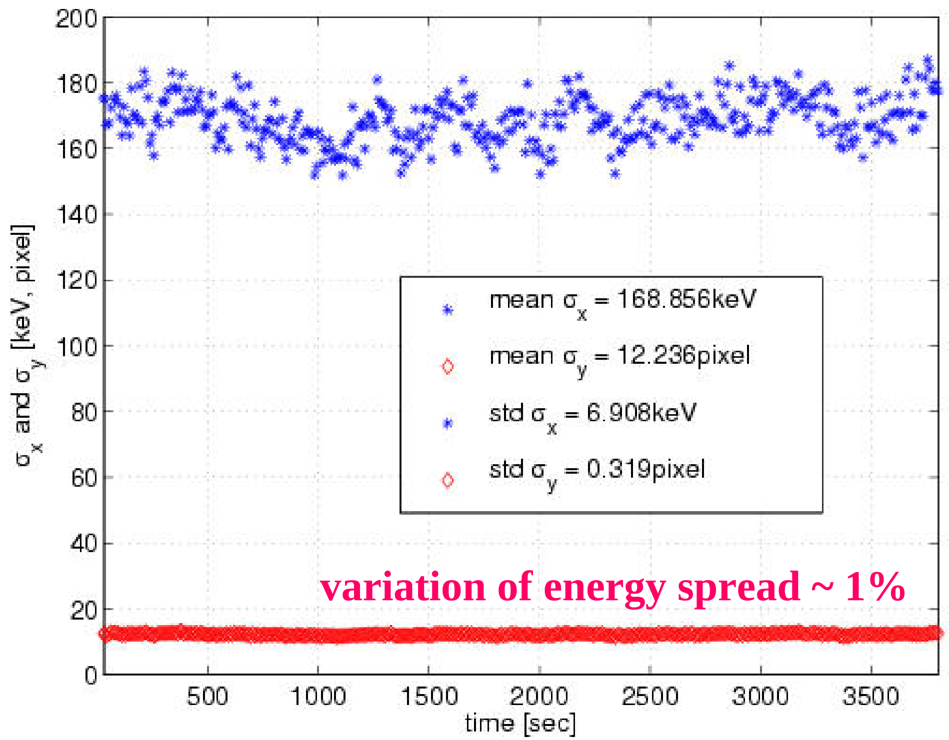


weak over-compression against ACC234 phase error

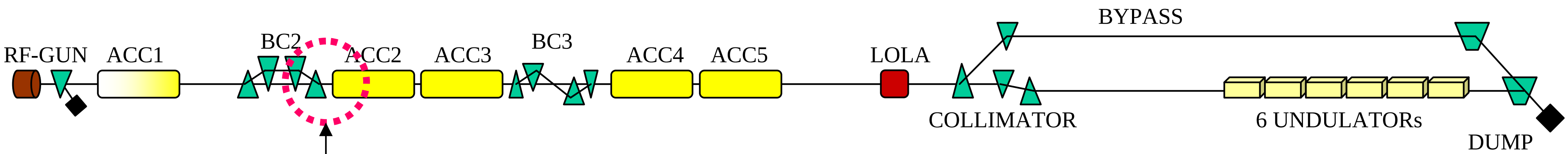
RF Jitter at TTF2

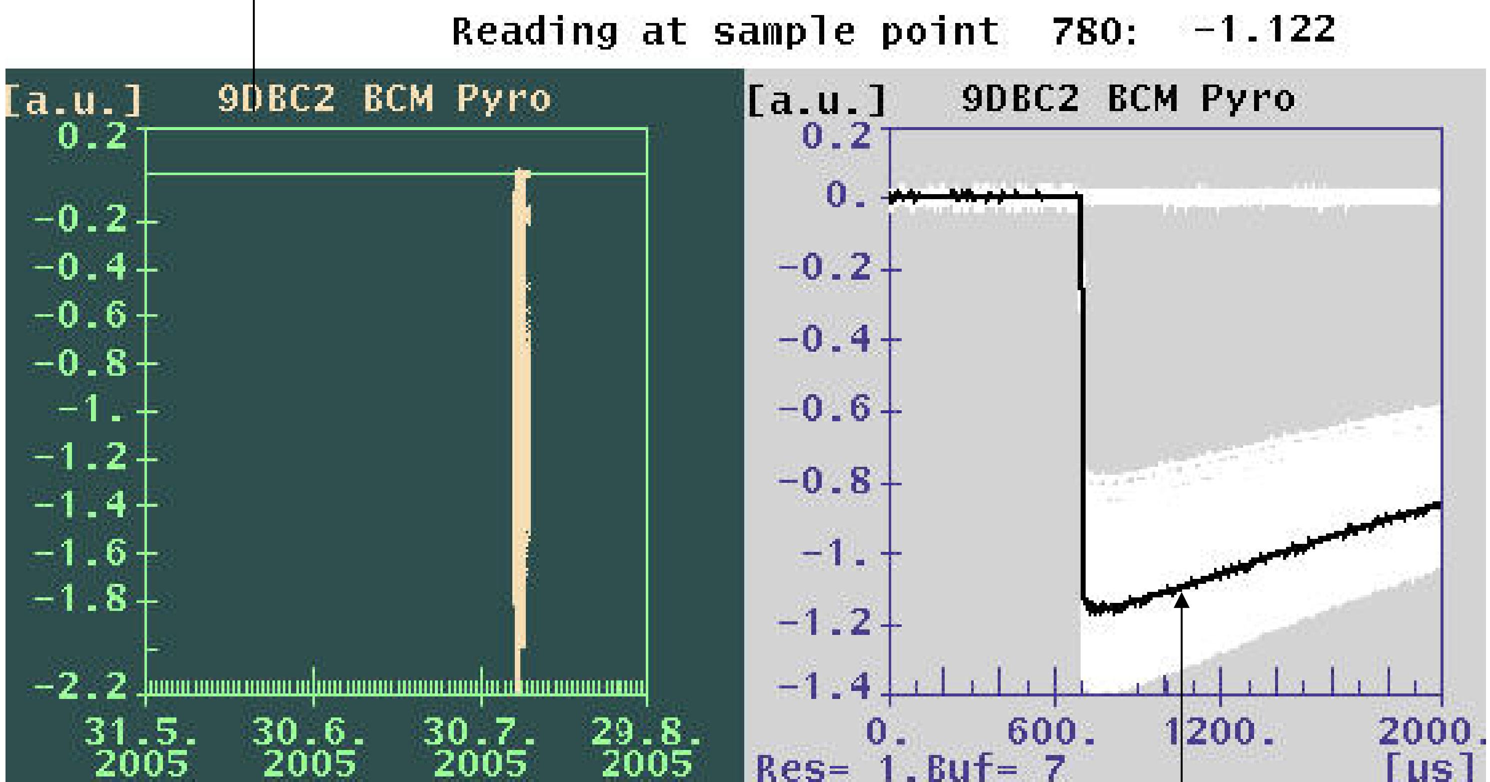






Drift of Bunch Length at TTF2

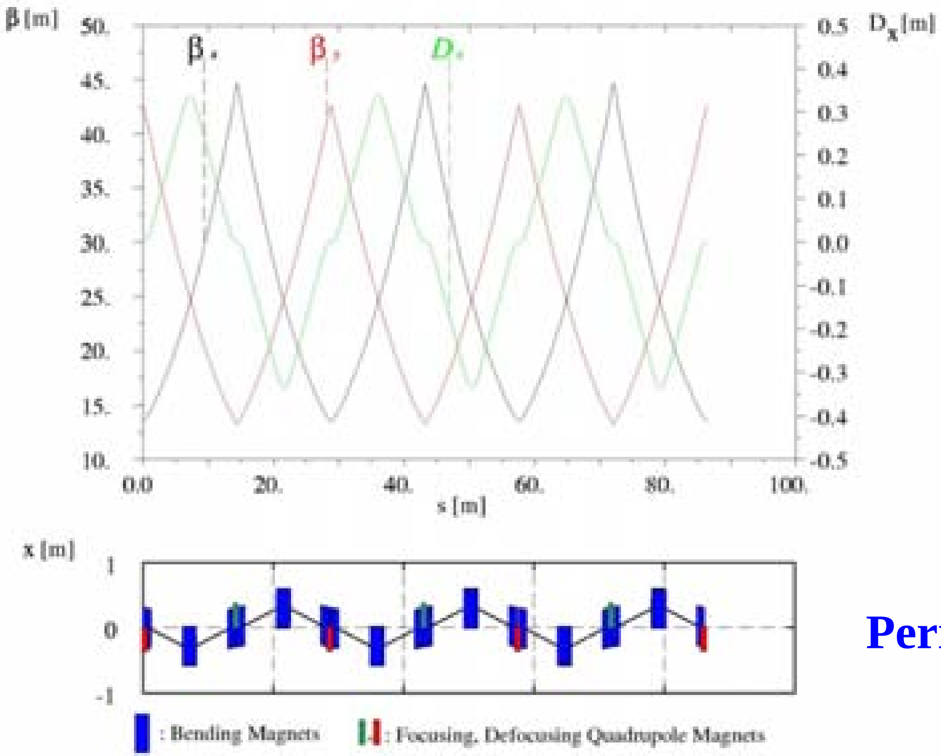




Drifting pyroelectric detector signal indicates status of drifting bunch length

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

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)

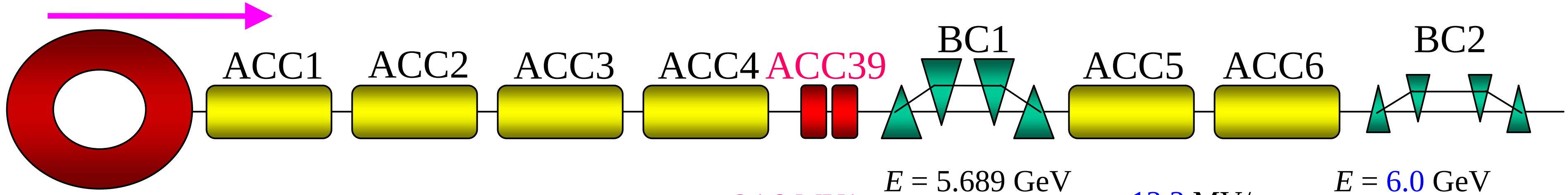
Initial parameters

Q=3.2 nC
e-beam

E = 5.0 GeV
σ_δ = 0.13% (small !)
σ_z = 6.0 mm
ε_{nx}= 8.0 μm, ε_{ny}= 0.02 μm

1/8.9 1/2.2

σ_z = 6.00 mm → 673 μm → 300 μm



23.4 MV/m
-45 deg

24.8 MV/m
170.0 deg

E = 5.689 GeV
σ_δ ~ 2.4%
R_{56} = 236 mm
θ = 5.3 deg

13.3 MV/m
-21.5 deg

E = 6.0 GeV
σ_δ ~ 2.174%
R_{56} ~ 17 mm
θ ~ 1.4 deg

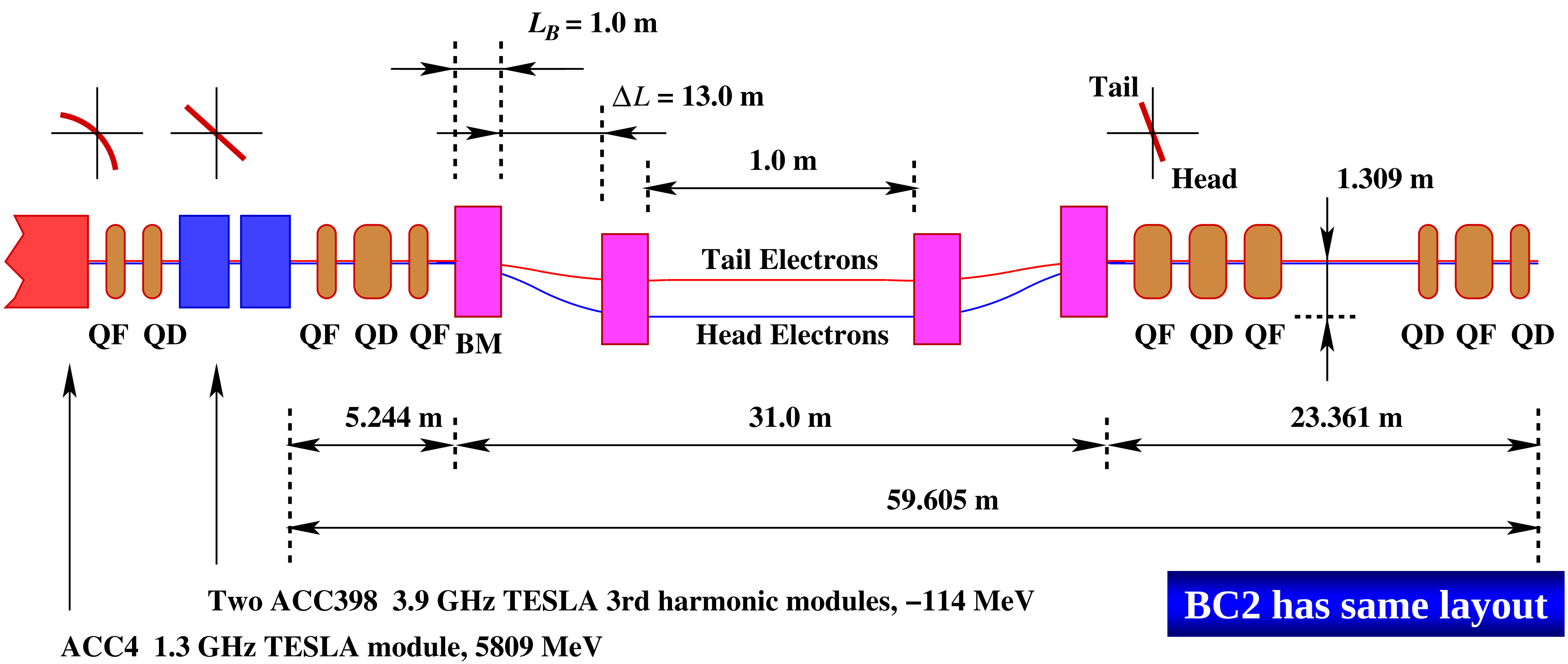
Up to main linac : ELEGANT with CSR, ISR, and geometric short-range wakefields.
but without space charge

Final parameters

E = 6.0 GeV
σ_δ = 2.173%
σ_z = 300 μm
ε_{nx}= 8.7 μm, ε_{ny}= 0.02 μm

1st Alternative ILC BC – Chicane Layout

From various experiences in Start-To-End simulations and BC designs for TTF2, European XFEL, SCSS, PAL XFEL, we have chosen two BC stages

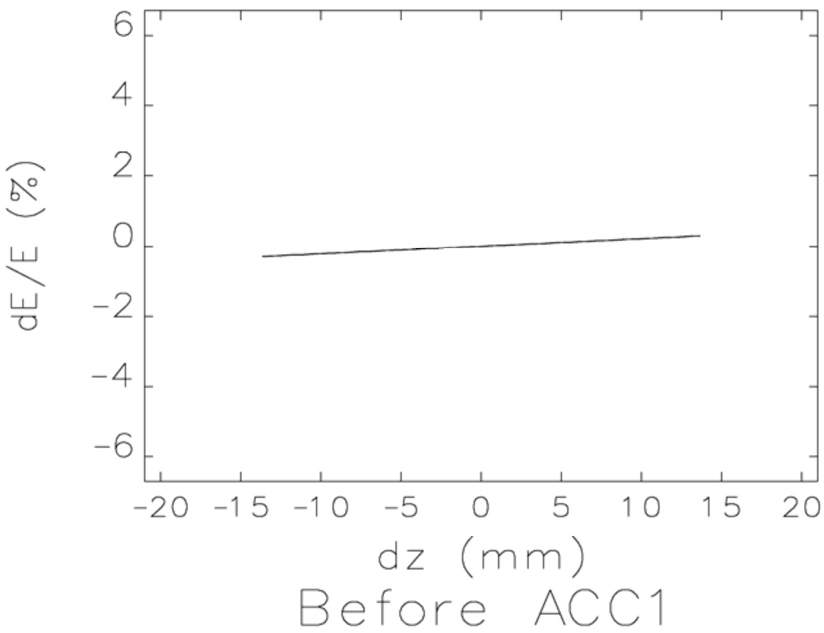


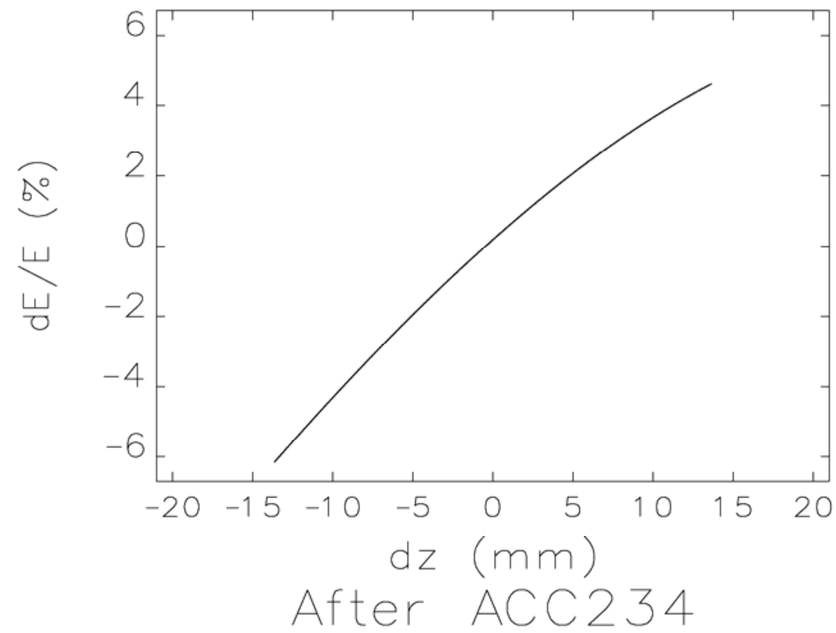
BC2 has same layout

1st Alternative ILC BC – Long. Phase Space

10NOV04 Version

strong nonlinearity due to RF curvature

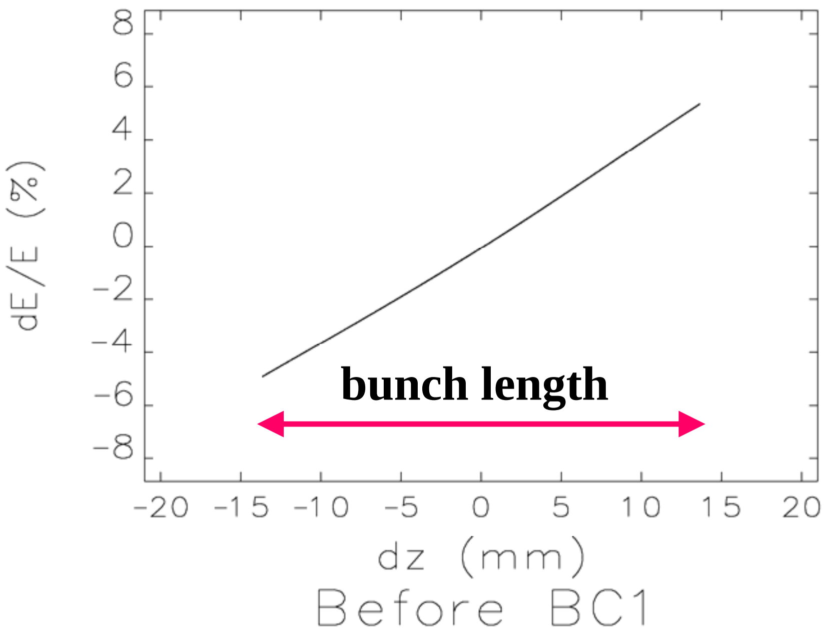


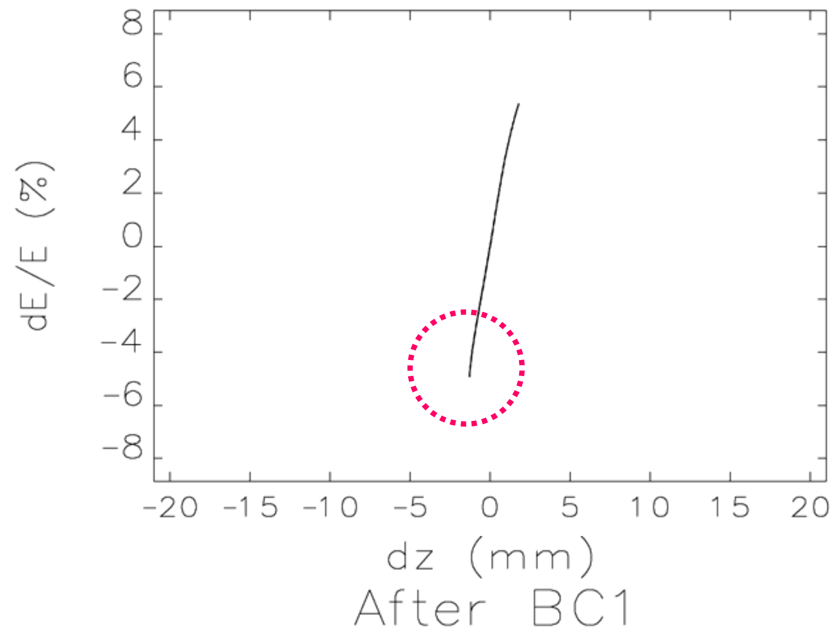


1st Alternative ILC BC – Long. Phase Space

10NOV04 Version

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





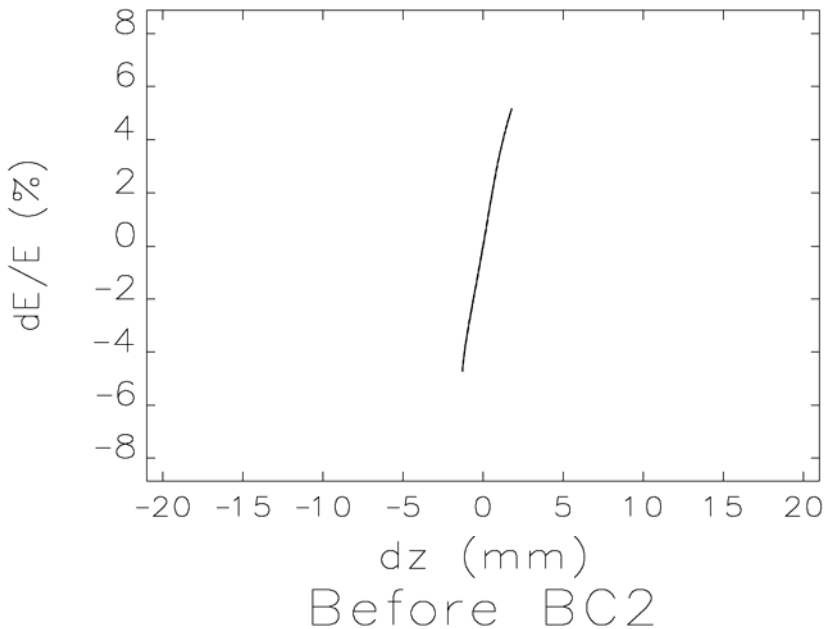
σ_z = 6.00 mm

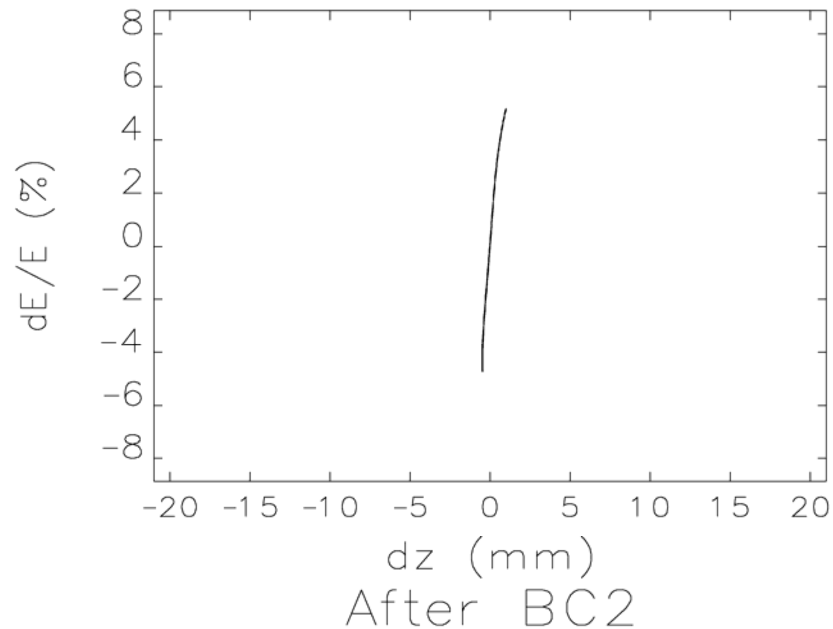
σ_z = 673 μm

1st Alternative ILC BC – Long. phase space

10NOV04 Version

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



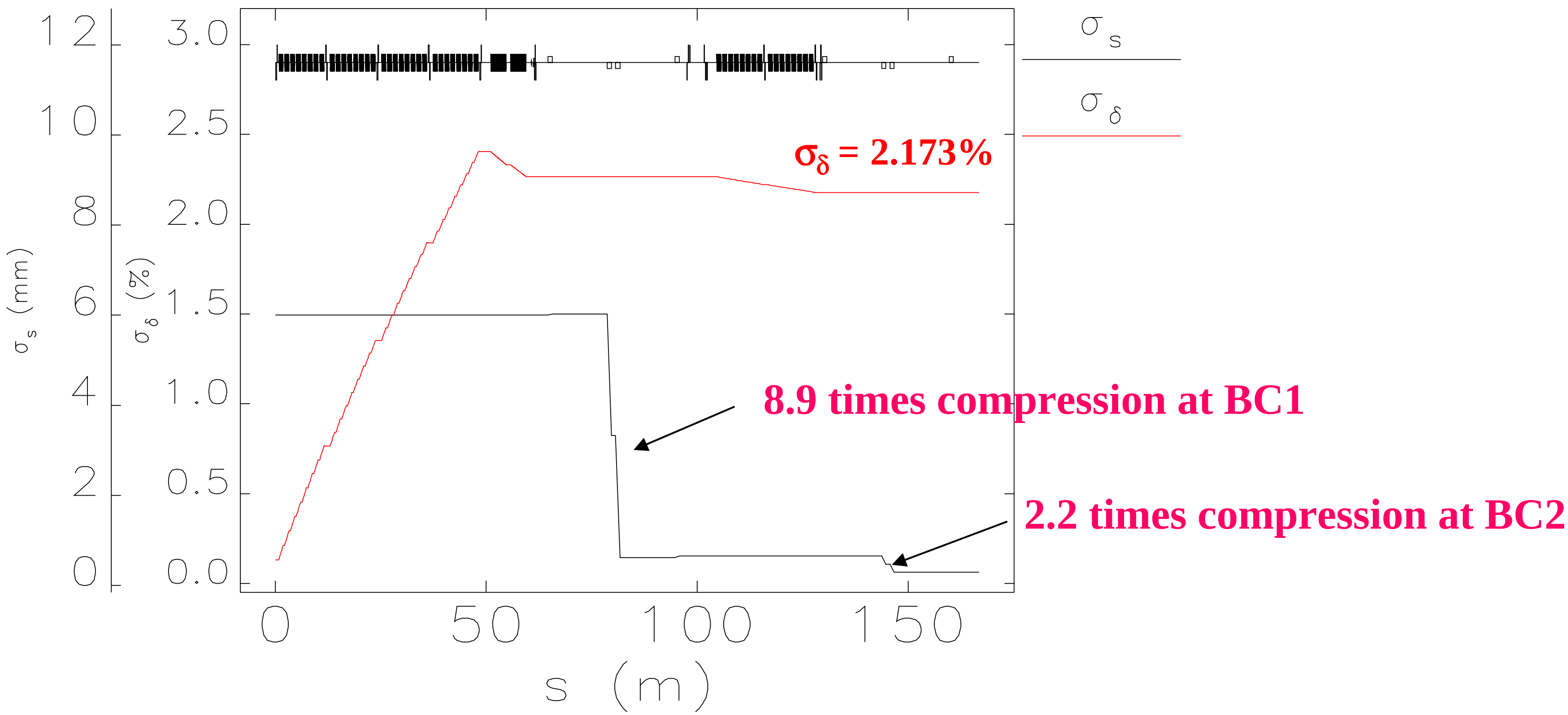


σ_z = 673 µm

σ_z = 300 µm

1st Alternative ILC BC – Compression Ratio

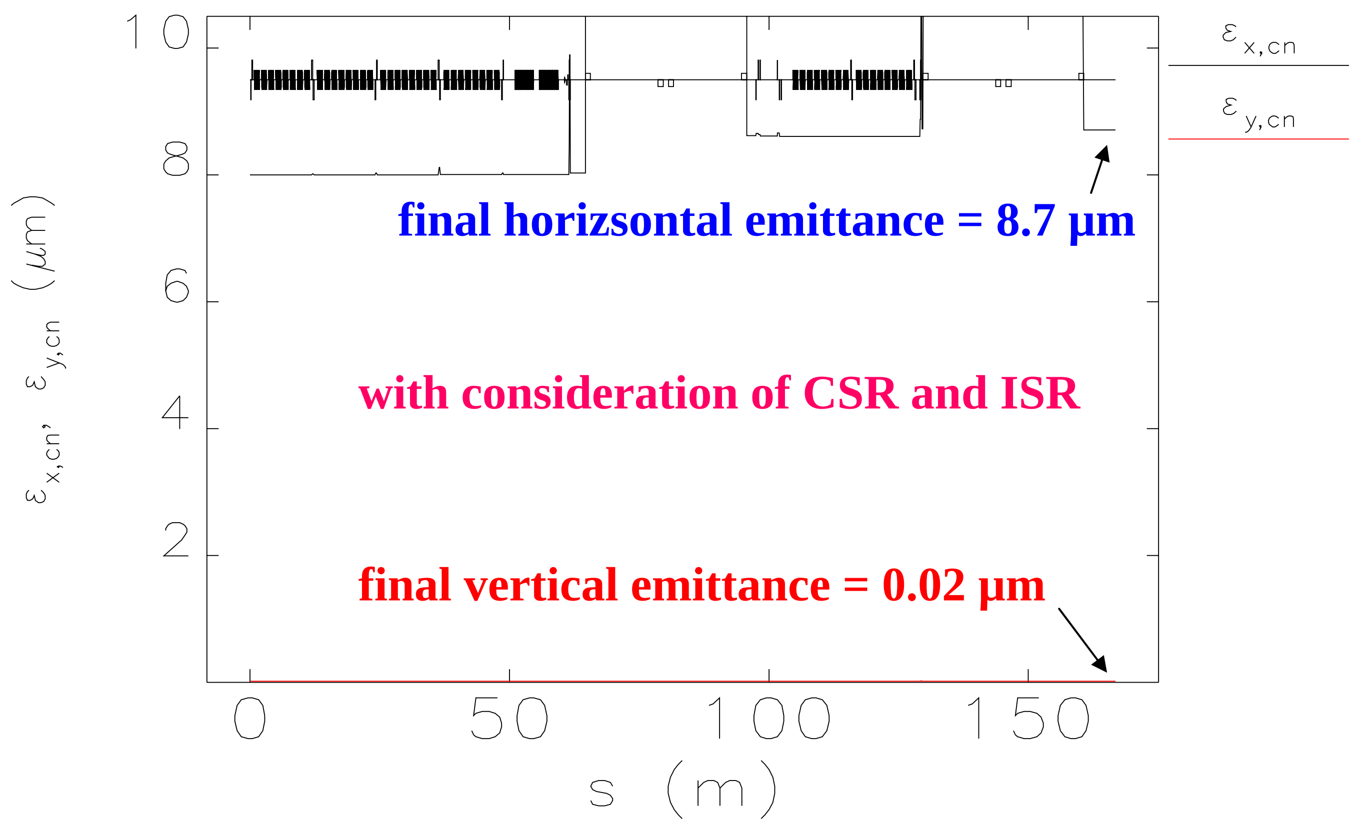
10NOV04 Version



1st Alternative ILC BC – Projected Emittance

10NOV04 Version

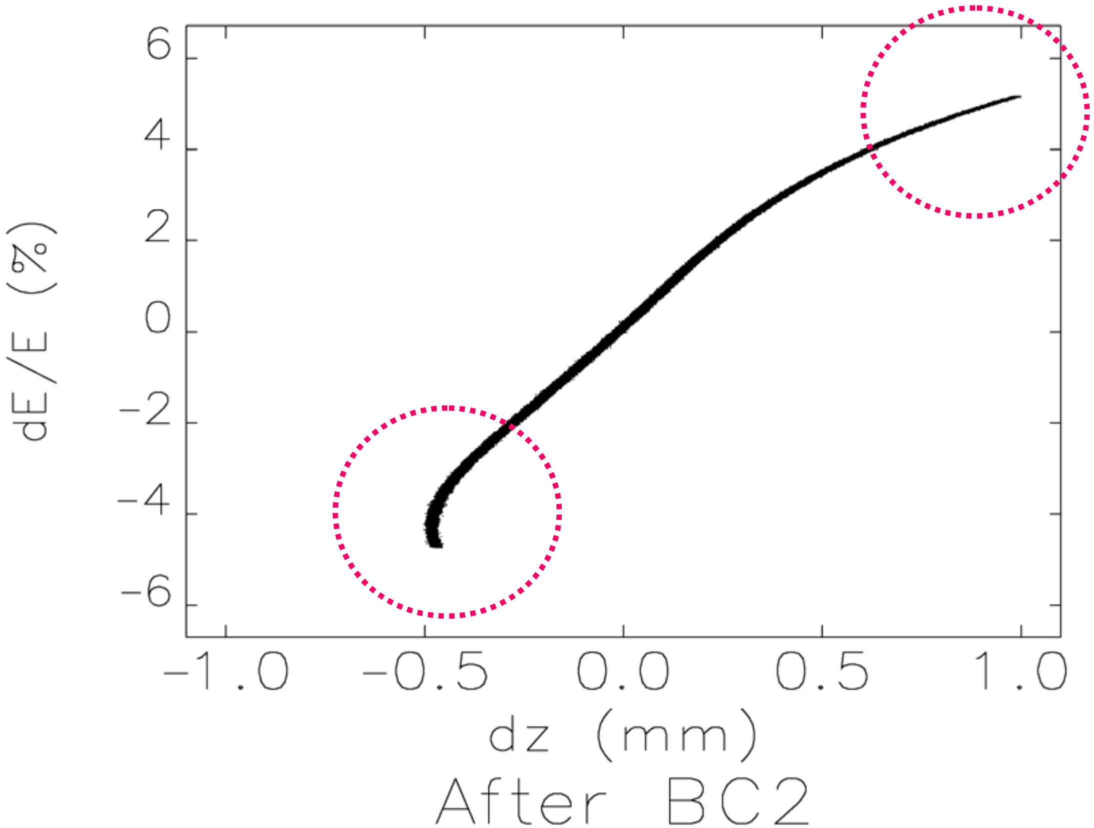
even rms horizontal emittance is increased to 8.7 μm due to ISR and CSR but vertical emittance is almost const (0.02 μm).



1st Alternative ILC BC – Zoomed after BC2

10NOV04 Version

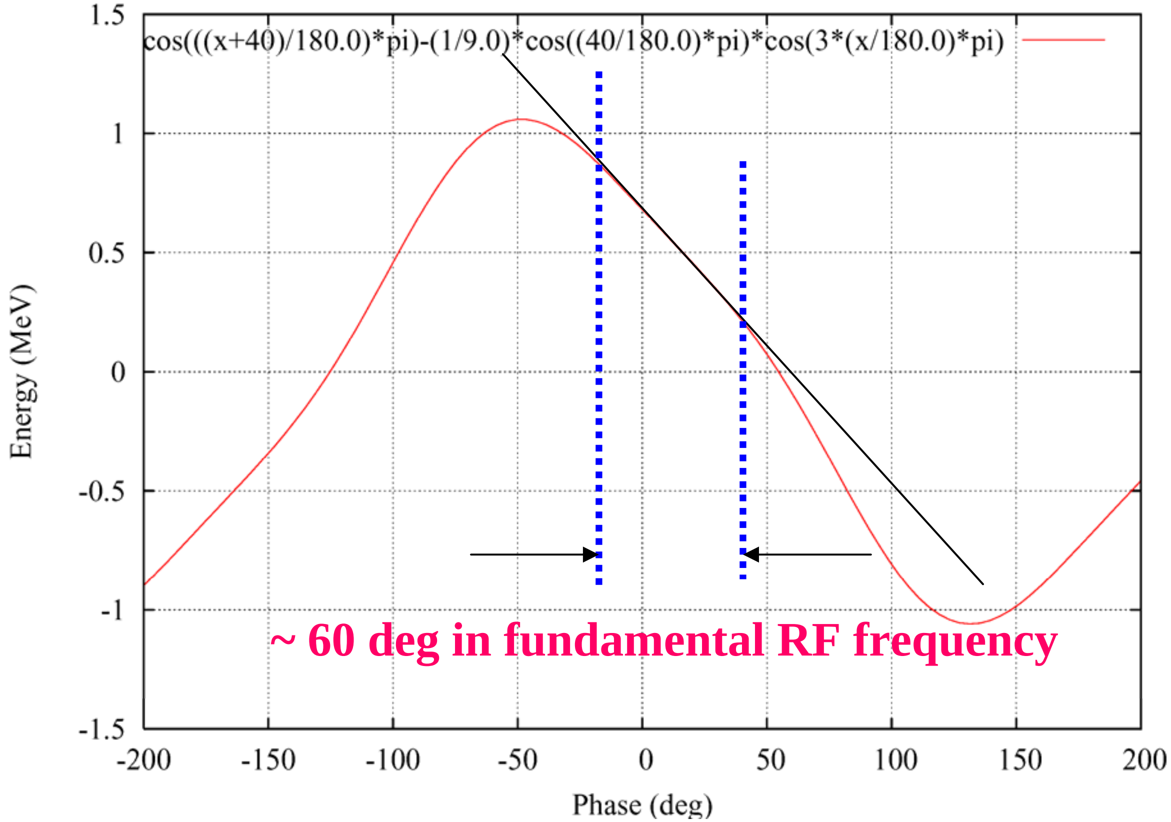
Edges : over (or under) -compression due to the nonlinearity



It seems that 3rd harmonic cavity is not enough to compensate the nonlinearity

Nonlinearity Compensation with 3rd Harmonic

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).



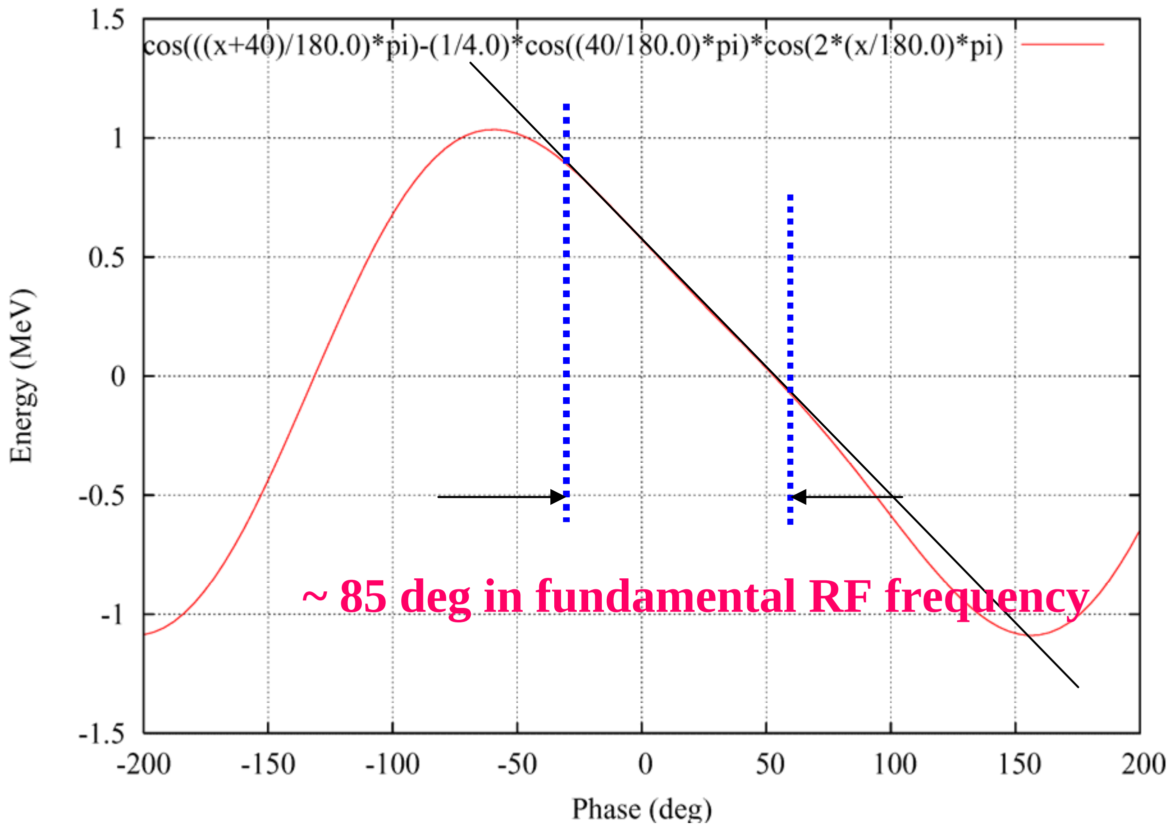
60 deg (FW) in 1300 MHz Linac
- **corresponding to 126 ps (FW)**
- **corresponding to 37.8 mm (FW)**
- **corresponding to 6.3 mm (RMS)**
  (close to current σ_z = 6.0 mm)

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 σ_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 σ_z = 9.0 mm)

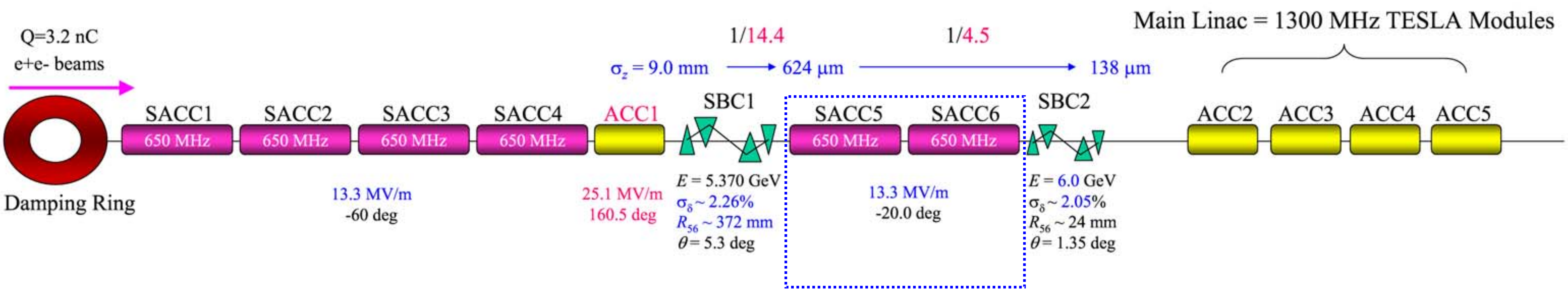
85 deg (FW) in 650 MHz Linac

- corresponding to 357 ps (FW)
- corresponding to 107.1 mm (FW)
- corresponding to 17.9 mm (RMS)
(much wider than σ_z = 9.0 mm)
- corresponding 2nd 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

2nd Alternative ILC BC – (04APR05 Version)

Initial parameters

E = 5.0 GeV

σ_δ = 0.13% (small !)

σ_z = 9.0 mm

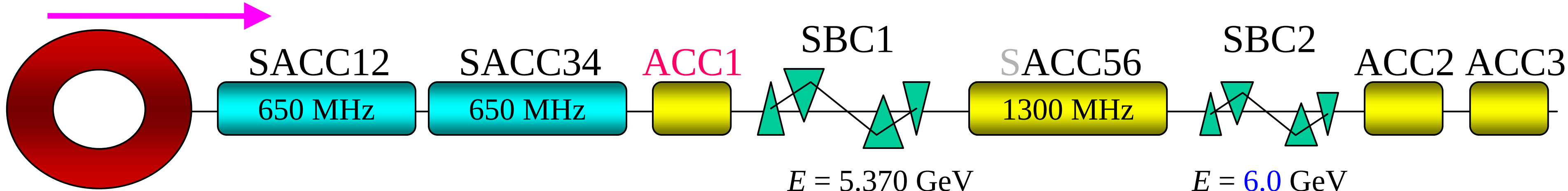
ε_{nx}= 8.0 μm, ε_{ny}= 0.02 μm

Q=3.2 nC

e-beam

1/14.4 1/4.5

σ_z = 9.00 mm → 624 μm → 138 μm



Damping Ring

13.3 MV/m
-60 deg

25.1 MV/m
160.5 deg

E = 5.370 GeV
σ_δ ~ 2.26%
R_{56} ~ 372 mm
θ = 5.3 deg

13.3 MV/m
-20.0 deg

E = 6.0 GeV
σ_δ ~ 2.05%
R_{56} ~ 24 mm
θ = 1.35 deg

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

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.

Final parameters

E = 6.0 GeV

σ_δ = 2.0491%

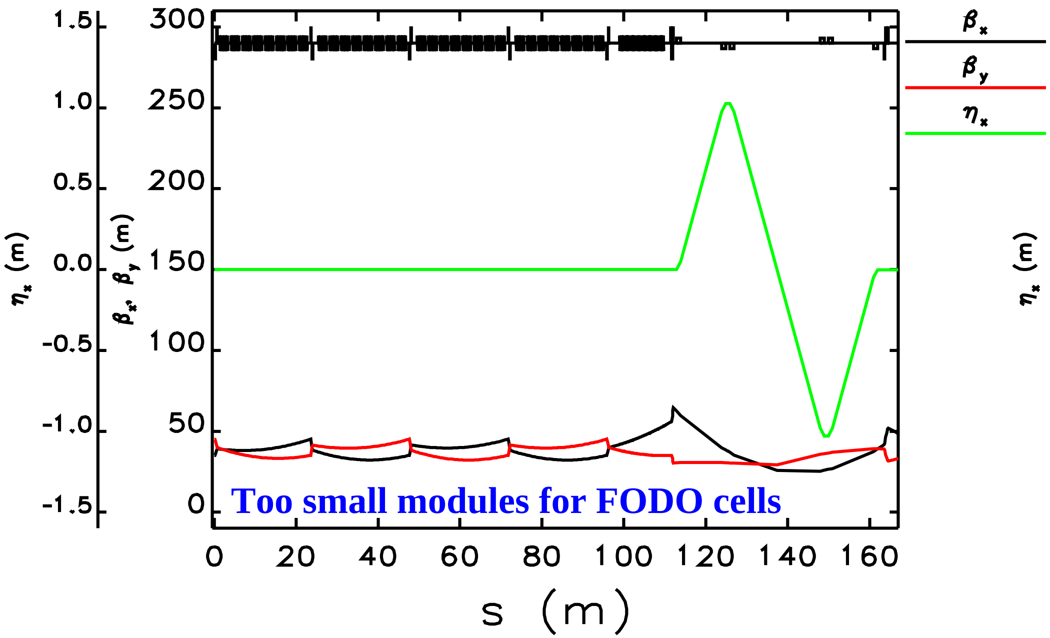
σ_z = 138 μm

ε_{nx}= 9.2 μm, ε_{ny}= 0.02 μm

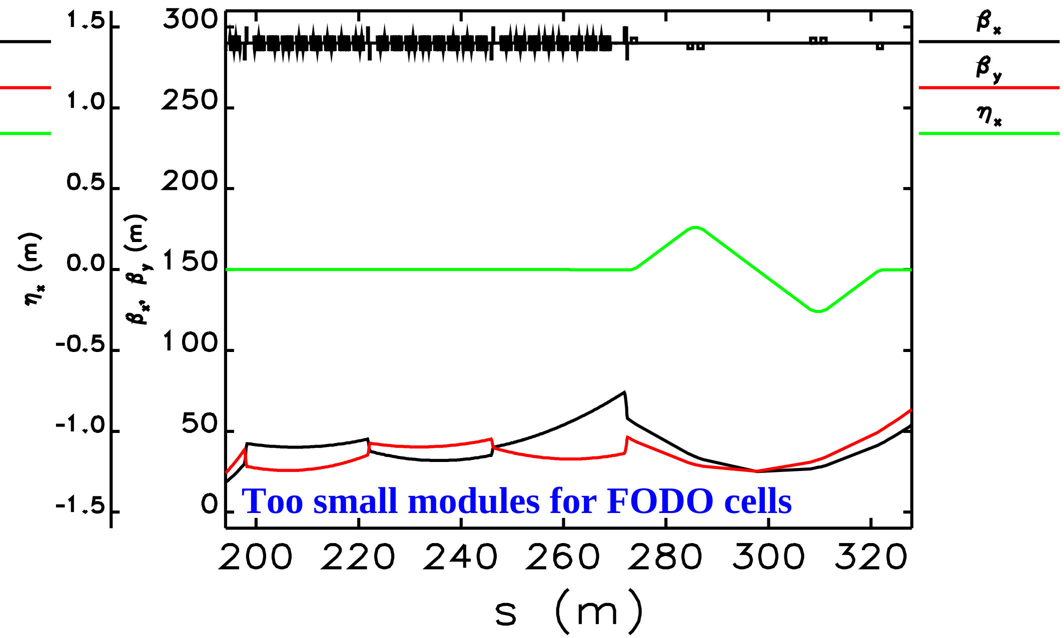
2nd Alternative ILC BC – Twiss Parameters

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

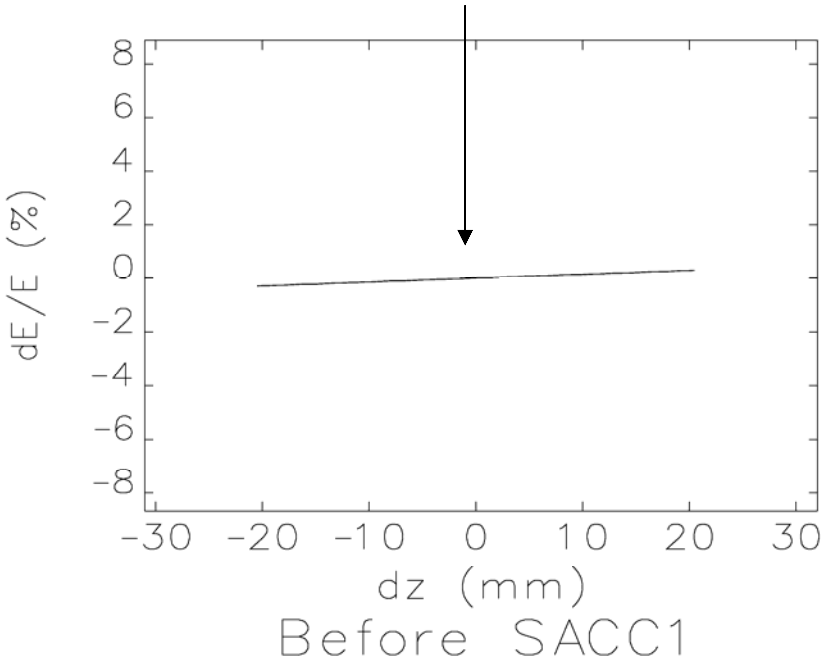


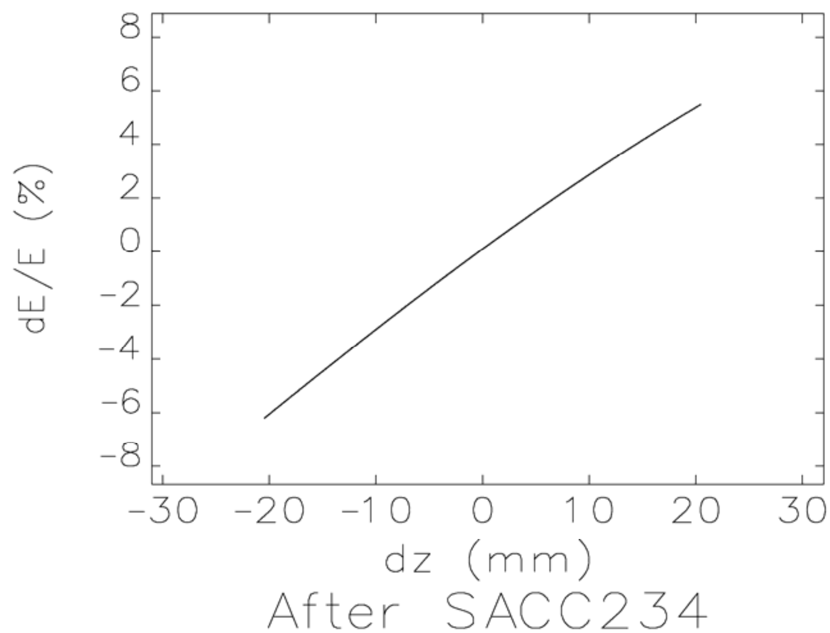
dispersion is within ±1.0 m
emittance growth due to CSR is compensated by reversed dispersion

2nd Alternative ILC BC – Long. Phase Space

04APR05 Version

edge-to-edge ~ 42 mm for 2σ cutting in initial beam distribution



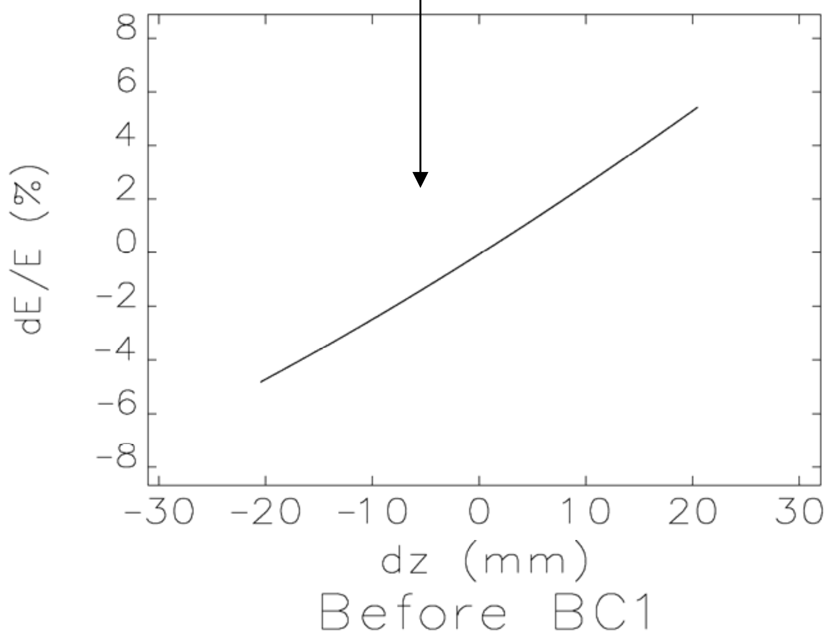


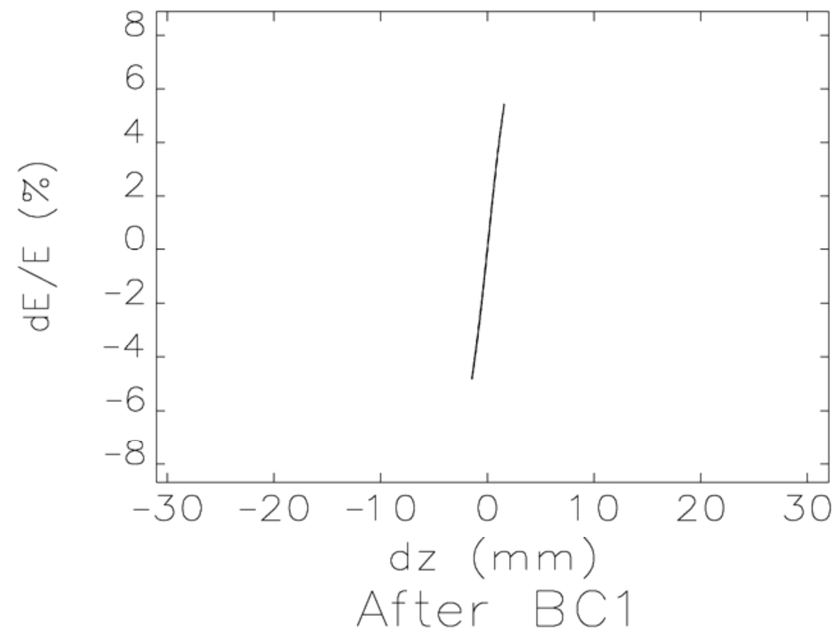
reduced nonlinearity due to weaker wakefield and weaker RF curvature in 650 MHz linac !

2^{nd} Alternative ILC BC – Long. Phase Space

04APR05 Version

Nonlinearity was compensated by 1300 MHz TESLA module (ACC1)



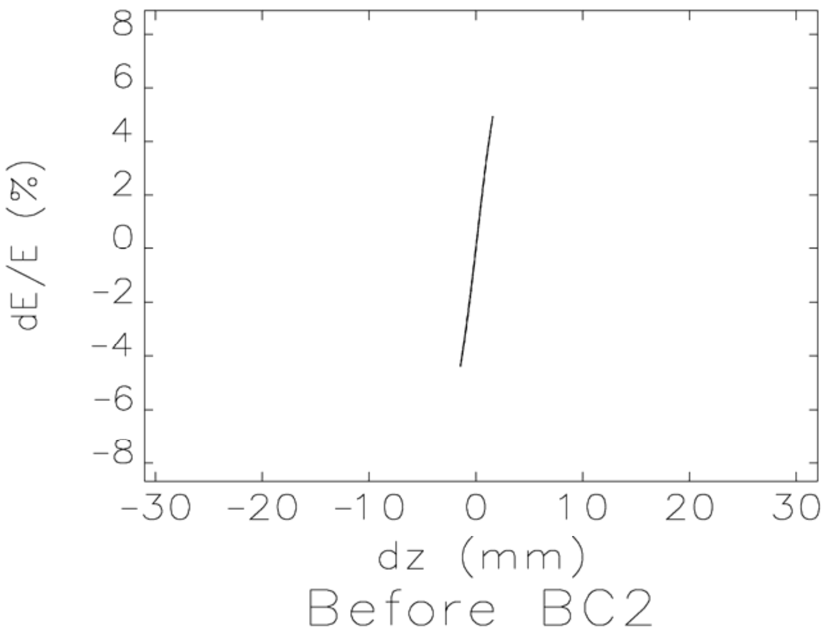


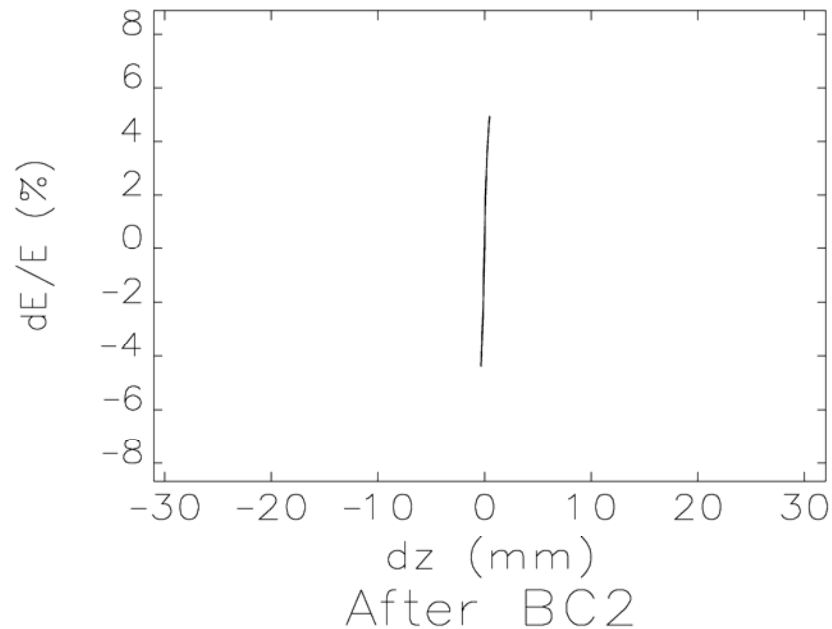
σ_z = 9.00 mm

σ_z = 624 μm

2nd Alternative ILC BC – Long. Phase Space

04APR05 Version





σ_z = 624 µm

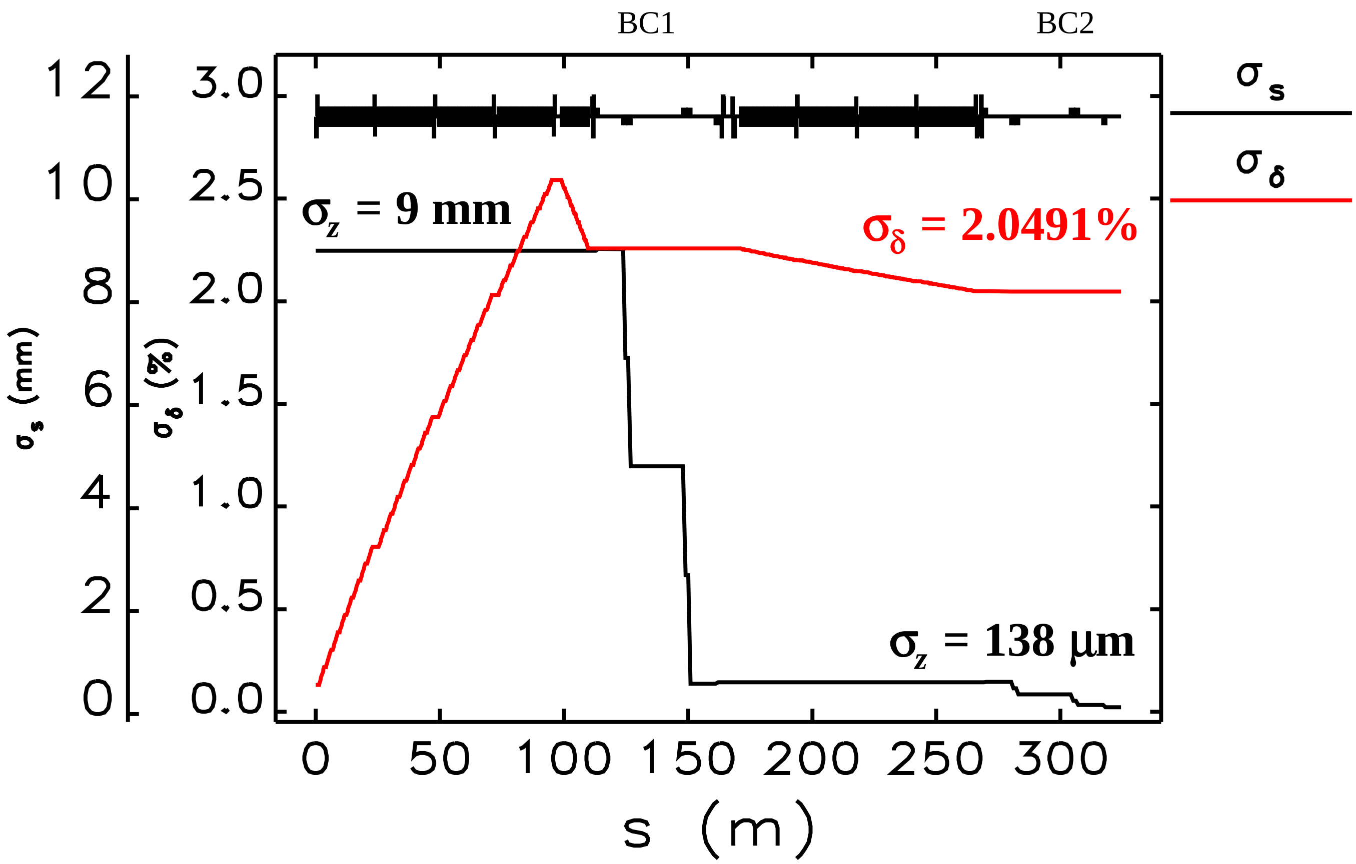
SBC2

σ_z = 138 µm for 1.35 deg at

σ_z = 100 µm for 1.40 deg at SBC2

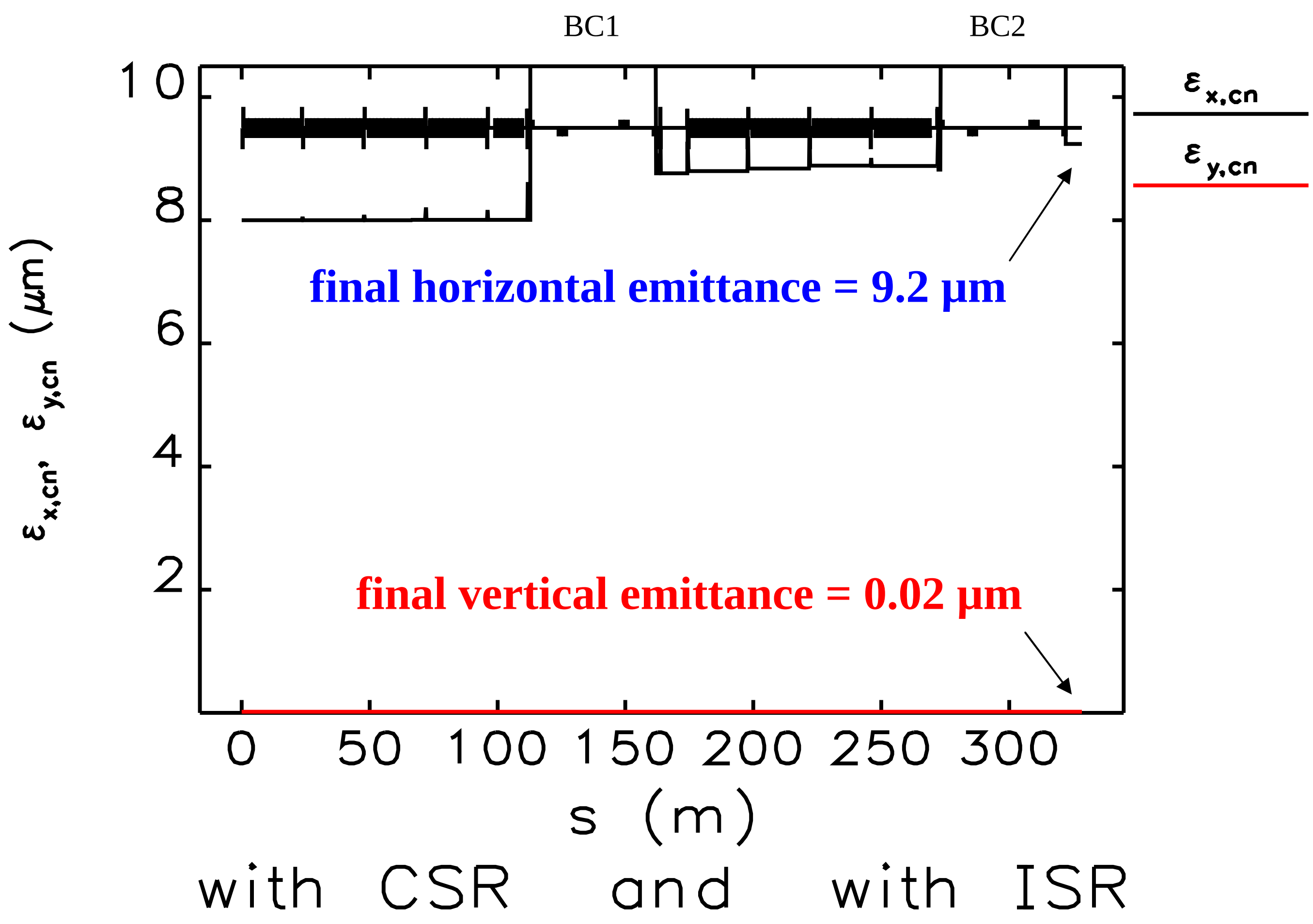
2nd Alternative ILC BC – Energy Spread

04APR05 Version



2^{nd} Alternative ILC BC – Projected Emittance

04APR05 Version

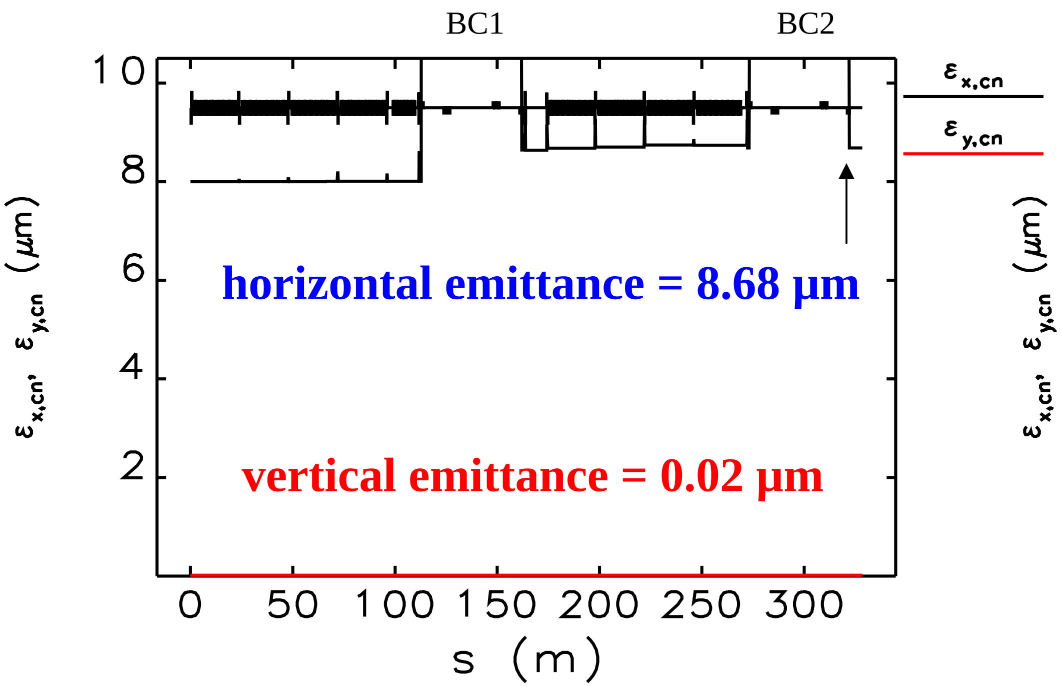


2nd Alternative ILC BC – CSR & ISR Effects

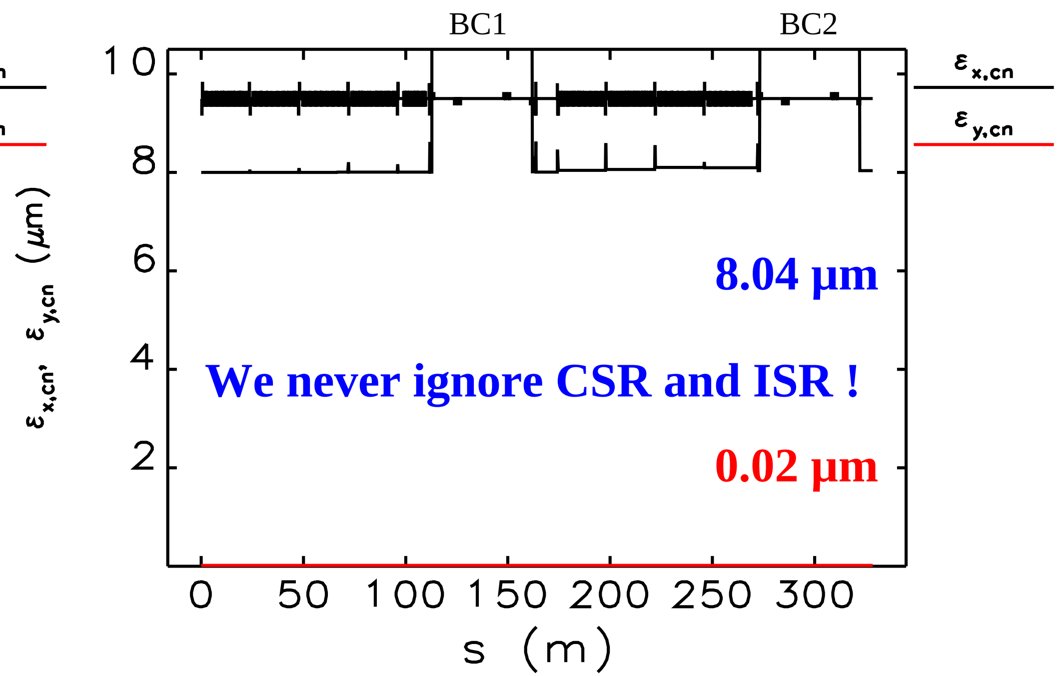
04APR05 Version

Action of CSR and ISR when we compress σ_z = 9.0 mm to 138 μm

- **Final horizontal emittance with consideration of CSR and ISR = 9.2 μm**
- **Final horizontal emittance with consideration of only ISR = 8.68 μm**
- **Final horizontal emittance without consideration of CSR and ISR = 8.04 μm**



without CSR but with ISR

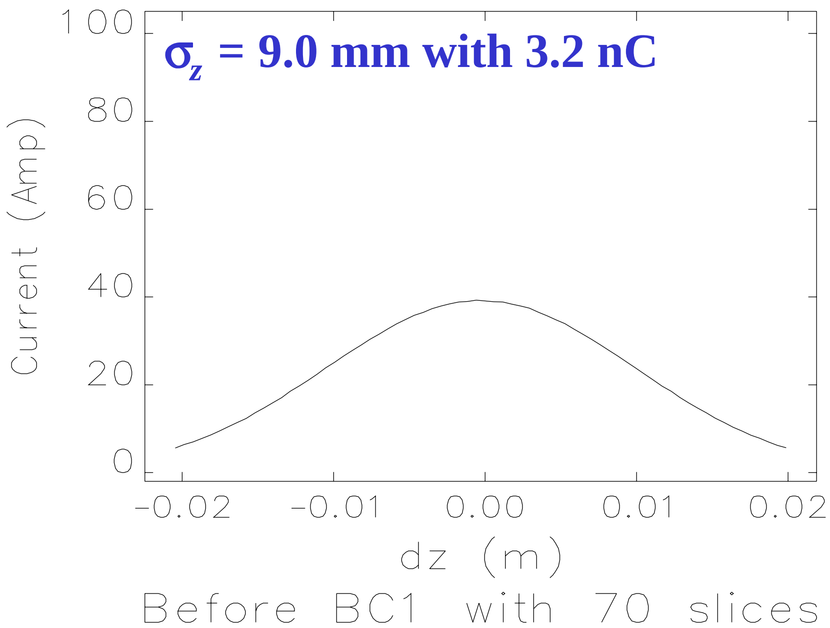


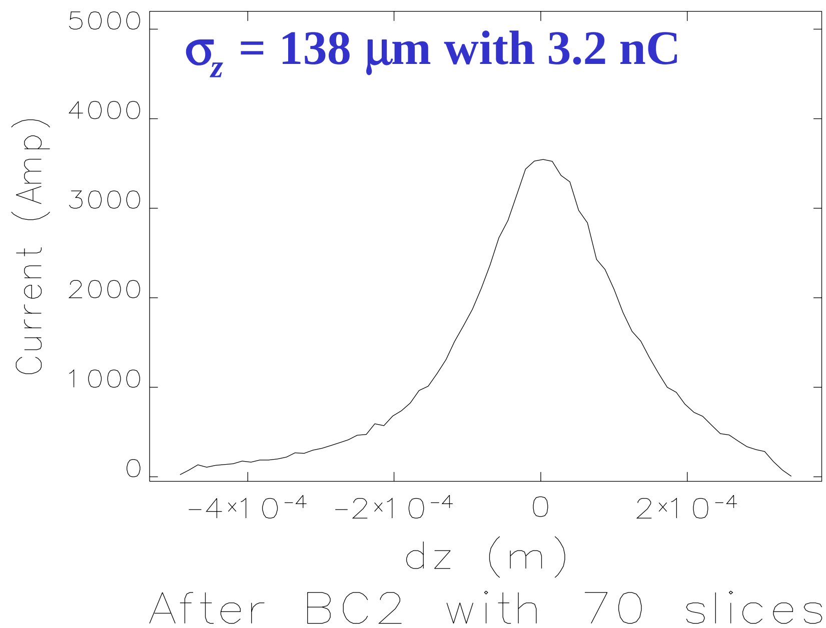
without CSR and without ISR

2nd Alternative ILC BC – Peak Current

04APR05 Version

good compensation by ACC1
good symmetric peak current





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 !)

3^{rd} Alternative ILC BC – (09JUL05 Version)

Initial parameters

E = 5.0 GeV

σ_δ = 0.13% (small !)

σ_z = 6.0 mm

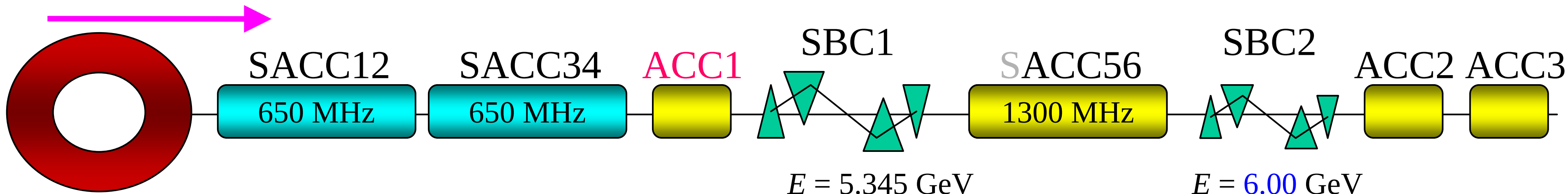
ε_{nx}= 8.0 μm, ε_{ny}= 0.02 μm

Q=3.2 nC

e-beam

1/12 1/3.3

σ_z = 6.00 mm → 500 μm → 150 μm



Damping Ring

13.3 MV/m
-61 deg

25.1 MV/m
160.5 deg

E = 5.345 GeV
σ_δ ~ 1.57%
R_{56} ~ 351 mm
θ = 5.15 deg

13.35 MV/m
-26.0 deg

E = 6.00 GeV
σ_δ ~ 1.44%
R_{56} ~ 24 mm
θ = 1.35 deg

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

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.

Final parameters

E = 6.0 GeV

σ_δ = 1.44%

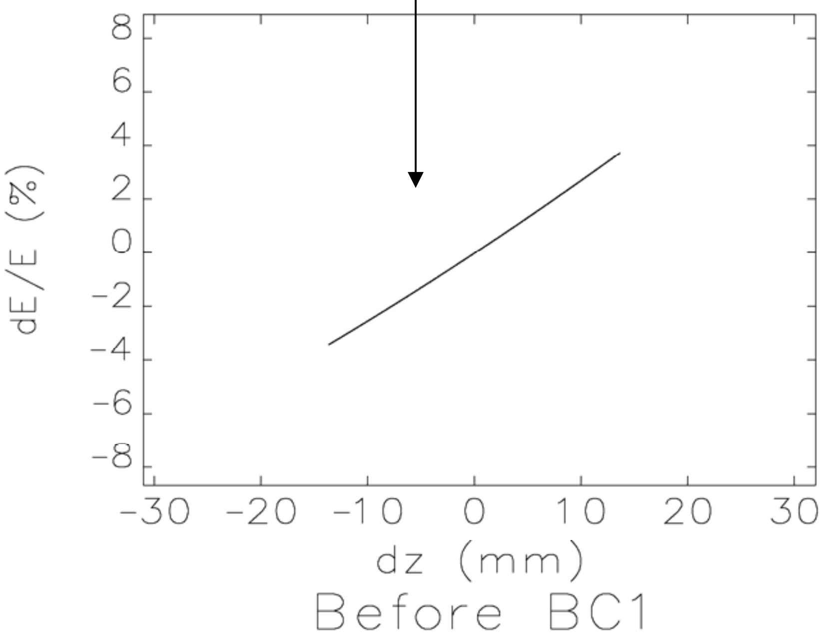
σ_z = 150 μm

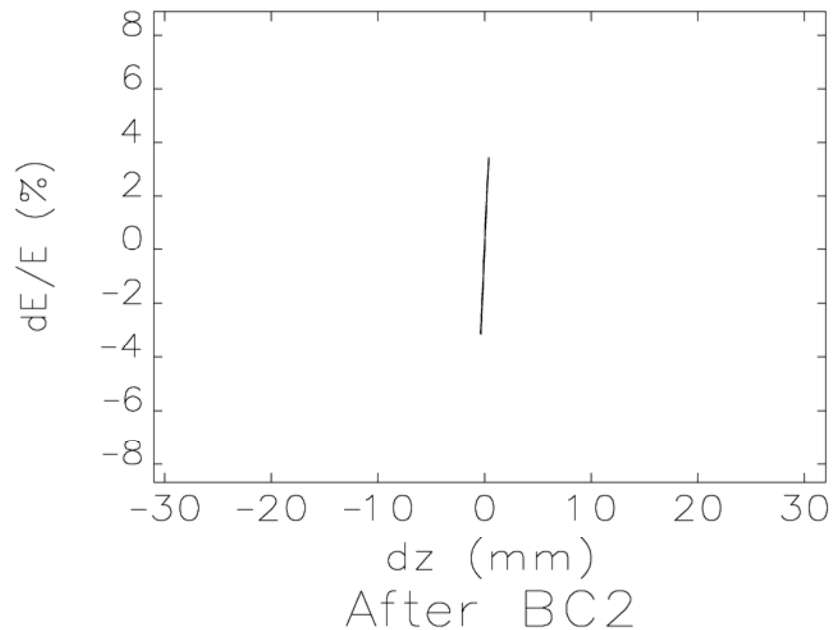
ε_{nx}= 8.8 μm, ε_{ny}= 0.02 μm

3rd Alternative ILC BC – Long. Phase Space

09JUL05 Version

Nonlinearity was compensated by 1300 MHz TESLA module (ACC1)



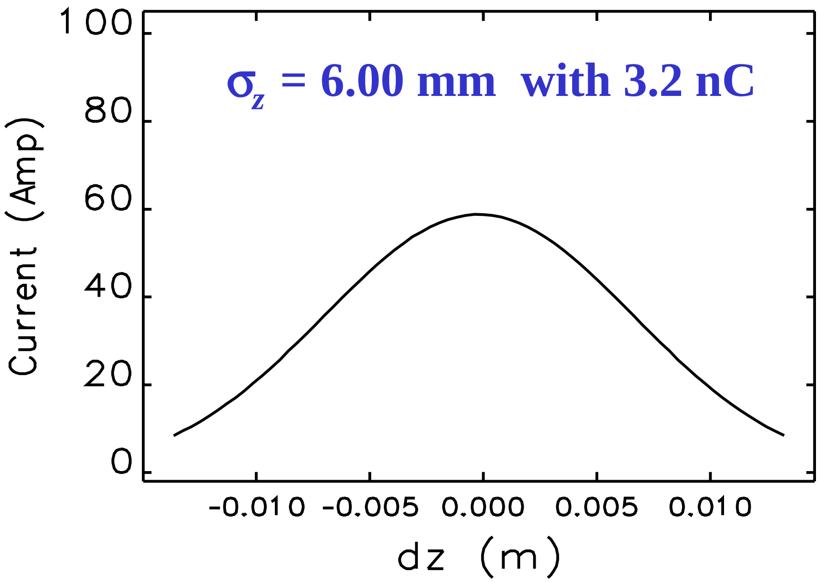


σ_z = 6.00 mm

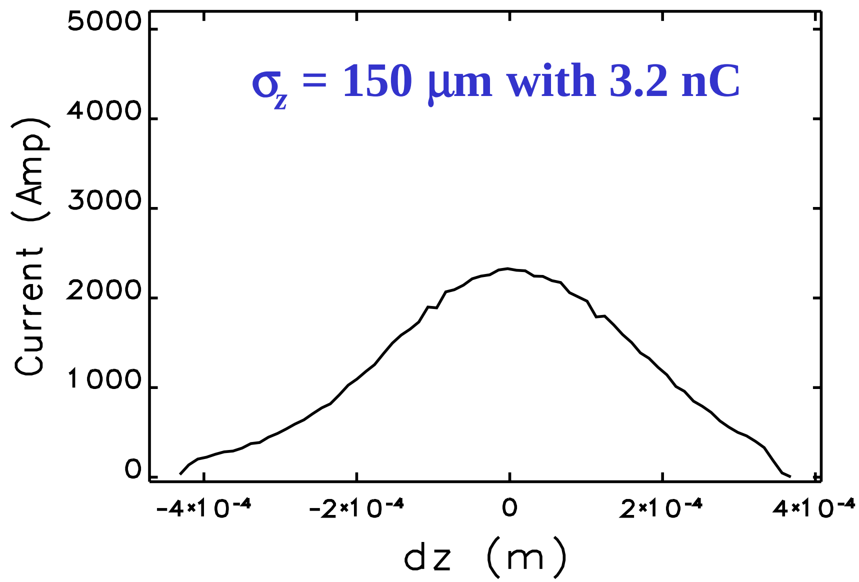
σ_z = 150 μm

3rd Alternative ILC BC – Peak Current

09JUL05 Version



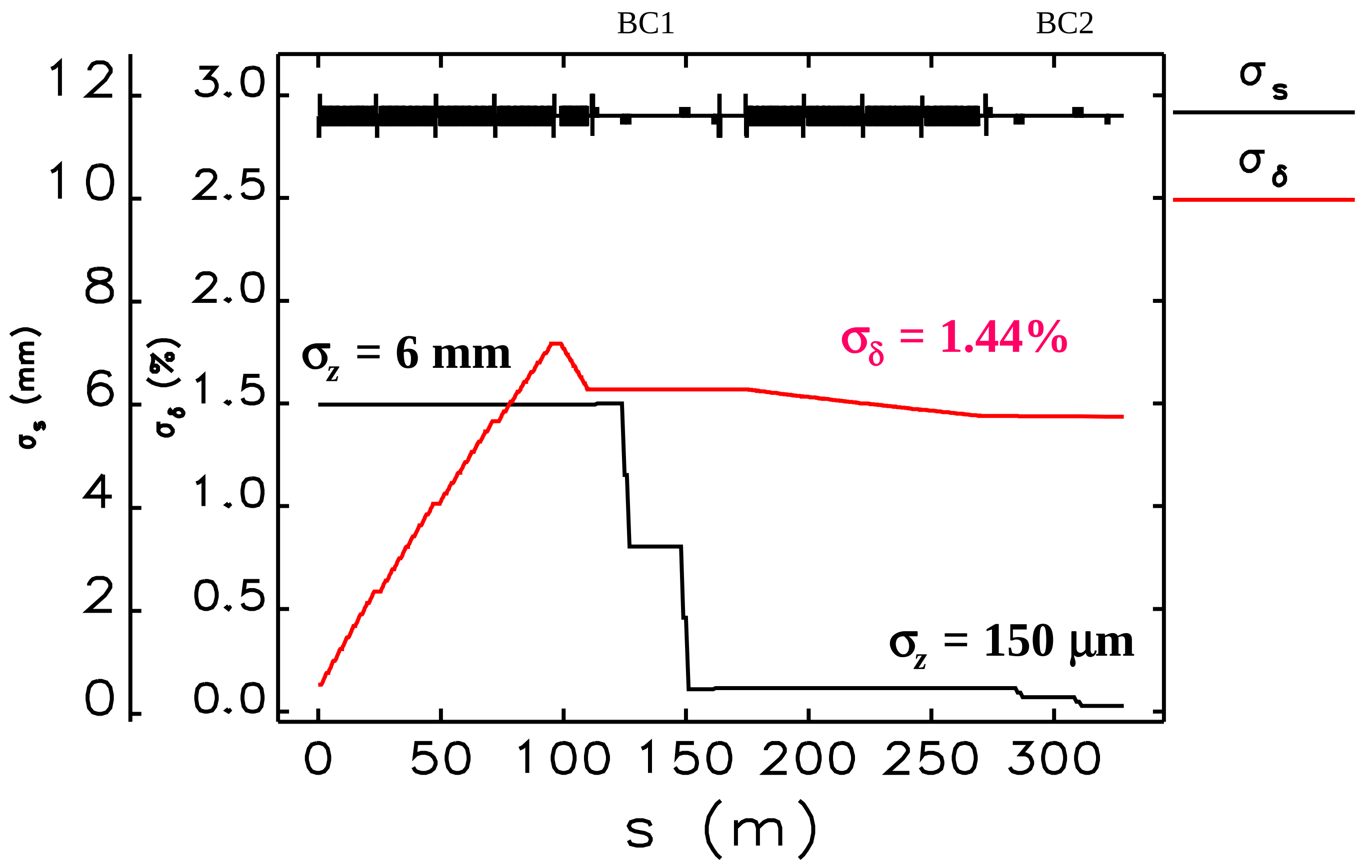
Before BC1 with 70 slices



After BC2 with 70 slices

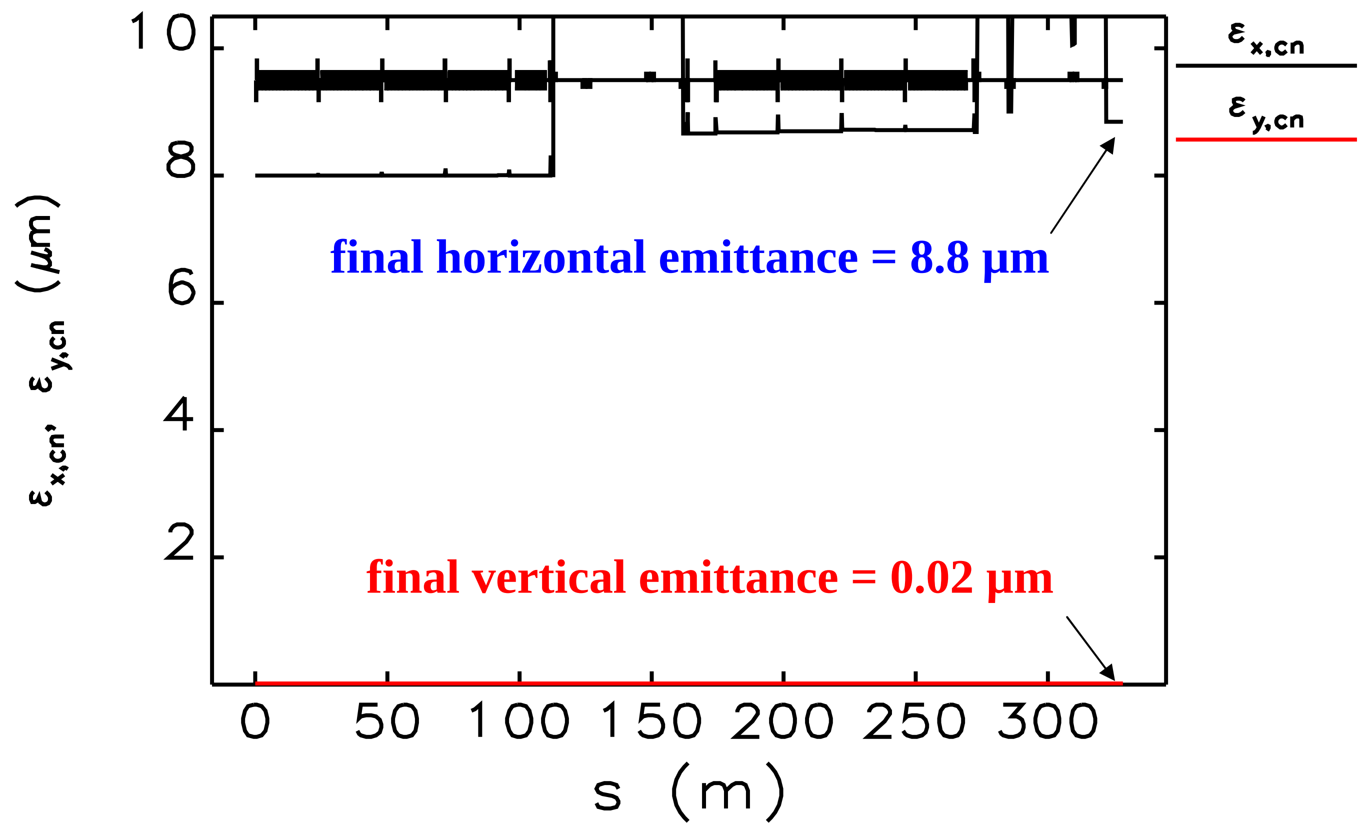
3rd Alternative ILC BC – Energy Spread

09JUL05 Version



3rd Alternative ILC BC – Projected Emittance

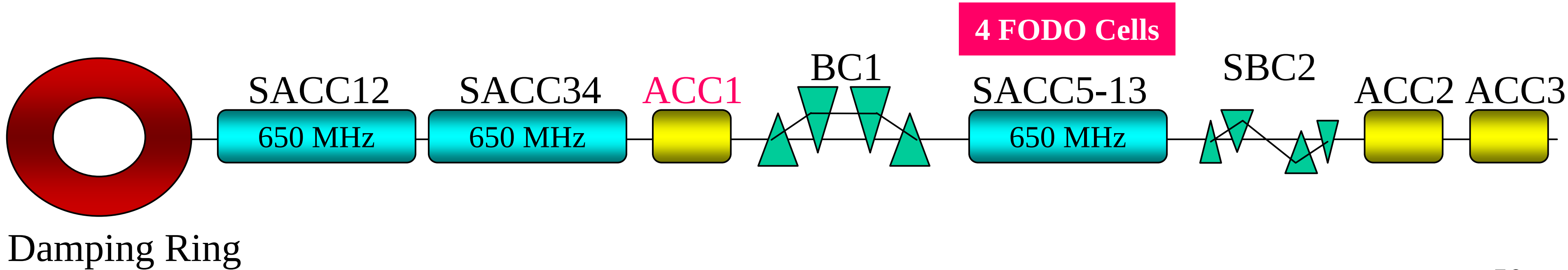
09JUL05 Version



with CSR and with ISR

4^{th} Alternative ILC BC – (01AUG05 Version)

- ☐ 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 GeV

σ_δ = 0.13% (small !)

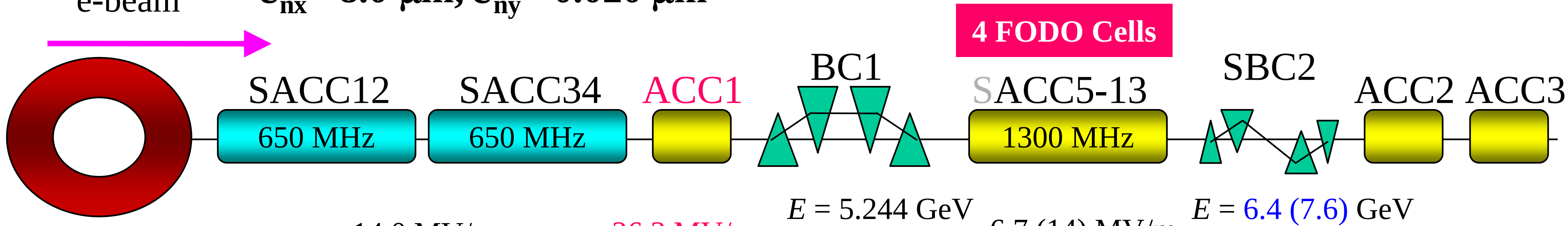
σ_z = 6.0 mm

ε_{nx}= 8.0 μm, ε_{ny}= 0.020 μm

Q=3.2 nC
e-beam

1/10.0 1/4.0

σ_z = 6.00 mm → 600 μm → 150 μm



14.0 MV/m
-66.5 deg

26.3 MV/m
163.0 deg

E = 5.244 GeV
σ_δ ~ 1.81%
R_{56} ~ 302 mm
θ = 5.3 deg

6.7 (14) MV/m
-27.7 deg

E = 6.4 (7.6) GeV
σ_δ ~ 1.55%
R_{56} ~ 30.3 mm
θ = 1.41 deg

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

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.

Final parameters

E = 6.4 (7.6) GeV

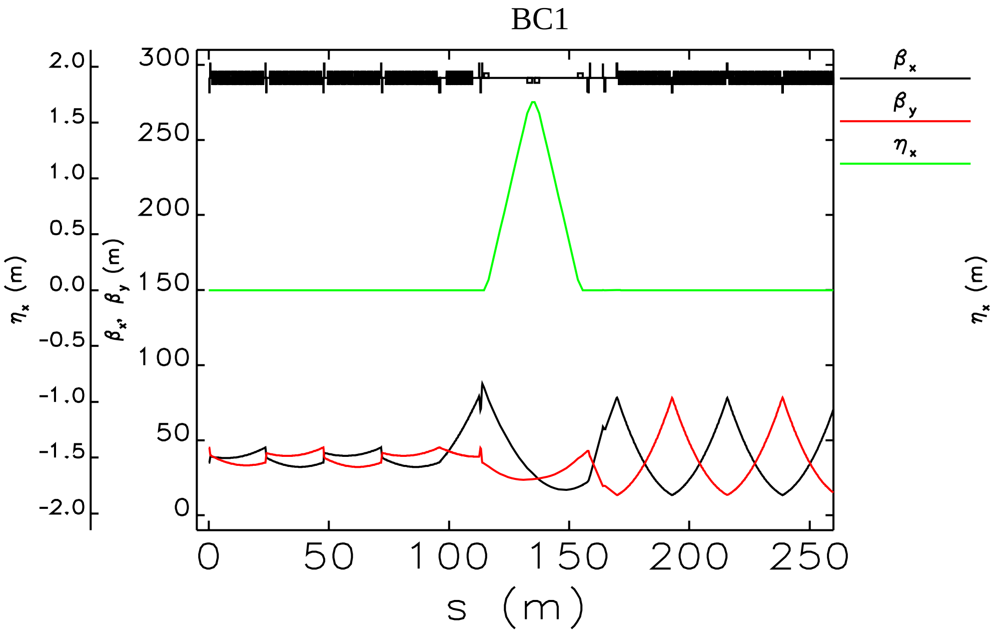
σ_δ = 1.55%

σ_z = 150 μm

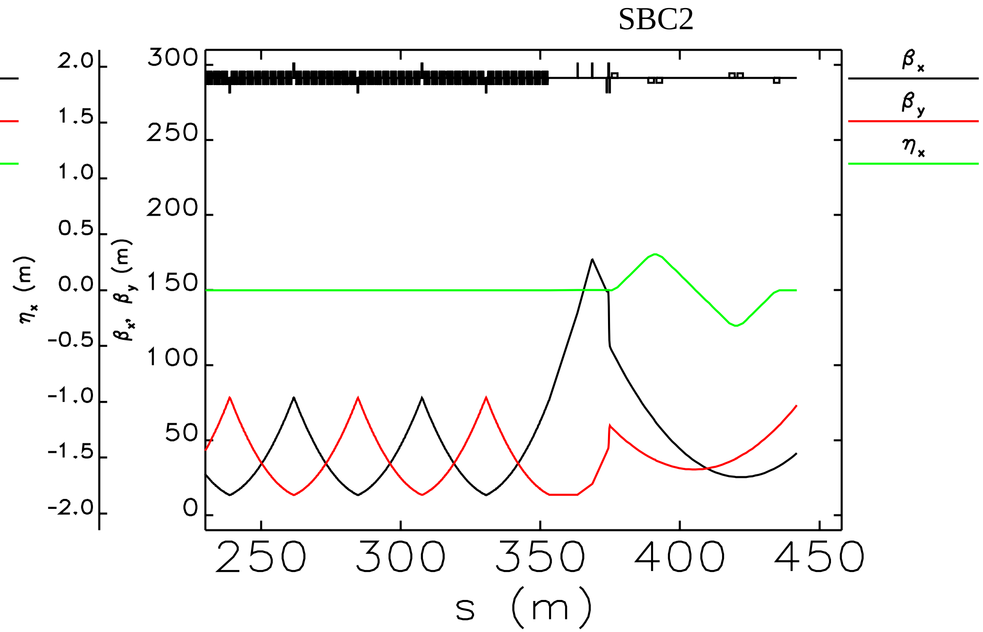
ε_{nx}= 8.28 μm, ε_{ny}= 0.020 μm

4th Alternative ILC BC – Twiss Parameters

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



90 deg four FODO cells between BCs



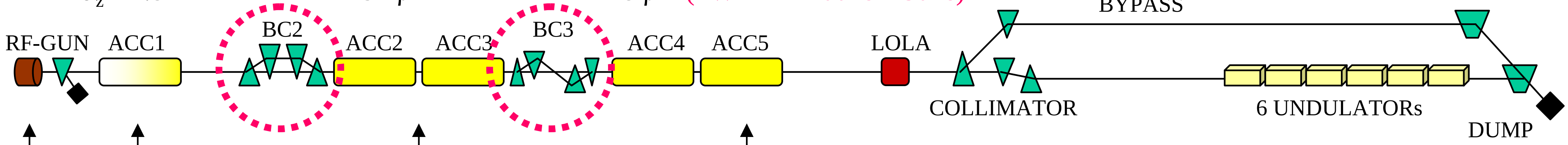
90 deg four FODO cells between BCs

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

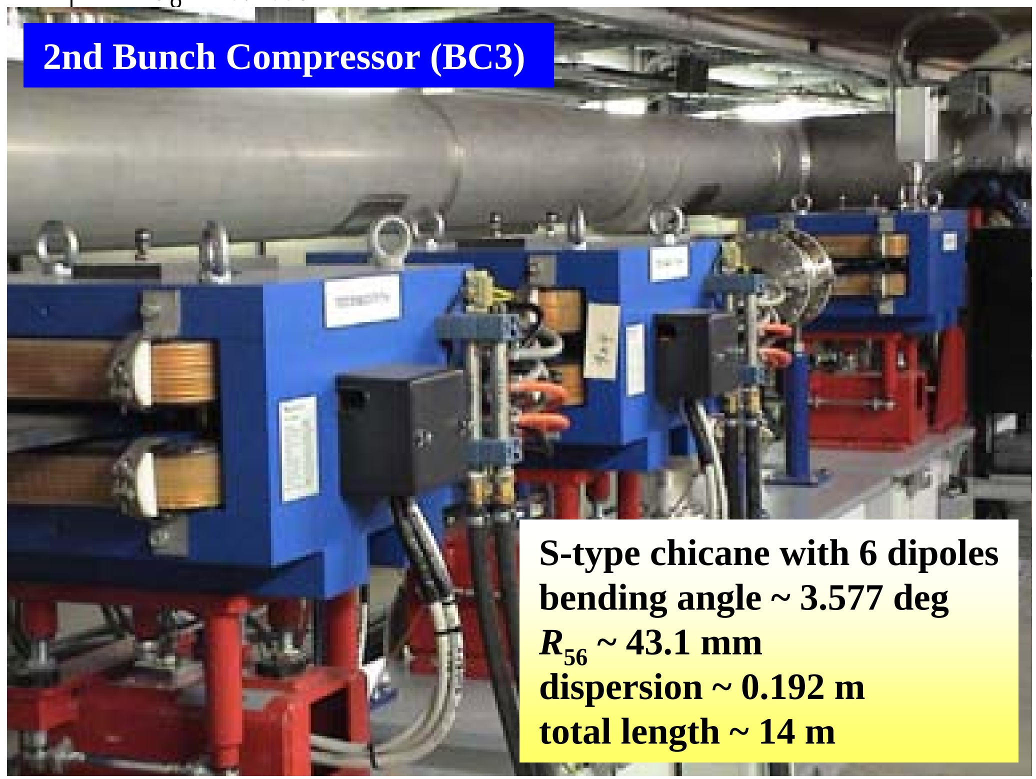
σ_z = 1.821 mm → 794 μm → 728 μm (FWHM = 200 fs ~ 50 fs)



E ~ 127 MeV
R_{56} = 181.3 mm
σ_δ = 0.60%
Θ = 18.0355 deg
(15 deg ~ 21 deg)

E = 380 MeV
R_{56} = 43.1 mm
σ_δ = 0.18%
Θ = 3.577 deg
(1.7 deg ~ 5.4 deg)

E = 445 MeV
σ_δ = 0.16%



12.95 MV/m
16.84 MV/m
-9.0 degree

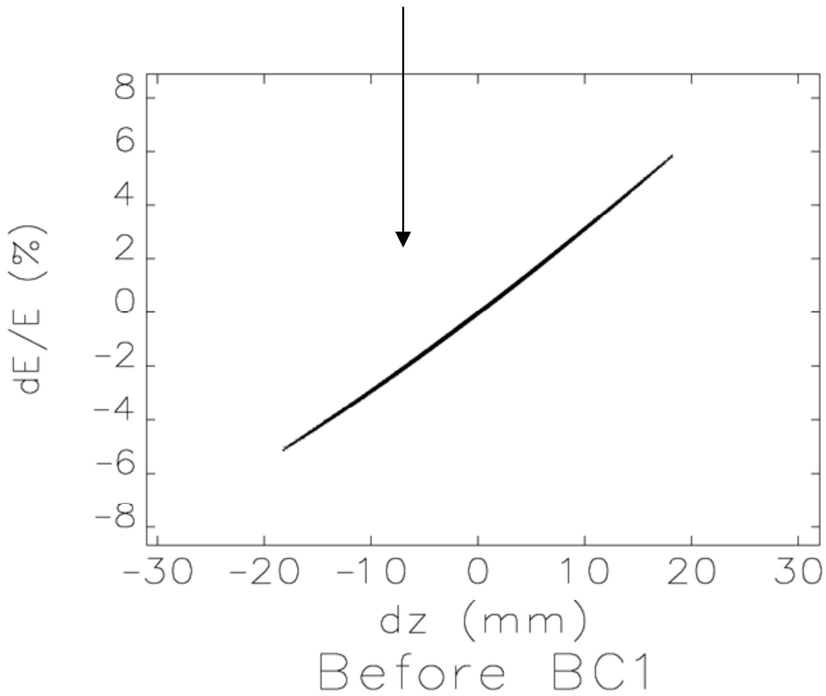
17.29 MV/m
13.53 MV/m
0.0 degree

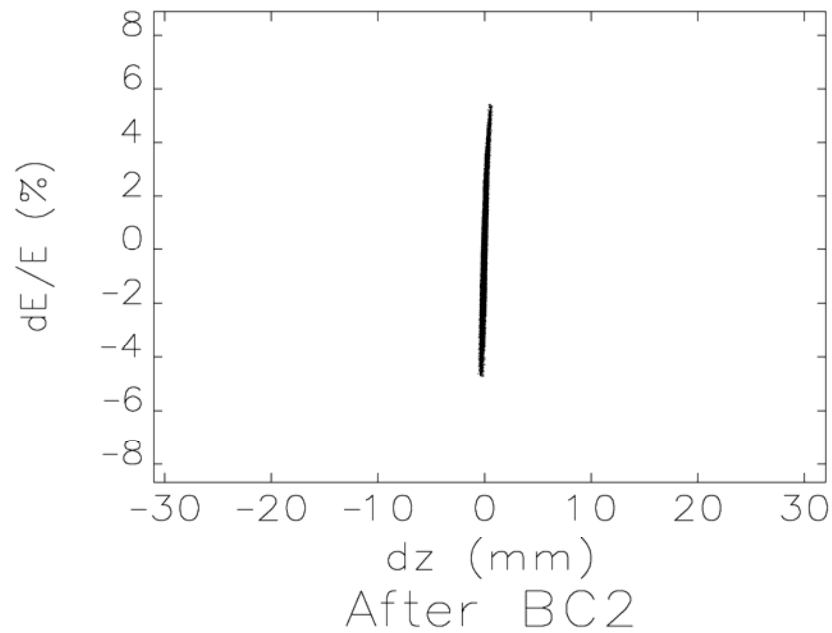
40.25 MV/m (peak)
38 degree
from zero crossing

4th Alternative ILC BC – Long. Phase Space

01AUG05 Version

Nonlinearity was compensated by 1300 MHz TESLA module (ACC1)





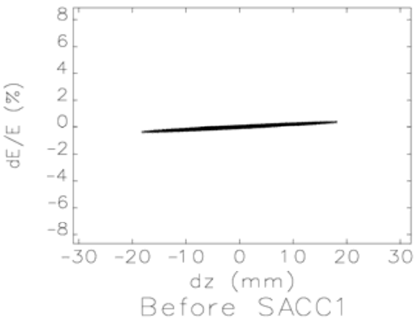
σ_z = 6.00 mm

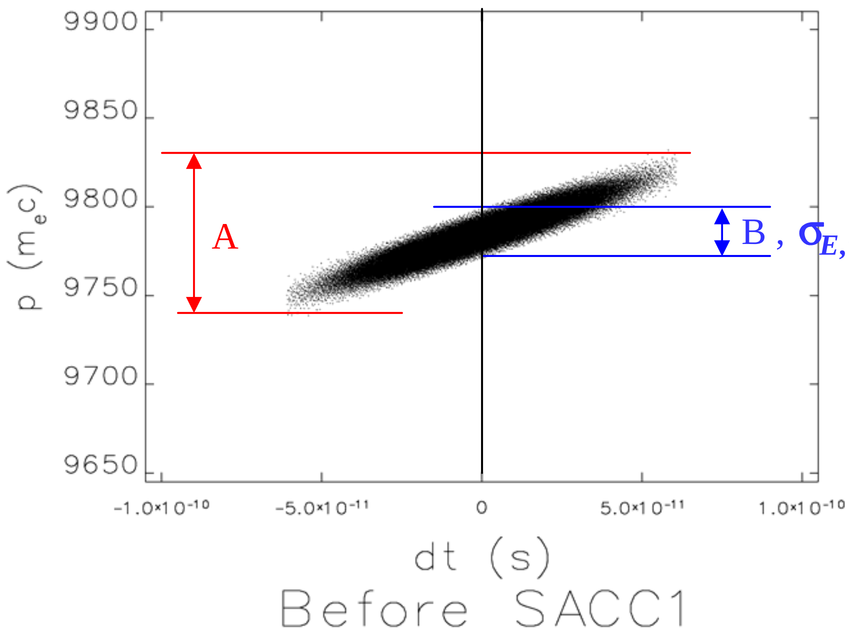
σ_z = 150 μm

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

4th Alternative ILC BC – Long Emittance

01AUG05 Version





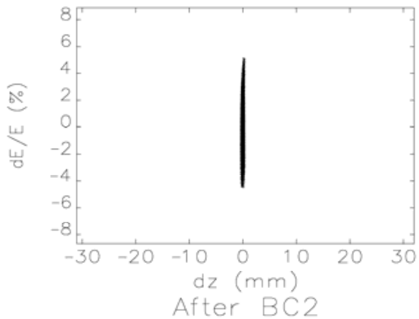
B , $\sigma_{E,u}$ ~ 2.55 MeV (RMS)

RMS value through region A gives total (or projected) rms energy spread, σ_E (or its relative RMS energy spread σ_δ). In our case, initial total rms relative energy spread $\sigma_\delta = 0.13\%$.

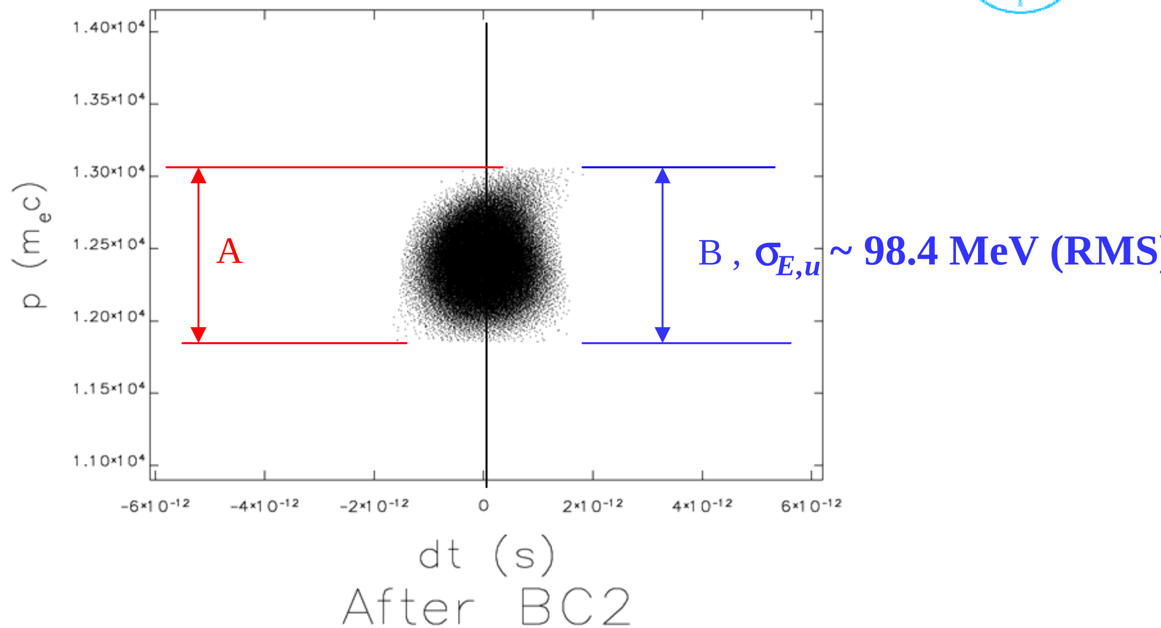
RMS value through region B gives uncorrelated (or slice) rms energy spread $\sigma_{E,u}$. In our case, peak-to-peak momentum change in region B is about 30 (=9800-9770). If we change its unit to MeV, it is 30*0.511 ~ 15.3 MeV. Since RMS value is about six times smaller than peak-to-peak one, its RMS 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).

4th Alternative ILC BC – Long Emittance

01AUG05 Version



zoom in



After BC2, longitudinal phase space is rotated about 90 deg such as shown in left plot. In this special case, total rms energy spread, σ_E (or σ_δ) 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 ~ 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 $\sigma_{\delta,u}$ ~ 98.4 /6400 ~ 0.0154 or 1.54%, which is slightly smaller than our total relative RMS energy spread σ_δ = 1.55% after BC2.

4^{th} Alternative ILC BC – Long Emittance

At SACC1 (=before BC1), $\sigma_{E,u} \times \sigma_z$ = 6.0 mm*2.55 MeV ~ 15.3 mm.MeV

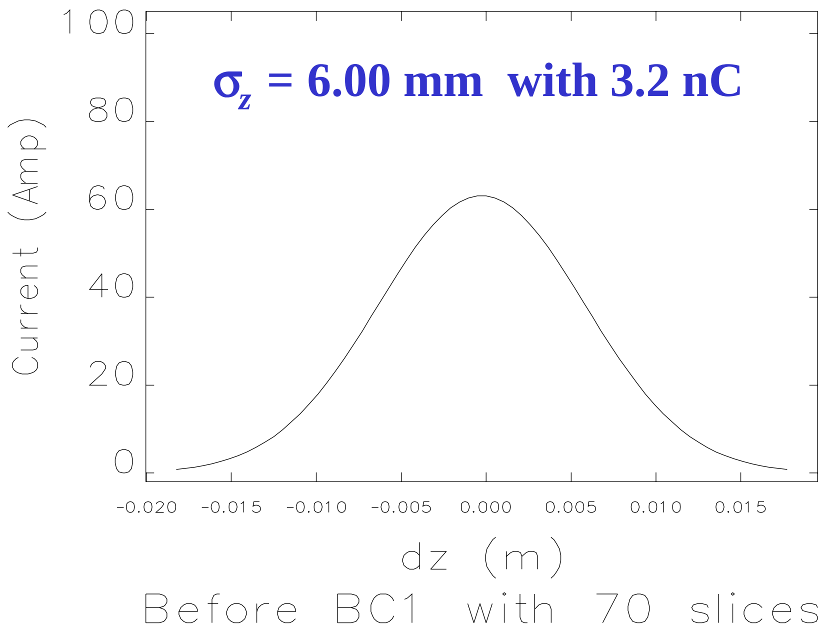
After BC2, $\sigma_{E,u} \times \sigma_z$ = 0.150 mm*98.4 MeV ~ 14.8 mm.MeV

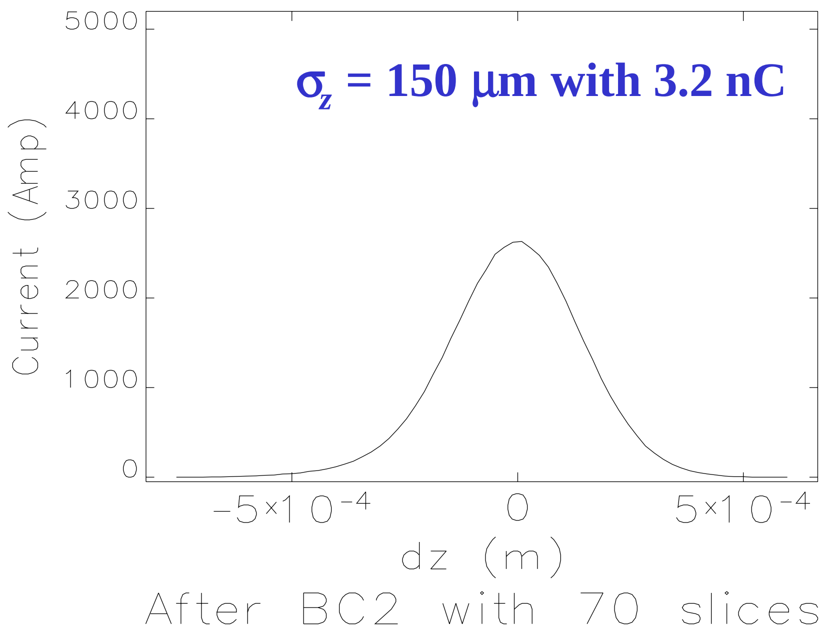
Since $(\sigma_{E,u} \times \sigma_z)_{SACC1} \sim (\sigma_{E,u} \times \sigma_z)_{BC2}$, the longitudinal emittance is well conserved during bunch compression. Small difference is due to the short-range wakefield in modules, CSR and ISR effects in BC.

Therefore there is no special problem in the longitudinal emittance conservation in the 4^{th} alternative ILC bunch compressor.

4^{th} Alternative ILC BC – Peak Current

01AUG05 Version

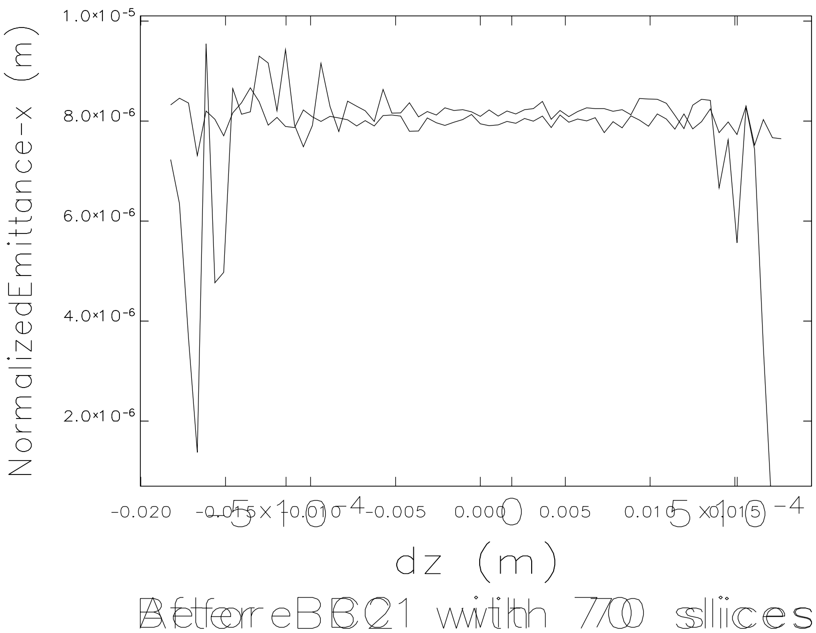




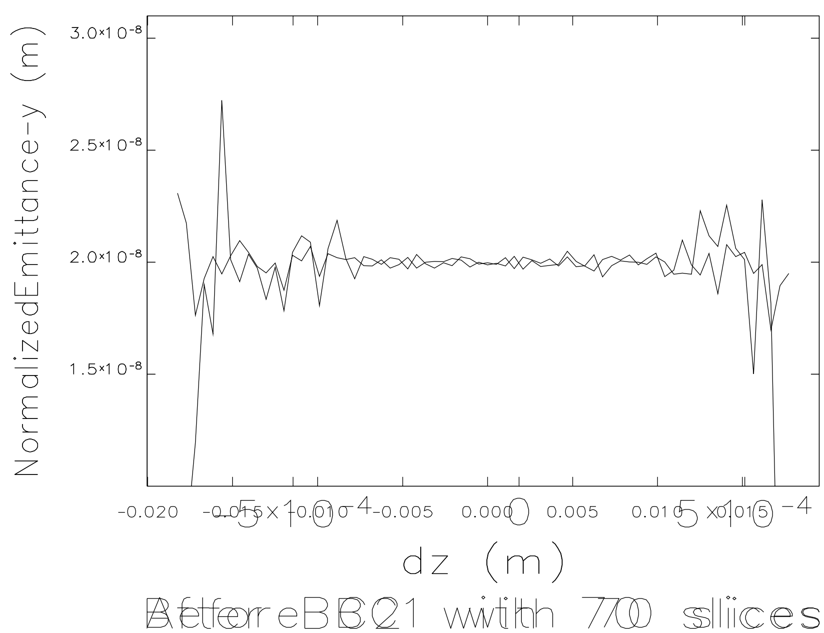
4^{th} Alternative ILC BC – Slice Emittances

01AUG05 Version

ε_{nx}= 8.00 μm



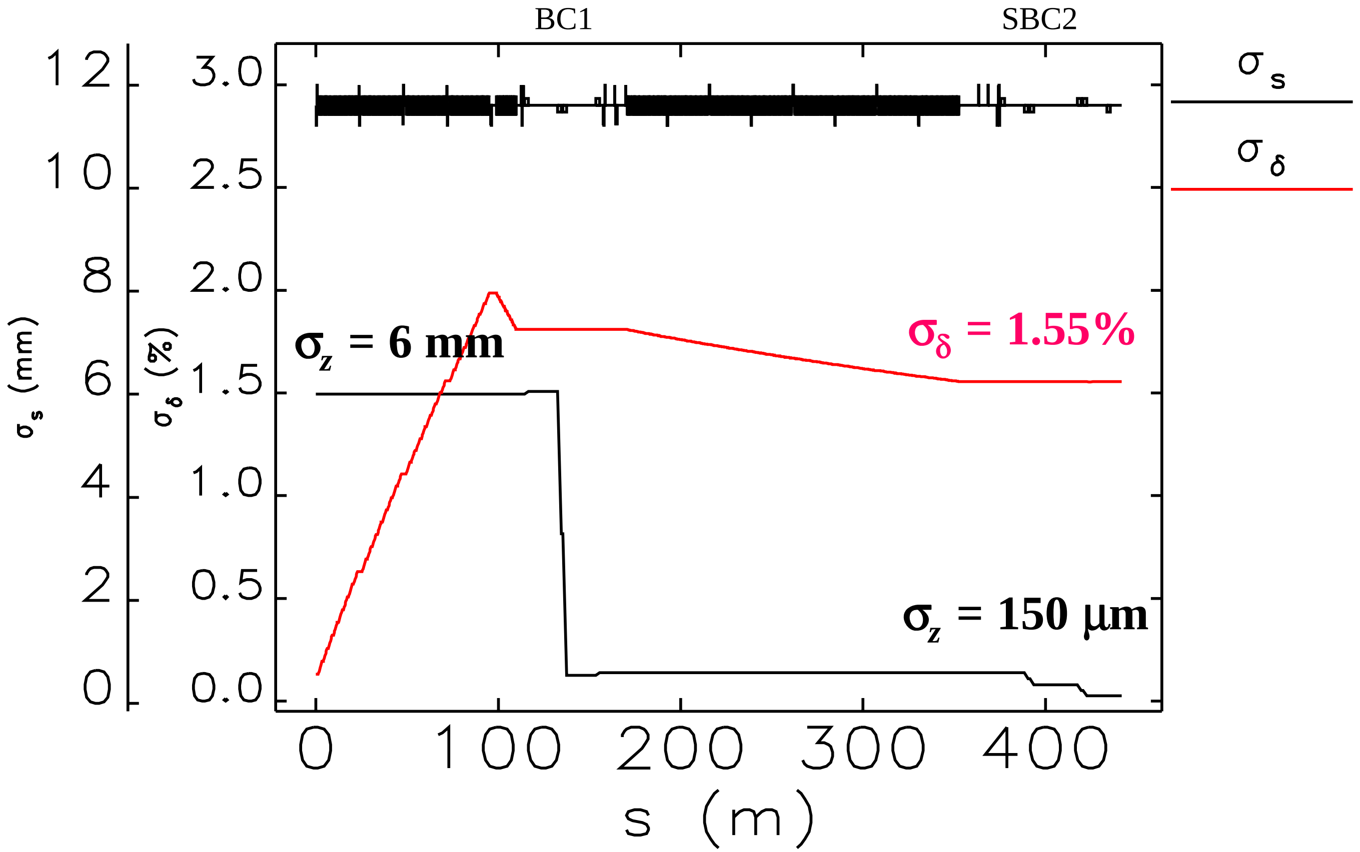
ε_{ny}= 0.020 μm



Emittance around head and tail is slightly increased by chromatic effects and CSR.

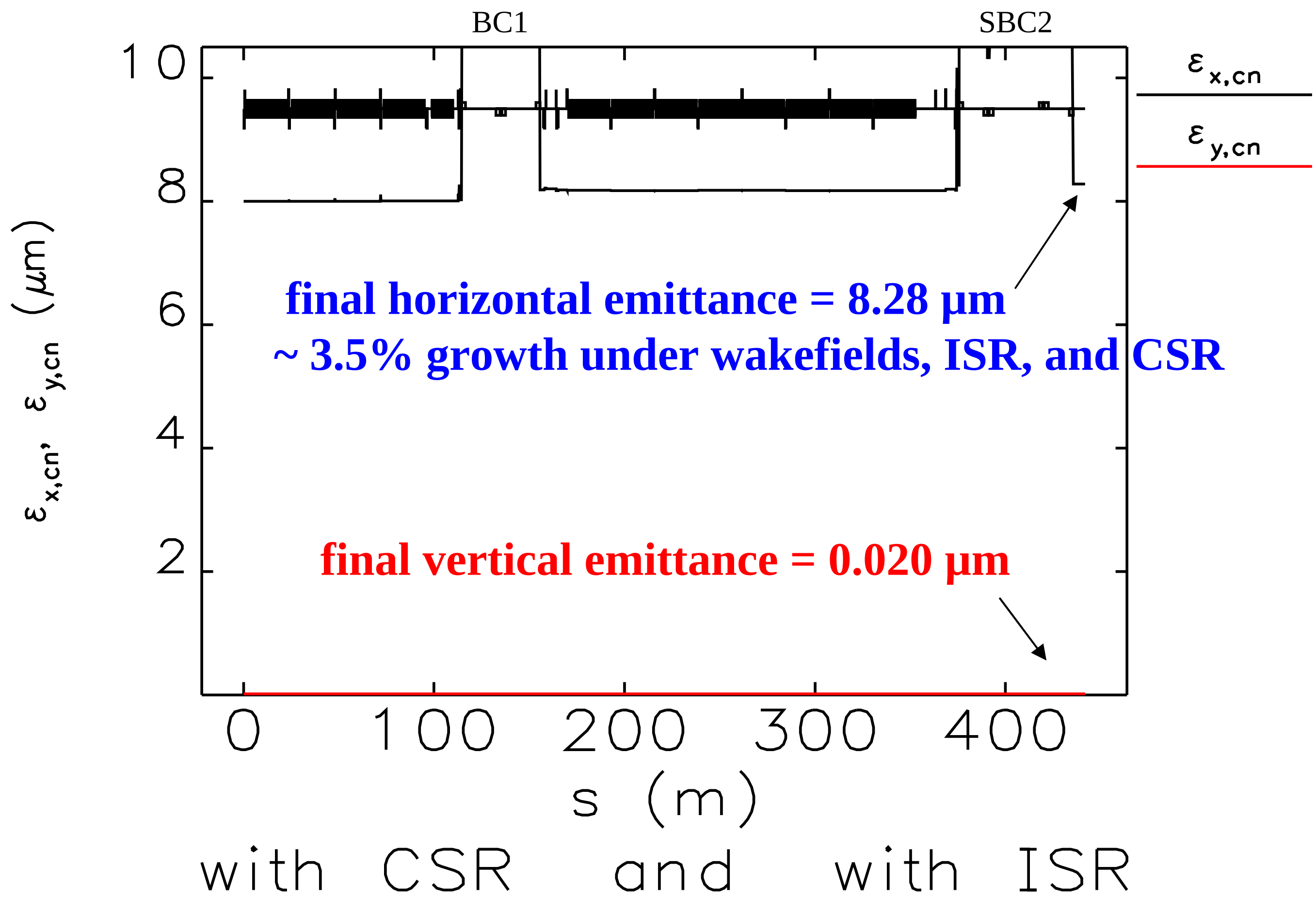
4th Alternative ILC BC – Energy Spread

01AUG05 Version



4^{th} Alternative ILC BC – Projected Emittance

01AUG05 Version



4th Alternative ILC BC – CSR & ISR Effects

01AUG05 Version

Action of CSR and ISR when we compress σ_z = 6.0 mm to 150 µm

- **Final horizontal emittance with consideration of CSR and ISR = 8.28 µm**
- **Final horizontal emittance with consideration of only ISR = 8.218 µm**
- **Final horizontal emittance without consideration of CSR and ISR = 8.04 µm**

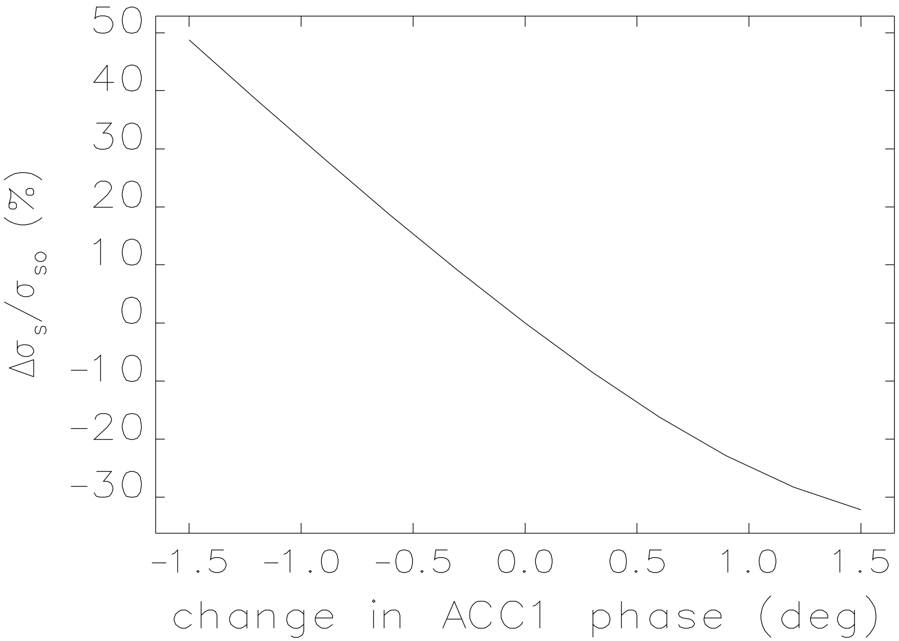
By optimizing BC layout, by choosing ACC1 module for linearization, and by choosing short 650 MHz modules around BCs, CSR effect becomes weak, but there is still small ISR effect.

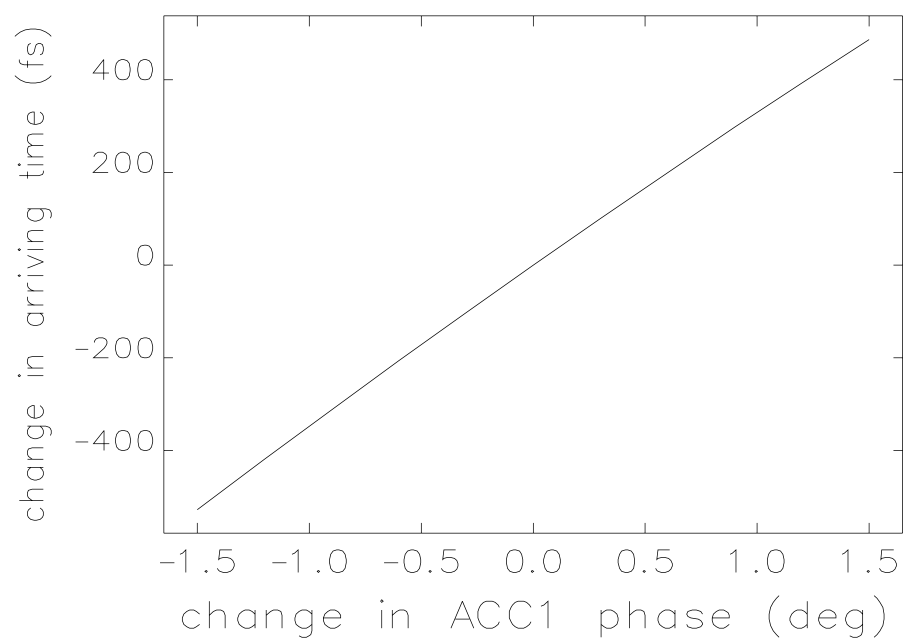
4th Alternative ILC BC – RF Jitter Sensitivity

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 !!!





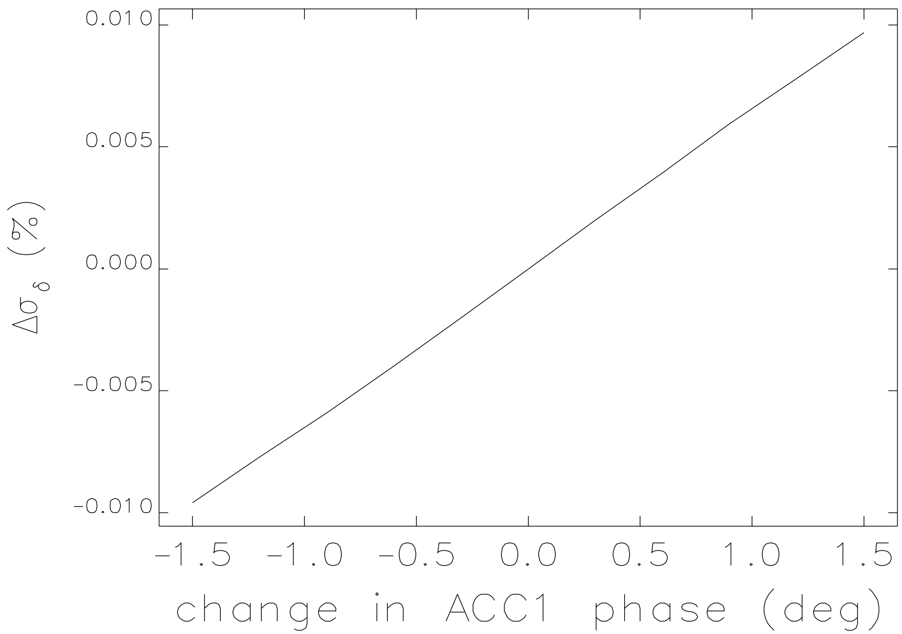
p2p jitter sensitivity = ±0.5 deg
rms jitter sensitivity = 0.17 deg (tightest)

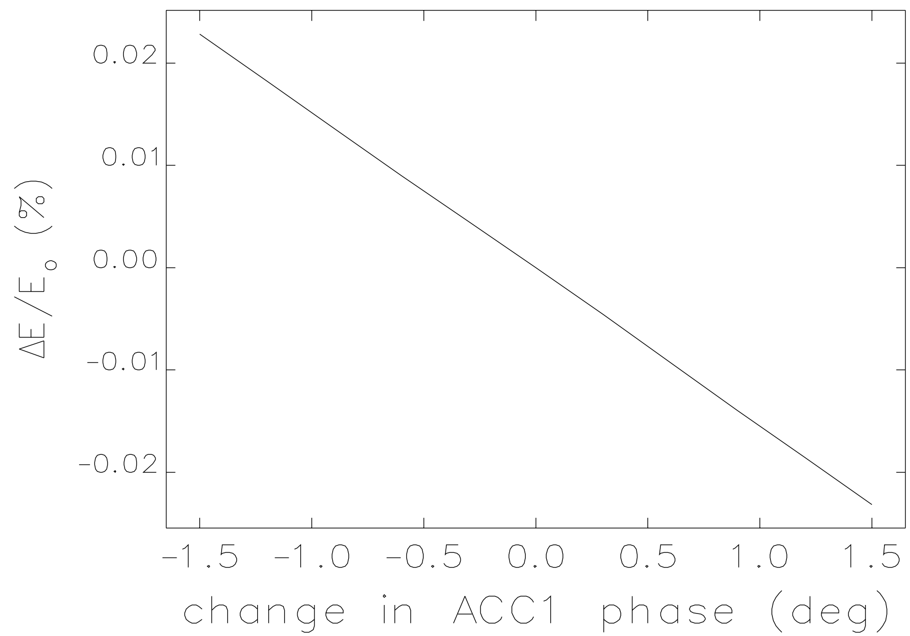
p2p jitter sensitivity = ±1.0 deg
rms jitter sensitivity = 0.33 deg

4^{th} Alternative ILC BC – RF Jitter Sensitivity

Threshold of Jitter Sensitivity (just chosen conditions)

- ±0.01% p2p change in relative energy spread
- ±0.02% p2p change in beam average energy





p2p jitter sensitivity = ±1.5 deg
rms jitter sensitivity = 0.5 deg

p2p jitter sensitivity = ±1.3 deg
rms jitter sensitivity = 0.43 deg

4th Alternative ILC BC – RF Jitter Tolerances

Linac Performance Based Tolerance - Y.Kim's EPAC2004 paper

For each Klystron	Sensitivity (p2p)	Tolerance (p2p)	Tolerance (rms)
dT(damping ring)	3.8 ps	3.8 ps	1.26 ps
dQ	6.0%	4.5%	1.5%
SACC1234 Phase	0.4 deg	0.4 deg	0.13 deg @ 650 MHz
SACC1234 dV/V	0.5%	0.5%	0.17% @ 650 MHz
ACC1 Phase	0.5 deg	0.5 deg	0.17 deg @1300 MHz
ACC1 dV/V	0.5%	0.5%	0.17% @1300 MHz
SACC5-13 Phase	1.0 deg	0.5 deg	0.17 deg @ 650 MHz
SACC5-13 dV/V	0.6%	0.5%	0.17% @ 650 MHz
BC1 dI/I	0.02%	0.02%	0.02%
BC2 dI/I	0.30%	0.02%	0.02%

Summary

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 nonleariy 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 σ_z = 9.0 mm (rms) to 100 μm or more shorter.

Summary & Acknowledgments

The 4th alternative bunch compressor can compress a bunch with σ_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.