Longitudinal Single Bunch Instability by Coherent Synchrotron Radiation

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Motivation

Short bunch length for a high luminosity

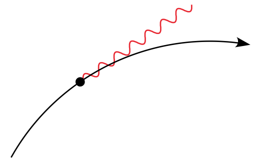
Topics

1. Introduction
2. CSR in KEKB and SuperKEKB
3. Longitudinal Instability in SuperKEKB LER
4. Threshold of Instability
5. Summary

Super B Factory Workshop in Hawaii, April 20-22, 2005

<u>1. Introduction</u>

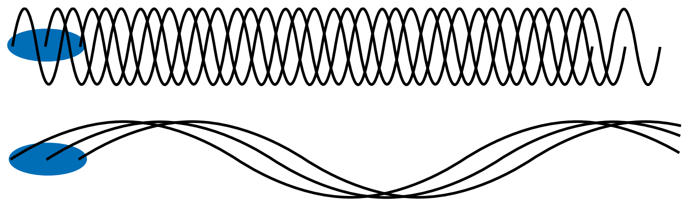
- Electrons moving in a bending magnet emit Synchrotron Radiation.



- In the spectrum of synchrotron radiation, the components such that $\lambda \gtrsim \sigma_z$ produce Coherent Synchrotron Radiation. (CSR)

Incoherent

Coherent



$\sigma_z = 3\text{mm} \Rightarrow \lambda \sim 3\text{mm}$

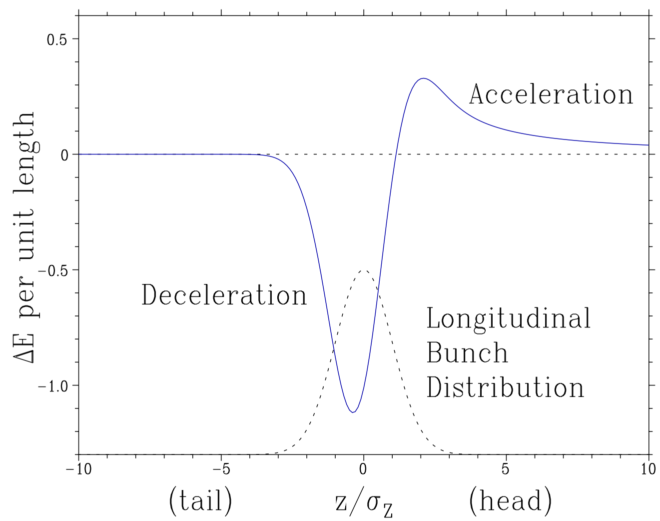
$\nu \sim 100\text{GHz}$

- Energy change of particles

Short range interaction

$\Rightarrow$ Energy spread

$\Rightarrow$ Single bunch instabilities (Longitudinal, Transverse)



- Shielded CSR by beam chamber

  If shielding is strong:

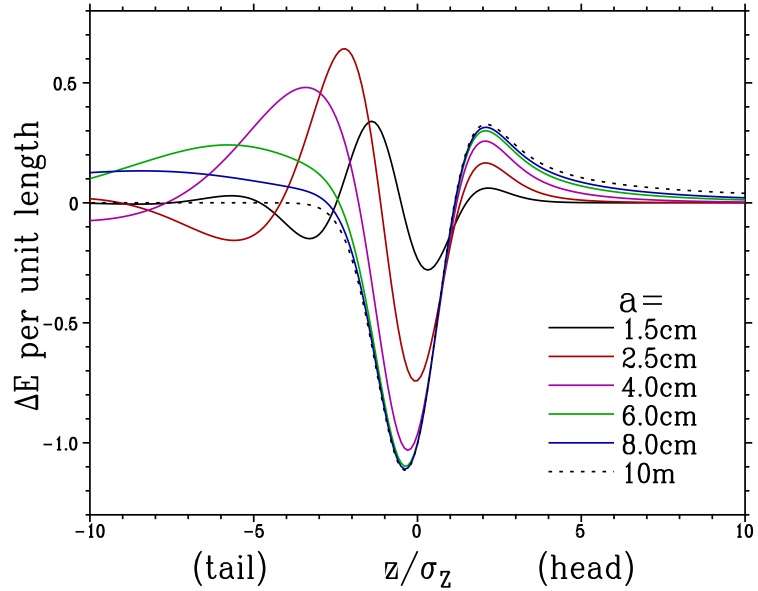
$$a \lesssim (\rho\sigma_z^2)^{1/3}$$

  ($a =$ chamber size)

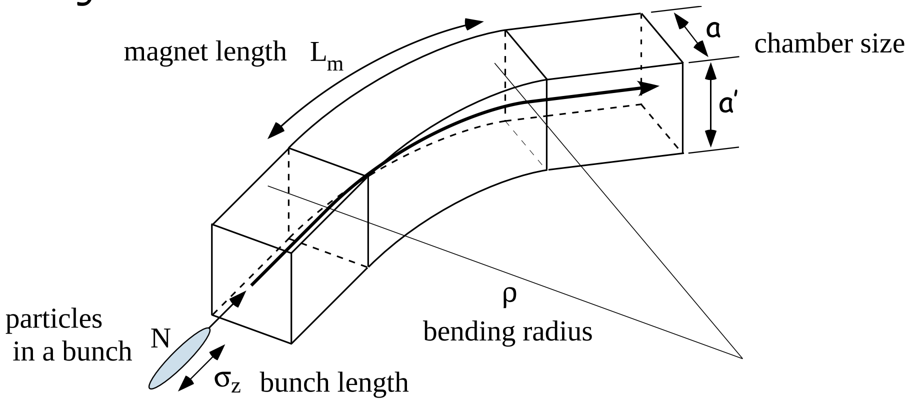
  CSR is suppressed with proper vacuum chambers.

  $\Updownarrow$

  CSR depends on the chamber size.



- At high energy, CSR is determined by
  - $*$ bunch distribution $\lambda(z)$ (σ_z)
  - $*$ bending radius ρ
  - $*$ size of beam pipe a
  - $*$ magnet length ℓ_m
  - $*$ bunch population N



- LER is affected with CSR in SuperKEKB. (Bends will be used again.)

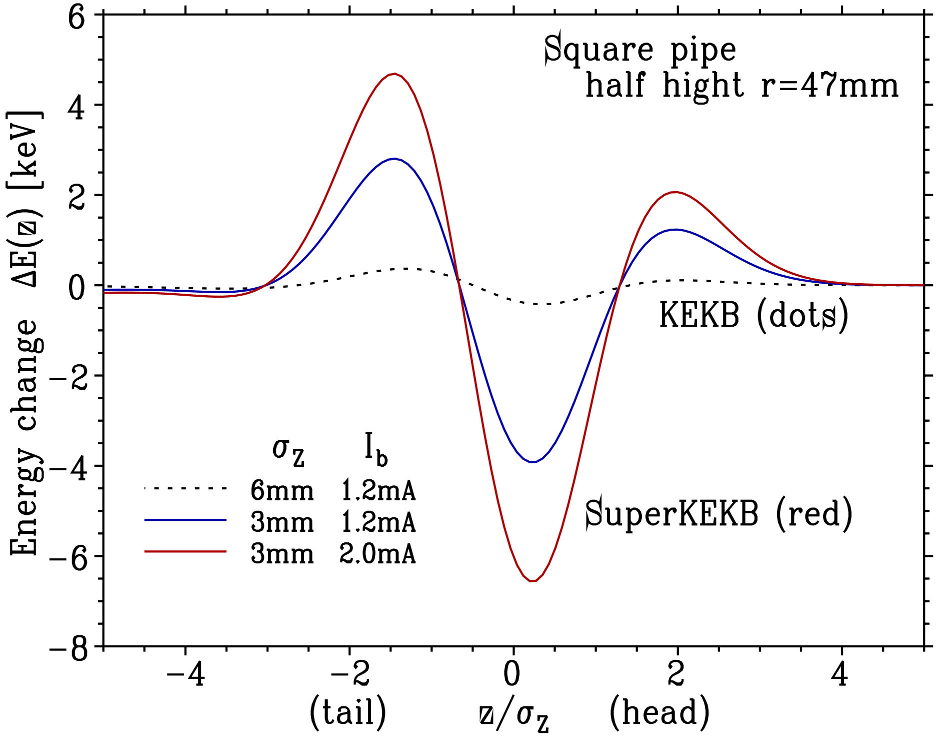
  LER : $\rho = 16.3$m small bending radius $\Rightarrow$ Intense CSR

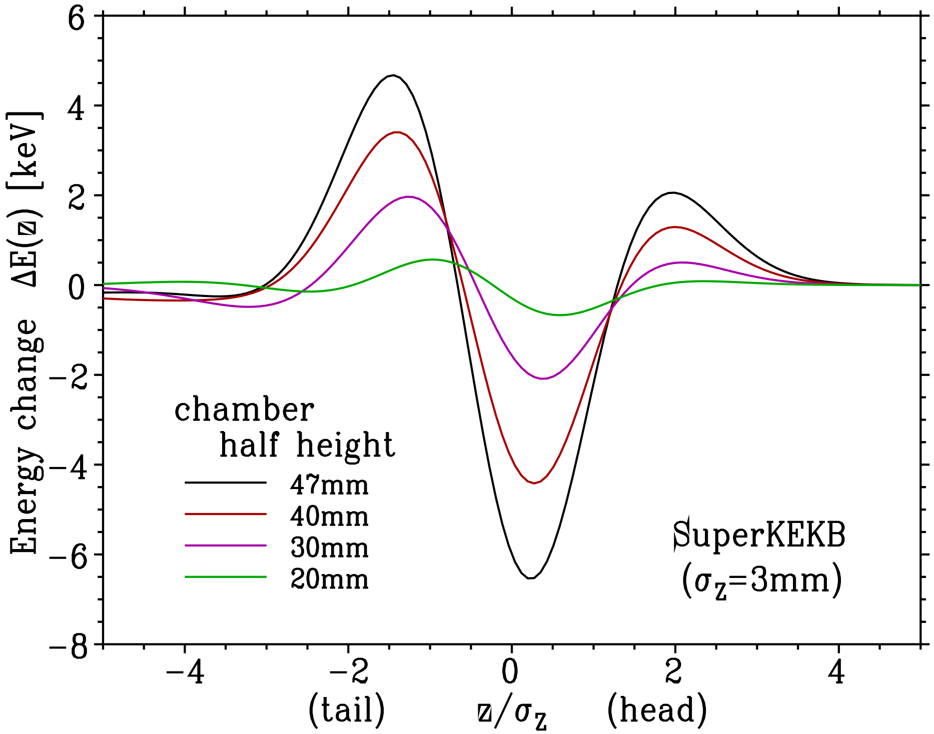
  HER : $\rho = 104.5$m CSR is moderate.

2. CSR in KEKB and SuperKEKB

	KEKB		SuperKEKB
Bunch length :	$\sigma_z = 6$mm	$\Rightarrow$	3mm
Bunch current :	$I_b = 1.2$mA	$\Rightarrow$	2mA ($\approx$ 20nC)

Energy change due to CSR in a bending magnet



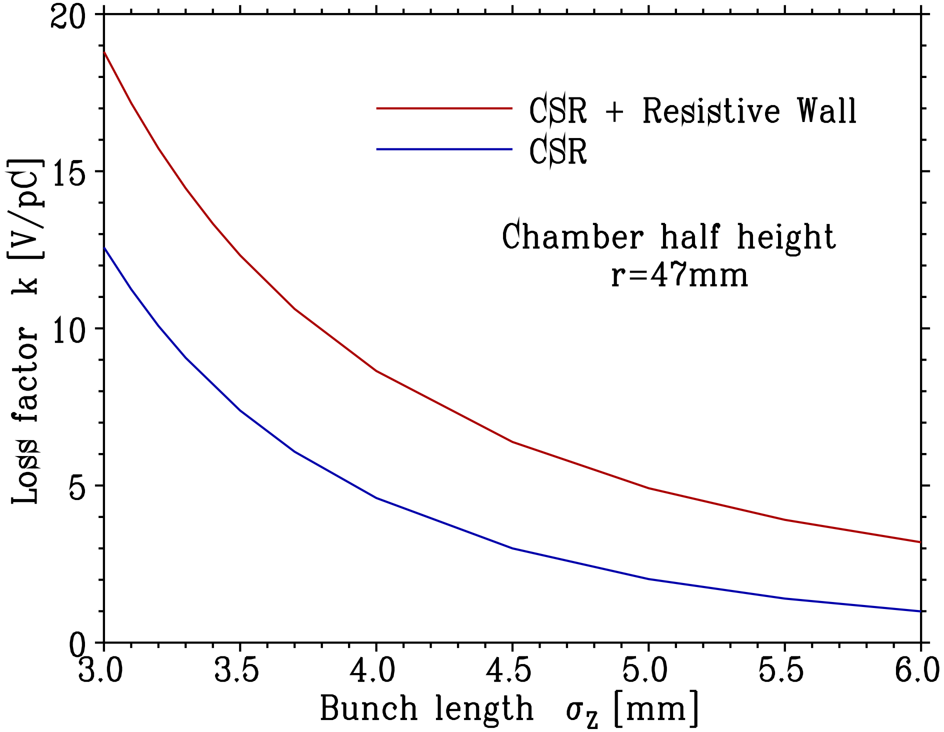


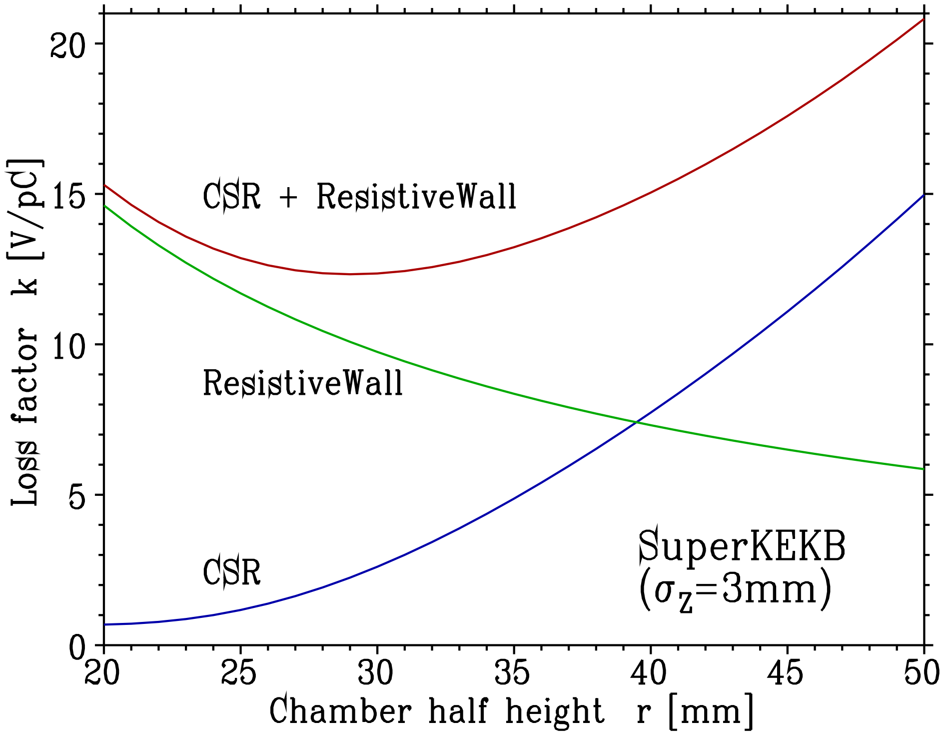
KEKB $\Rightarrow$ SuperKEKB

14 times larger ΔE

CSR can be suppressed by using chambers of small cross section.

Loss factor due to CSR and Resistive Wall wakefield





$\sigma_z = 3\text{mm}$	$\sigma_z = 6\text{mm}$
CSR	CSR
$k = 12.6\,\text{V/pC}$	$k = 1.0\,\text{V/pC}$
CSR + RW	CSR + RW
$k = 18.8\,\text{V/pC}$	$k = 3.2\,\text{V/pC}$

Loss factor due to CSR+RW is always larger than 12.3 V/pC.

The minimum value is determined by the dipole magnets (ρ, ℓ_m).

3. Longitudinal Instability in SuperKEKB LER

- Field calculation of CSR = Paraxial Approximation in a beam pipe
  T.Agoh, K.Yokoya, Phys.Rev.ST-AB, 7, 054403 (2004)
- Equations of Longitudinal Motion (1 Million macro-particles)

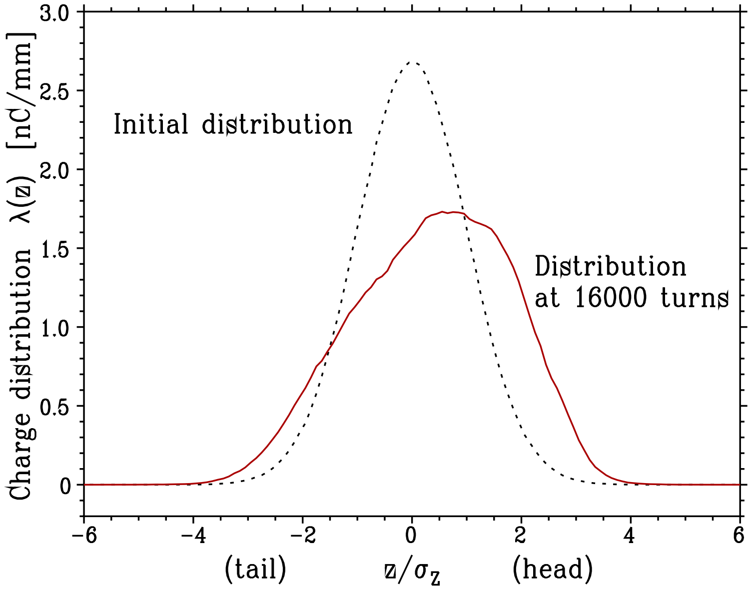
$$\begin{cases} z' = -\eta\delta \\ \delta' = \dfrac{(2\pi\nu_s)^2}{\eta C^2} z - \dfrac{2U_0}{E_0}\delta + Q + \mathrm{CSR} + \mathrm{RW} \end{cases}$$

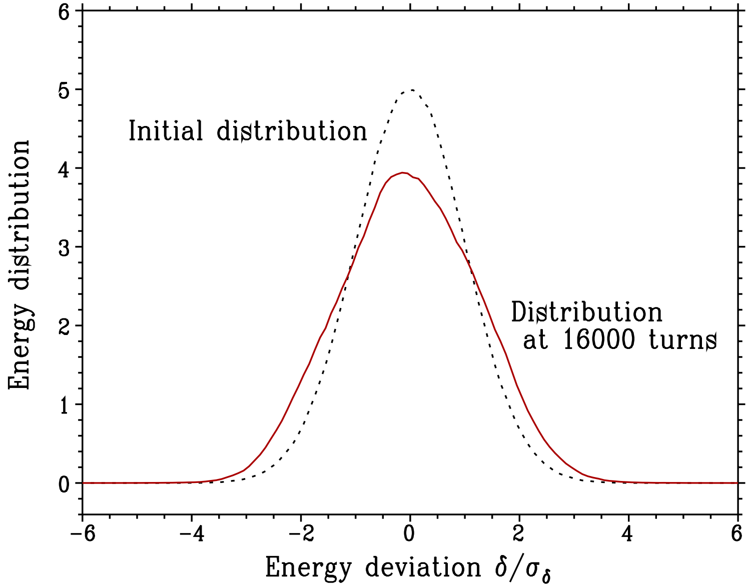
- 134 bends in the arc section are considered for CSR, but CSR in wiggler is ignored.
  (It should be considered.)
- Wiggler is taken into account in computing the radiation damping U_0.
- Copper pipe of square cross section
  (Actual one is round.)
- RW = Resistive Wall wakefield in the straight section
- Initial condition = Equilibrium without CSR, RW

- parameters
  - $E_0 = 3.5\,\mathrm{GeV}$
  - $C = 3016.26\,\mathrm{m}$
  - $\sigma_z = 3\,\mathrm{mm}$
  - $\sigma_\delta = 7.1\times10^{-4}$
  - $V_{\mathrm{rf}} = 15\,\mathrm{MV}$
  - $\omega_{\mathrm{rf}} = 508.887\,\mathrm{Hz}$
  - $h = 5120$
  - $\alpha = 2.7\times10^{-4}$
  - $U_0 = 1.23\,\mathrm{MeV/turn}$
  - $\nu_s = 0.031$

- Bunch distribution
- Energy spread

($r = 47$mm)





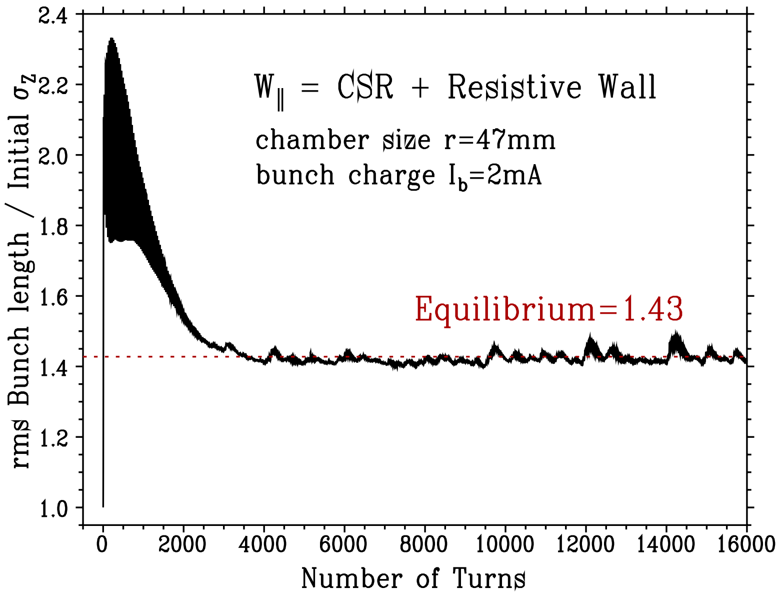
Initial

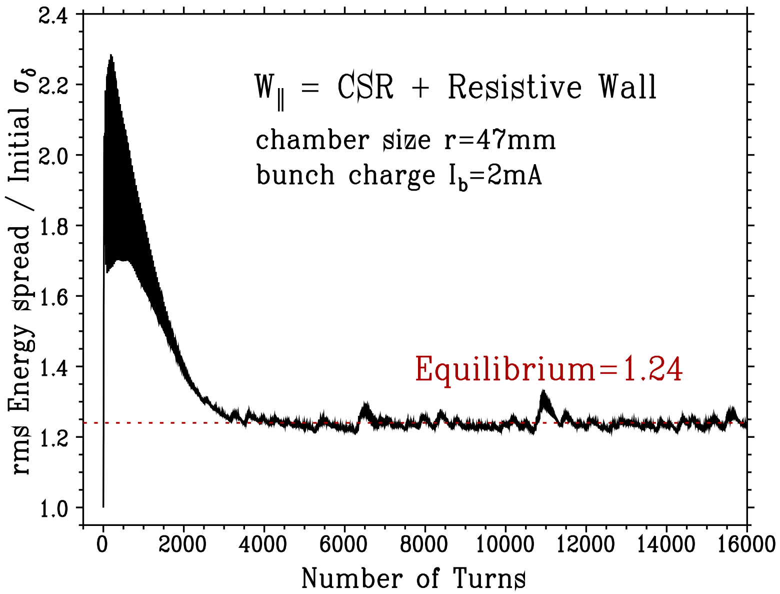
Bunch length

$\sigma_z = 3.0$mm

Energy spread

$\sigma_\delta = 7.1 \times 10^{-4}$





Equilibrium

Bunch length

$\sigma_z \sim 4.3$mm

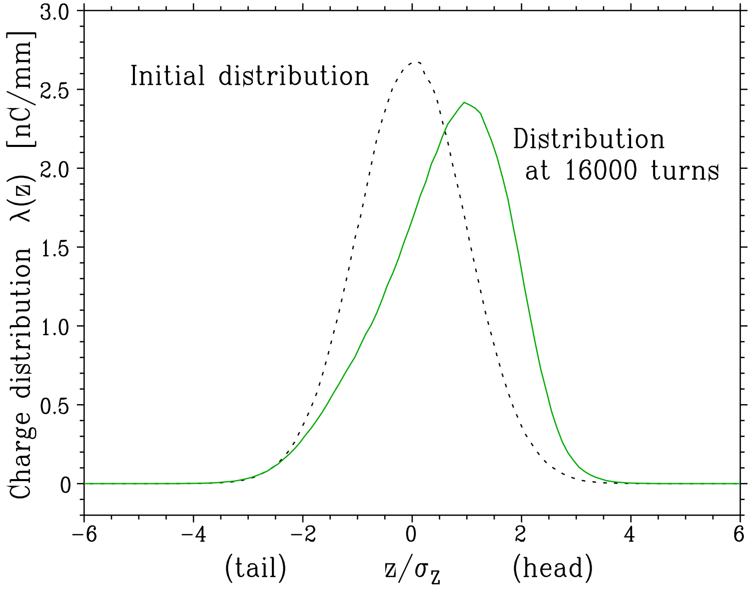
Energy spread

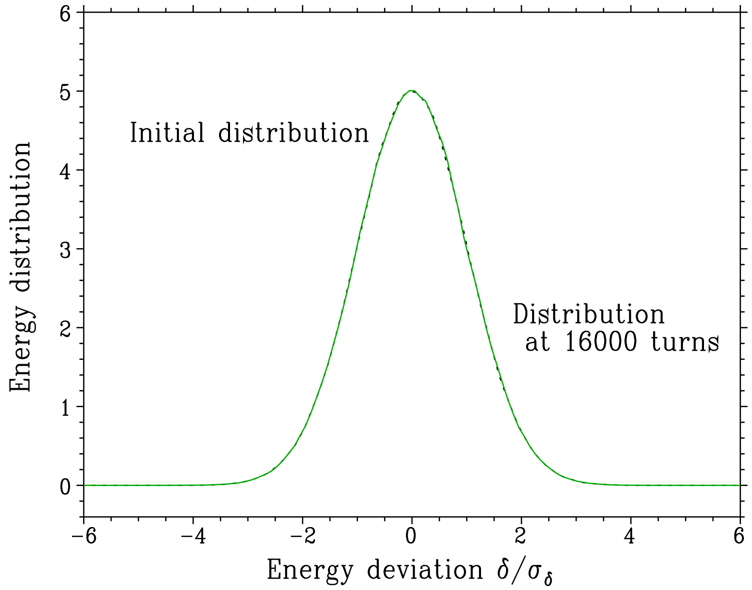
$\sigma_\delta \sim 8.8 \times 10^{-4}$

UNSTABLE

- Bunch distribution
- Energy spread

($r = 25$mm)





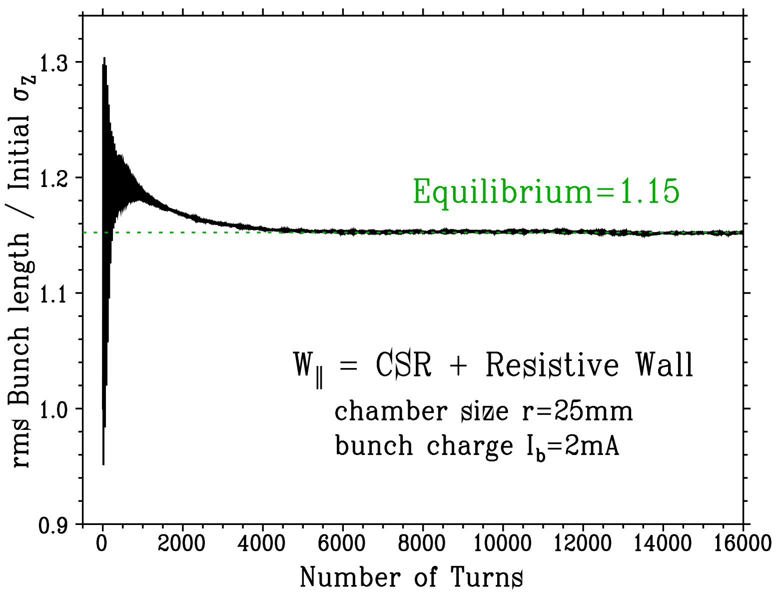
Initial

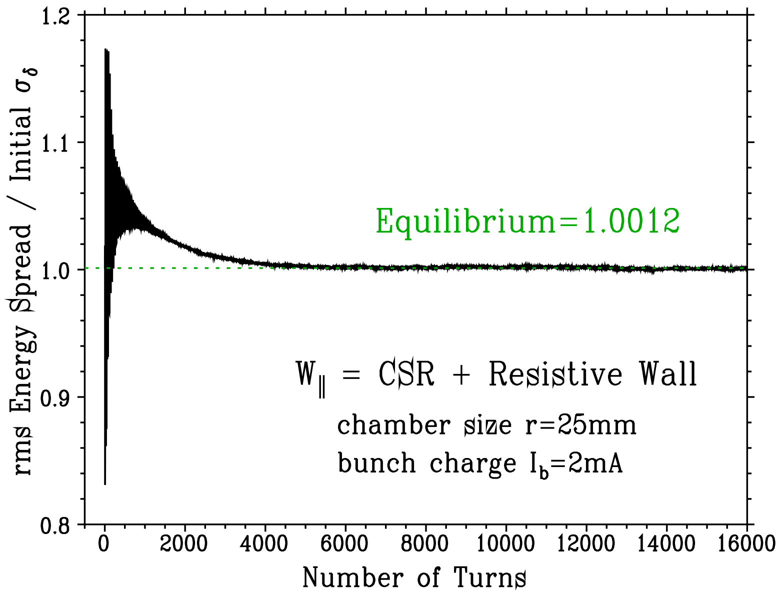
Bunch length

$\sigma_z = 3.0$mm

Energy spread

$\sigma_\delta = 7.1 \times 10^{-4}$





Equilibrium

Bunch length

$\sigma_z \sim 3.5$mm

Energy spread

$\sigma_\delta \sim 7.1 \times 10^{-4}$

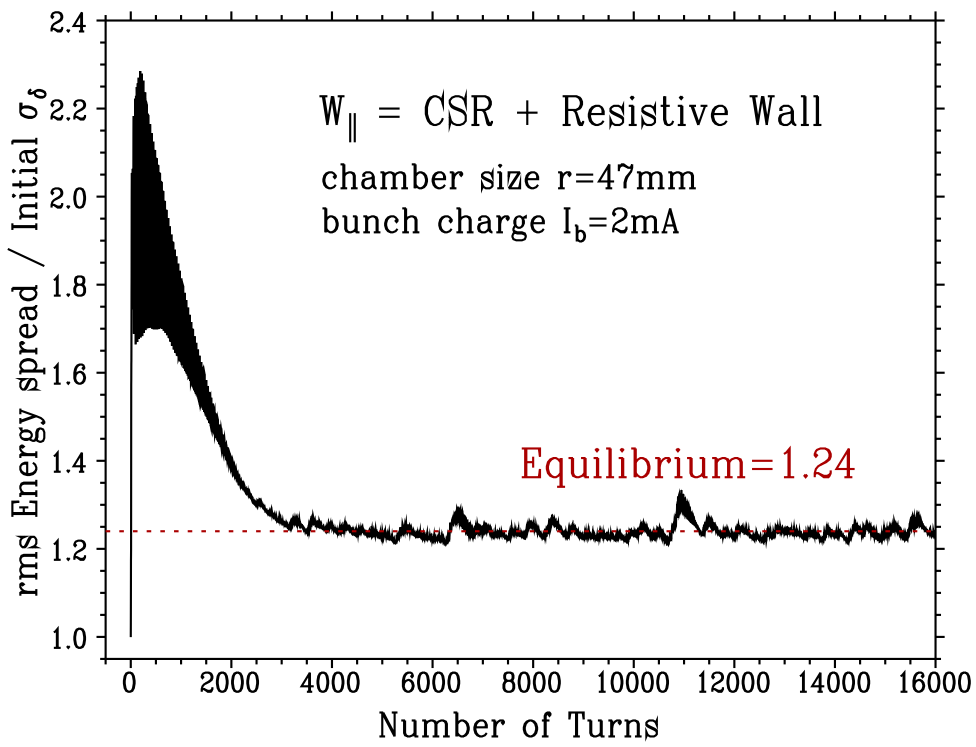
STABLE

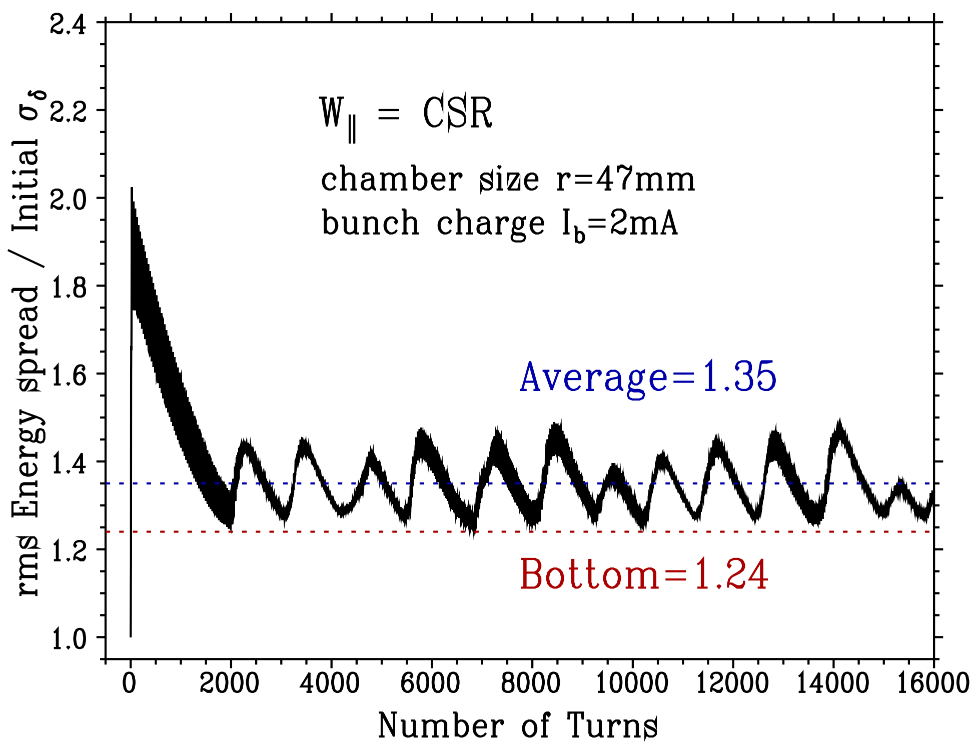
Sawtooth Instability

Resistive wall wakefield reduces the sawtooth amplitude.

But above a certain threshold, the energy spread is increased by CSR, the bunch is not stationary but unstable.

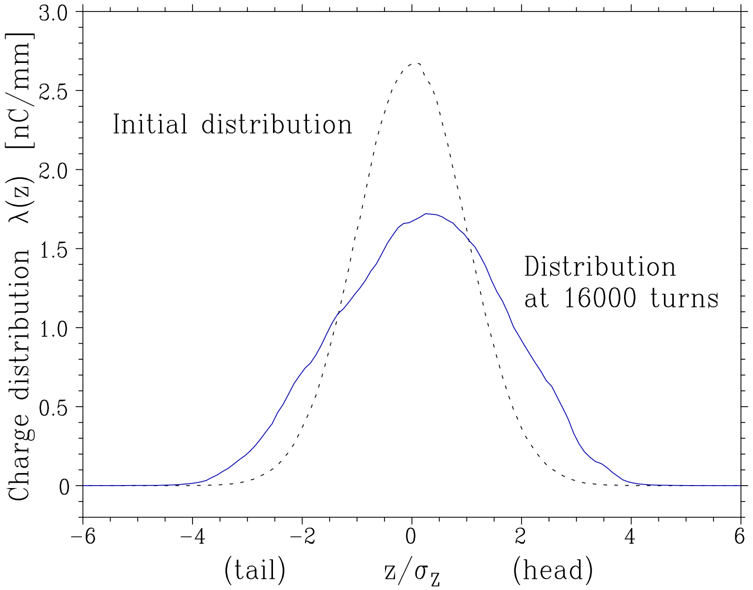
Oscillation: Radiation damping $\Leftrightarrow$ CSR burst

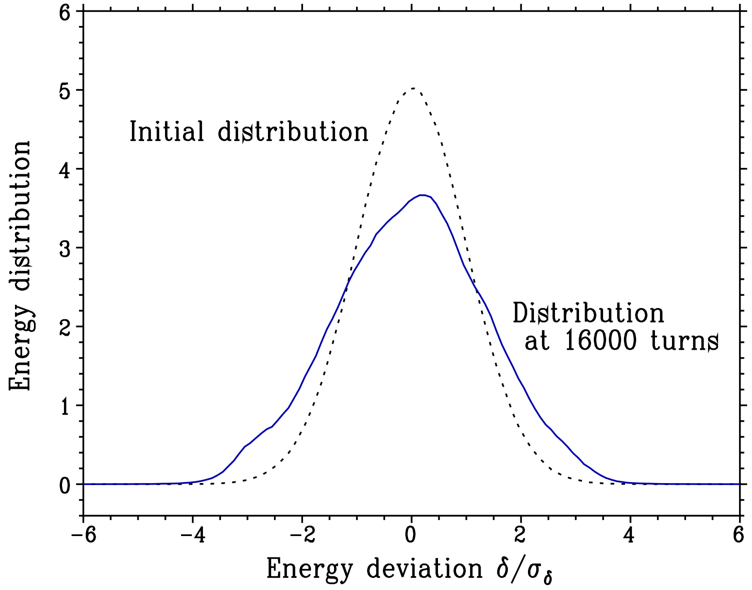




Equilibrium/ Initial $\sigma_\delta = 1.24$ Equilibrium/ Initial $\sigma_\delta = 1.35$

• Bunch distribution • Energy spread ($r = 47$mm)





$W_{||} = $ CSR

Initial

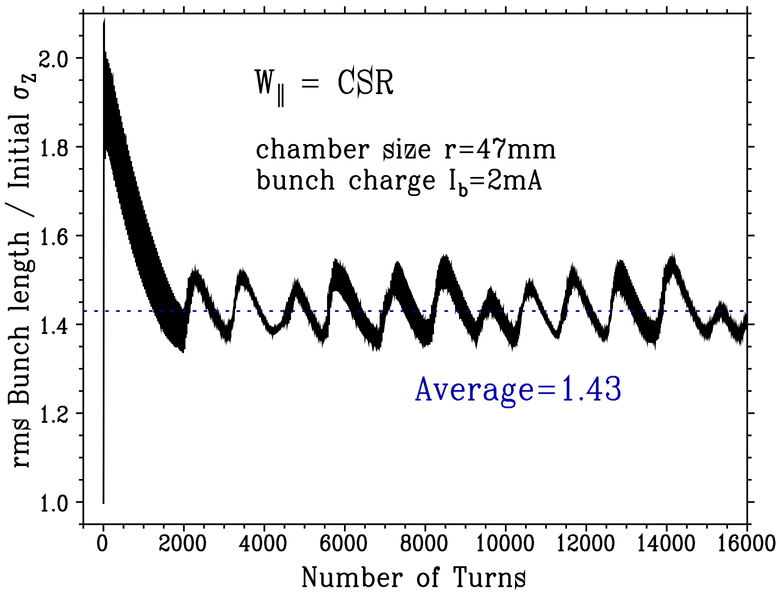
Bunch length

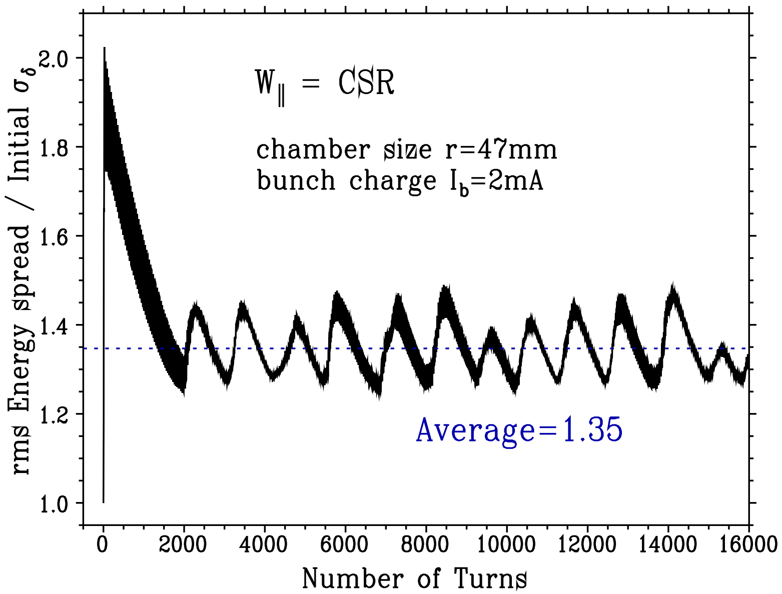
$\sigma_z = 3.0$mm

Initial

Energy spread

$\sigma_\delta = 7.1 \times 10^{-4}$





Average

Bunch length

$\sigma_z \sim 4.3$mm

Average

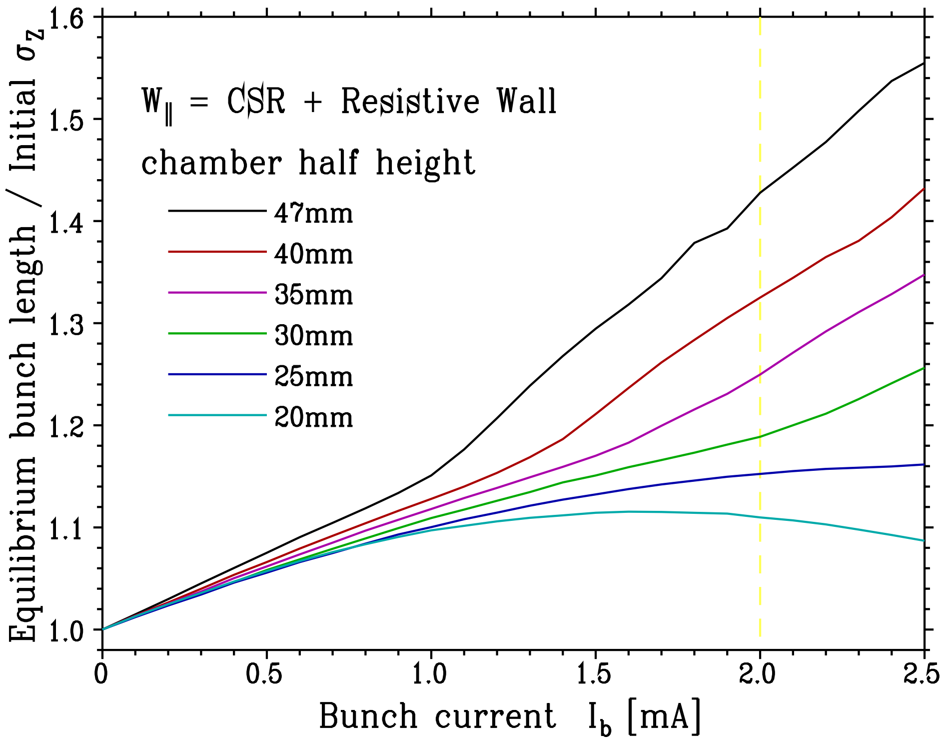
Energy spread

$\sigma_\delta \sim 9.6 \times 10^{-4}$

4. Threshold of longitudinal instability

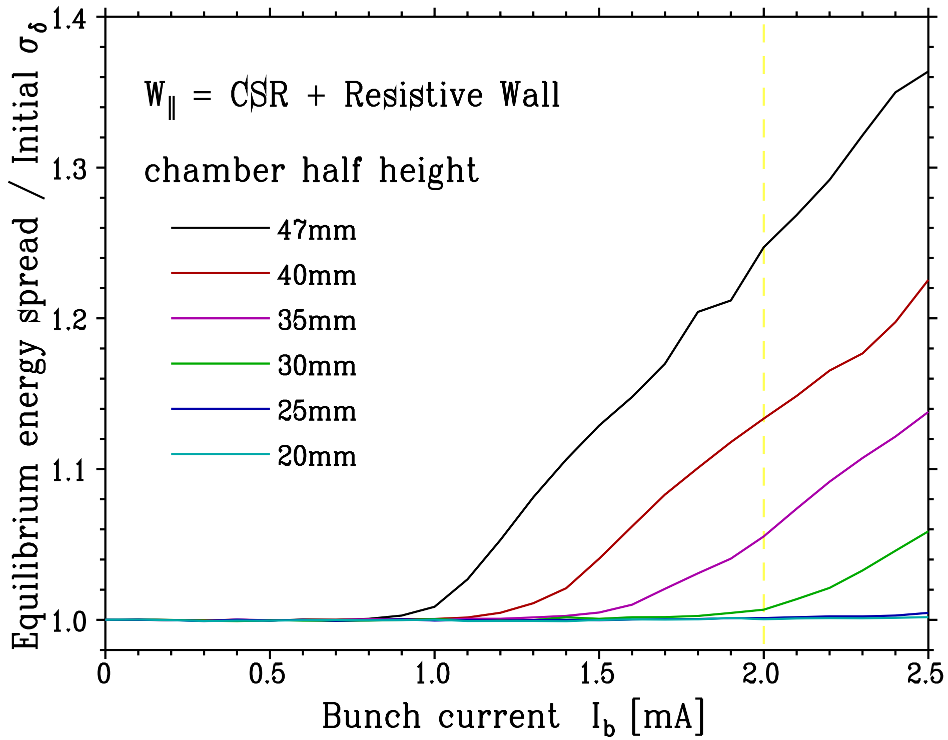
Bunch length vs Bunch current

Initial $\sigma_z = 3\text{mm}$



Energy spread vs Bunch current

Initial $\sigma_\delta = 7.1 \times 10^{-4}$

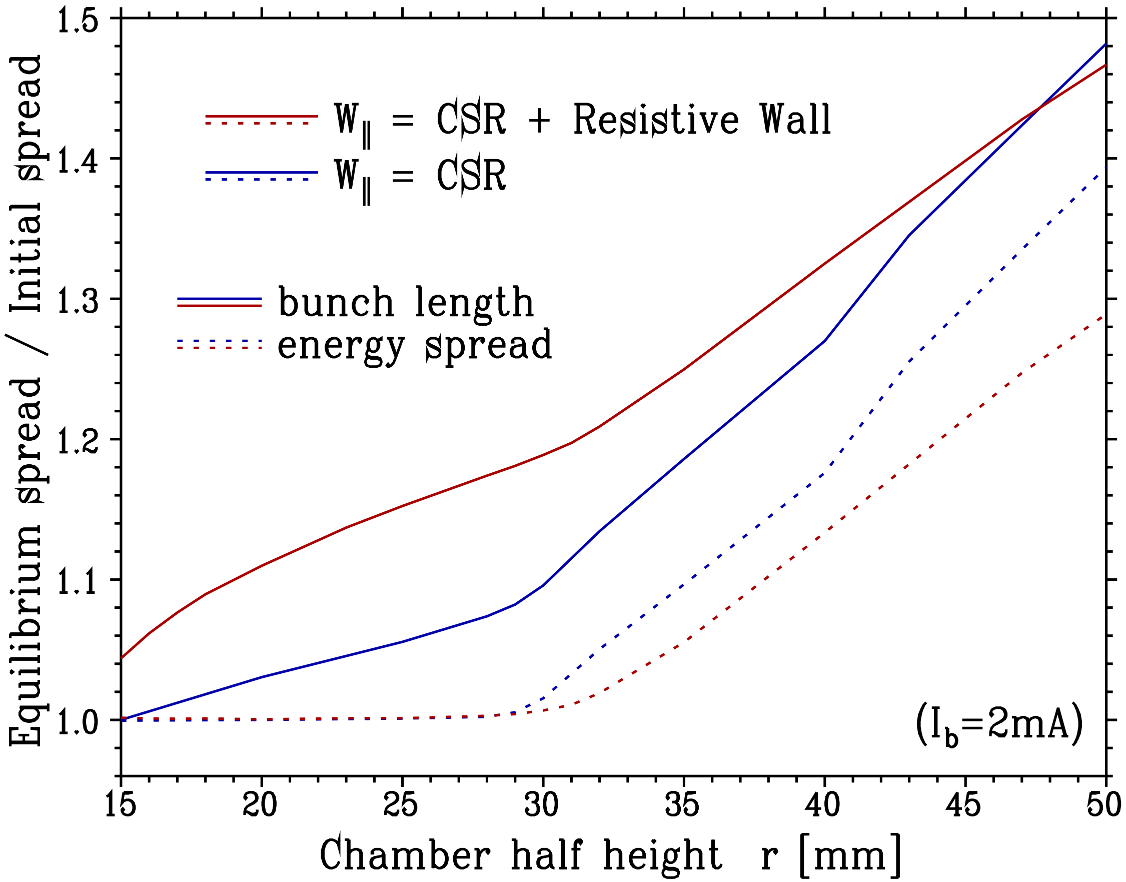


The length increases fast, and the energy spread starts increasing above a threshold which is determined by the chamber size.

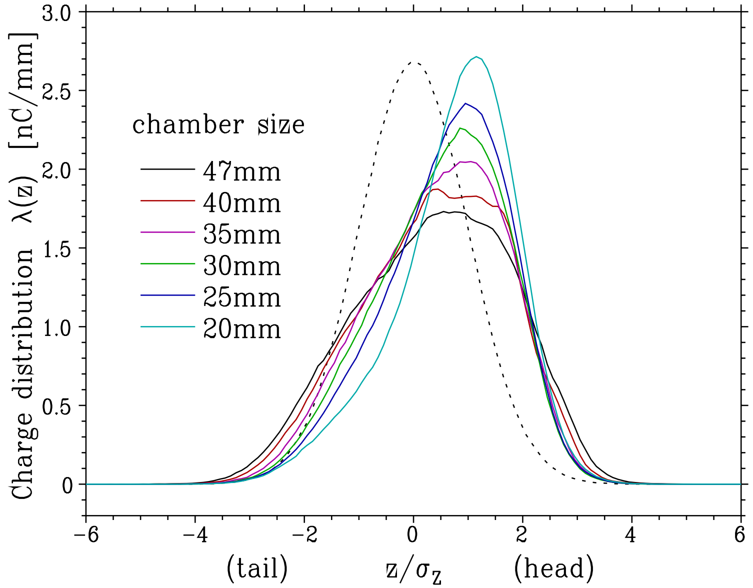
The limit current is 0.8mA ($Ne \sim$ 8nC) in the chamber of $r = 47$mm.

Threshold for chamber size

- rms Bunch length and Energy spread



- Longitudinal bunch distribution

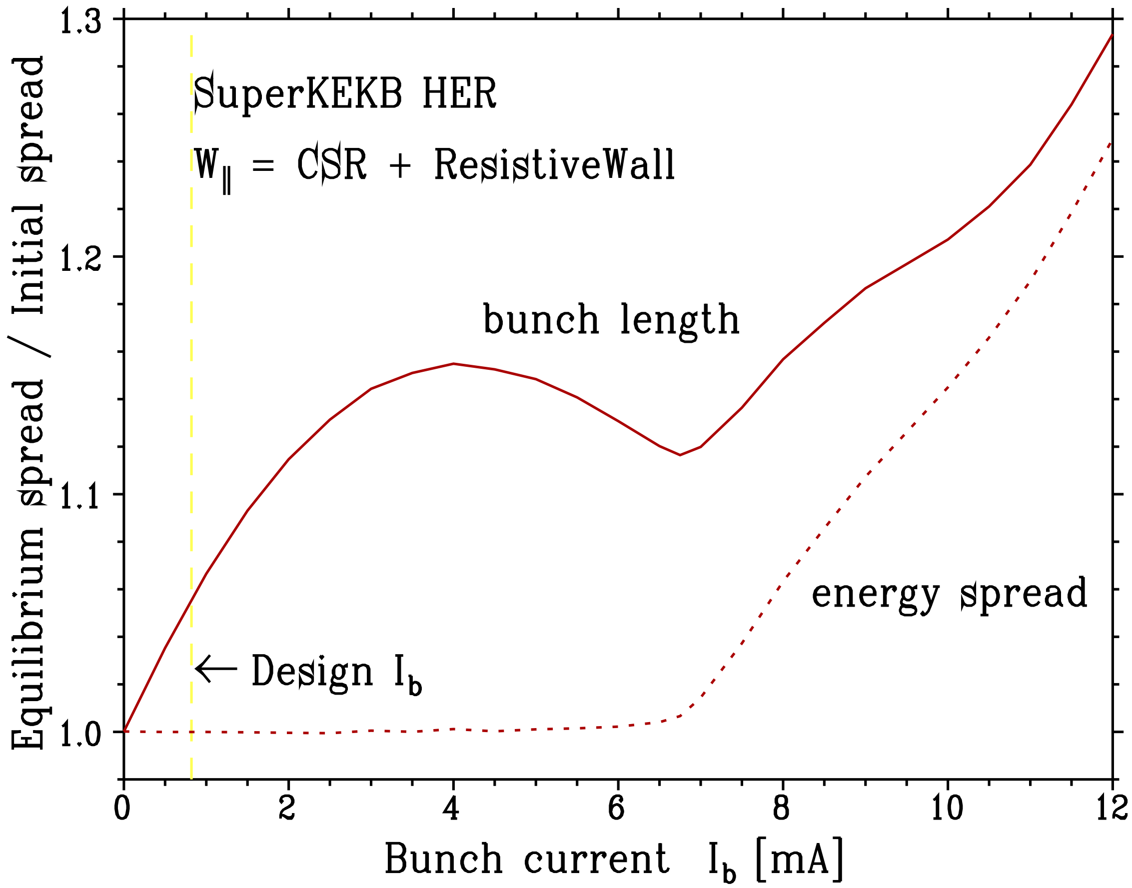


The bunch leans forward because of the energy loss due to the resistive wall.

Threshold for the chamber half height is $r_{\text{th}} \sim$ 30mm, when the bunch current is $I_b =$ 2mA ($Ne \sim$ 20 nC).

SuperKEKB HER

Bunch length, Energy spread vs Bunch current



- Initial Bunch length
  $\sigma_z = 3\text{mm}$
- Bend
  $\rho = 104.5\text{m}$
  $\ell_\text{m} = 5.8\text{m}$
- Vacuum chamber (rectangular)
  $w \times h = 100\times 50\text{mm}$ (full width, height)
- Others
  $\alpha = 1.8 \times 10^{-4}$
  $V_\text{rf} = 20\text{MV}$
  $U_0 = 3.48\text{MeV/turn}$
  $\nu_s = 0.019$

The limit bunch current is 6.8 mA ($\sim$ 68 nC).

(Design $I_b = 0.82\,\text{mA}$: No problem)

Bunch lengthening = 5.6% at $I_b = 0.82\text{mA}$

5. Summary

- SuperKEKB HER has no problem with CSR.
  Design $I_b = 0.82\,\mathrm{mA} \ll$ Limit $6.8\,\mathrm{mA}$ ($Ne \sim 68\,\mathrm{nC}$)
  Only 5.6% bunch lengthening at design I_b
- LER is affected with CSR because of (1) short bunch length, (2) high bunch charge, (3) small bending radius.
  The bunch of 3mm length and 2mA current is unstable due to CSR in the present chamber $r = 47$mm.
- Above a bunch current, the longitudinal instability occurs.
  The threshold is $I_b = 0.8$mA ($\sim$8nC) in the present chamber.
- Small vacuum chambers suppress CSR.
  The threshold half height is $r = 30$mm for $I_b = 2$mA ($\sim$20nC).
- Resistive wall wakefield moderates the sawtooth instability.
  However, the instability threshold does not change so much.
- Loss factor by CSR + RW is $k = 18.8\,\mathrm{V/pC}$ for $r = 47$mm.
  It cannot be smaller than $12.3\,\mathrm{V/pC}$ for any vacuum chamber.
- Small vacuum components may have large impedances.
  Bunch length in the SuperKEKB LER is limited by CSR.