Design of Damping Ring

KEKB Review, Kikuchi, M. 2004.2.17

- Introduction
- Beam Parameters
- Lattice design
- DR parameters
- From DR to SuperKEKB
- Summary

Introduction

Damping Ring is necessary :

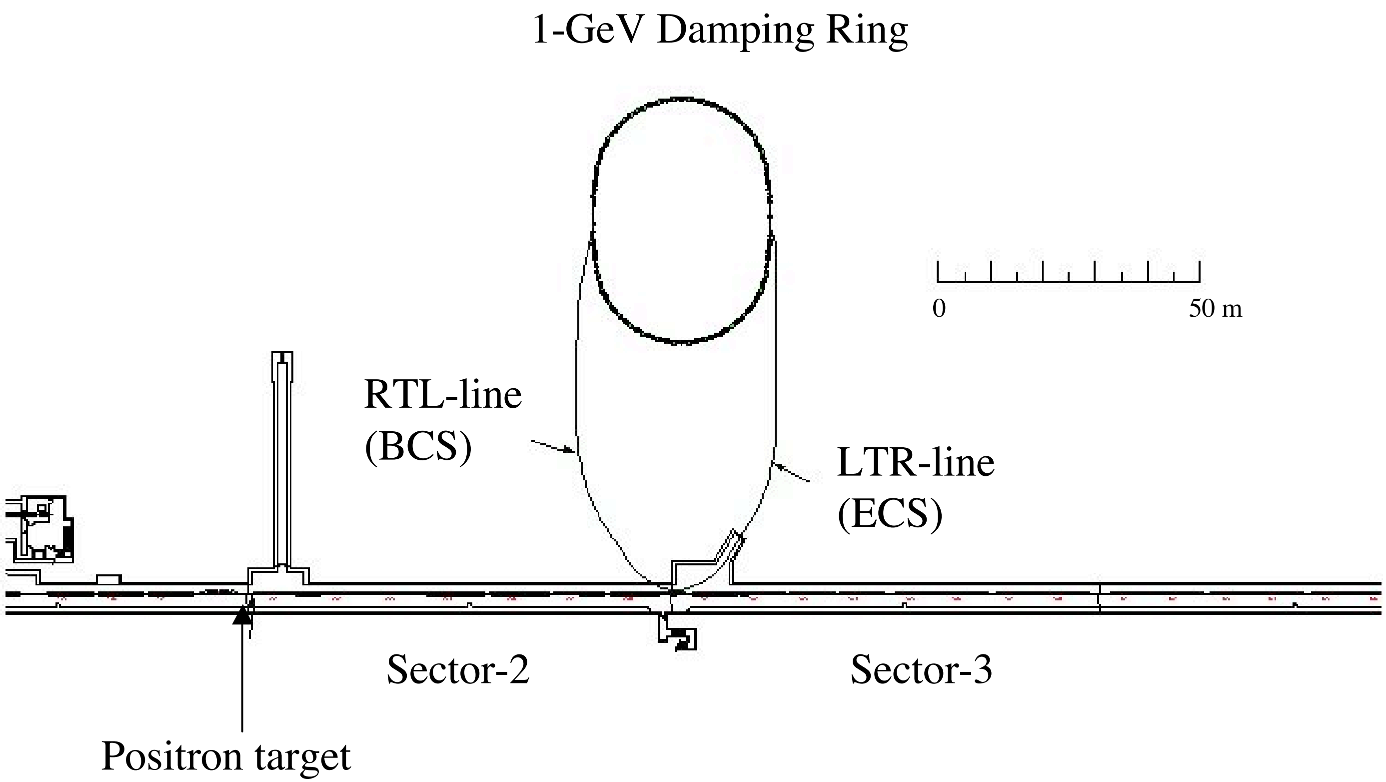
- IR: In SuperKEKB βy^* is squeezed to 3 mm
  - IR design needs lower emittance for the beam (e+)
- C-band linac: lower emittance is needed (e+)
- Beam background: Injected beam-charge is doubled.
  - needed damped beam for smaller energy-tail and emittance-tail. (e+ and e-)

■ Positron DR is placed before C-band linac: from the layout of linac the energy should be ~ 1 GeV.

■ Electron DR is preferable from the detector background, though its priority being lower.

✧ I will talk only on the positron DR.

Layout of Beam Lines



Beam parameters -1-

DR emittance:

IR Design assumed the emittance of injected beam to be $\gamma\varepsilon = 3.13 \times 10^{-4}$ (= emittance of KEKB electron-beam *i.e.* no electron DR)

==> DR emittance < 160 nm (for 1 GeV)

However, considering the possibility of electron DR in far future, the emittance of positron DR should be the same as that of possible electron DR:

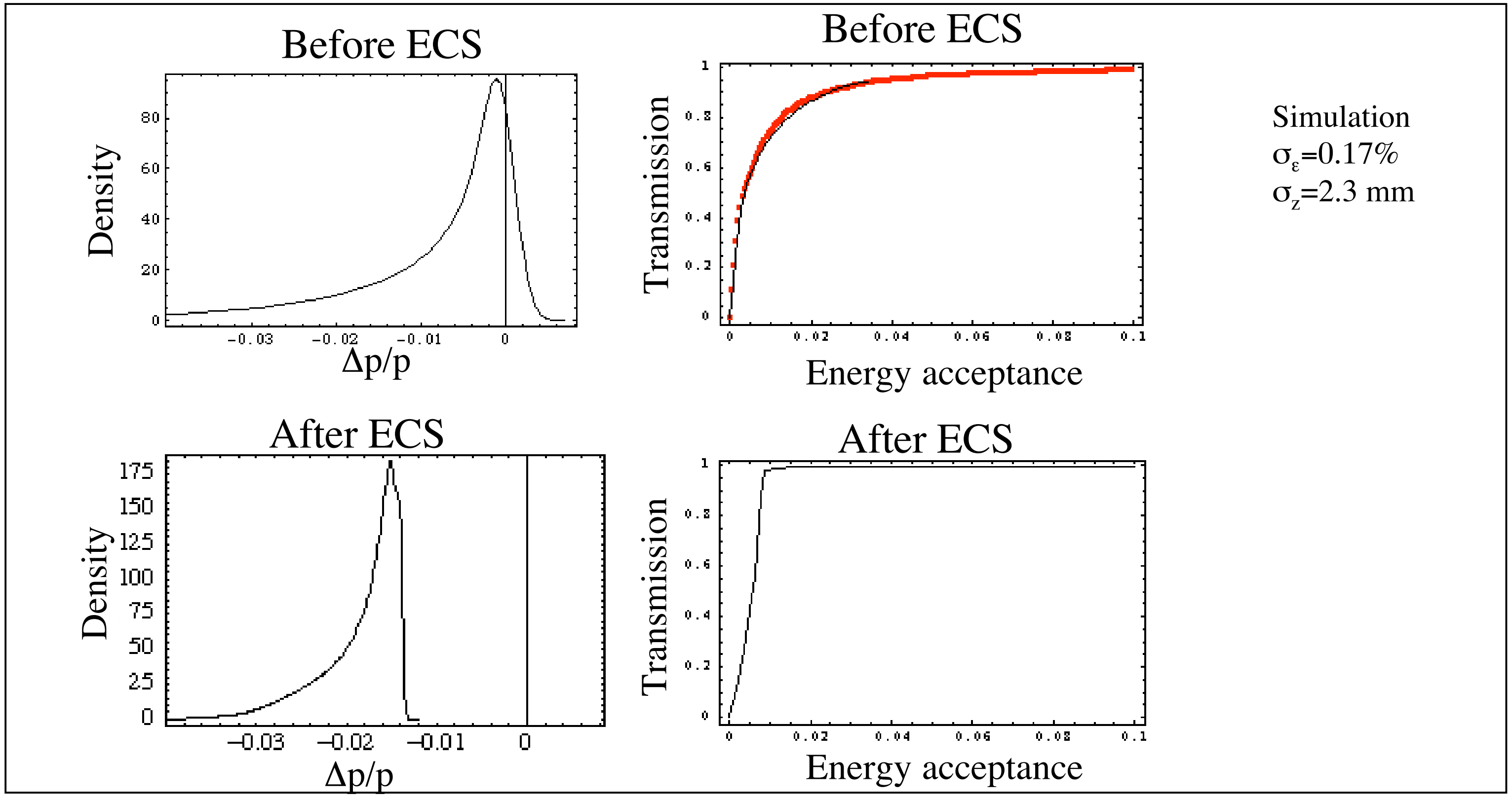
Design emittance of positron DR should be smallest value, achievable in the lattice design.

Beam parameters -2-

ECS before injection to DR

Employing ECS, almost 100% of particles are included within the energy band-width of ±1.5%

(Note momentum acceptance of transport line: ±5%)



Beam parameters -3-

Parameters of injected beam

- Assume two-bunch mode for injection

	before ECS	after ECS	Unit
Energy	1.0		GeV
Repetion frequency	50		Hz
Emittance	1.23E-06		m
Energy spread *)	1.30	0.406	%
Bunch length *)	2.30	6.05	mm
Number of bunches/pulse	2		
Bunch spacing	98		ns
Bunch charge	1.2		nC
ECS cavity voltage	30.5		MV
ECS cavity frequency	2.856		GHz
R56 component	-0.486		m

*) defined as extension that contains 95.5% divided by 4.

Lattice design -1-

Requirements:

- Large acceptance (transverse and longitudinal)
- Fast damping

FODO has advantage that

- Fast damping: bends embedded in every drift space
- Large dynamic aperture (transverse and longitudinal)

but has drawback

- Tendency to higher momentum-compaction

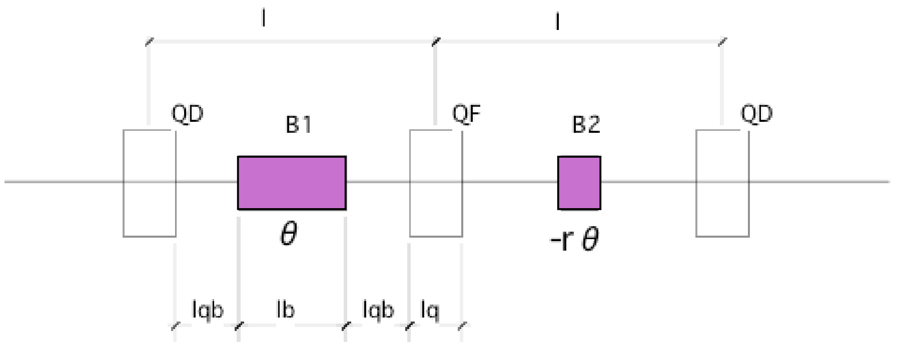
We propose a variant of the FODO:

FODO with alternating bend

that preserves good nature of FODO and have a very low positive/negative momentum-compaction factor.

Lattice design -2-

Thin lens model:



FODO w/ alternating bend. It reduces to ordinal FODO when r = -1.

$\theta = \dfrac{2\pi}{n(1-r)}$: bend angle of main bend

n : number of cells

ρ : bending radius

r : ratio of reverse bend to main bend

μ : phase advance per cell

E_0 : beam energy in GeV

$l_1 = 2l_q + 4l_{qb} = 2l - 2l_b$

Assumptions:

- equal phase advance $\mu_x = \mu_y = \mu$
- same bending radius for B1 and B2

Lattice design -3-

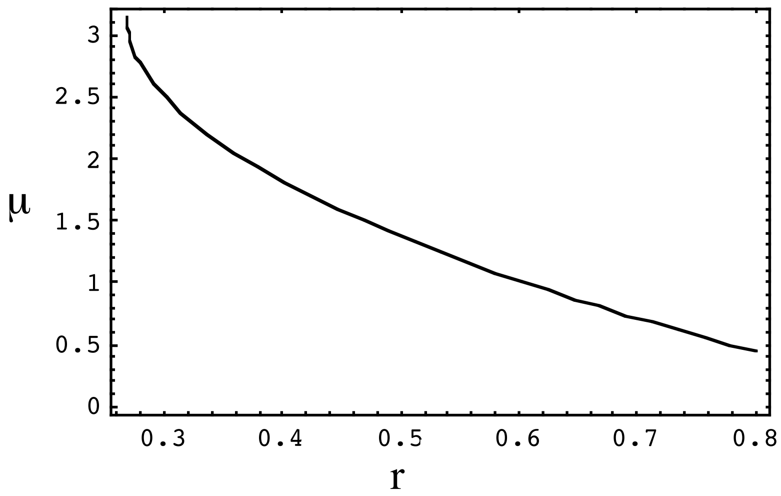
Momentum compaction factor

$$\alpha_p = G(r,\mu)\theta^2$$

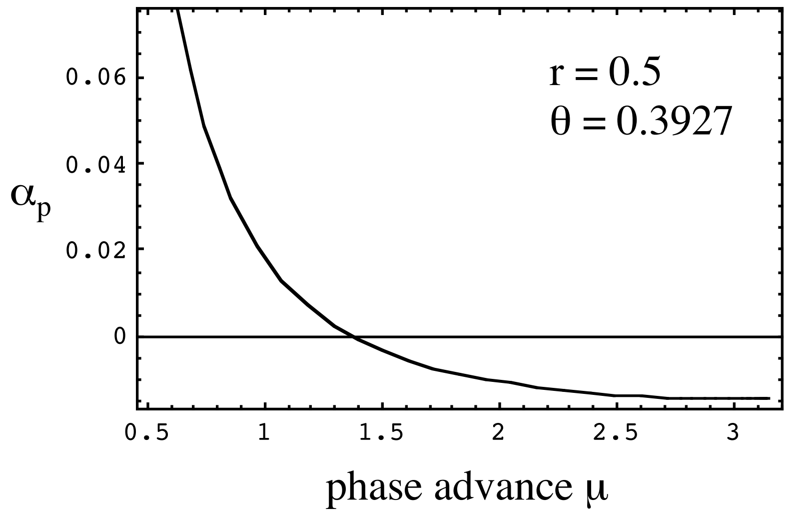
$$G(r,\mu) = \frac{3 - 8r + 3r^2 + (1 + r^2)\cos\mu}{16\sin^2\mu/2}$$

When r > $2 - \sqrt{3} = 0.268$

there exist a combination of r and μ that satisfies $\alpha_p = 0$



For fixed r, by adjusting the phase advance, low positive or negative α_p can be achieved.



Lattice design -4-

Emittance

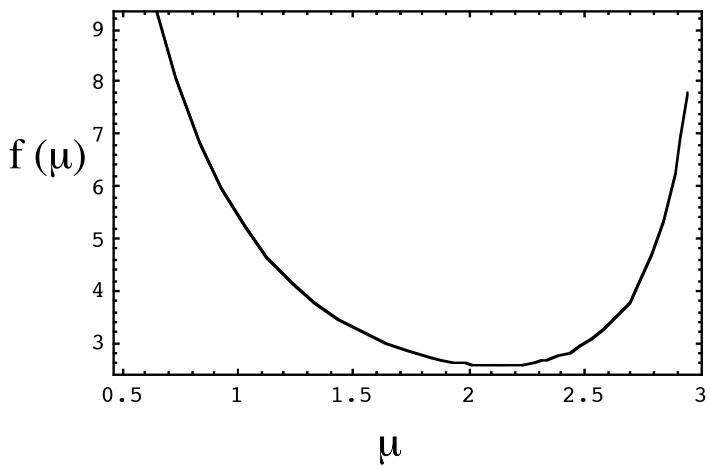
$$\boxed{\varepsilon_0 = C_q \frac{\ell\theta^2}{8\rho}\gamma^2 F(r,\mu)}$$

$$F(r,\mu) = \frac{1}{\sin^2\mu/2\sin\mu}\left\{3-4r+3r^2+(1-4r+r^2)\cos\mu - r\frac{1-|r|}{1+|r|}\left(3\sin\frac{\mu}{2}-\sin\frac{3\mu}{2}\right)\right\}$$

with $C_q = \frac{55}{32\sqrt{3}}\frac{\hbar}{mc}$. Since we select μ and r such that $\alpha_p \approx 0$, ε_0 can be rewritten as

$$\boxed{\varepsilon_0 = C_q \frac{\ell\theta^2}{8\rho}\gamma^2 f(\mu)}$$

- f (μ) has its minimum at μ = 2.1 (r = 0.35)



Lattice design -5-

■ Optimization of parameters

- Damping time

$$\tau = \frac{2E_0}{J_x U_0}\frac{C}{c} = \frac{2}{cC_\tau}\frac{\rho}{J_x \gamma^3}\left\{2\pi\rho + \frac{1-r}{1+|r|}(n\ell_1 + 2\ell_2)\right\}$$

$$\left[\begin{array}{lll} C_\tau = \frac{4\pi}{3} r_e & \text{n : number of cells} & \ell_1 \text{ : (cell length) - (length of bends)} \\ J_x = 1 & & 2\ell_2 \text{ : length of straight sections} \end{array}\right]$$

For fixed ℓ_1 and ℓ_2, ρ is written as a function of τ, r, and n:

$$\rho = \rho(\tau, r, n) = \rho(\tau, \mu, n)$$

if $\alpha_p = 0$

- Emittance

$$\left.\begin{array}{l} \theta = \dfrac{2\pi}{(1-r)n} \\ 2\ell = \ell_1 + (1+|r|)\rho\theta \end{array}\right\} \longrightarrow \varepsilon_0 = \varepsilon_0(\tau, \mu, n)$$

Lattice design -6-

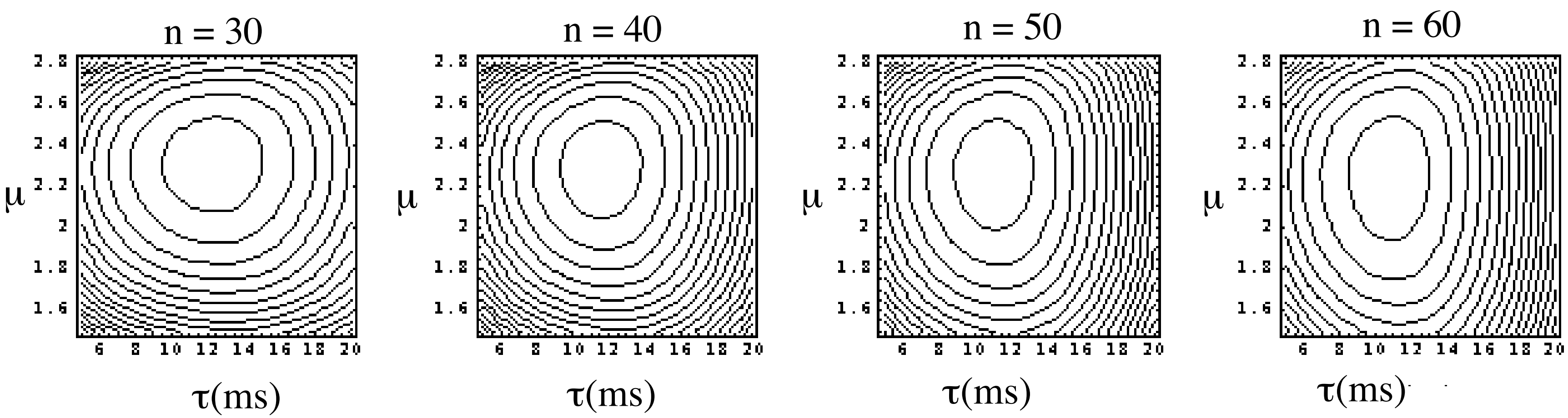
The emittance at extraction

$$\varepsilon_{\mathrm{ext}} = \varepsilon_0 + (\varepsilon_{\mathrm{i}} - \varepsilon_0)\exp(-2T/\tau) \equiv \varepsilon_{\mathrm{ext}}(\tau,\mu,n)$$

where ε_i is the emittance at injection and T is store time.

We optimize the emittance at extraction in (τ, μ, n) space

- Assumption: T = 40 ms (*i.e.*, two bunch-trains)
- For any n, minimum emittance is obtained around (τ = 12 ms, μ=2.3)



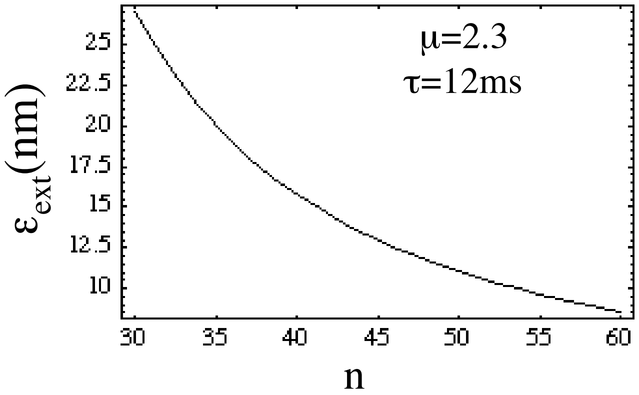
Lattice design -7-

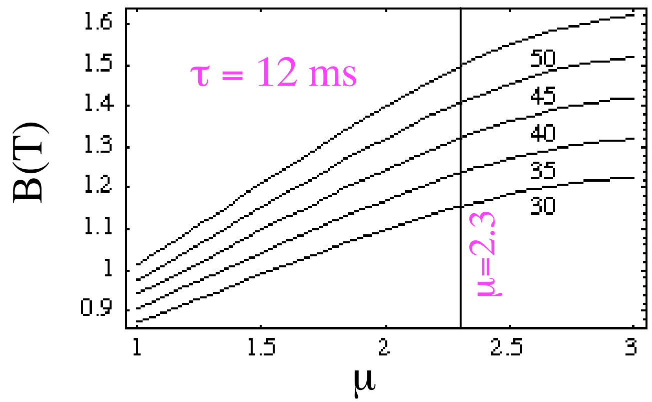
- Minimum emittance itself depends on number of cells $\propto n^{-2}$
- To determine the number of cell, the bend field and the circumference must be taken into account.

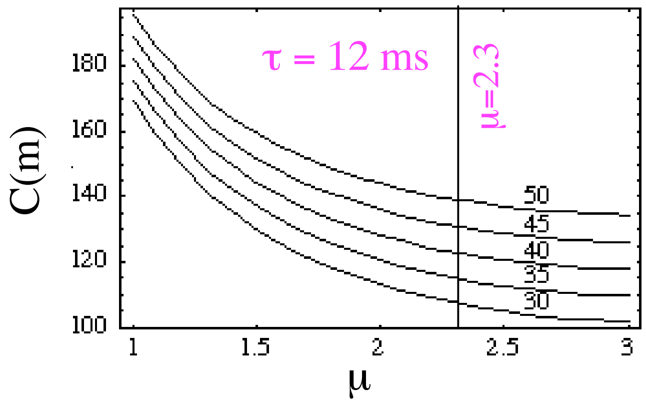
◆ Kicker rise/fall time = 100ns

⇨ C > 120 m and n > 40

◆ For n = 40, B < 1.3 T







DR parameters

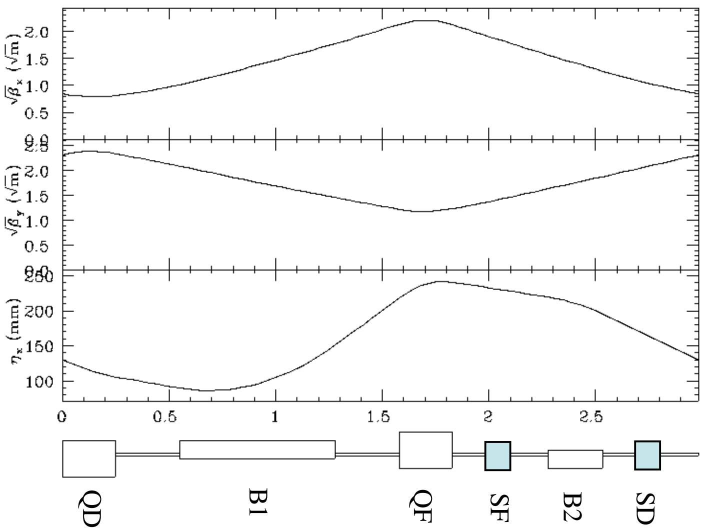
		Unit
Energy	1.0	GeV
Number of bunch trains	2	
Number of bunches/train	2	
Bunch spacing	98	ns
Bunch charge	1.2	nC
Repetition frequency	50	Hz
Circumference	131.3	m
Energy loss per turn	73	keV
Horizontal damping time	12	ms
Momentum compaction factor	0.0019	
Number of normal cells	40	
Emittance at equilibrium	12.2	nm
Emittance at injection	1.23	um
Emittance at extraction	13.7	nm
Energy spread of injected beam	4.06E-03	
Bunch length of injected beam	6.05	mm
Energy spread	5.29E-04	
Bunch length	5.03	mm
Bend-angle ratio of reverse-bend	0.35	
Phase advance/cell	1.932	rad

- Cavity voltage of 0.26MV is within the spec. of KEKB ARES cavity (0.5 MV/cavity)

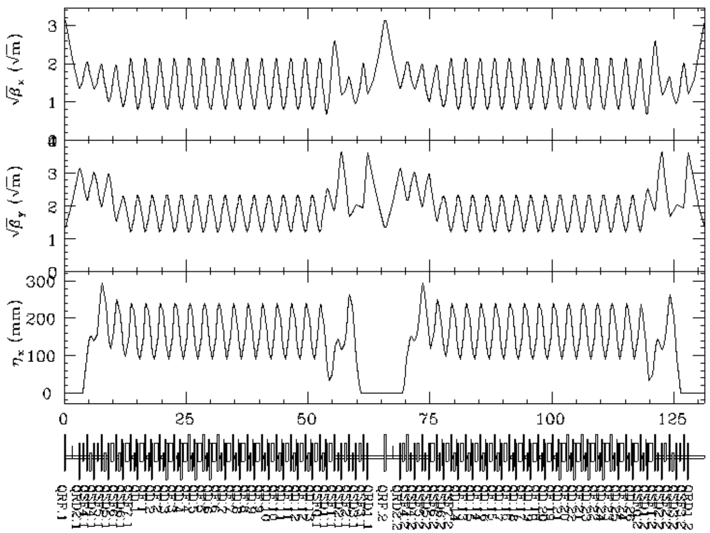
		Unit
Bend field	1.267	T
Quad field	16.3	T/m
Sextupole field	426	T/m^2
Length of straight sections	2 x 6	m
Length of main bend	0.7286	m
Length of reverse bend	0.255	m
Length of quad	0.25	m
Length of sext	0.1	m
Minimum space between magnets	0.1	m
Cavity voltage for 1.5% bucket height	0.261	MV
RF frequency	509	MHz

DR optics

Optics functions of normal cell



Optics functions of entire ring

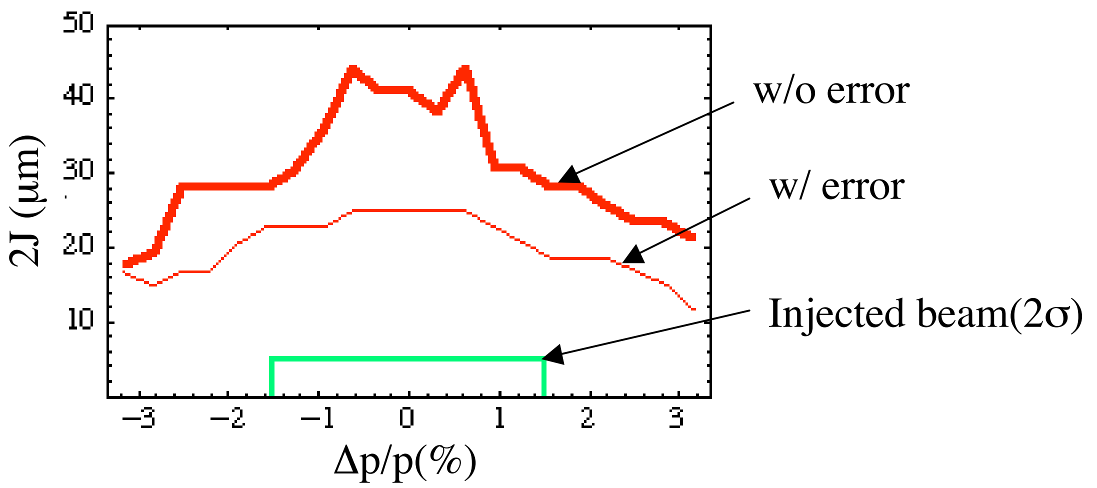


- Dispersion suppressor: 1 half-length bend + 7 adjustable quads
- Chromaticity correction: 2-family sextupoles

Dynamic aperture -1-

Tracking simulation results: very large DA

- $(\nu_x, \nu_y) = (12.24, 4.26)$
- 4000 turns
- RF bucket height = 4%
- Machine errors (just 1 sample):
  - strength error: 3×10^{-4} for quad, 5×10^{-4} for sext
  - misalignments: 0.5 mm, orbit corrected by correctors

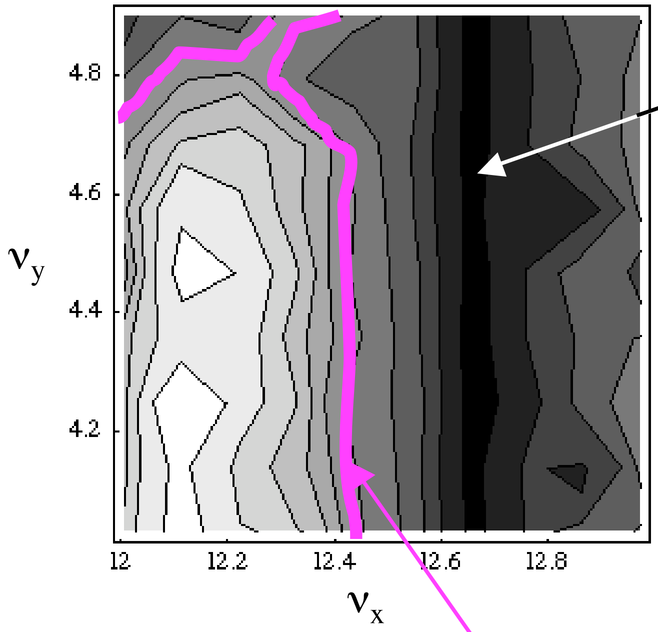


Initial momentum and action that survived 4000 turns

Dynamic aperture -2-

Tune survey results: wide operational tune space

Without machine errors



• Third-order resonance driven by sextupoles. The phase advance between sexts was accidentally near to $2\pi/3$.

• Phase advance/cell, accordingly the bend ratio r, should be changed to avoid this resonance

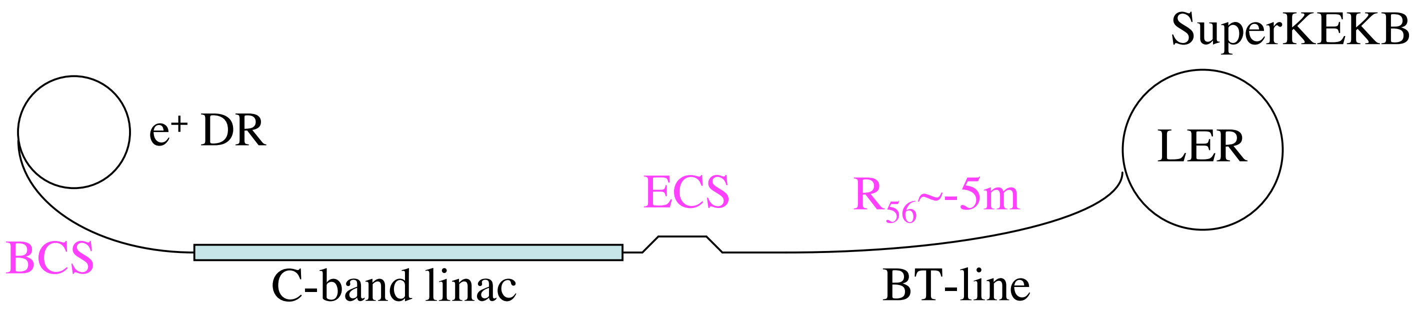
Tune space where the DA is larger than the extent of the beam

From DR to SuperKEKB -1-

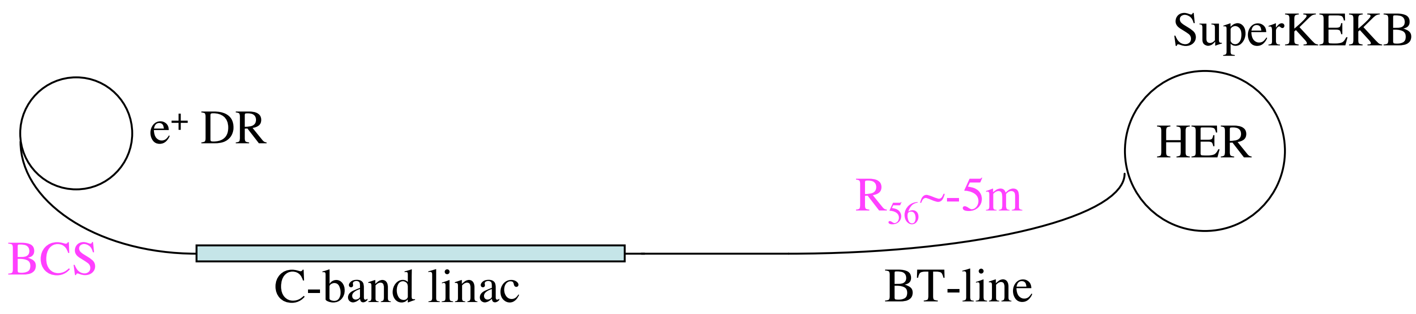
Beam transport in longitudinal phase-space

- Bunch length compression to match the subsequent C-band linac.
- Energy spread to meet the aperture of SuperKEKB.

■ 3.5-GeV case



■ 8-GeV case

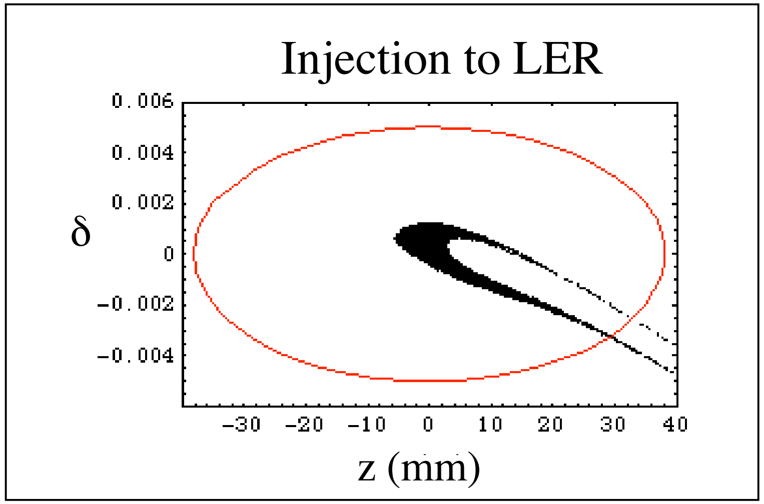


From DR to SuperKEKB -2-

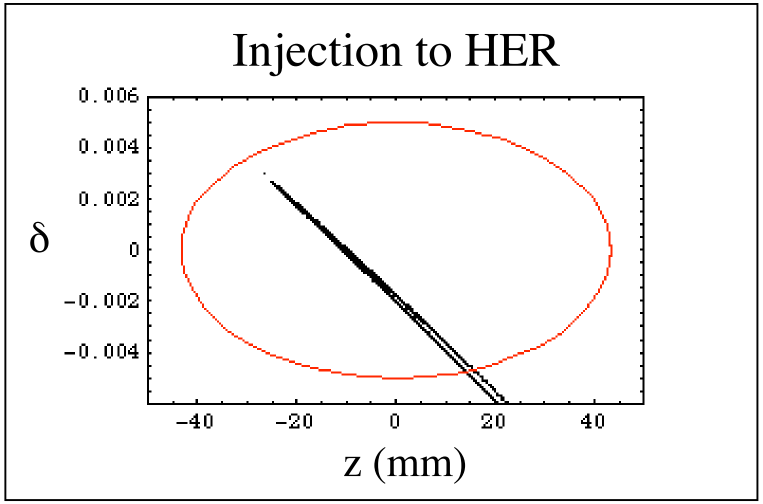
Longitudinal beam parameters

		DR	after BCS	end of linac	after ECS	after BT	Unit
3.5-GeV case	Energy spread	0.053	0.499	0.286	0.065	0.065	%
	Bunch length	5.03	0.59	0.59	2.65	4.25	mm
8.0-GeV case	Energy spread	0.053	0.510	0.145		0.145	%
	Bunch length	3.54*	0.37	0.37		2.96	mm

* For 8-GeV case, the bunch length in the DR was reduced to 3.54 mm by changing RF voltage to 0.5 MV.



The 99.5% of beams are within the assumed acceptance of the ring

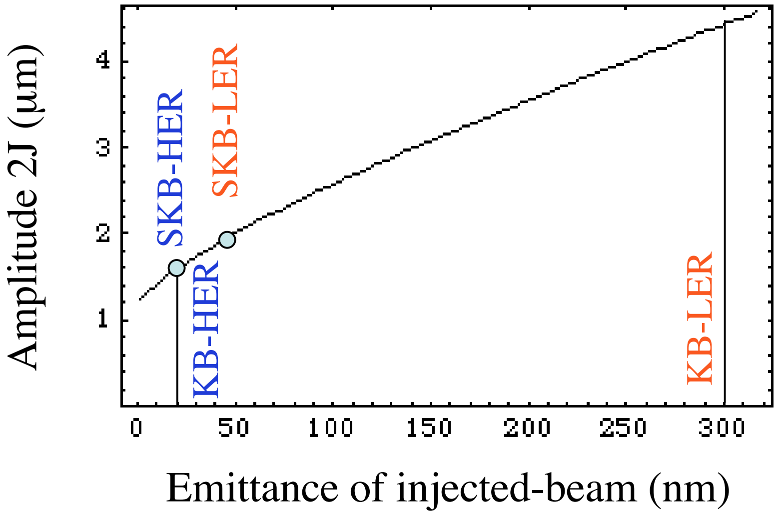


The 98.7% of beams are within the assumed acceptance of the ring

Summary

1. We found realistic parameters of ECS in the LTR line.
   - Employing ECS, almost 100% of particles are included within the energy band-width of ±1.5%

2. We have proposed new design for the positron Damping Ring, based on the ‘Alternating-bend FODO’ lattice.
   - Low emittance
   - Low positive/negative momentum compaction
   - Very large dynamic aperture
   - Robust to machine-errors
   - …
3. We have found consistent longitudinal beam-parameters from DR to SuperKEKB rings that satisfy the requirement.



- Effective septum thickness: 6 mm
- Ring emittance: 24 nm
- βx at septum: 100 m