Beam Transport and Injection for SuperKEKB

7/Feb/2011

N.Iida

The 16th KEKB Accelerator Review Committee

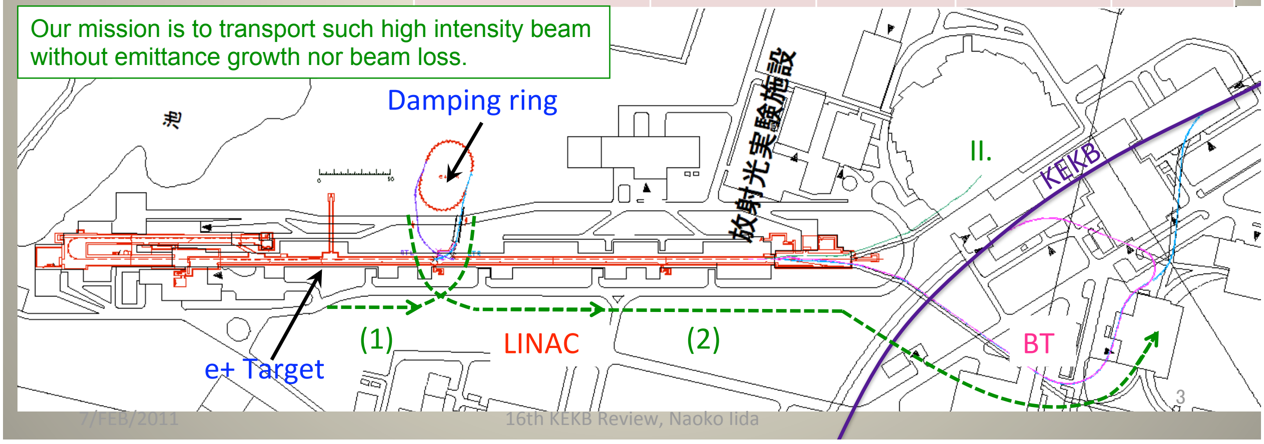
Issues

- Low emittance beam preservation
  - Sources of the emittance growth
    - Misalignments of Accelerating structures and Quadrupoles
    - Emission of Synchrotron Radiation (SR)
- Injection scheme of HER
  - Betatron injection or Synchrotron injection
- Beam loss in the Damping ring
  - Selection of L-band or Large-S-band at the e+ capture section

Contents

injection beam	SuperKEKB (LER)	KEKB (LER)	SuperKEKB (HER)	KEKB (HER)
Energy (GeV)	4.0	3.5	7.0	8.0
εx / εy (nm)	12.5 / 0.9	300 / 200	1.46	50/20
Charge (nC)	4 (Max: 8)	1	5	1

Our mission is to transport such high intensity beam without emittance growth nor beam loss.



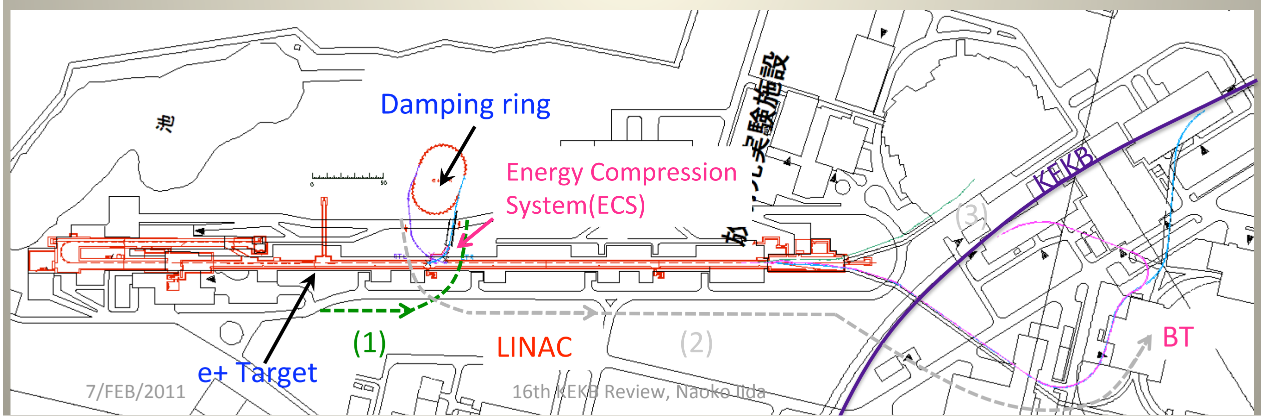
(1) e+ Target → Damping ring (DR)

- Design of the injection line

e+ beam from the target	
Charge (nC/ bunch)	4 (Max: 8)
Emittance @1.1GeV εx (μm)	1.7
εy (μm)	1.7
Energy spread σ_δ (%)	±5.0
Bunch length (Half width) (mm)	±8

Large amount of charge

Very huge



[I]-(1)

Initial parameters of e+ capture section

T.Kamitani

	present capt. section (Present KEKB)	L-band capt. section (SuperKEKB)
accelerating structures	1m x 2 + 2m x 2	2m x 2 + 2m x 4
RF frequency	2856 MHz (λ=10.5cm)	1298 MHz (λ=23.1cm)
aperture of the structures	20 mm in diameter	30 mm in diameter
accel. field gradient	14.0 - 13.2 MV/m	10.0 MV/m
accel. phase	-30 deg	-30 deg
solenoid field (strong)	2.0 T x 45 mm QWT	6.0 T x 220 mm AMD
solenoid field (weak)	0.4 T x 7.9 m	0.4 T x 13.1 m
energy after capt. sec.	~ 80 MeV	~ 120 MeV

Increase e+ capture efficiency by enlarging these acceptances !

- longitudinal acceptance by longer wave length of L-band RF
- transverse acceptance by larger aperture of L-band structure
- energy acceptance by adiabatic matching device(AMD)

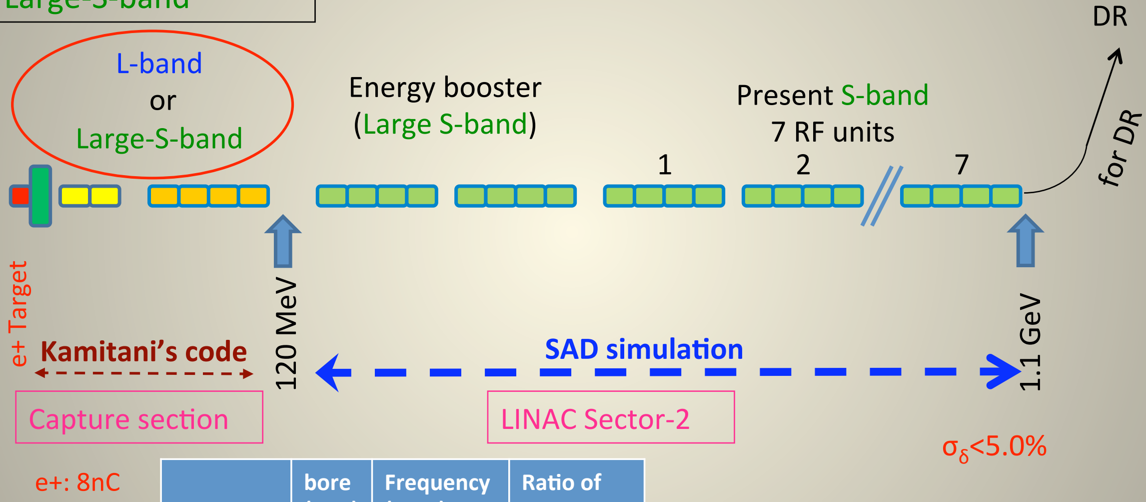
Q_{e+} = 1 nC ⇨ 4 nC

prelim. simulation result by N. Iida suggests Q_{e+} ~ 8 nC @ DR

[I]-(1)

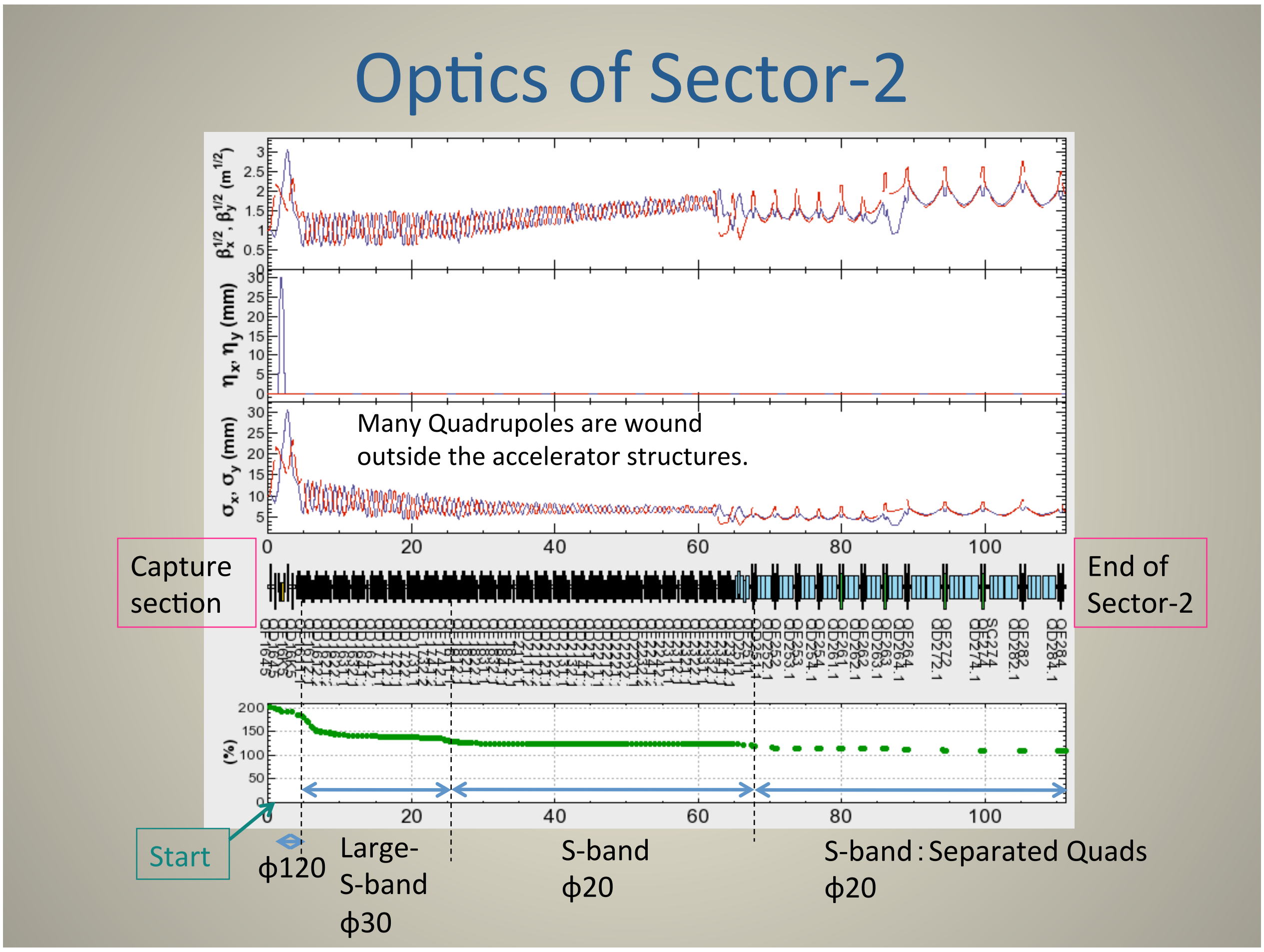
e+ Capture section — End of Sector-2 Layout

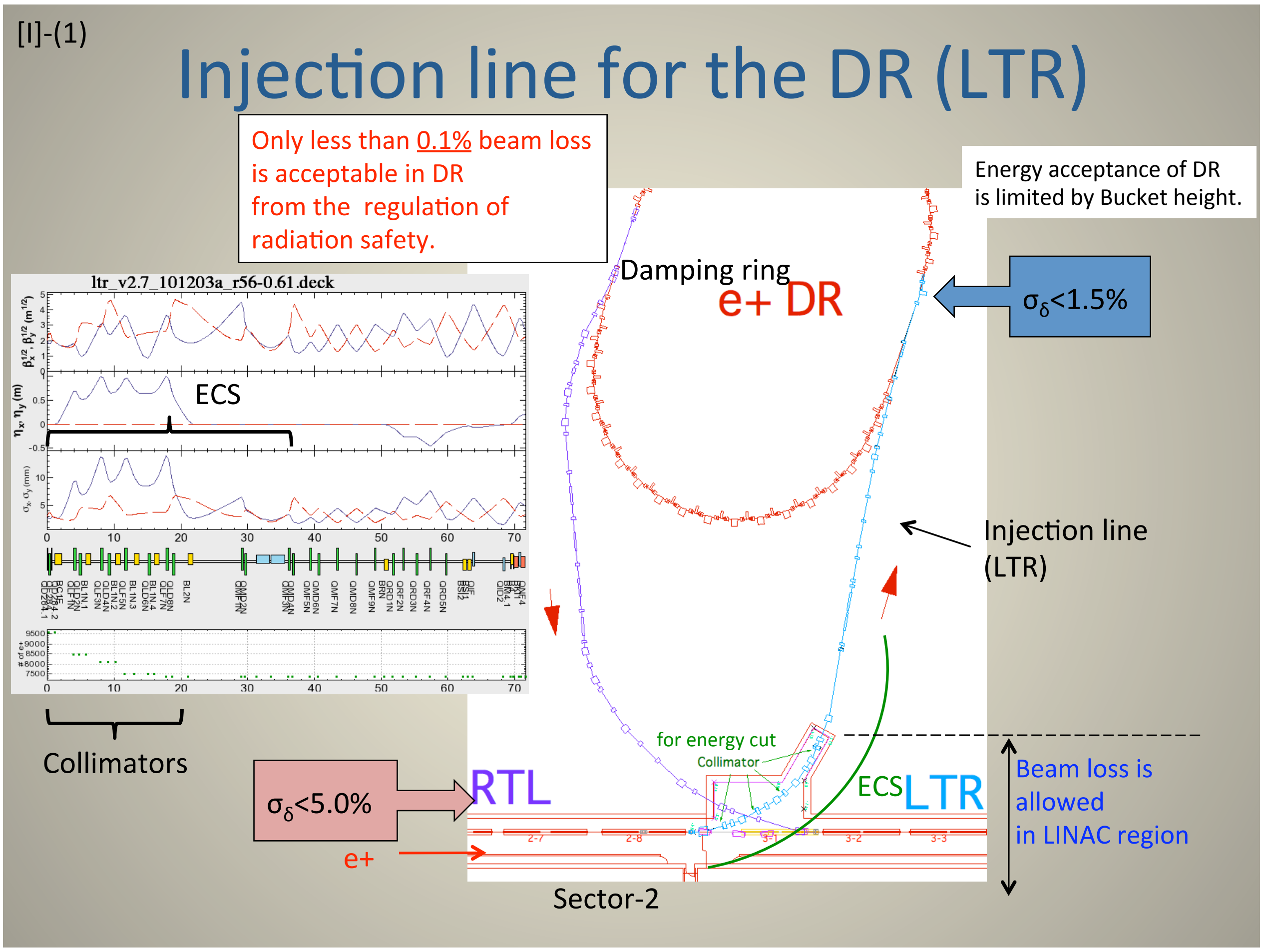
Selection L-band or Large-S-band



	bore (mm)	Frequency (MHz)	Ratio of Frequency
L-band	30	1298	5
Large-S-band	30	2856	11
S-band	20	2856	11

The ratio of frequency (5:11), which is required by two-bunch injection, is quite important to suppress beam loss at the injeciton for DR.

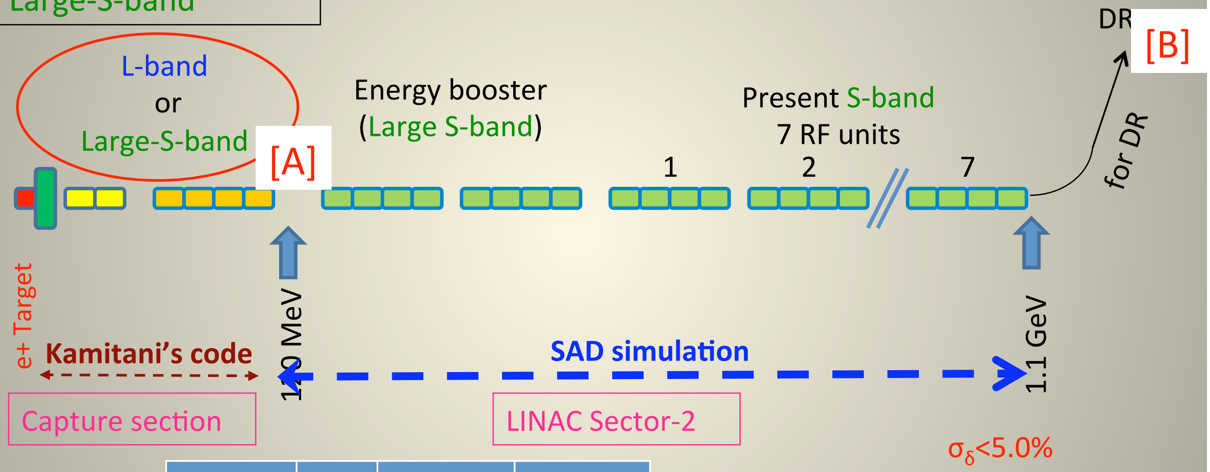

Optics of Sector-2
Many Quadrupoles are wound
outside the accelerator structures.
Capture
section
End of
Sector-2
Start
ϕ120
Large-
S-band
ϕ30
S-band
ϕ20
S-band : Separated Quads
ϕ20


[I]-(1)
Injection line for the DR (LTR)
Only less than 0.1% beam loss
is acceptable in DR
from the regulation of
radiation safety.
Energy acceptance of DR
is limited by Bucket height.
ltr_v2.7_101203a_r56-0.61.deck
ECS
Collimators
Damping ring
e+ DR
σδ<1.5%
Injection line
(LTR)
for energy cut
Collimator
ECS
LTR
RTL
σδ<5.0%
e+
Beam loss is
allowed
in LINAC region
Sector-2

[I]-(1)

e+ Capture section — End of Sector-2 Layout

Selection L-band or Large-S-band



	bore (mm)	Frequency (MHz)	Ratio of Frequency
L-band	30	1298	5
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S-band	20	2856	11

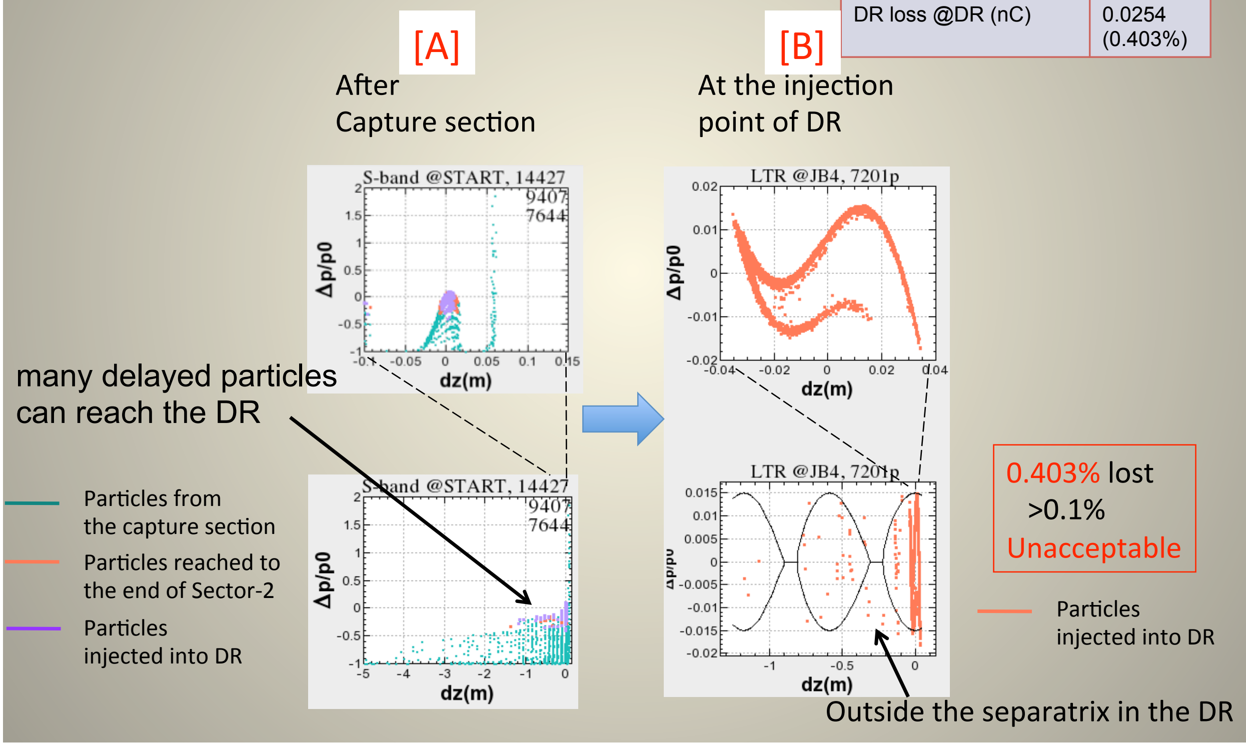
The ratio of frequency (5:11), which is required by two-bunch injection, is quite important to suppress beam loss at the injeciton for DR.

[I]-(1)

・Comparison of S-band and L-band of the e+ capture section

(a) 6 Large-S-bands

Charge @DR (nC)	6.301
DR loss @DR (nC)	0.0254 (0.403%)



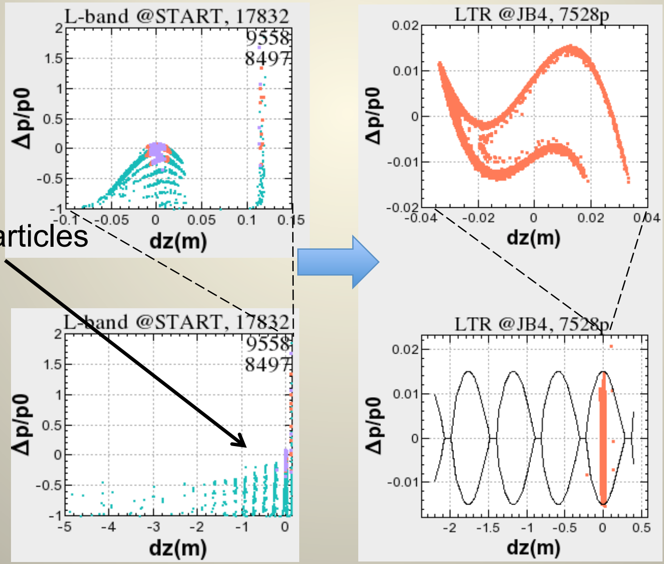
[I]-(1)

(b) 6 L-band

Charge @DR (nC)	6.587
DR loss @DR (nC)	0.0035 (0.053%)

[A] After Capture section

[B] At the injection point of DR



Very few delayed particles can reach the DR

- Particles from the capture section
- Particles reached to the end of Sector-2
- Particles injected into DR

0.053% lost
<0.1%
Acceptable
(0.403% for S-band)

- Particles injected into DR

[I]-(1)

Comparison of L-band and Large-S-band at the e+ Capture section

	Charge at DR (nC)	Beam loss in DR (%)
(a) 6 L-bands	6.587	0.053 < 0.1
(b) 6 Large-S-bands	6.301	0.403 > 0.1
(c) 2 L-bands and 4 Large-S-bands	6.225	0.267 > 0.1

- Mixture of L-band and S-band
  - There are some delayed particles in the solenoid after e+ target.
  - The ratio of acceleration frequency of L-band and S-band is 5:11, which is essential. This ratio is shifted from a simple integer.
  - In the case of mixture of L-band and S-band after the target, the delayed particles are not accelerated properly and are lost in the LINAC.

[I]-(2)

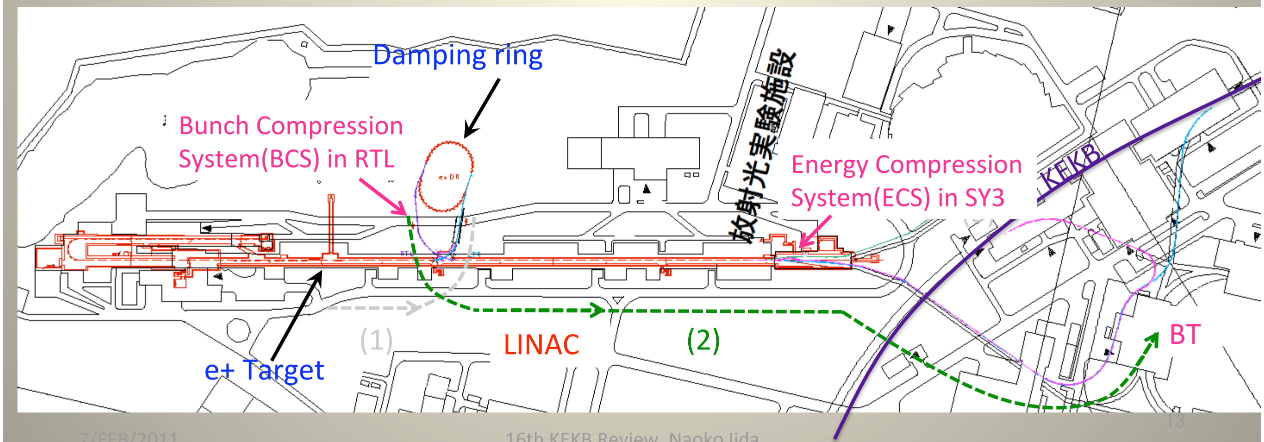
(2) Damping ring (DR) → Low Energy Ring (LER)

- e+ beam from DR

Charge	(nC/bunch)	4 (Max: 8)
Emittance @1.1GeV	εx (nm)	42.5
	εy (nm)	3.15
Energy spread σ_δ	(%)	0.055
Bunch length($1\sigma_z$)	(mm)	8.0

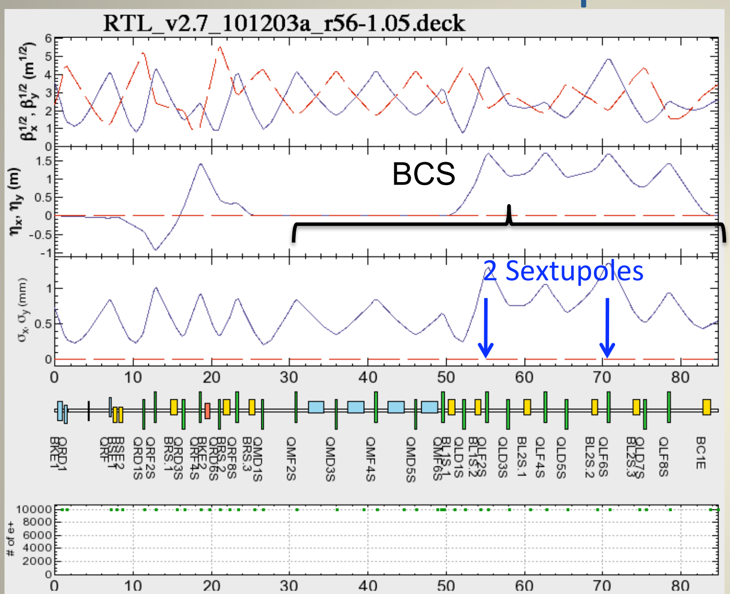
very low

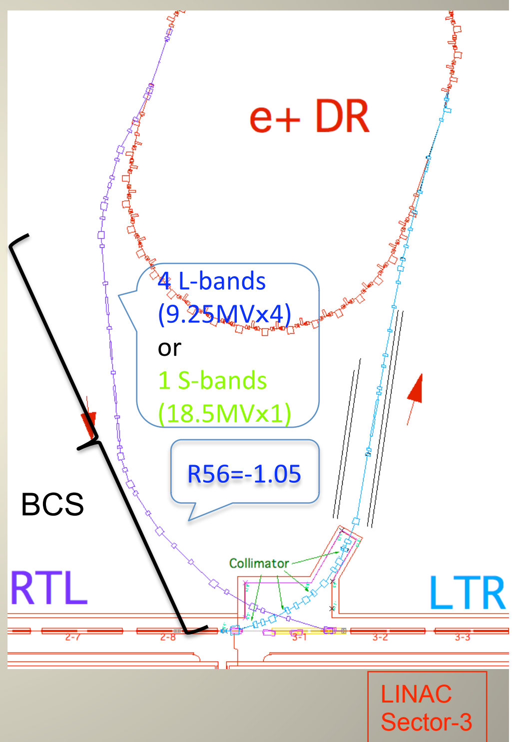
long



[I]-(2)

Extraction line from DR (RTL) Optics



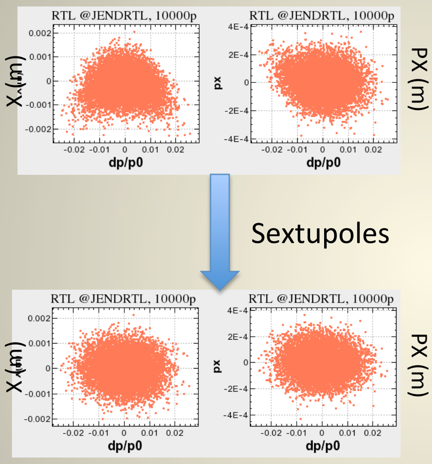


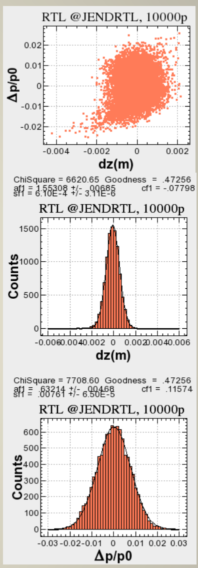
	ε@B4 w/o Sext	ε@B4 w Sext
x(nm)	47.6	42.6
y (nm)	3.14	3.15

	ε@B4 w Sext
σz (mm)	0.61
σδ	0.0076

[I]-(2)

Entrance of LINAC Sector-3





	ε@Sector-3 w/o Sext	ε@Sector-3 w Sext
x(nm)	47.6	42.6
y (nm)	3.14	3.15

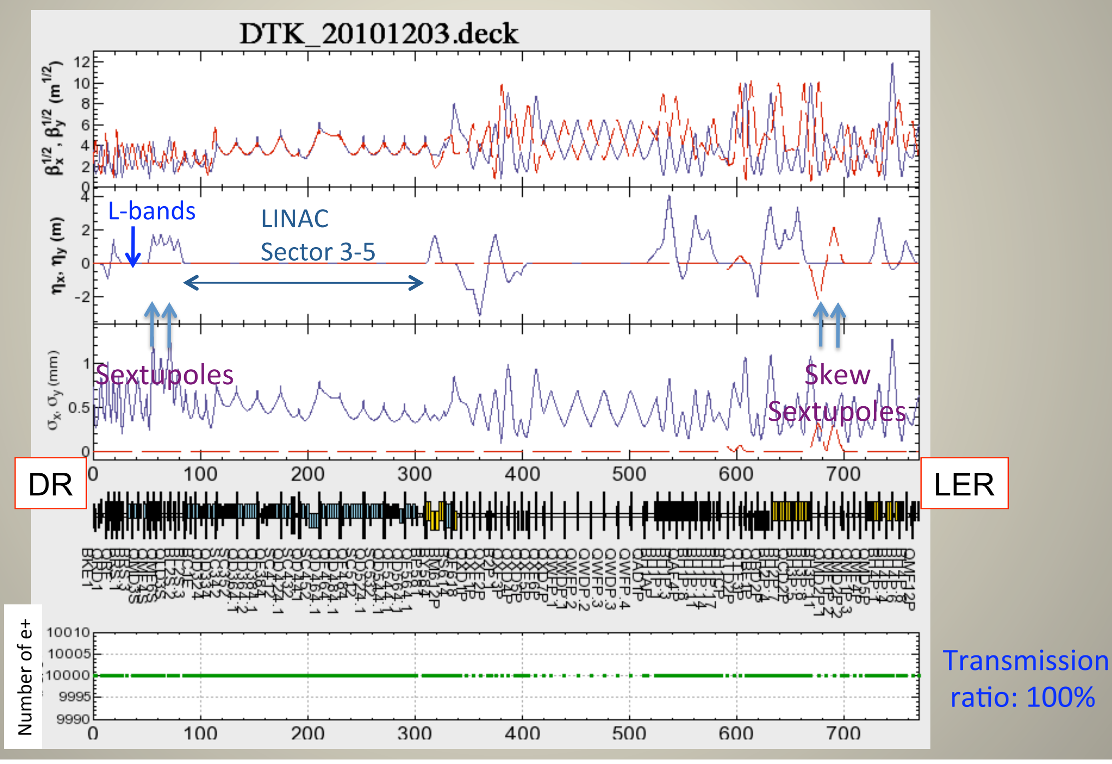
	ε@Sector-3 w Sext
σz (mm)	0.61
σδ	0.0076

Sextupole supress the second order dispersion.

[I]-(2)

DR – Entrance of LER Optics

e+ : 8nC



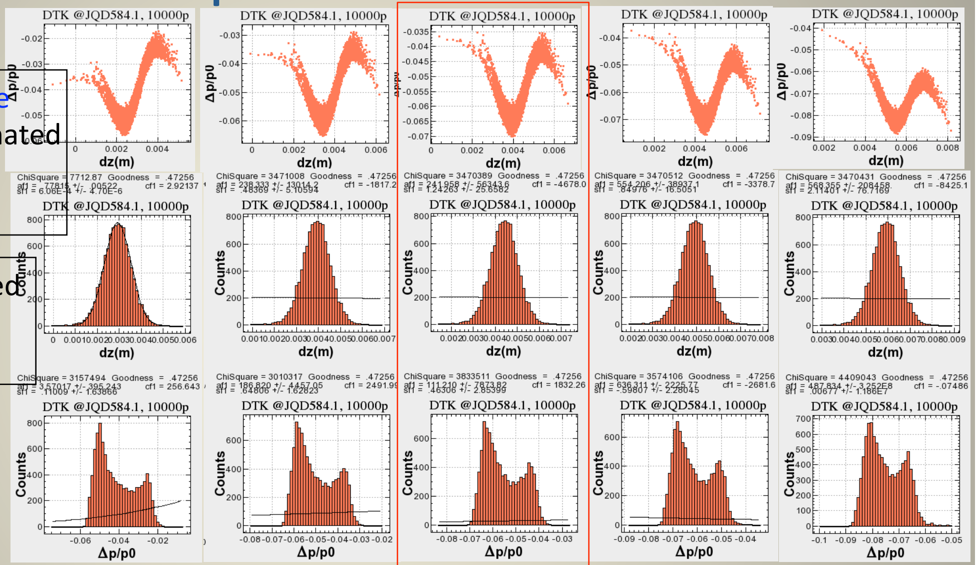
[I]-(2)

LINAC(3 – 5sector) RF-phase Optimization

e+ : 8nC

The longitudinal wake (K.Yokoya's approximated formula) effect is included.

The phase is optimized as all particles are transported.

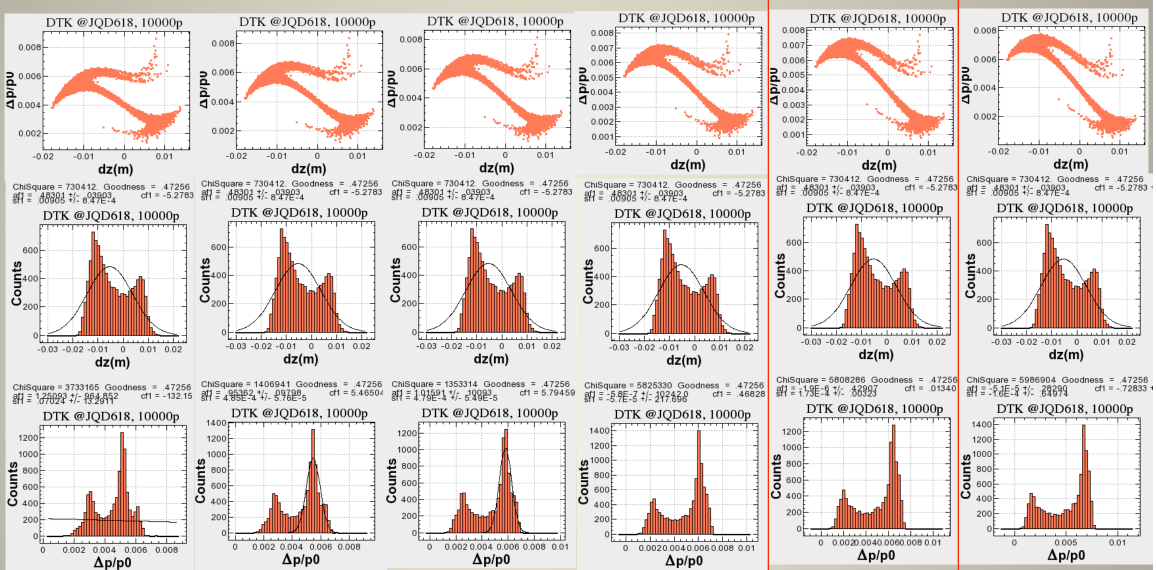


(RF-Phase)	Z0(sec.3) [m]	0.003	0.004	0.0045	0.005	0.006
	Wδ(95%) [%]	±1.581	±1.398	±1.317	±1.241	±1.106
	Wδ(98%) [%]	±1.687	±1.495	±1.417	±1.349	±1.238
	Wδ(100%)[%]	±2.016	±1.818	±1.729	±1.893	±2.359

[I]-(2)

SY3-ECS Vc scan

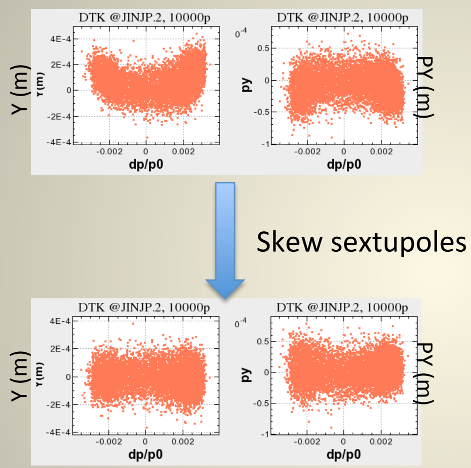
8nC

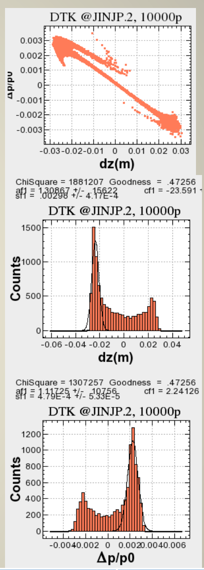


Vc (SY3-ECS)[MV]	43	44	45	46	47	48
Wδ(95%) [%]	±0.190	±0.211	±0.232	±0.255	±0.280	±0.305
Wδ(98%) [%]	±0.212	±0.230	±0.250	±0.272	±0.294	±0.318
Wδ(100%) [%]	±0.360	±0.356	±0.353	±0.350	±0.347	±0.361

[I]-(2)

Injection point at LER





Skew sextupoles supress the second order vertical dispersion.

	ε@INJP w/o Sext	J@INJP w/o Sext	ε@INJP w Sext	J@INJP w Sext
x(nm)	12.2	12.5	12.3	12.5
y (nm)	1.03	1.06	0.903	0.911

Hard Edge	ε@INJP w Sext
Wz (mm)	±29.5
Wδ [%]	±0.347

No emittance growth is observed so far.

[I]-(2)

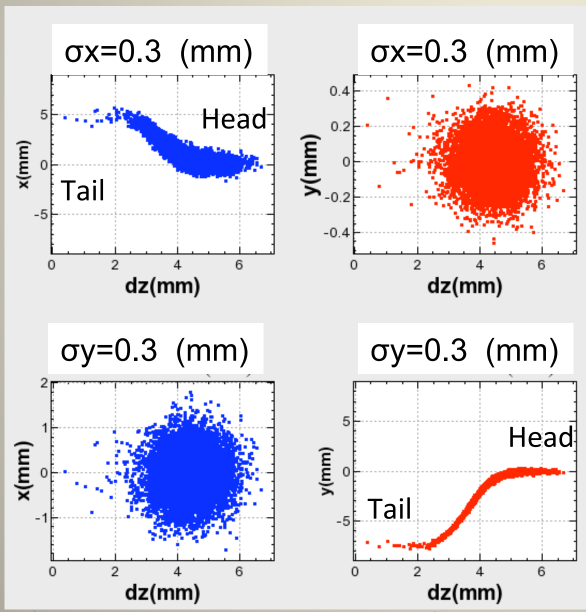
Emittance growth due to Misalignments of Accelerating structures and Quadrupoles

- The transverse wake effect is included in this tracking simulation.
- Misalignments :
  - Accelerating structures and quadrupoles are misaligned independently.
  - Amplitudes of the misalignments are given by Gaussian distribution.
  - The orbit distortion due to quadrupole misalignments are corrected by steering magnets.

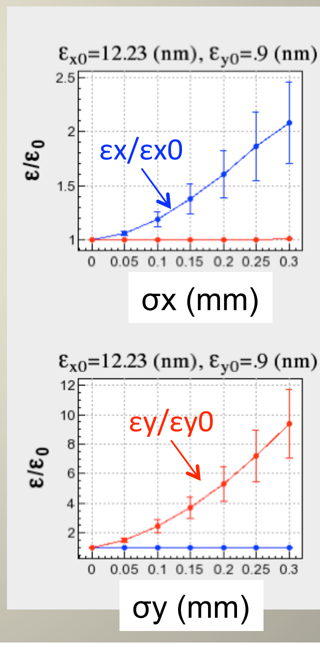
[I]-(2)

Emittance growth due to Misalignments of Accelating structures and Quadrupoles

End of LINAC Sector-5



Injection point at LER



[I]-(2)

Emittance growth due to Emission of Synchrotron Radiation (SR) in the end of LINAC to LER injection

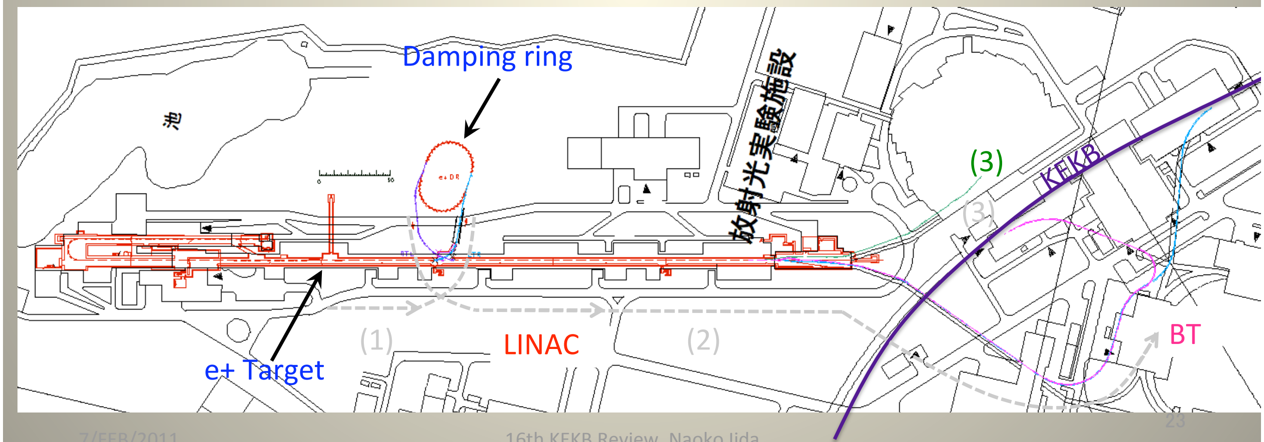
LER	εx (nm)	εy (nm)
w/o SR	12.2	0.898
w SR	13.9	0.911
Growth rate	1.14	1.01

The growth rate is not so large.

[II] Injection

(1) LER
- Injection Aperture
- Injection with beam-beam effect

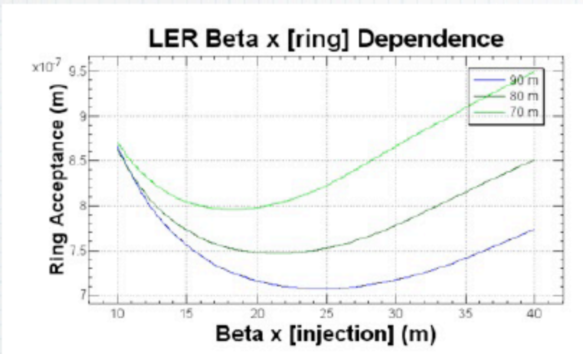
(2) HER
- Injection Aperture
- Synchrotron injection

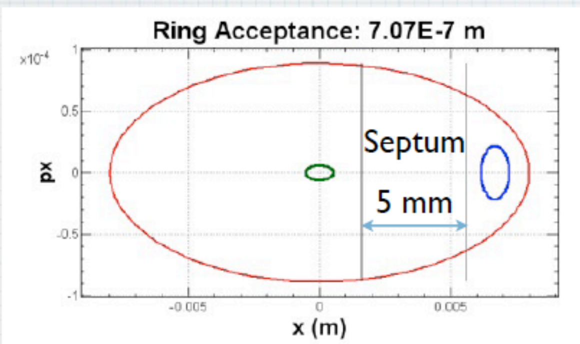


(1) Injection of LER

LER Injection Acceptance

Y.Ohnishi





	ε_x	ε_y	unit
ext. @DR	42.5	3.15	nm
inj. @LER	11.7	0.87	nm
	Ax	Ay	
Required* Aperture	707	8.7	nm

* no emittance growth between DR ext. and linac end

$\beta_{x,inj} = 24.5$ m

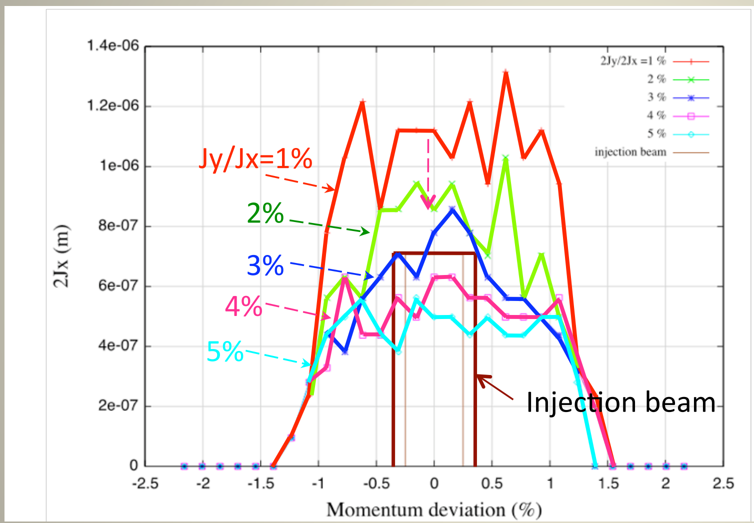
$\beta_{x,ring} = 90$ m

[II]-(1)

The dynamic aperture of LER

Y.Ohnishi

For larger vertical emittance of the injected beam, the dynamic aperture is narrower.



Jy/Jx	Ay (nm)
1%	7.07
2%	14.1
3%	21.2
4%	28.3
5%	35.4

Jy/Jx=1.3(%)
Ay=9(nm)
w/o emittance growth

If the emittance growth due to the misalignments is fixed by the method talked by M.Yoshida, the injection to the LER is OK.

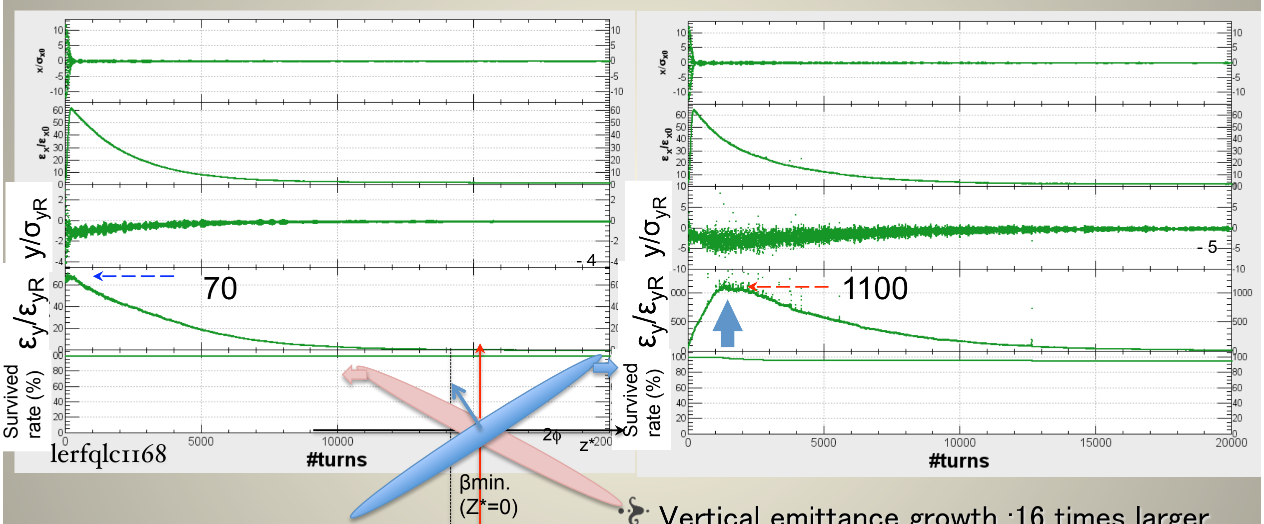
[II]-(1)

LER Injection with Beam-Beam effect

Y.Ohnishi

Strong(Stored beam) – Weak(Injected beam) model

w/o Beam-Beam w/ Beam-Beam



The particles oscillating horizontally collide with the other beam at the position which is shifted from the waist point.
Due to this effect, 5.5% beam are lost.

(In the case of synchrotron oscillation, there is no shift)

- Vertical emittance growth :16 times larger than that of w/o Beam-Beam
- Vertical coherent oscillation

Beam loss will arise by the b-b effect anyway.
Insensitive to the εy of the injected beam ???
Needs more study.

(2) HER

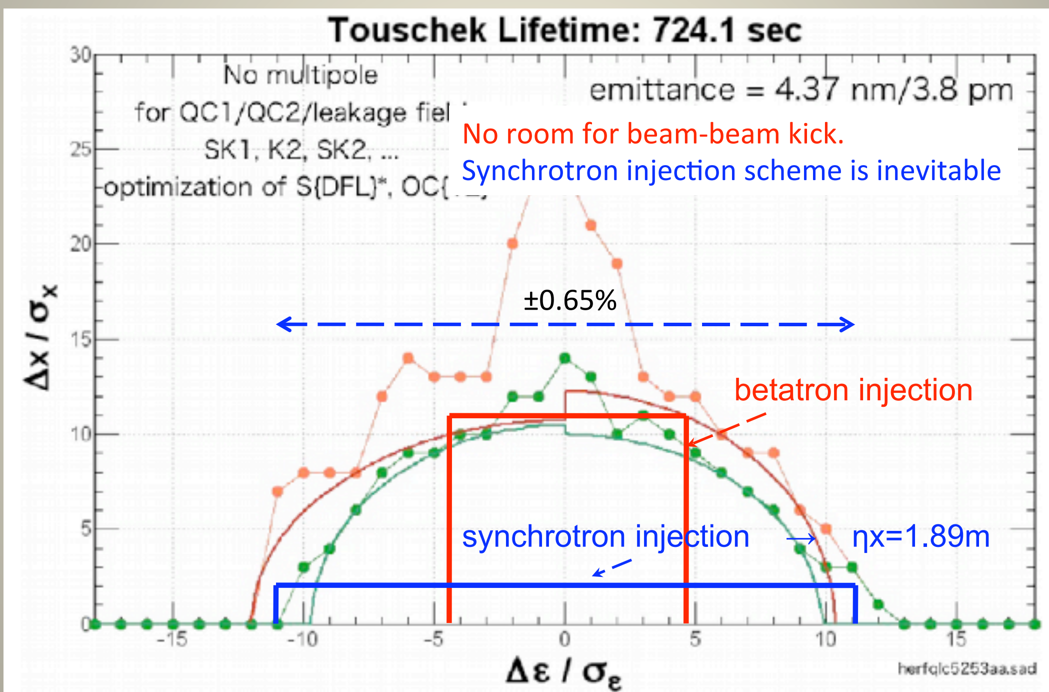
- Energy of e- beam is 7 GeV.
- Tracking simulation is done only from the end of LINAC to the HER injection point.
- Emittance growth due to emission of SR is large especially in horizontal direction.

HER (7GeV)	εx (nm)	εy (nm)
from LINAC	1.46	1.46
w/o SR	1.86	1.48
w SR	5.57	1.57
Growth rate	3.0	1.06

Required ring acceptance:
Ax = 474 (nm) → 575 (nm)

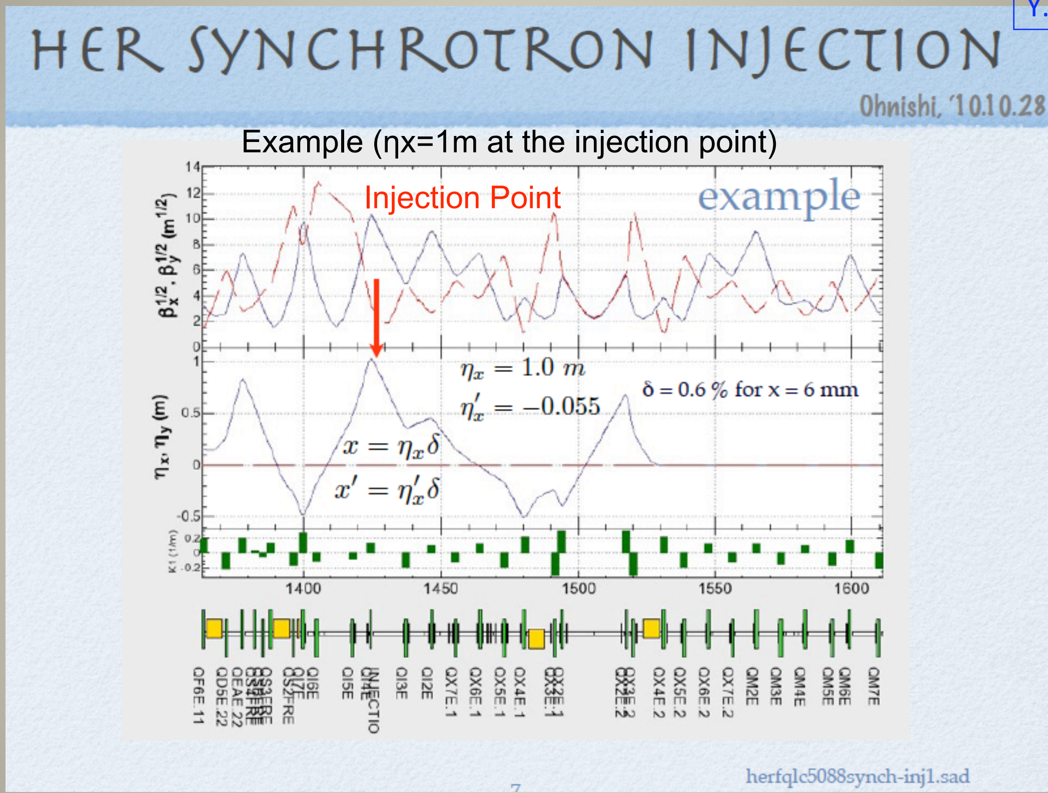
The dynamic aperture of HER

from A. Morita



[II]-(2)

Y.Ohnishi



We need more horizontal dispersion !
ηx = 1.89m may be difficult.

Mixed scheme should be considered.

[III]

[III] Future plan

- The lattice optics of Sector 1-5 will be refined.
  - Considering the compatible optics of injection beams into LER, HER and PF for simultaneous injection.
- Simulation for suppressing the emittance growth due to misalignments should be done.
  - Searching for the initial orbit of the capture section for cancellation.
  - BNS method.
  - …
- Injection scheme of HER should be considered.

Backup

[I]-(1)

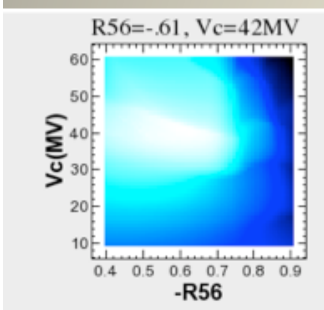
Damping ring Injection line(LTR)

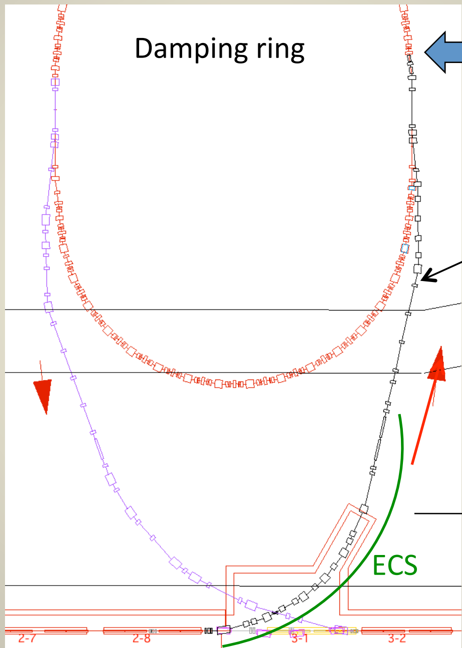
Energy acceptance of DR

σ_δ<1.5%

Only less than 0.1% beam loss is acceptable in DR

ECS Parameter scan





Injection line (LTR)

σ_δ<5.0%

e+

Beam loss is permissible in LINAC region

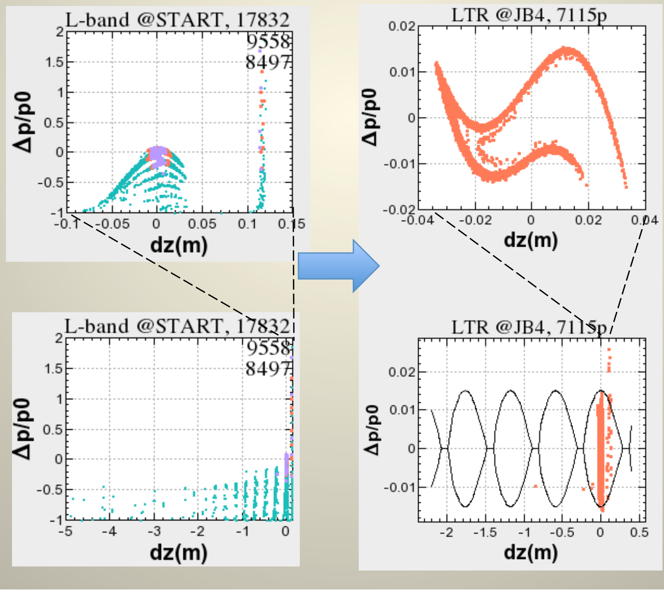
[I]-(1)

(c) 2 L-bands and 4 Large-S-bands

Charge @DR (nC)	6.225
DR loss @DR (nC)	0.0166 (0.0267%)

After Capture section

At the injection point of DR



Particles from the capture section

Particles reached to the end of Sector-2

Particles injected into DR

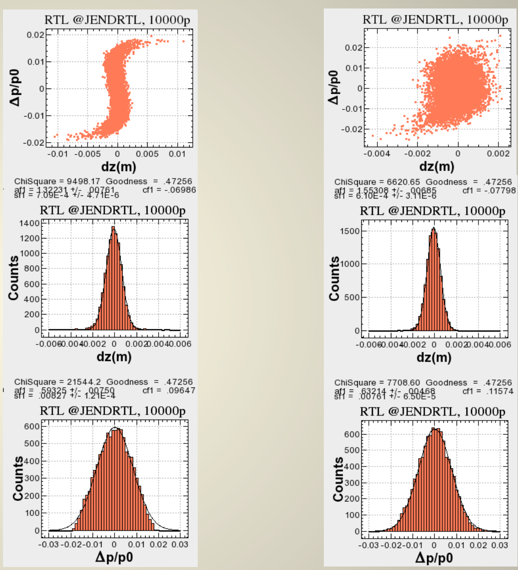
0.0267% lost
(0.403% for S-band)
(0.053% for L-band)

Particles injected into DR

[I]-(2)

Entrance of Sector-3

Accelerator device in RTL: S-band L-band



Almost same values as L-band

	ε@ENDRTL w Sext
x(nm)	42.6
y (nm)	3.15

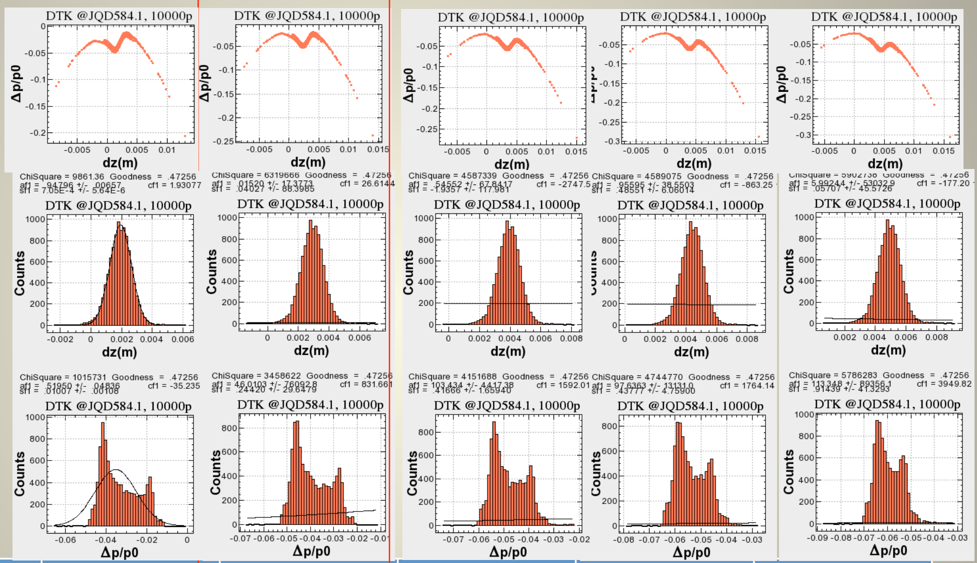
	ε@ENDRTL w Sext
σz (mm)	0.71
σδ	0.0083

	ε@ENDRTL w Sext
σz (mm)	0.61
σδ	0.0076

[I]-(2)

8nC

LINAC(3～5sector) phase tuning
RTL: S-band



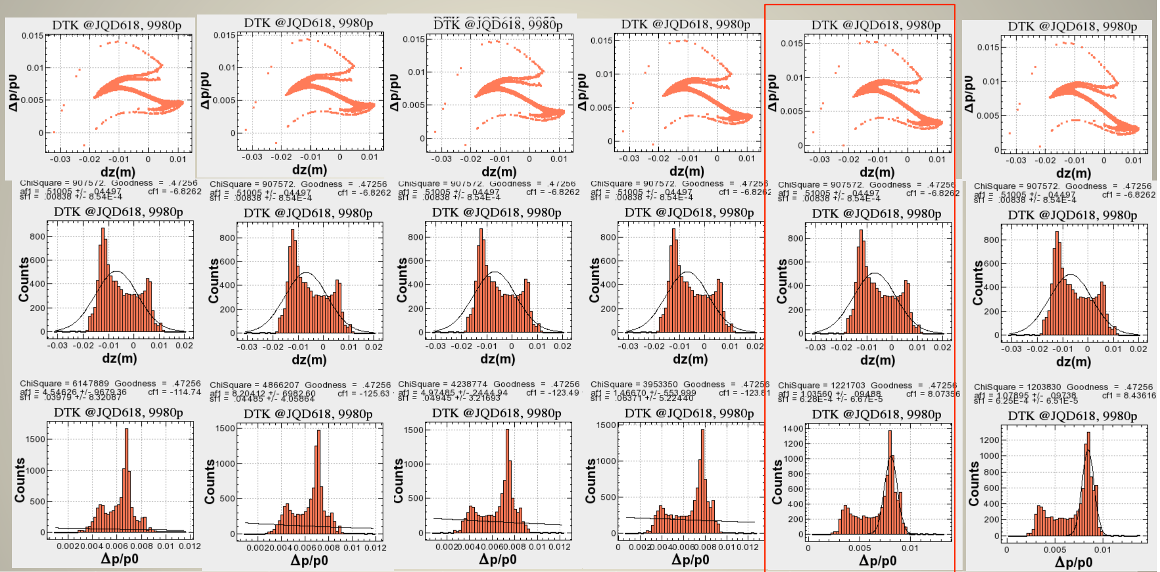
Z0(sec.3) [m]	0.002	0.003	0.004	0.0045	0.005
Wδ(95%) [%]	±1.466	±1.270	±1.127	±1.072	±1.030
Wδ(98%) [%]	±1.608	±1.403	±1.305	±1.273	±1.399
Wδ(100%)[%]	±9.68	±10.8	±12.4	±13.3	±14.2

[I]-(2)

8nC

SY3-ECS Vc scan
RTL: S-band

Z0(Sec3)=0.003



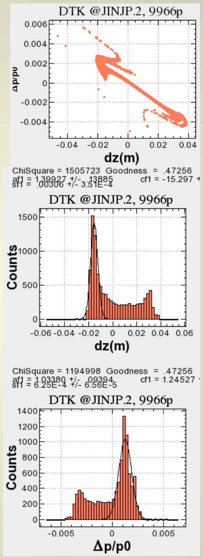
Vc (SY3-ECS)[MV]	43	44	45	46	47	48
Wδ(95%) [%]	±0.222	±0.241	±0.259	±0.279	±0.297	±0.318
Wδ(98%) [%]	±0.268	±0.278	±0.289	±0.304	±0.322	±0.342
Wδ(100%) [%]	±0.796	±0.787	±0.779	±0.770	±0.762	±0.757

[I]-(2)

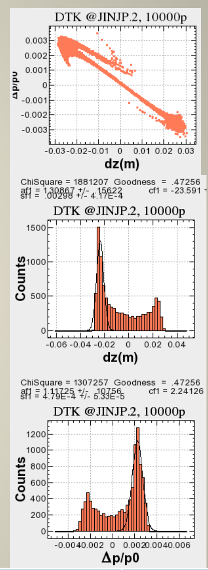
8nC

Injection point at LER (RTL: S-band)

S-band



L-band



	ε@INJP w Sext	J@INJP w Sext
x(nm)	13.3	13.4
y (nm)	0.924	0.926

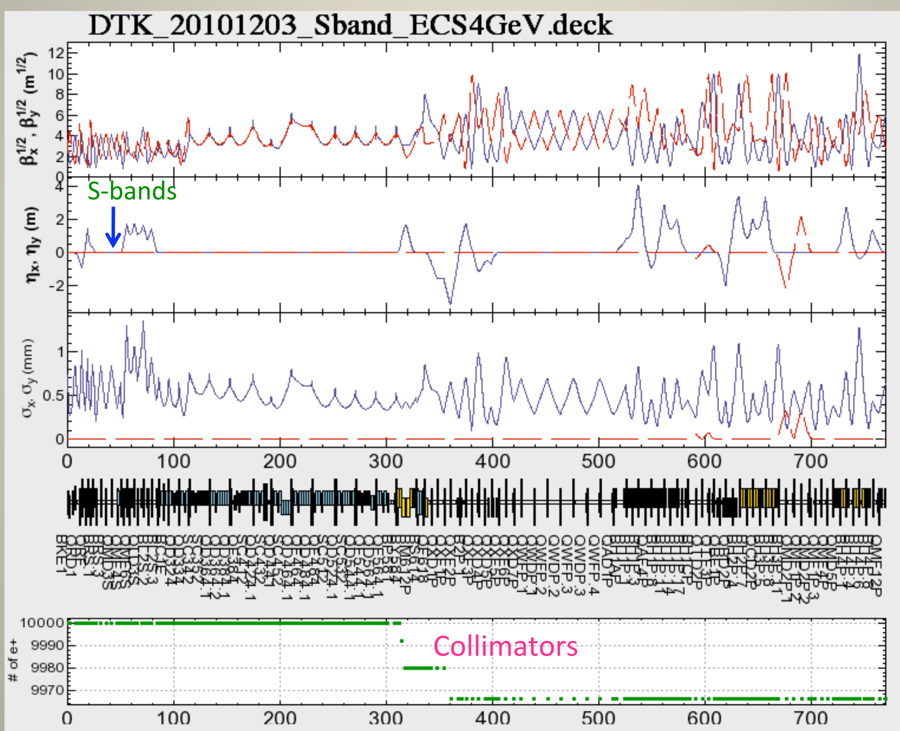
Hard Edge	98% @INJP	100% @INJP
Wz (mm)	±27.2	±42.7
Wδ [%]	±0.320	±0.528

Hard Edge	100% @INJP
Wz (mm)	±29.5
Wδ [%]	±0.347

[I]-(2)

8nC

e+ Passing ratio （RTL: S-band）



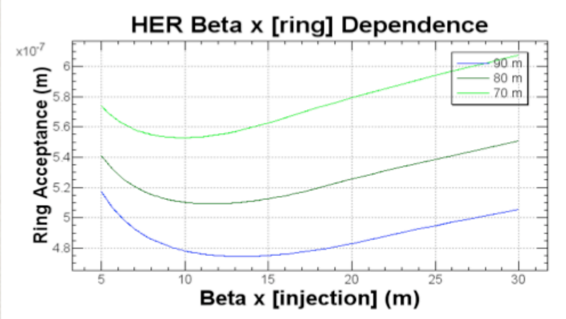
100% for L-band in RTL

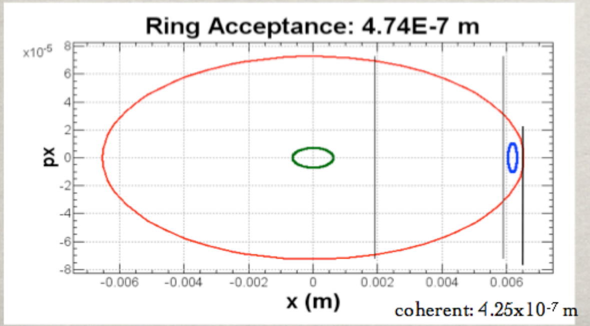
99.66% x 98% =97.7%

Y.Ohnishi

HER Injection Acceptance

(Betatron Injection)





	εx	εy	unit
normalized	20	20	μm
inj. @HER	1.46	1.46	nm
	Ax	Ay	
Required* Aperture	474	14.6	nm

* no emittance growth until linac end

$\beta_{x,inj}$ = 13.3 m

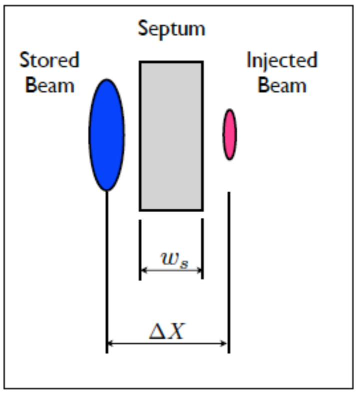
$\beta_{x,ring}$ = 90 m

3

M.Kikuchi

HER : Injection aperture

Parameters of the synchrotron injection scheme



$$\Delta X = \eta\, \delta_0$$

$$\Delta X = n_s\sqrt{\beta_R\epsilon_R + (\eta\sigma_{\delta R})^2} + w_s + n_i\sqrt{\beta_i\epsilon_i + (\eta_i\sigma_{\delta i})^2}$$

β_R =60 m	β_i =20 m
ϵ_R =4.3 nm	ϵ_i =1.46 nm
$\sigma_{\delta R}$ =0.059 %	$\sigma_{\delta i}$ =0.1 %
n_s =3.0	n_i =2.5

$\delta_0 + 2\sigma_{\delta i} = 0.65\,\%$

$\eta_i = 0$

$w_s = 4$ mm

⟶ $\eta = 1.75$ m

Transverse Aperture

Beta-mismatch B

if $\alpha_R/\beta_R = \alpha_i/\beta_i$

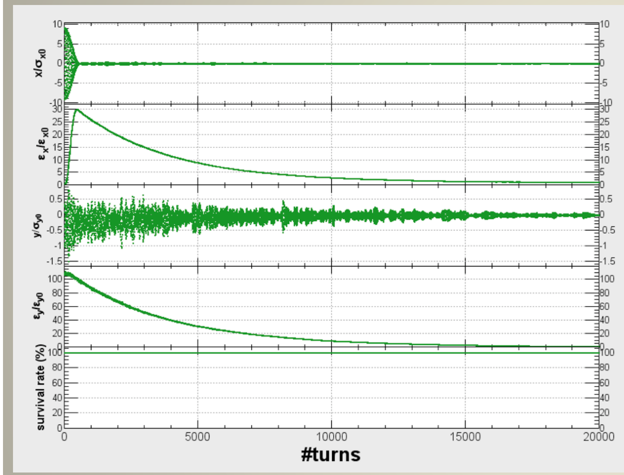
$$B = \frac{1}{2}\left(\frac{\beta_R}{\beta_i} + \frac{\beta_i}{\beta_R}\right) = 1.67$$

$A_x = 10\,\epsilon_i\, B = 24.4$ nm

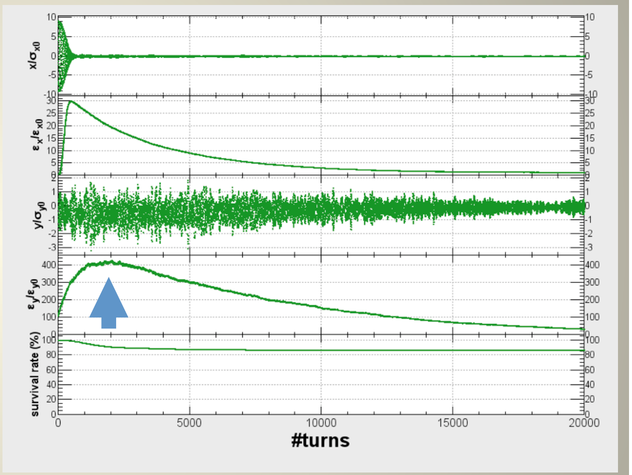
Y.Ohnishi

HER Injection with Beam-Beam

w/o Beam-Beam



w/ Beam-Beam



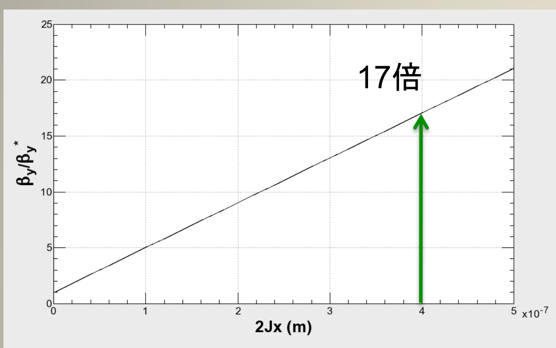
herfqlc5092

- Vertical emittance growth :4 times larger than that of w/o Beam-Beam
- Vertical coherent oscillation
- Beam loss : 15 %, CW can recover beam loss.

Y.Ohnishi

Beta function at IP

水平振幅とベータ関数増大の関係

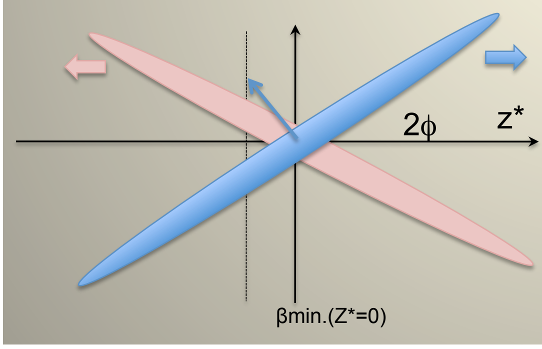


$$\beta_y(z) = \beta_y^* + \frac{z^2}{\beta_y^*}$$

zに関して二次関数的に増大する。

$$z = \frac{x}{\tan 2\phi} \qquad x = \sqrt{2J_x\beta_x}$$

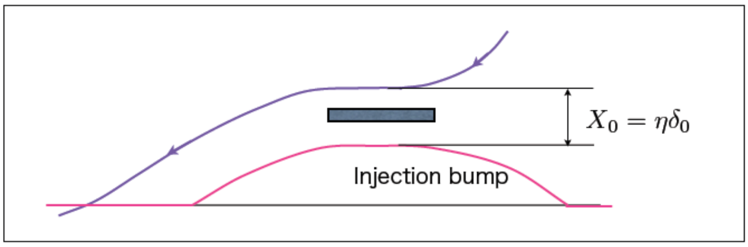
$$\beta_y(z) = \beta_y^* + \frac{2\beta_x^*}{\beta_y^* \tan^2 2\phi} J_x$$



M.Kikuchi

Synchrotron injection

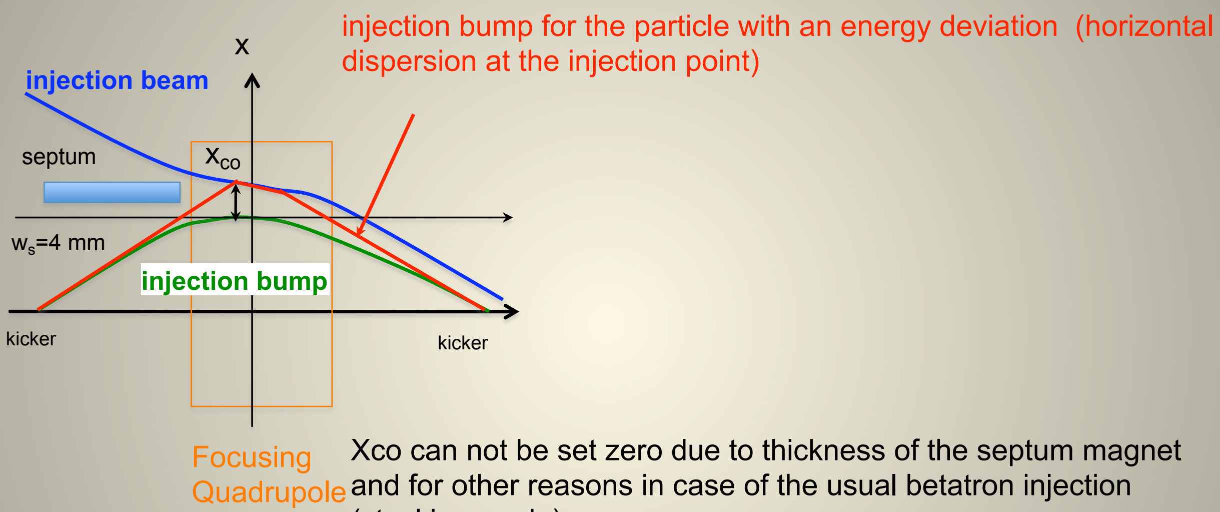
- Synchrotron phase space injection



The energy of injected beam is shifted to δ_0

Y.Funakoshi

Synchrotron injection scheme



Xco can not be set zero due to thickness of the septum magnet and for other reasons in case of the usual betatron injection (stacking mode).

In case of synchrotron injection, Xco can be zero but the synchrotron oscillation is induced, since the energy of the injected beam should be different from that of the stored beam.

VIVA SuperKEKB