Beam Dynamics in

Positron Injector Systems

for the Next Generation B Factories

8 Sep. 2011

IPAC2011 at San Sebastian, Spain

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for the SuperKEKB group

Next Generation B-factories

SuperB
Italy

SuperKEKB
Japan

These projects aim to increase,

Peak luminosity ~ 10^{36}

For realizing the super-high luminosities,
the injector improvements must be very important, especially in positrons.

S. Guiducci and A. Variola

WEZA02, H. Koiso

SuperB and SuperKEKB

Parameters of main (collider) ring	unit	SuperB	SuperKEKB	KEKB
Energy	GeV	6.7	4.0	3.5
Stored beam current	A	1.892	3.6	< 1.8
Number of bunches		978	2500	1580
Circumference	km	1.2584	3.016	3
Beam lifetime at collision	sec.	254	340	>6000

compensate the short life time

Beam-gas, Touschek, Radiative Bhabha.

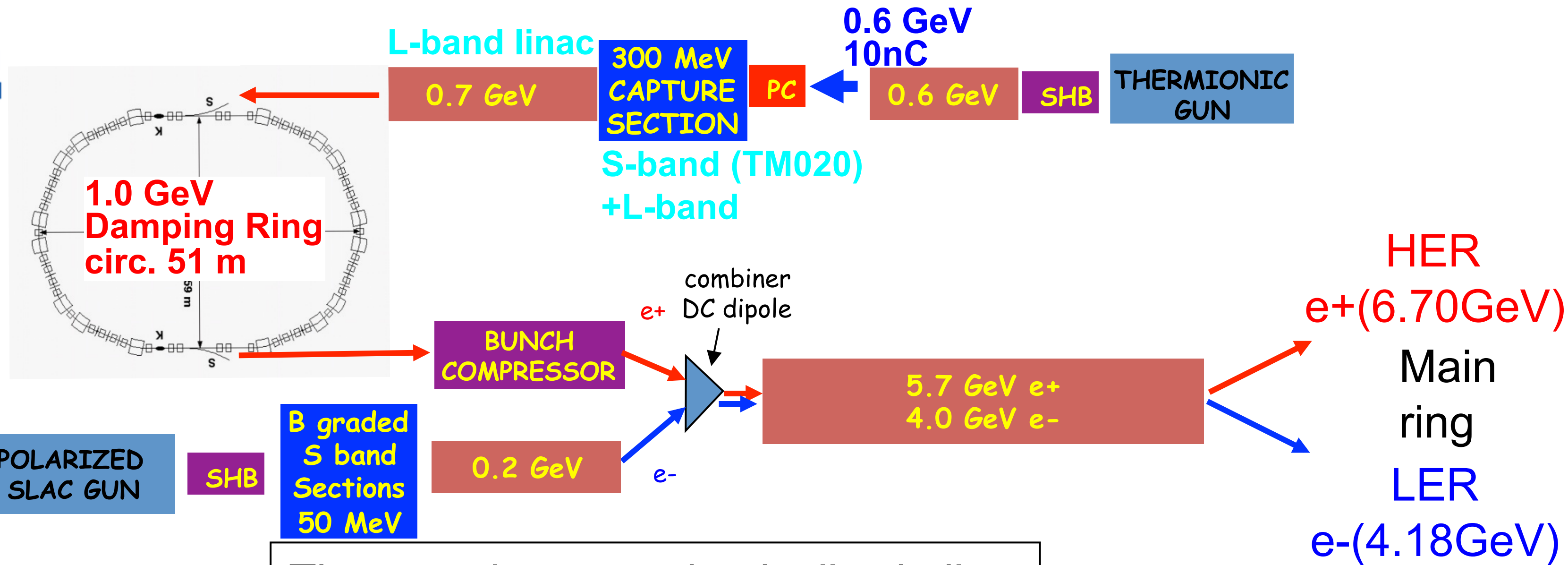
Parameters of injection beam	unit	SuperB	SuperKEKB	KEKB
Charge/bunch required from main ring	nC	0.65	2.1	0.15
Charge/bunch deliverable by injector	nC	0.5 – 2.0	4.0 (Max. 8.0)	1.0
bunch/pulse		1 (Max. 5)	2	2
Maximum repetition rate	Hz	100	50	25
Horizontal emittance (εx)	nm	4.1	12.5	300
Vertical emittance (εy)	nm	0.72 (κ = 1%)	0.26 (κ = 0%) 0.58 (κ = 5%)	200

We need even higher charge considering the refill from scratch as high as possible

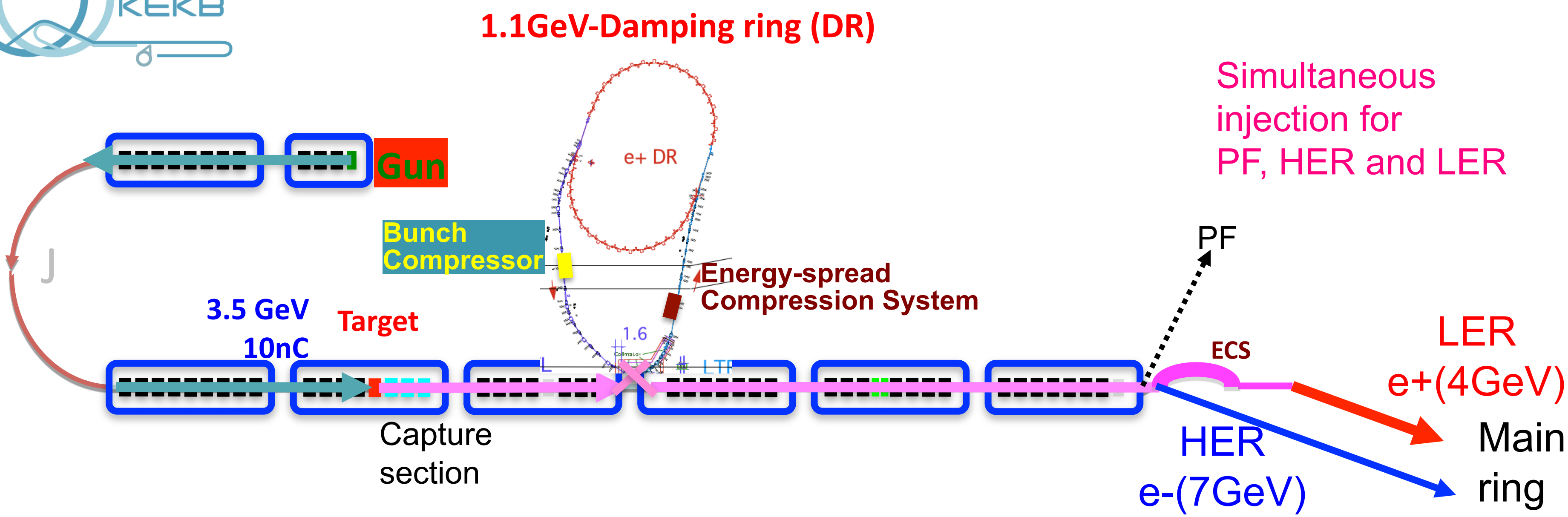
narrow physical and dynamic apertures of the collider ring

Higher charge and Lower emittance are required for both B-factories to achieve their Super-high luminosities.

Positron injector complex



The complexes are basically similar.



S. Guiducci and A. Variola

SuperB and SuperKEKB (2)

Parameters of Positron Injector	Unit	SuperB	SuperKEKB
Electron gun		Thermionic	Thermionic
Primary electron charge/bunch	nC	10	10
Primary electron energy	GeV	0.6	3.5
linac frequency before DR	MHz	L-band(TM020) 1428	S-band 2856
Energy compressor before DR		NO	YES
Energy of DR	GeV	1.0	1.1
Bunch compressor after DR		1	1
linac frequency after DR	MHz	C-band	S-band
Energy of the colliding ring	GeV	6.7 (HER)	4.0 (LER)
Nunber of Pulse-to-pulse injection		2	3

Bedises the primary electron energy, SuperB uses L-band accelerator before the DR, which make it possible to eliminate the ECS.

S. Guiducci and A. Variola

SuperB and SuperKEKB (3)

Parameters of injection beam for damping ring	Unit	SuperB	SuperKEKB
Charge (Maximum)	nC	2.0	8
Injected beam emittance	nm	1100	1400
Energy spread	%	1.5	5.0 → 1.5 (w ECS)

Very huge !

Parameters of damping ring	Unit	SuperB	SuperKEKB
Energy	GeV	1.0	1.1
Circumference	m	51.1	135.5
Equilibrium εx	nm	23	42.0
Equilibrium εy	nm	0.2(k=0.01)	0.95(k=0)/2.10(k=0.05)
Betatron damping time	ms	7.3	10.87
Momentum compaction		5.7×10^{-3}	1.41×10^{-2}
RF voltage	MV	0.5	1.4
Bucket height	%	2.5	1.5
Equilibrium energy spread		6.2×10^{-4}	5.5×10^{-4}
Bunch length (low current)	mm	4.8	6.57

Very low !

not very short !

S. Guiducci and A. Variola

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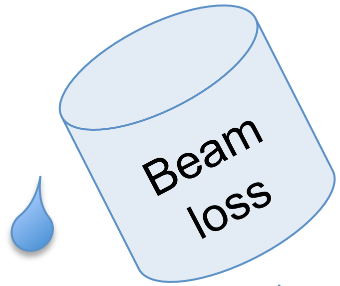
Our mission is to transport such high intensity beams without emittance growth and beam loss.

We can say that the issues are common for the two B-factories

Common Issues

1. From e+ target to Damping ring
   – Large amount of charge
   – Huge emittances (ε_x, ε_y, ε_z)
     • the huge positron beam causes the serious beam loss.



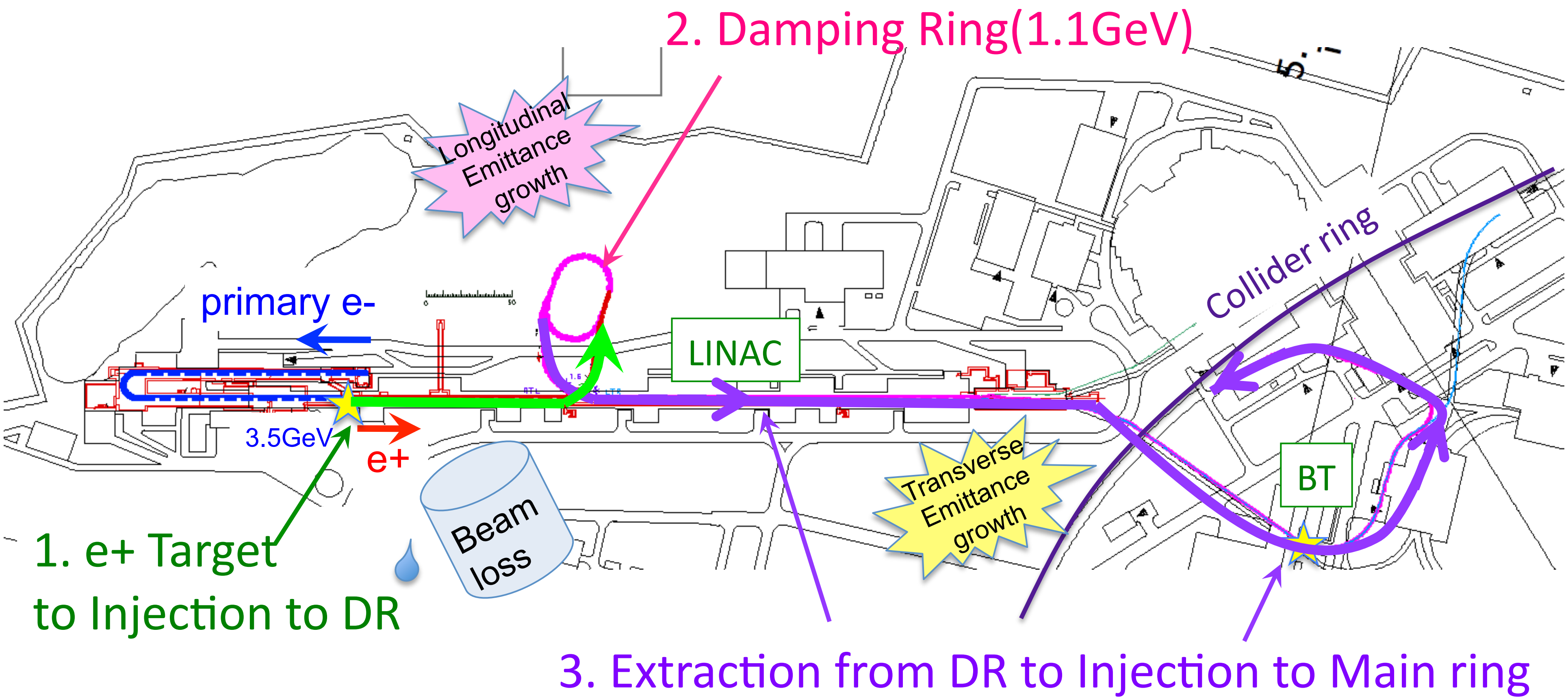
2. Damping ring
   – Microwave instabilities due to CSR will be a problem.
     • Because of the large beam pipe for capturing the large injection beam.

3. From Damping ring to Main ring
   – The beam should be transported keeping the low emittance.

For an example, the issues at SuperKEKB are presented today.

SuperKEKB

Positron Injector of SuperKEKB



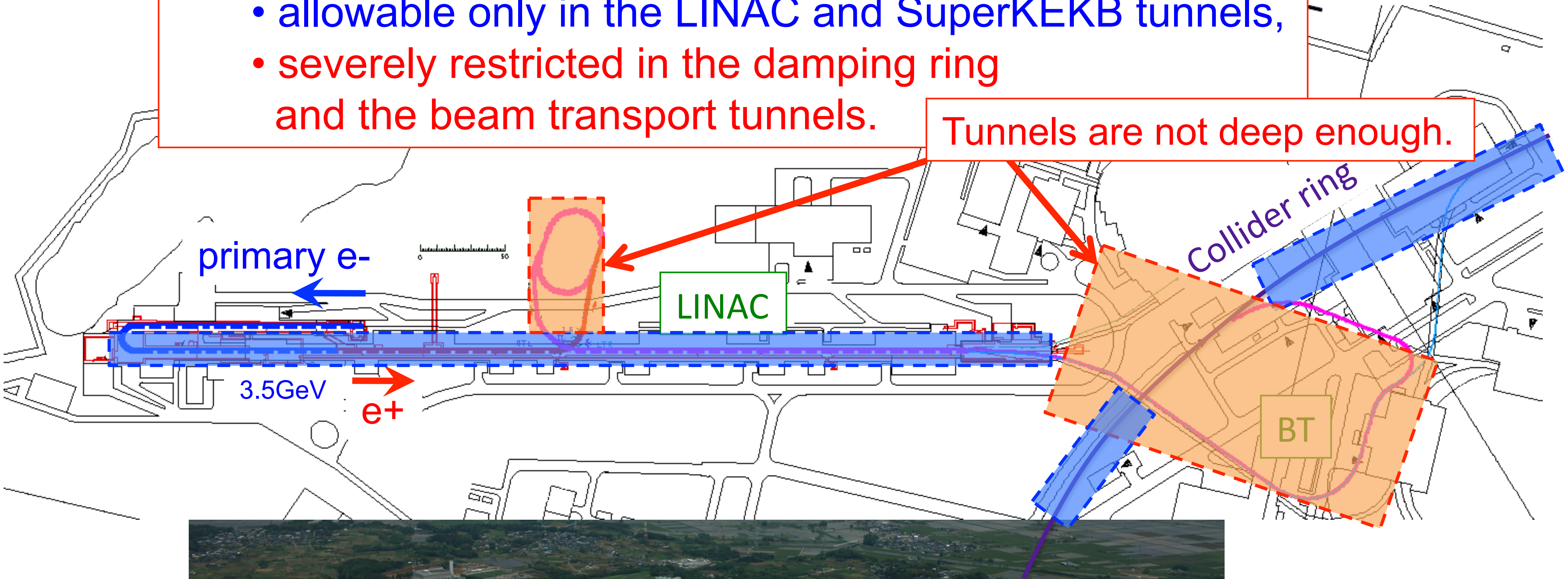
We did **the overall tracking simulation** from the e+ generation to Main ring injection, assuming 8nC charge.

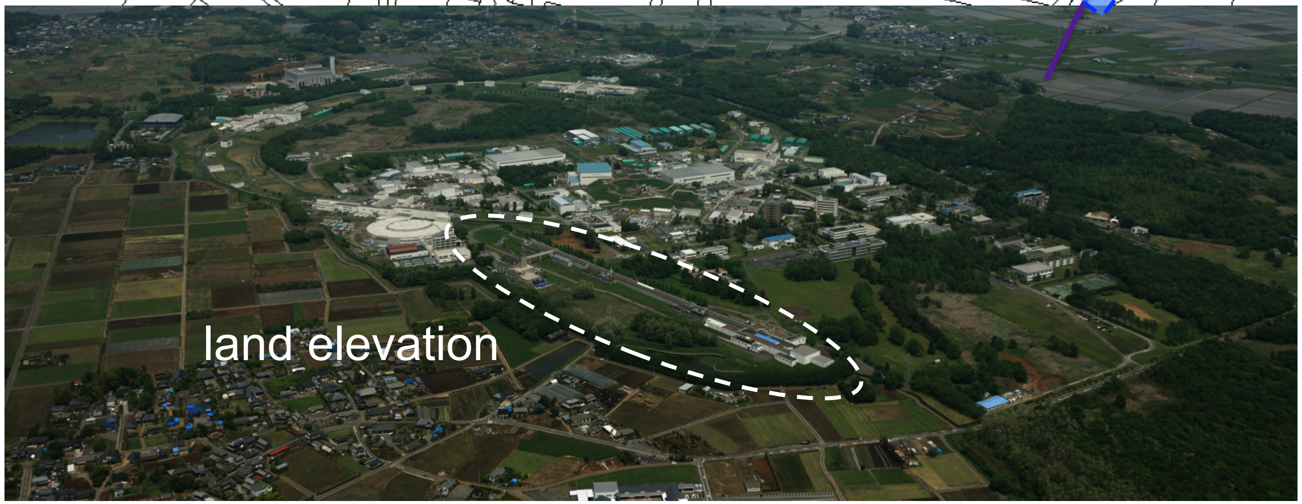
SuperKEKB has a very specific issue on,

Beam loss

Beam loss

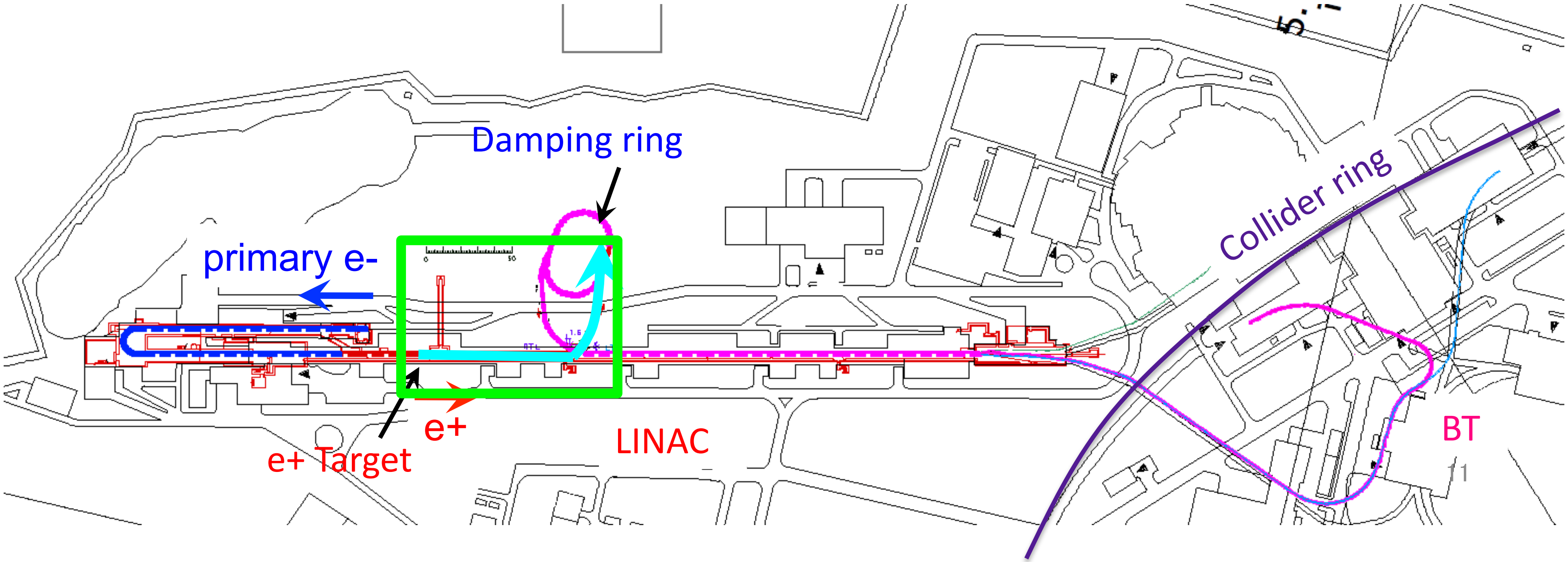
- allowable only in the LINAC and SuperKEKB tunnels,
- severely restricted in the damping ring and the beam transport tunnels.





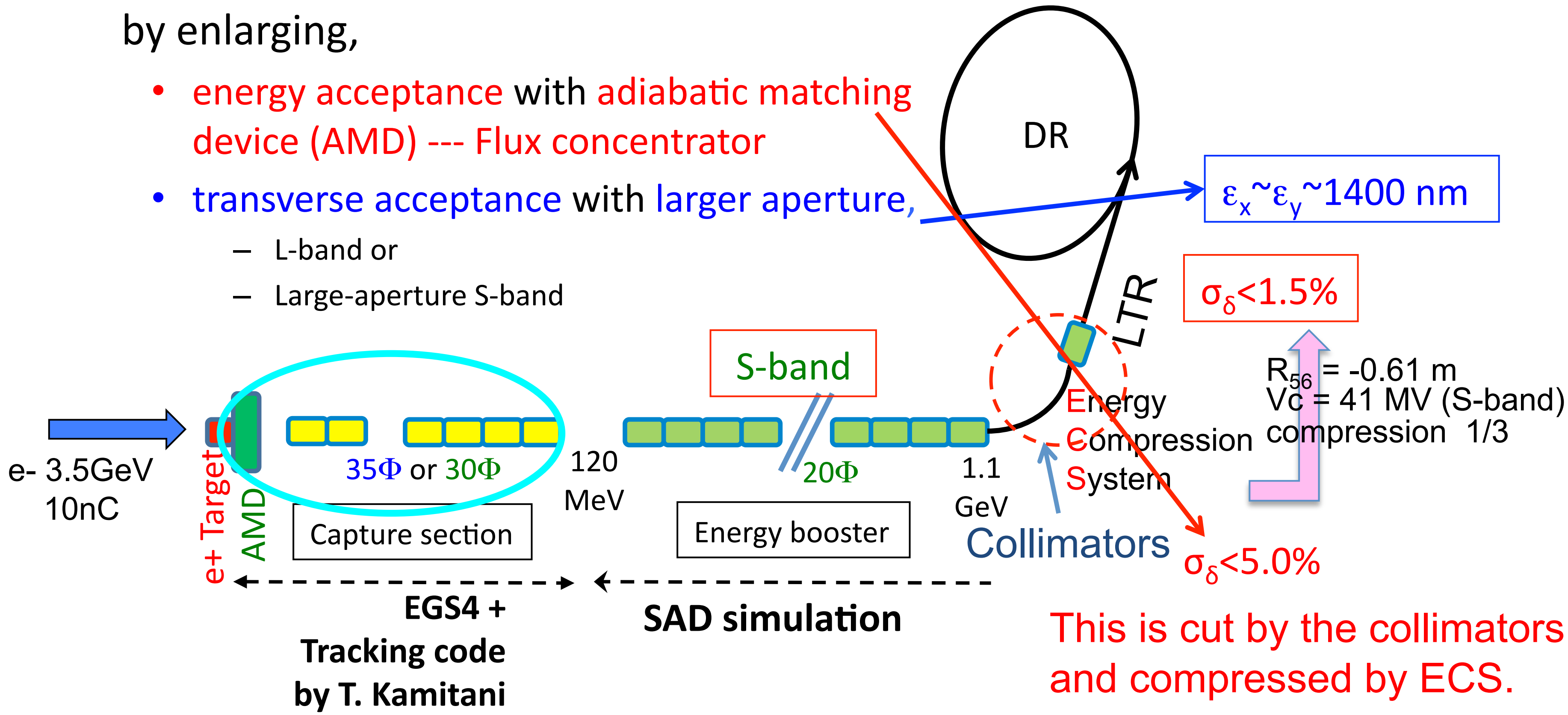
1. e^+ Target → Damping ring (DR)

is a main problem.



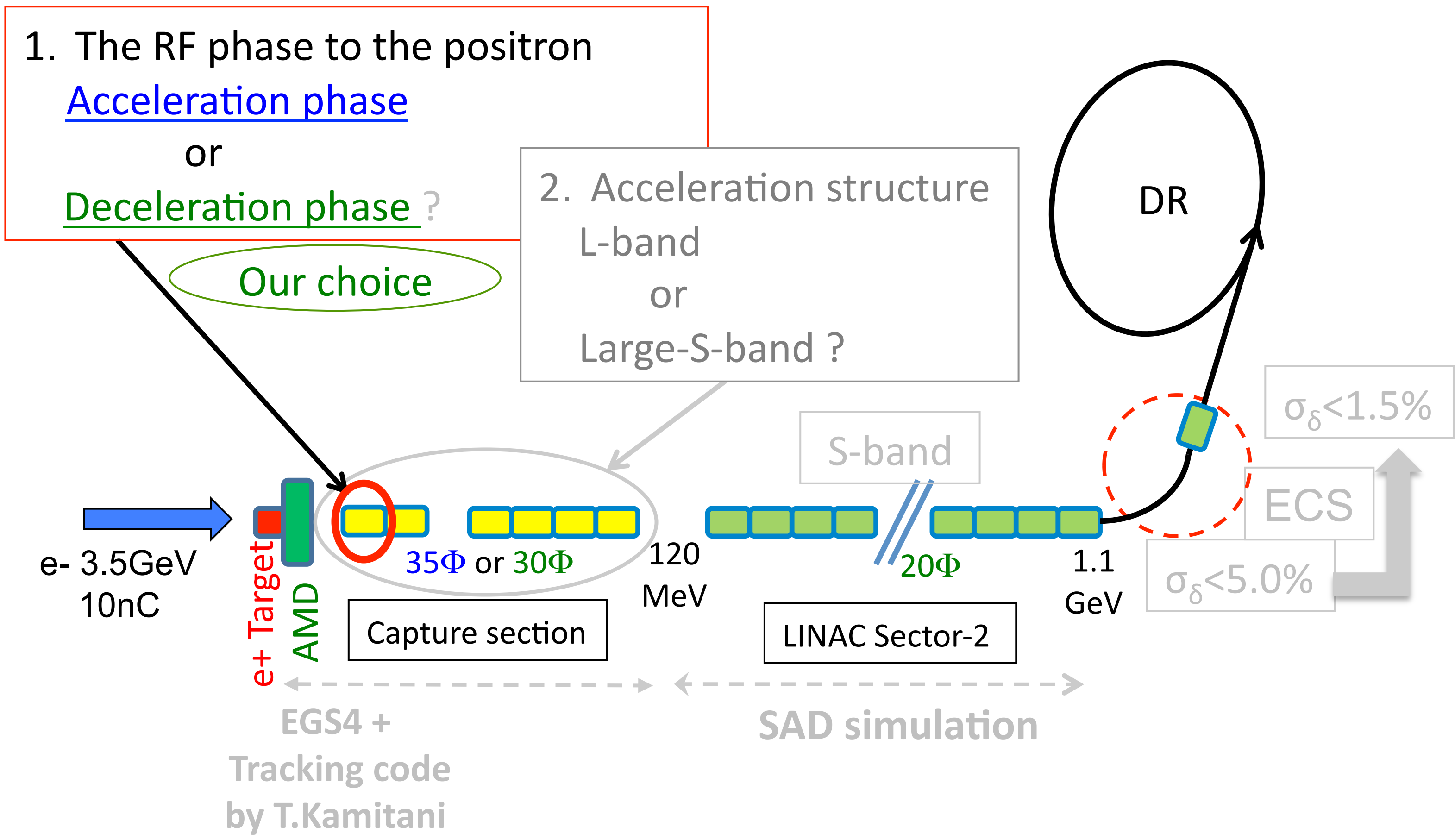
e+ Capture section — Entrance of DR

- Capture section
  - Positrons are captured as much as possible by enlarging,
    - energy acceptance with adiabatic matching device (AMD) --- Flux concentrator
    - transverse acceptance with larger aperture,
      - L-band or
      - Large-aperture S-band



e+ Capture section

There are two subjects to make decision:



Watch the movies at: http://research.kek.jp/people/iida/THYA01_talk_movie.ppt

Target – Capture section

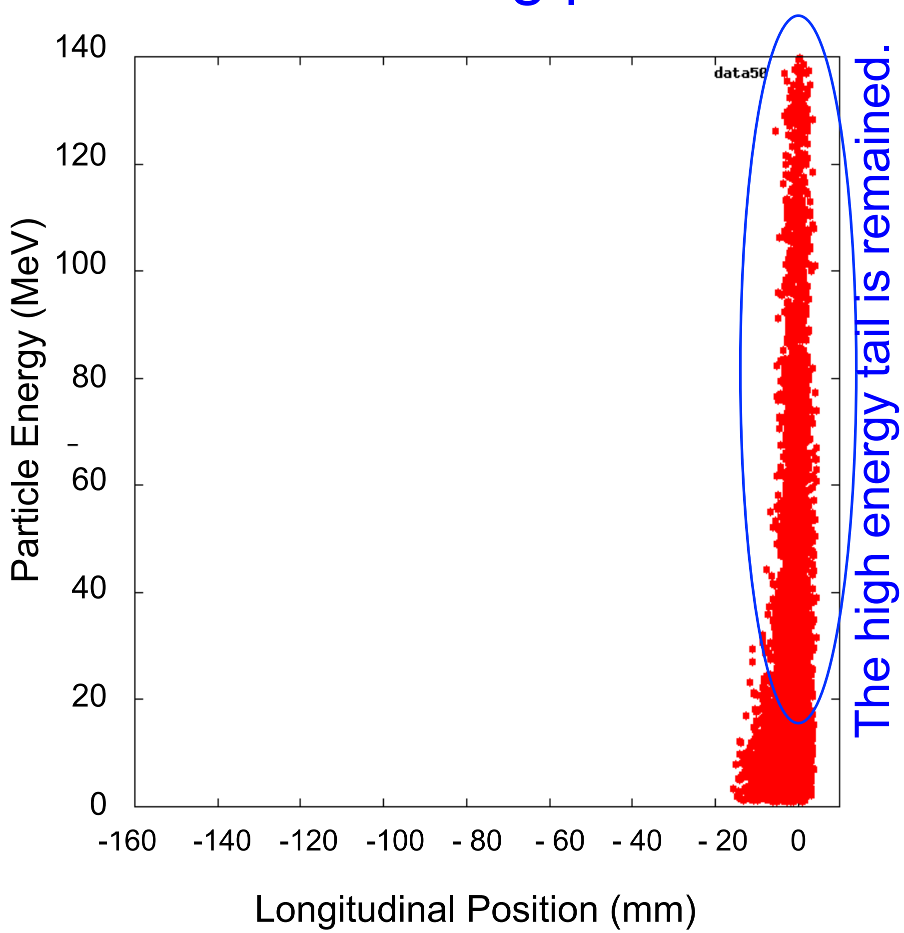
T. Kamitani

Phase of the positron to the RF frequency

The positrons are decelerated to very low velocity, and the RF slips to the next acceleration phase.

120 MeV

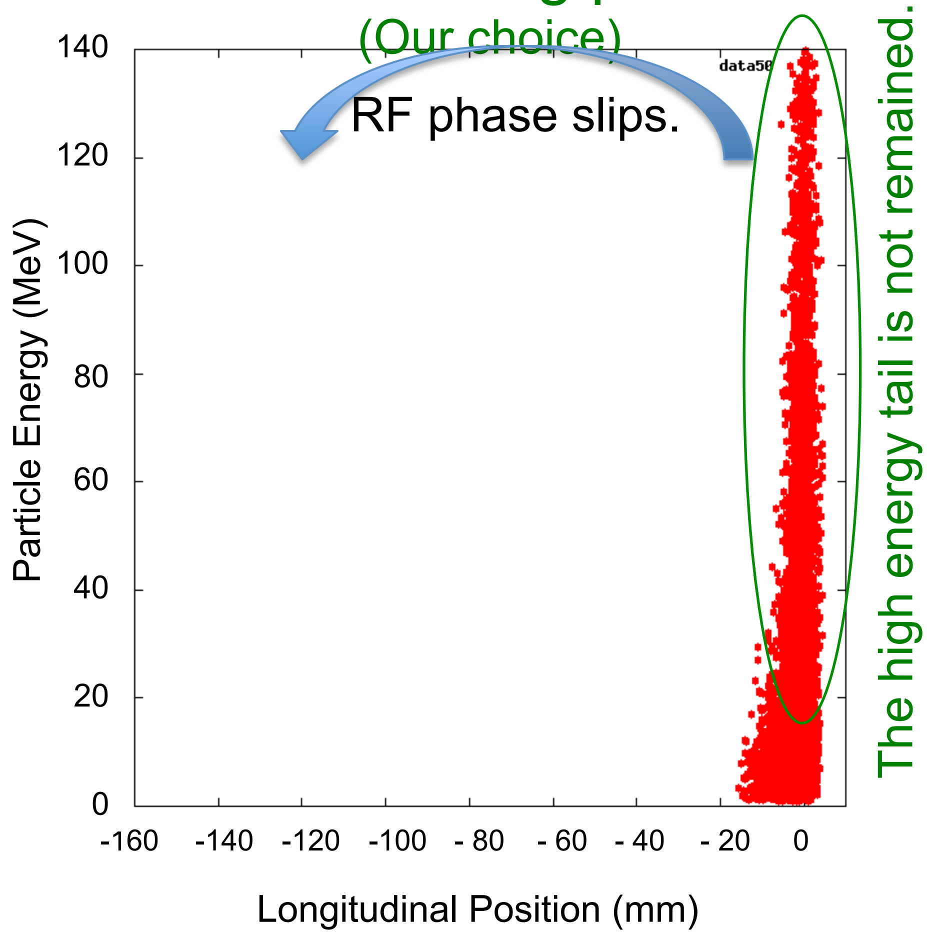
Accelerating phase



Decelerating phase

(Our choice)

RF phase slips.



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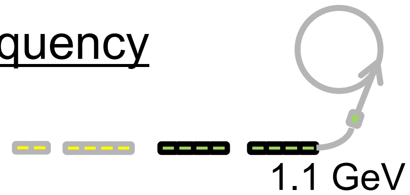
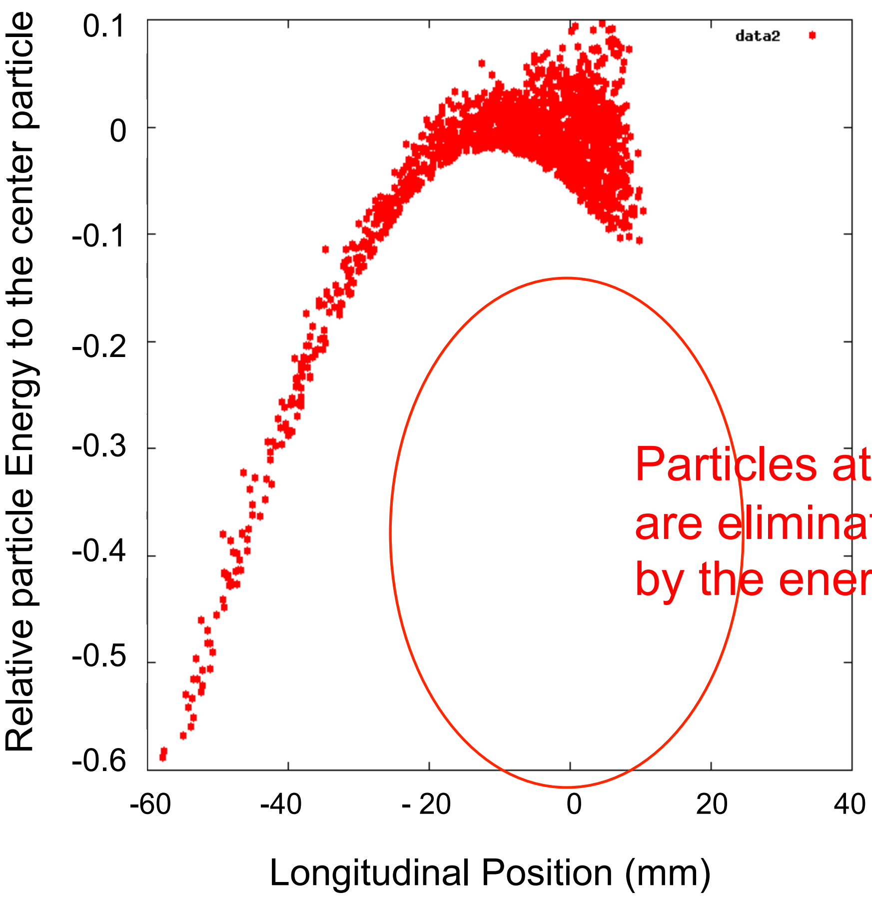
e+ acceleration 0.12 to 1.1 GeV

T. Kamitani
and N.Iida

Phase of the positron to the RF frequency

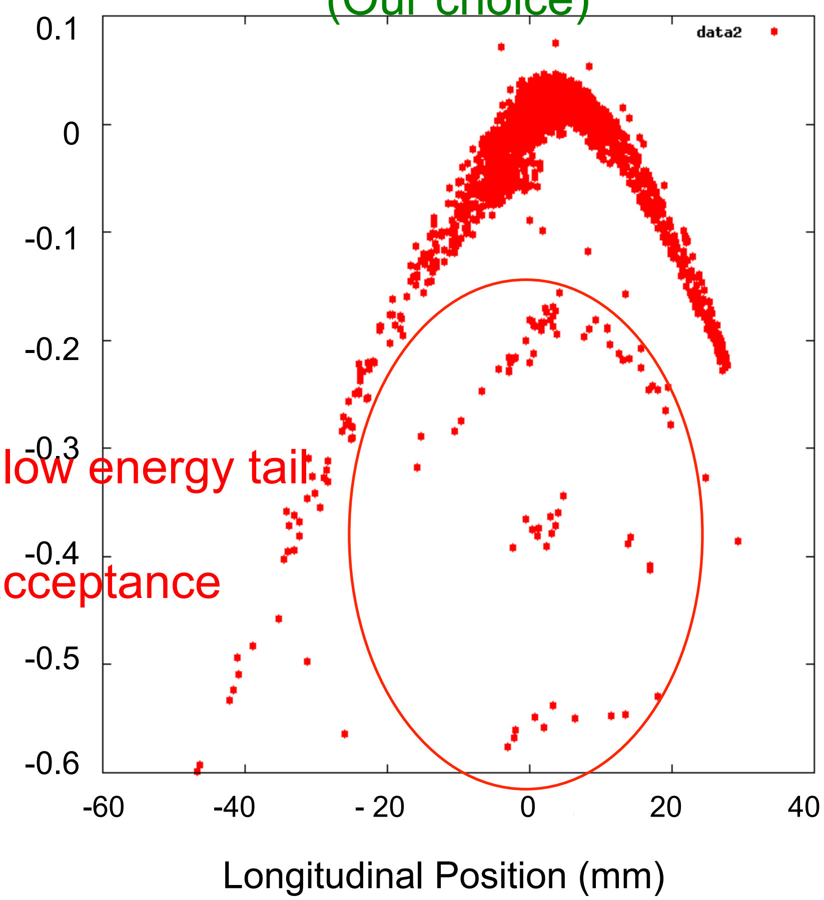


Accelerating phase



Decelerating phase

(Our choice)



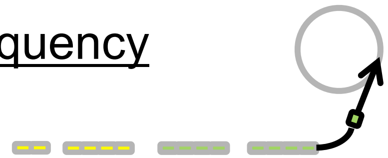
Particles at the low energy tail
are eliminated
by the energy acceptance

Watch the movies at: http://research.kek.jp/people/iida/THYA01_talk_movie.ppt

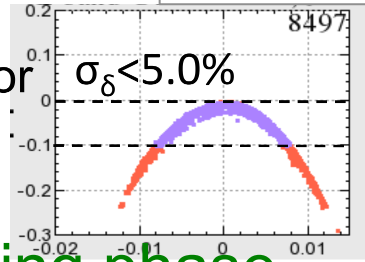
T. Kamitani and N.Iida

Energy Spread Compression

Phase of the positron to the RF frequency

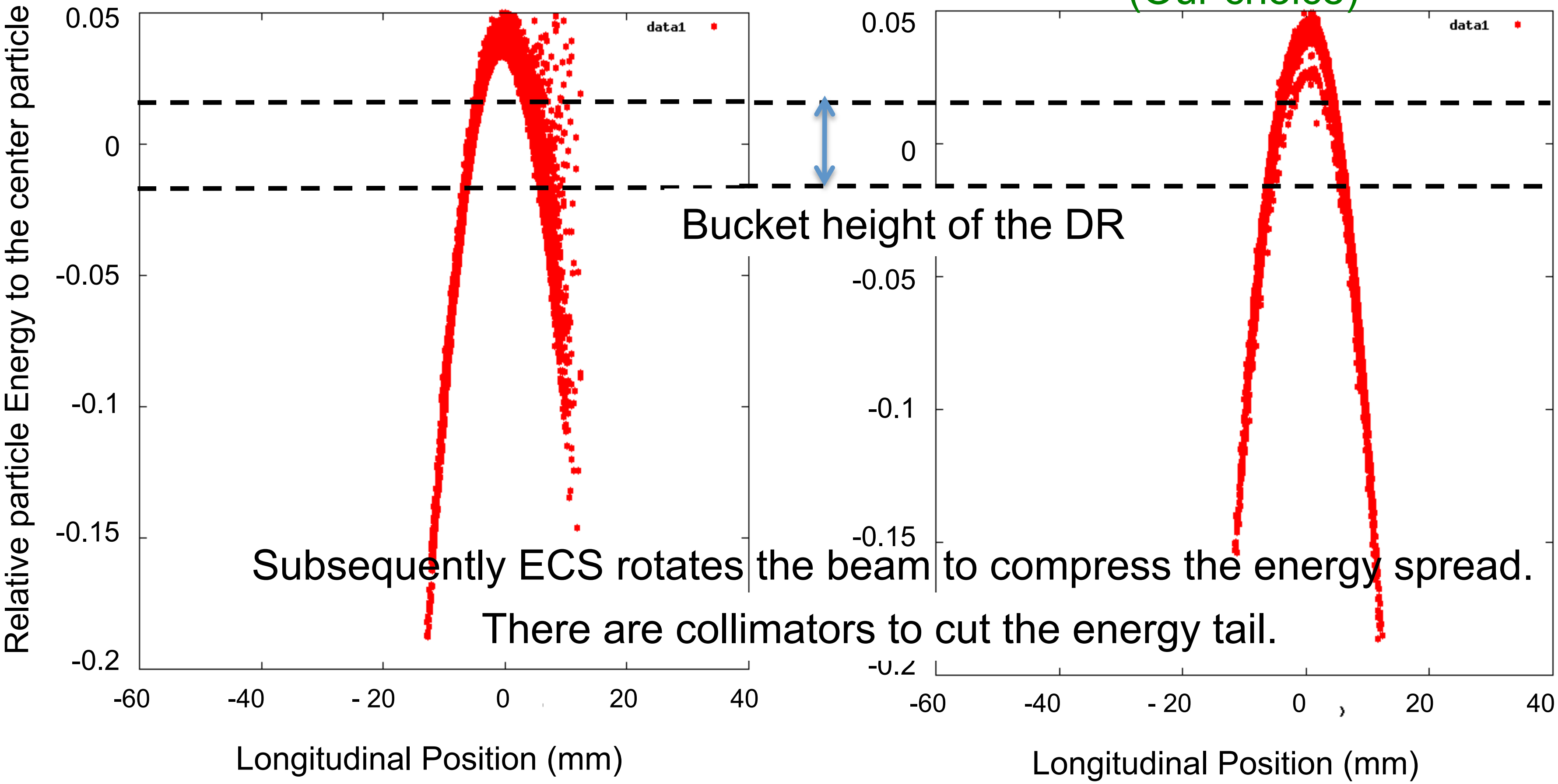


Collimator



Accelerating phase

Decelerating phase
(Our choice)



Subsequently ECS rotates the beam to compress the energy spread.

There are collimators to cut the energy tail.

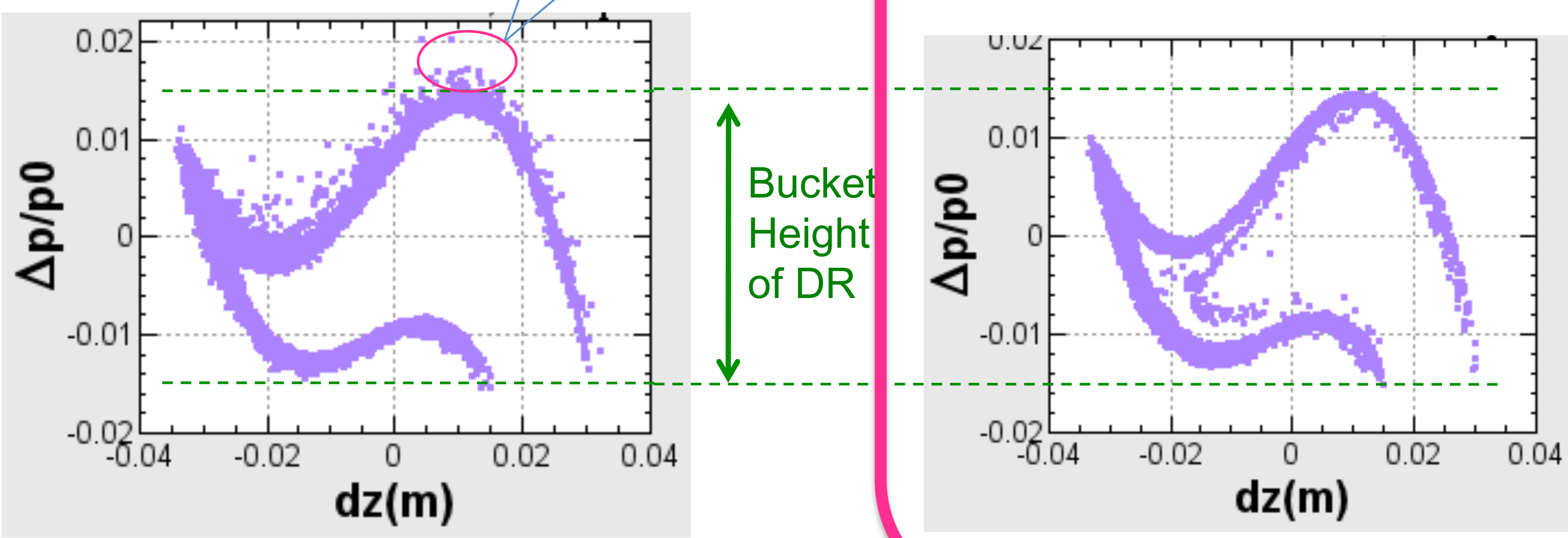
Comparison of Acceleration and Deceleration phases
in the longitudinal phase space

The entrance of DR

There are still long high-energy tail

"Acceleration phase"

"Deceleration phase"

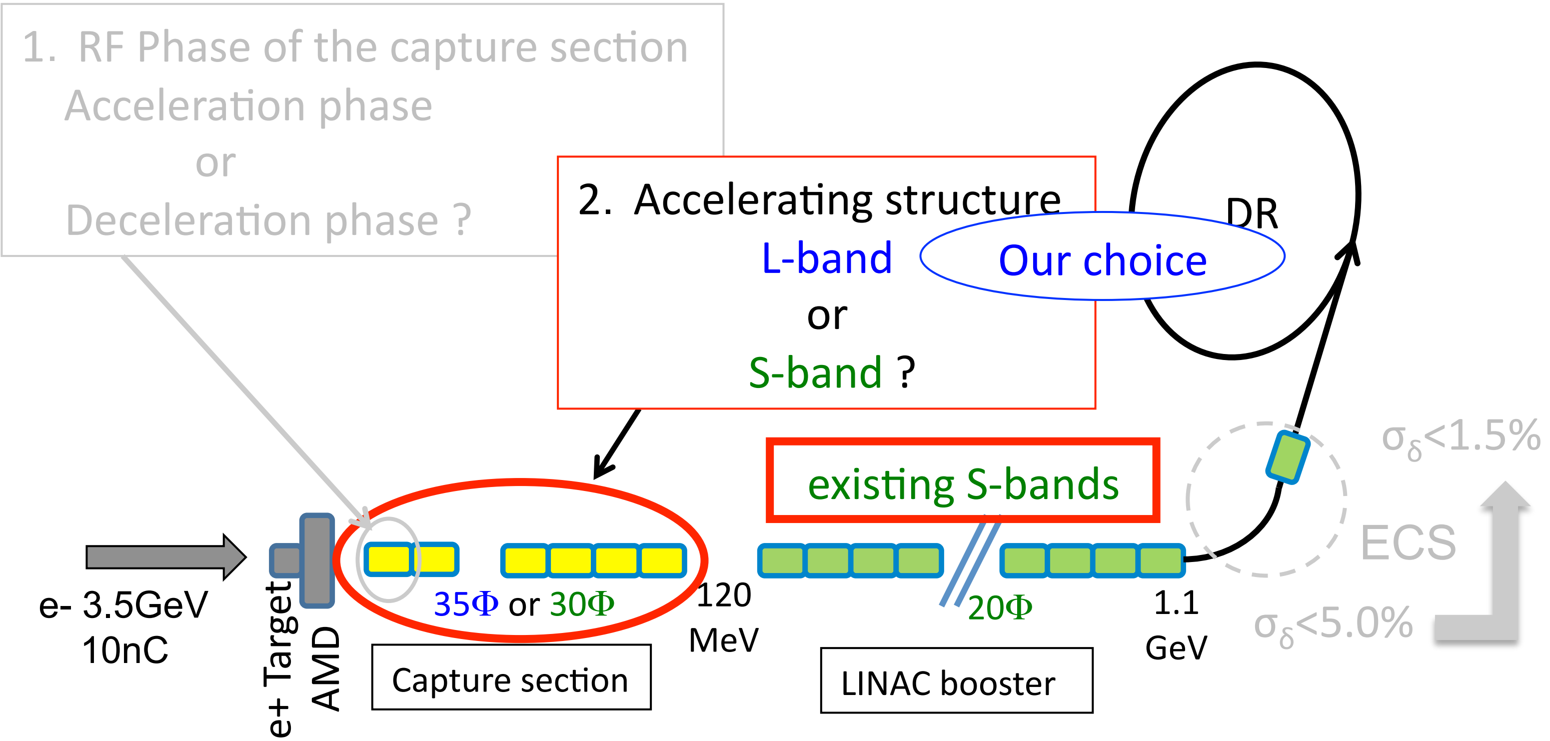


Charge: 6.75 nC

Charge: 6.59 nC

We chose "Deceleration phase"

e+ Capture section — Entrance of DR



In SuperKEKB,

L-band	1298 MHz
S-band	2856 MHz

$f_L : f_S = 5:11$
Coprime ratio

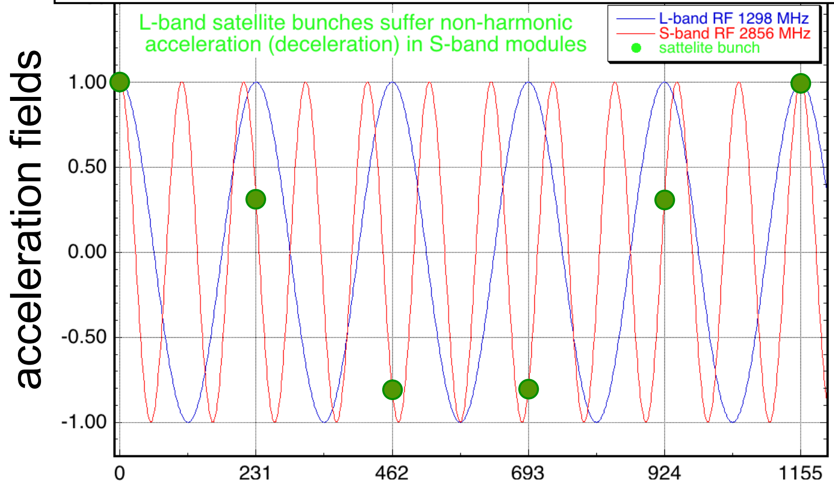
The important thing is that the L-band is not just the half of S-band, but 5/11 of the S-band frequency.
As we have to use the existing S-band linac as much as possible, the downstream accelerating structures must be S-band, anyway.

Satellite bunch elimination

a) Satellite bunches (delayed particles) generated in the capture section make beam loss in the DR injection.

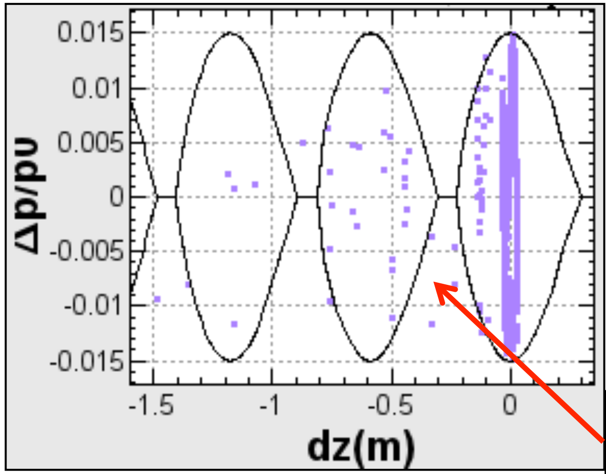
b) Choosing a coprime (**5:11**) frequency ratio of L-band (1298 MHz) and downstream S-band (2856MHz), most of the L-band satellites are eliminated by the S-band acceleration in LINAC.

L-band satellite bunches suffer non-harmonic acceleration (deceleration) in S-band modules



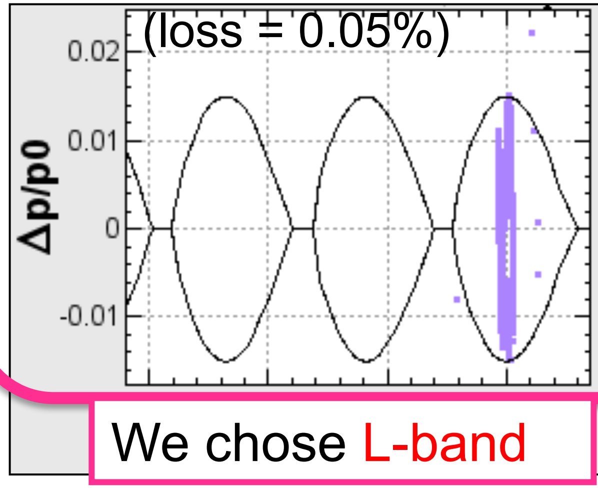
At entrance of DR

a) only S-band case (loss = 0.40%)



particles outside the separatrix are lost at DR

b) L + S-band combination case (loss = 0.05%)



We chose L-band

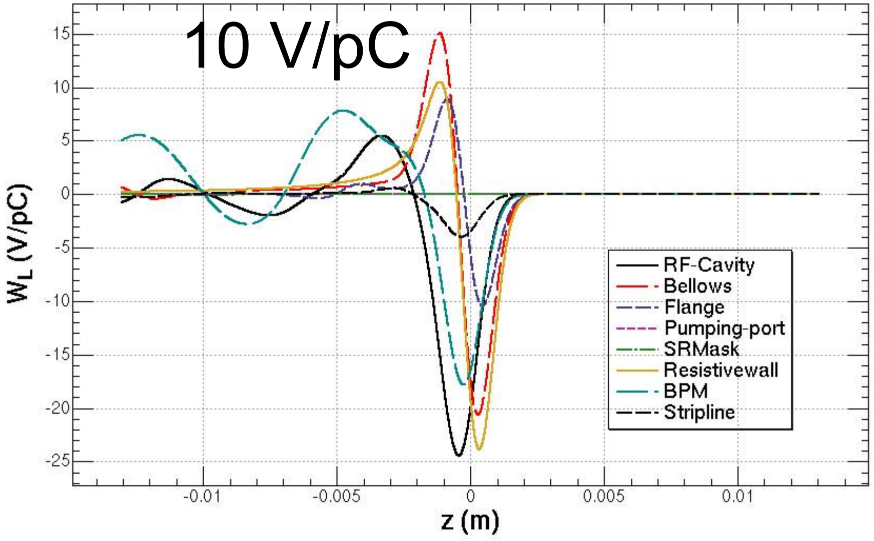
2. Damping ring (DR)

Microwave instability due to CSR

- One of the most serious common issue to e+ damping rings with high bunch charge.
- That is because we need high bunch charge, which has
  - ➢Large injection emittance from e+ production, which needs
    - ➢Large beam pipe in the ring, which increase
      - ➢Large CSR, causing
        - ➢Microwave instability, resulting
          - ➢$\sigma\delta$, σz blowup

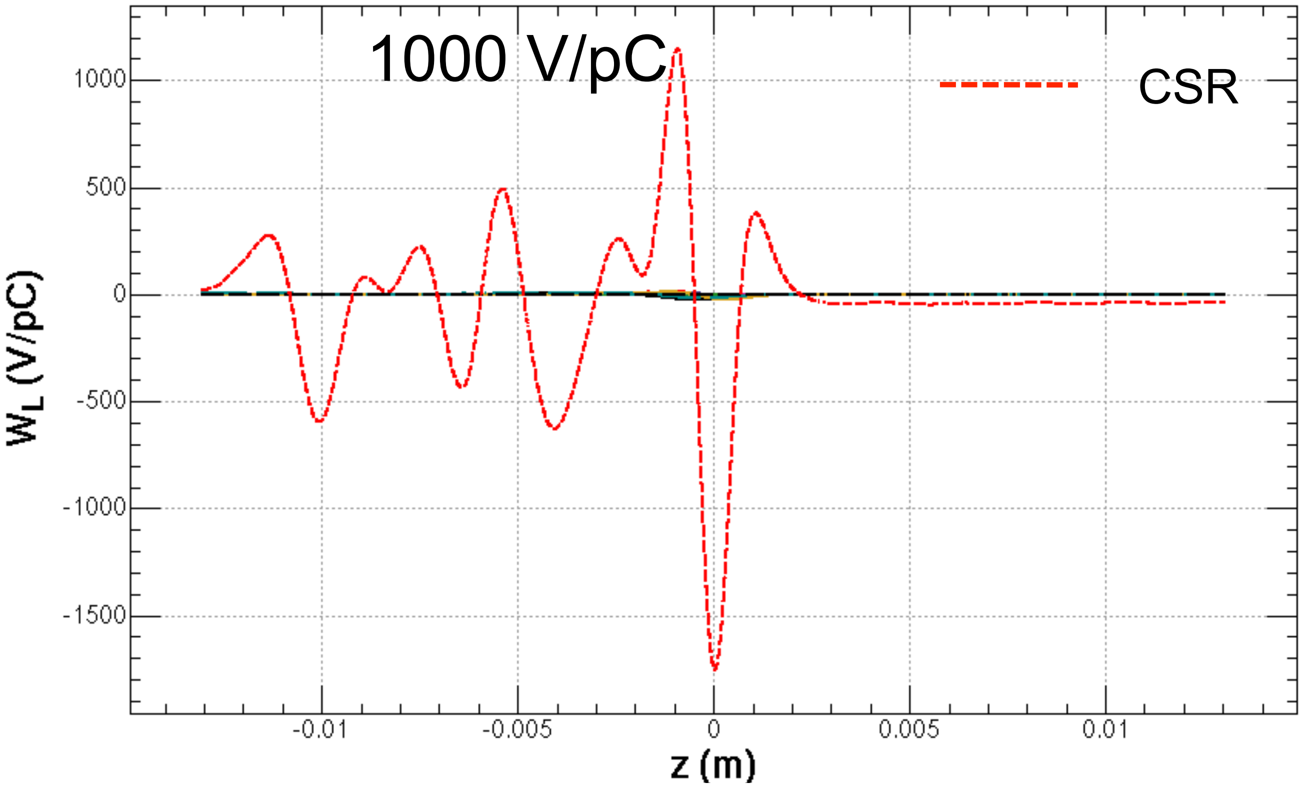
↓

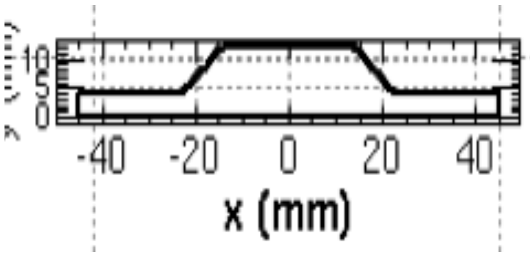
It may be very relevant to the positron damping rings, including SuperB, ILC, CLIC, etc…



• The usual wake potentials of the various components of the DR are not serious.
• The wake potential due to CSR is two-orders larger than the others.

Shape of the chamber
Vertical aperture: ±12mm





Antechamber is necessary to suppress the electron cloud.

Enlargements of σ_δ and σ_z due to CSR in DR

- Tracking simulation with 5M macro particles -

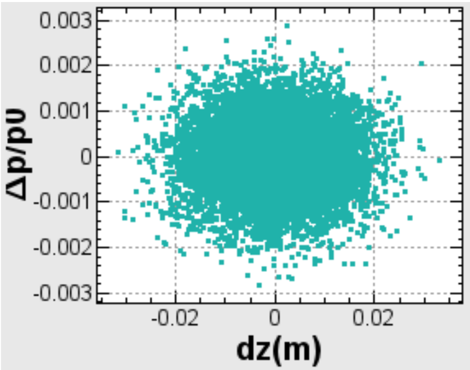
This afternoon !

THPZ021

H. Ikeda and K.Oide

Initial beam:

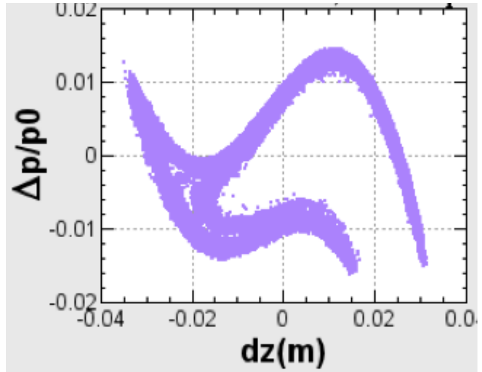
a) Damped beam in DR with Gaussian shape



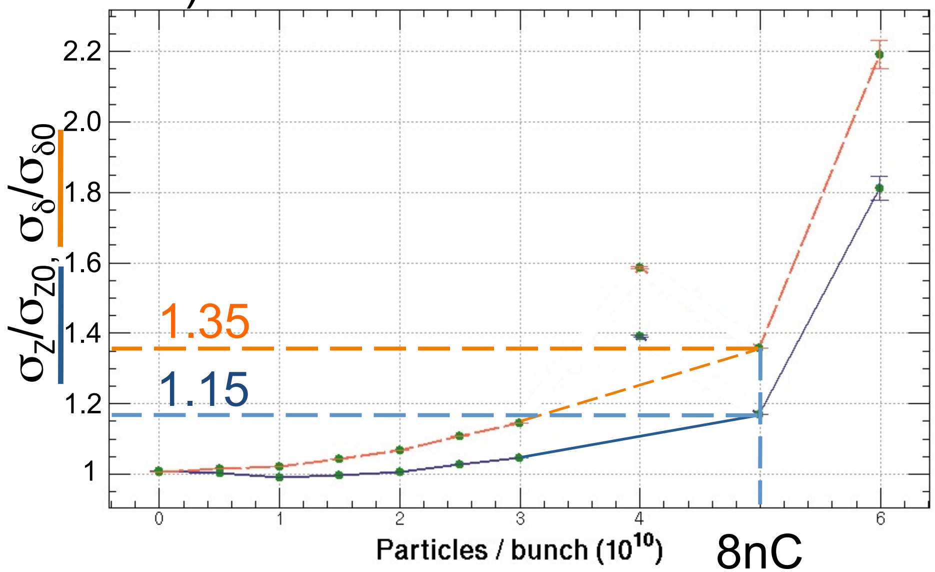
- The resulted bunch length and energy spread are somewhat different.
- The quasi-equilibrium states depend on the initial beam distribution !

Not on the energy spread

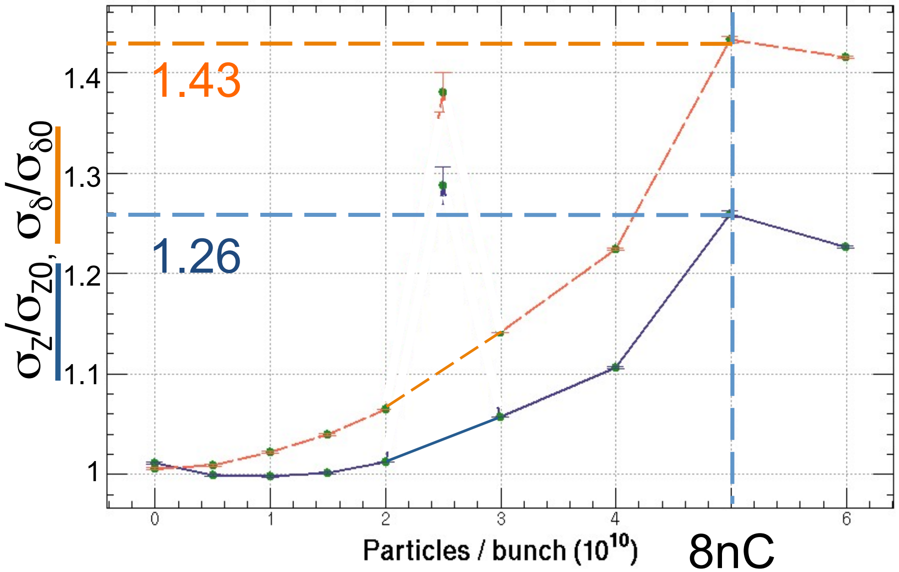
b) Beam from Linac



a)



b)

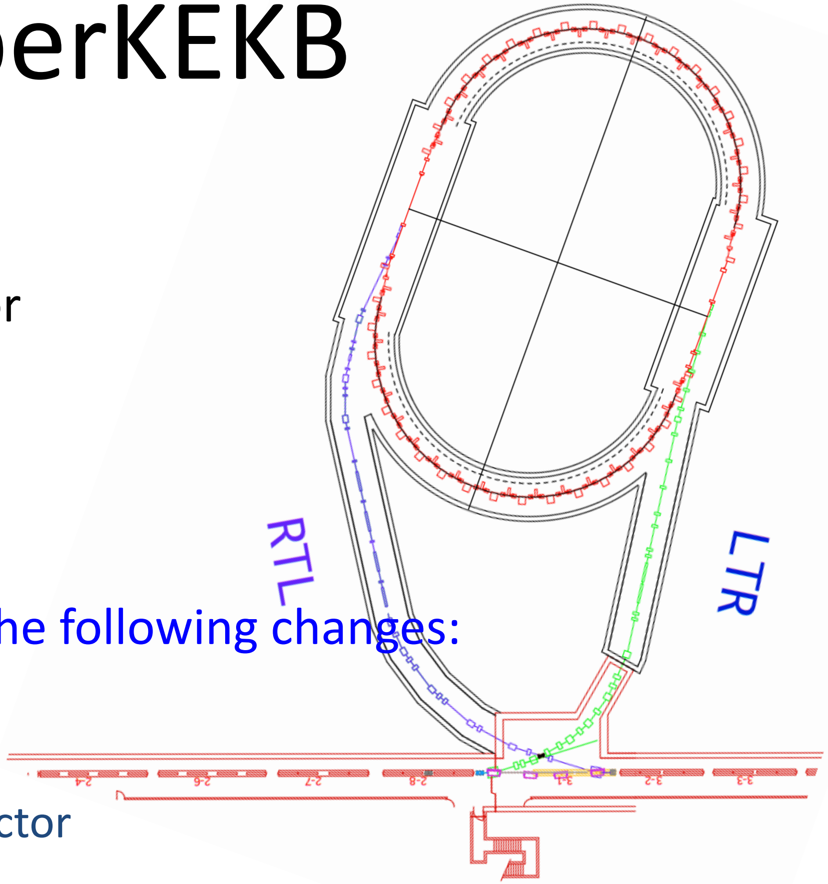


Anyway these enlargements of bunch length and energy spread are within acceptable range for the injection.

A quadrupole oscillation appears around 2.5 1010 to make the damping slower.

M.Kikuchi

DR of SuperKEKB

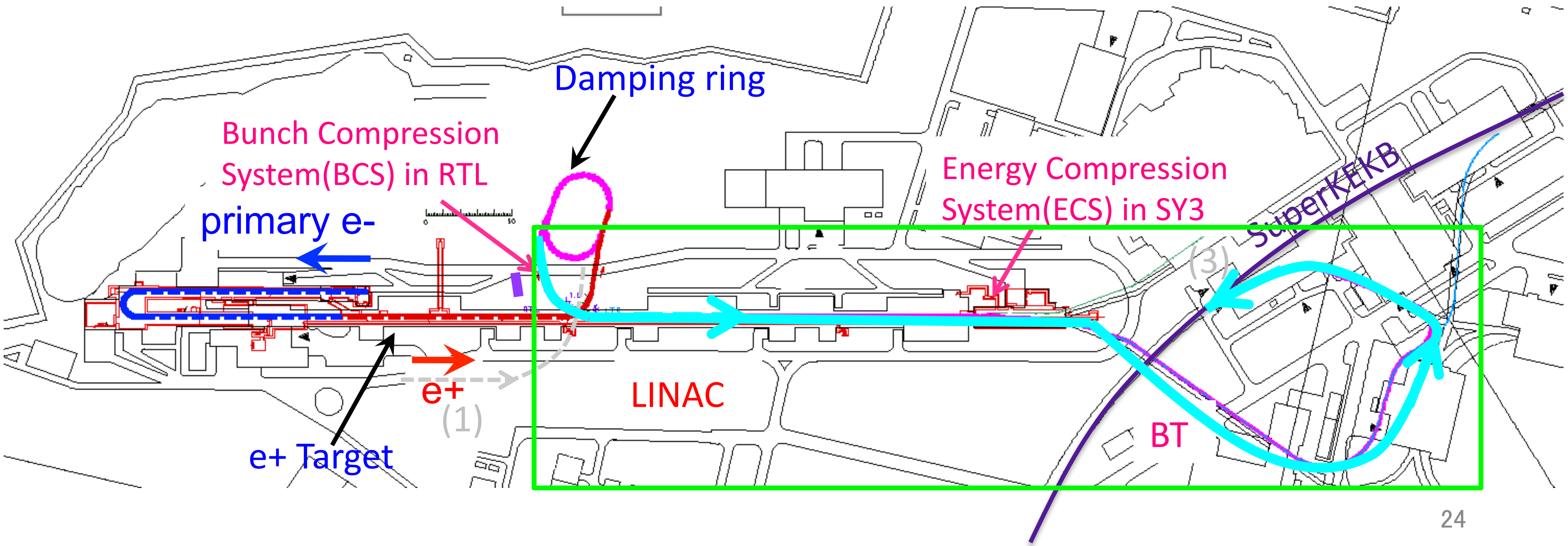


- Reversed-bend FODO cell
  - Low momentum compaction factor
  - Wide momentum aperture
- Large Coherent Synchrotron Radiation (CSR) effects
  - This isuue has been mitigated by the following changes:
    - Higher beam energy
      - 1.0GeV → 1.1GeV
    - Larger momentum compaction factor
      - 0.0019 → 0.0141
    - Higher cavity voltage for higher synchrotron tune
      - 0.261MV → 1.4MV
    - Reduce the vertical aperture of chamber
      - 34mm → 24mm

Microwave Instability By CSR

3. Damping ring (DR) → Main Ring (LER)

The damped emittance should be preserved to the entrance of the main ring.



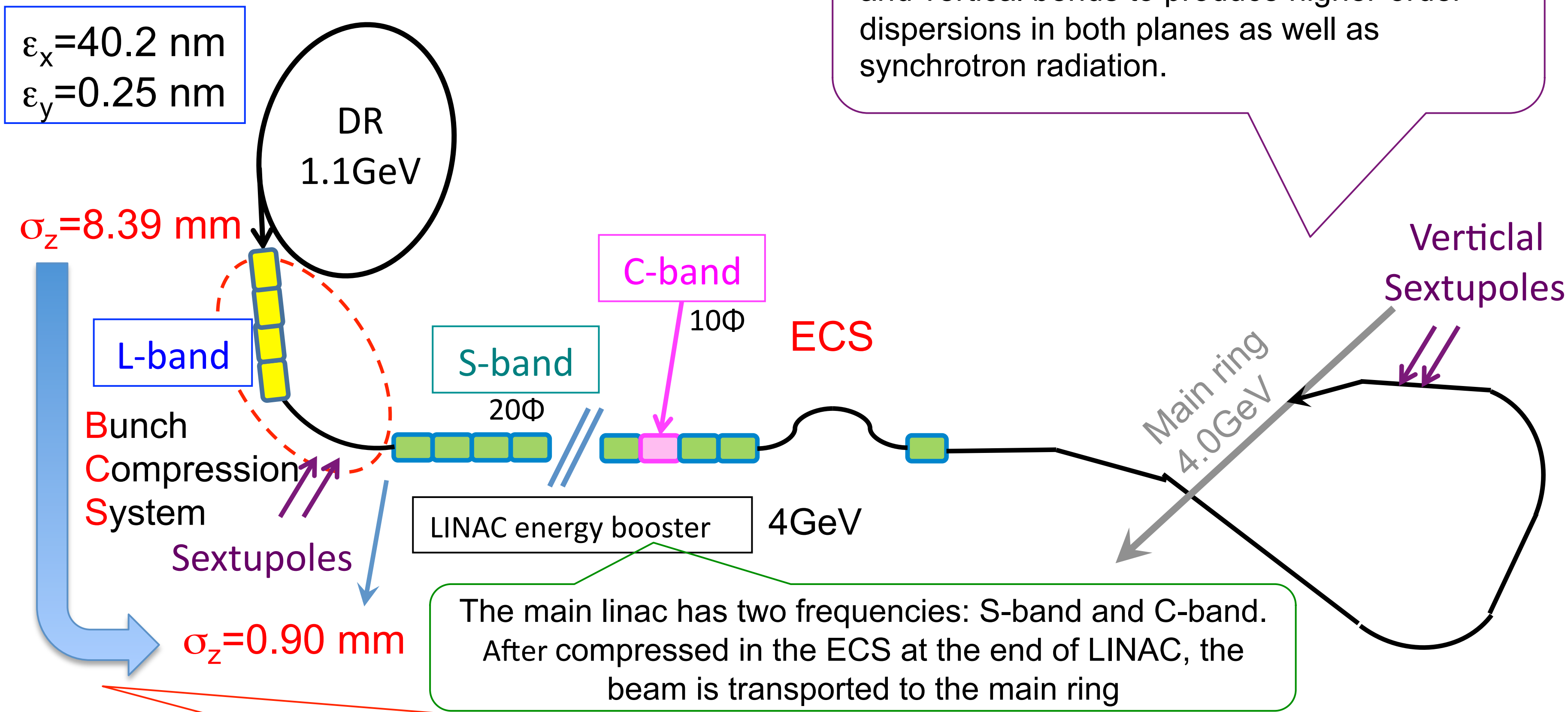
DR - Entrance of LER

e+ beam from DR:

Transverse emittance is small.

Bunch length is not so short yet.

The transport line has a number of horizontal and vertical bends to produce higher-order dispersions in both planes as well as synchrotron radiation.



The bunch length is one-order reduced by the BCS to match the S-band frequency of the linac.
We should use an L-band accelerating structure for longitudinal focusing such a long bunch.

Various sources of Emittance growth
after the Damping Ring

8 nC

- Longitudinal bunch gymnastics
  - Adjusting RF-phases to compensate the beam loading by the RF-curvature.
- Transverse emittance blows up at least by;
  1. Misalignments of accelerating structures and quadrupoles
  2. Second-order dispersion in the transport line
  3. Synchrotron radiation at the beam transport line
  4. Beam-beam effect after the injection to the colliding ring

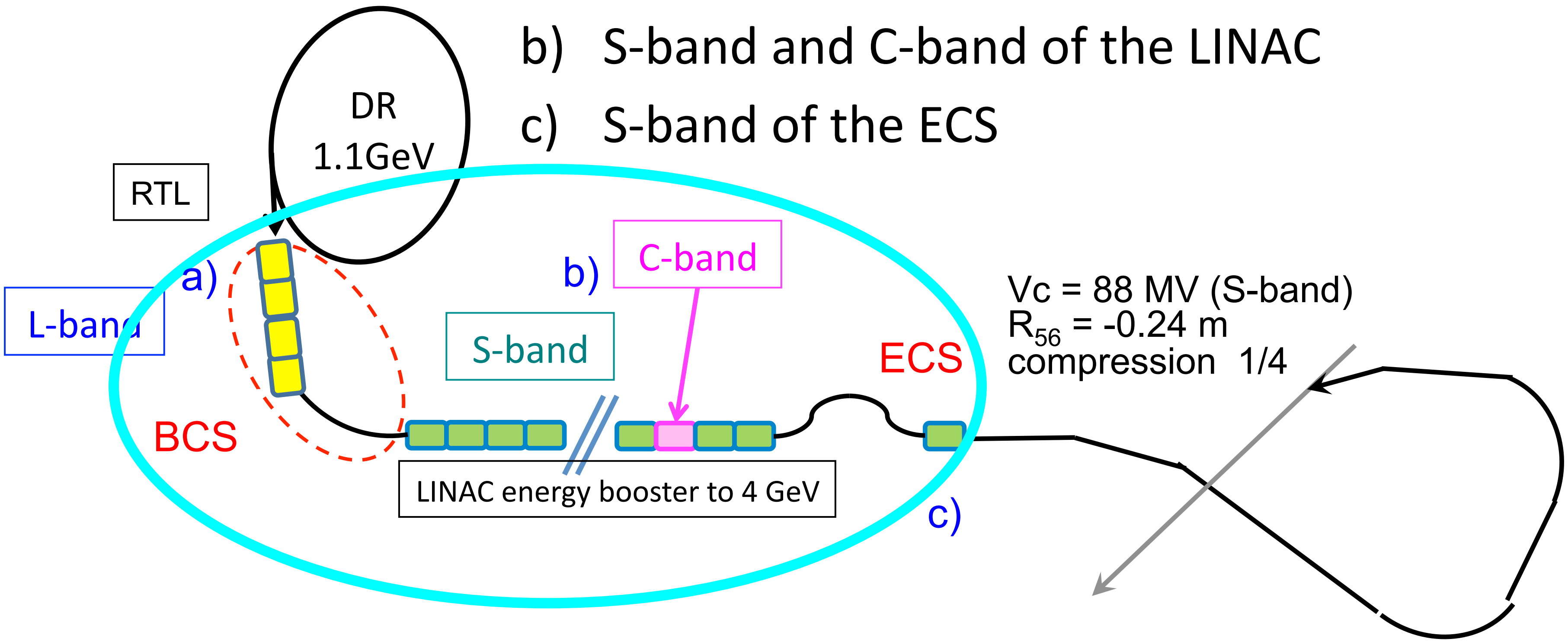
Minimization of Energy spread

Longitudinal Emittance growth

8 nC

In our simulation, the wake effects are calculated using K. Yokoya's approximated formula.

- We should adjust the three parts of the RF phases:
  a) L-bands of the BCS
  b) S-band and C-band of the LINAC
  c) S-band of the ECS

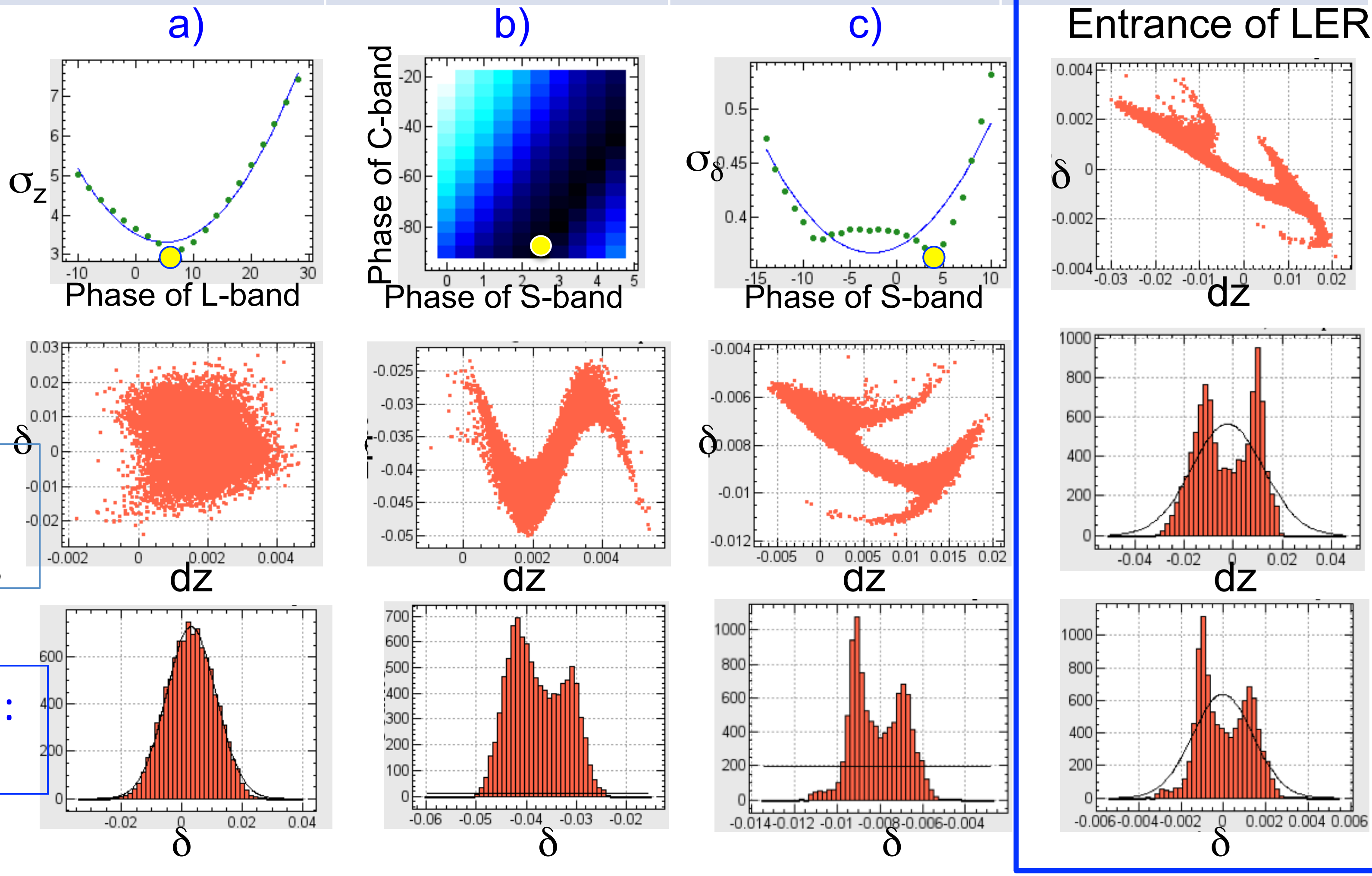


Optimization of acceleration phase

for minimization of the energy spread

Tuning knob	a) L-band of BCS	b) S,C-band in LINAC	c) S-band of ECS	
Place	Entrance of LINAC	End of LINAC	Exit of ECS	Entrance of Main eing
σz [mm]	±0.896	±2.15 (99% incl.)	±10.87 (99% incl.)	±21.93 (99% incl.)
σδ [%]	±0.825	±1.13 (99% incl.)	±0.271 (99% incl.)	±0.271 (99% incl.)

8nC



By these careful adjustments

Transmission: 100%

Optimization of acceleration

for minimization of the energy sprea

The widths of energy and bunch length are acceptable level for injection to LER.

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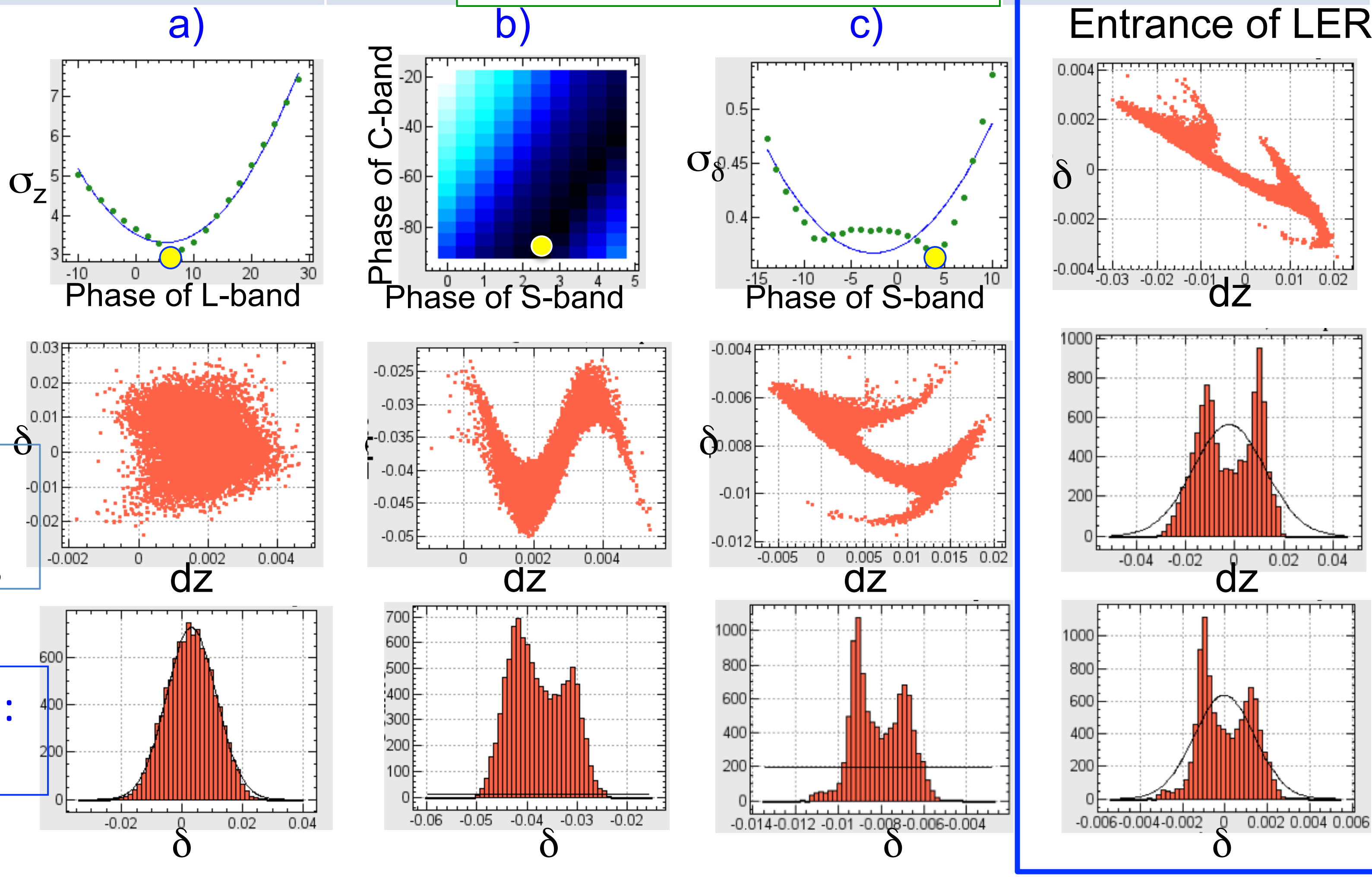
Place	Entrance of LINAC	End		Entrance of Main eing
σz [mm]	±0.896	±2.15		±21.93 (99% incl.)
σδ [%]	±0.825	±1.13		±0.271 (99% incl.)

The scanning shape is not parabola at the bottoms, which are for their strange distribution, not Gaussian shape.

8nC



By these careful adjustments

Transmission: 100%

Various sources of Emittance growth
after the Damping Ring

8 nC

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  - Adjusting RF-phases to compensate the beam loading.
- Transverse emittance blows up at least by;
  1. Misalignments of accelerating structures and quadrupoles
  2. Second-order dispersion in the transport line
  3. Synchrotron radiation at the beam transport line
  4. Beam-beam effect after the injection to the colliding ring

Transverse emittance growth

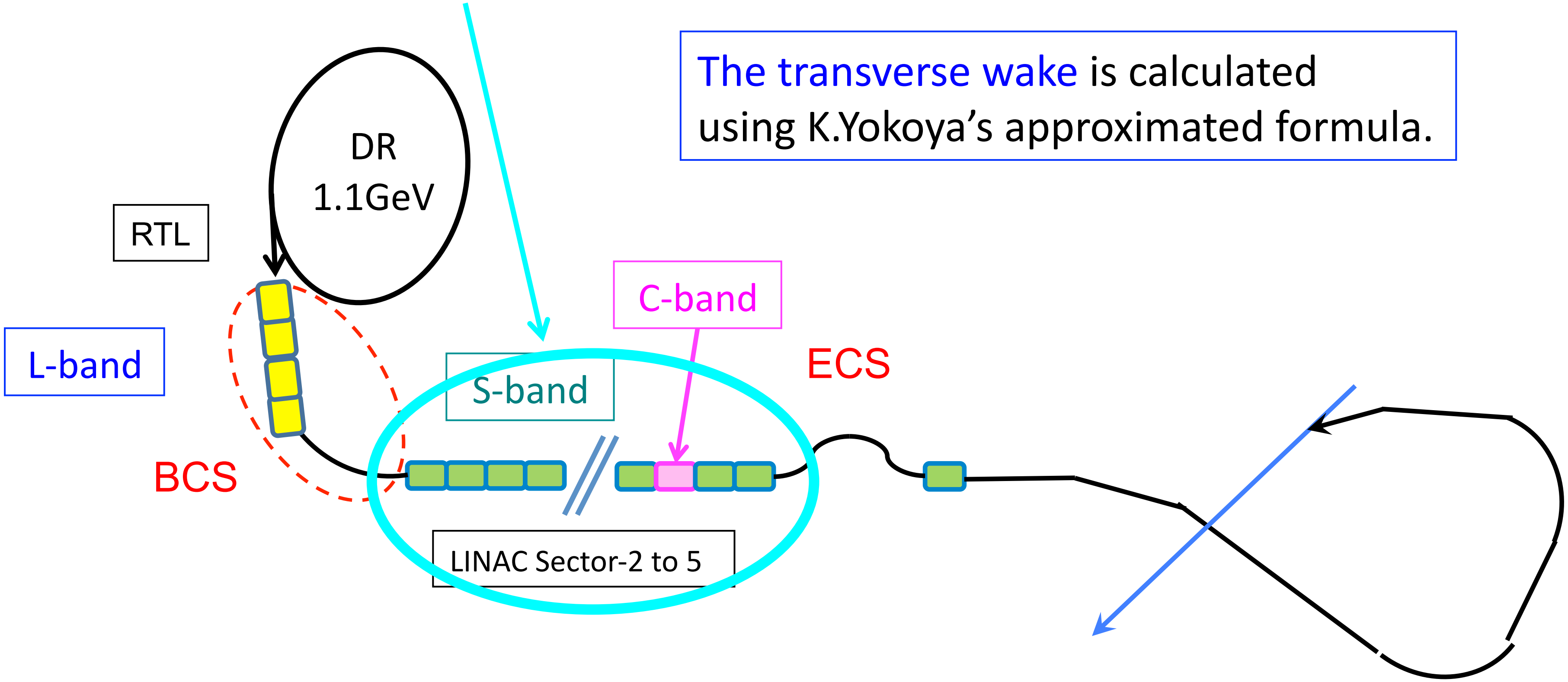
1. Caused by misalignments

Transverse Emittance growth

<u>Misalignments in the tracking simulationwere done by the following steps:</u>

- 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.

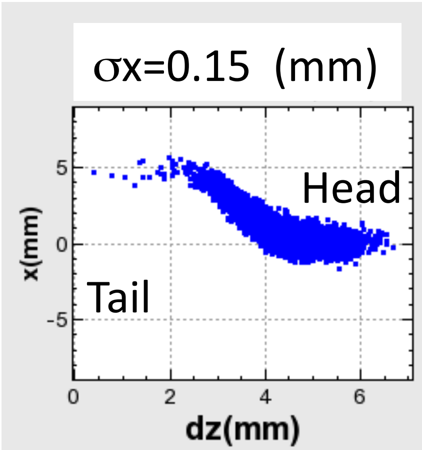
The transverse wake is calculated using K.Yokoya's approximated formula.

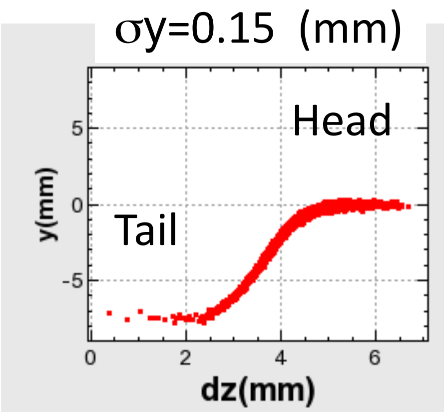


Transverse emittance growth (Cont'd)

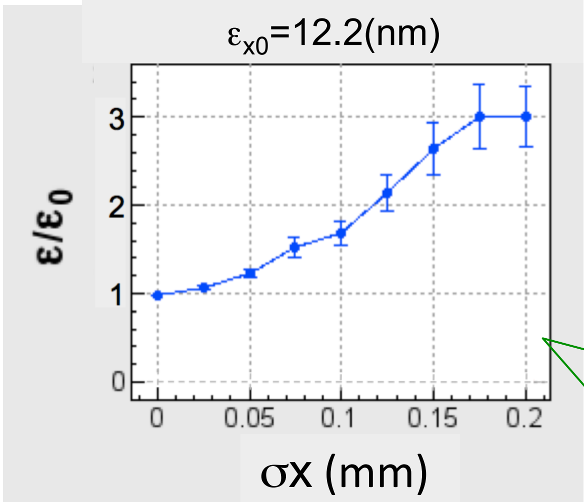
1. Caused by misalignments

Examples of the particle distributions at the end of LINAC



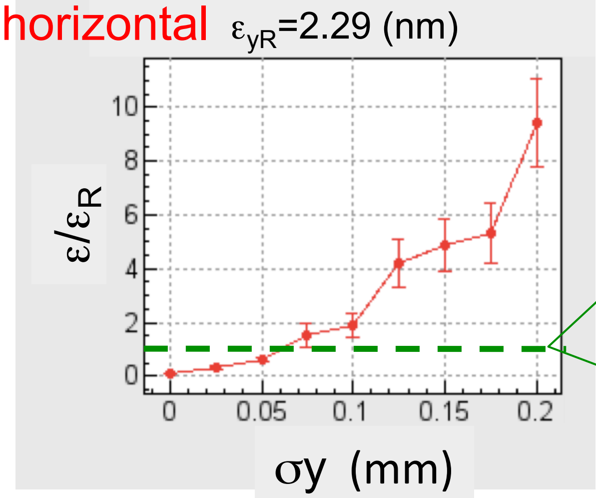


Emittance growth at the entrance of LER



x 1.6 with 100μm misalignment

Vertical emittance alignment is more important than the horizontal



Severe !

The green line is Max. Allowable ε_{yR} for injection for MR. Only 60μm misalignment is allowed.

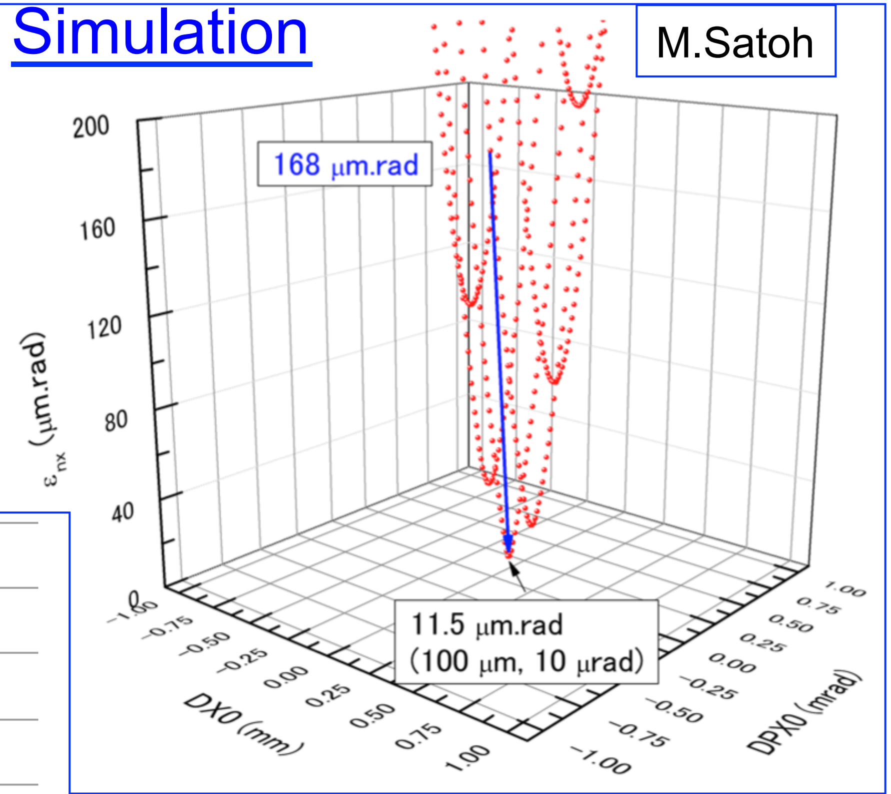
MOPS058,
L. Zang, et.al.

Emittance minimization by changing the initial offset

The emittance growth due to the misalignments can be suppressed by choosing the initial offsest and angle of the beam at the entrance of LINAC.
at some level.

Simulation

M.Satoh

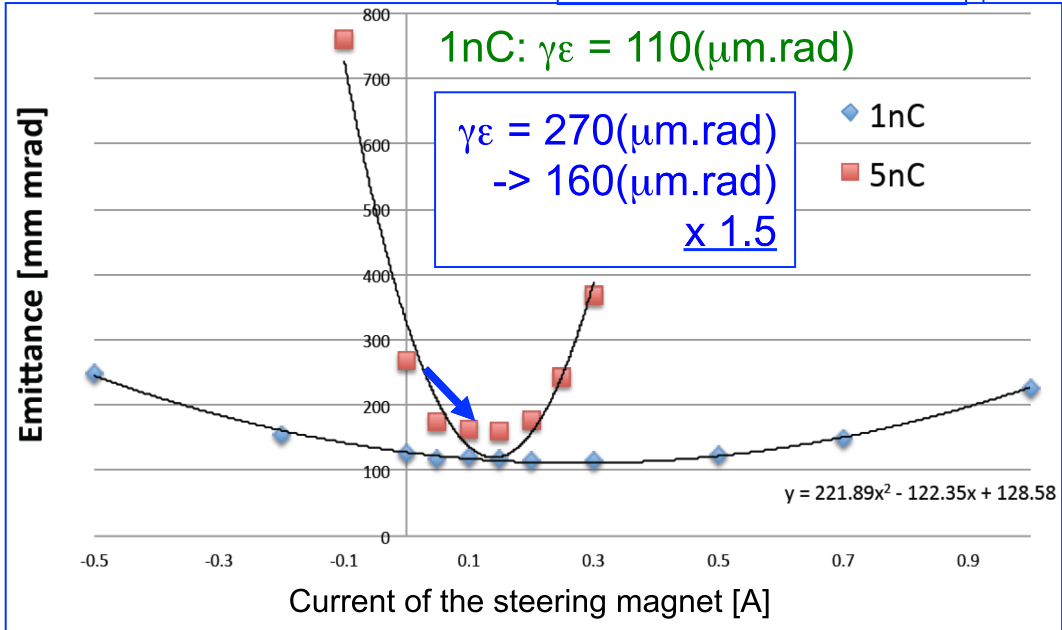


Initial: γε = 10(μm.rad)

γε = 168(μm.rad)
-> 11.5(μm.rad)
x 1.15

Measurement

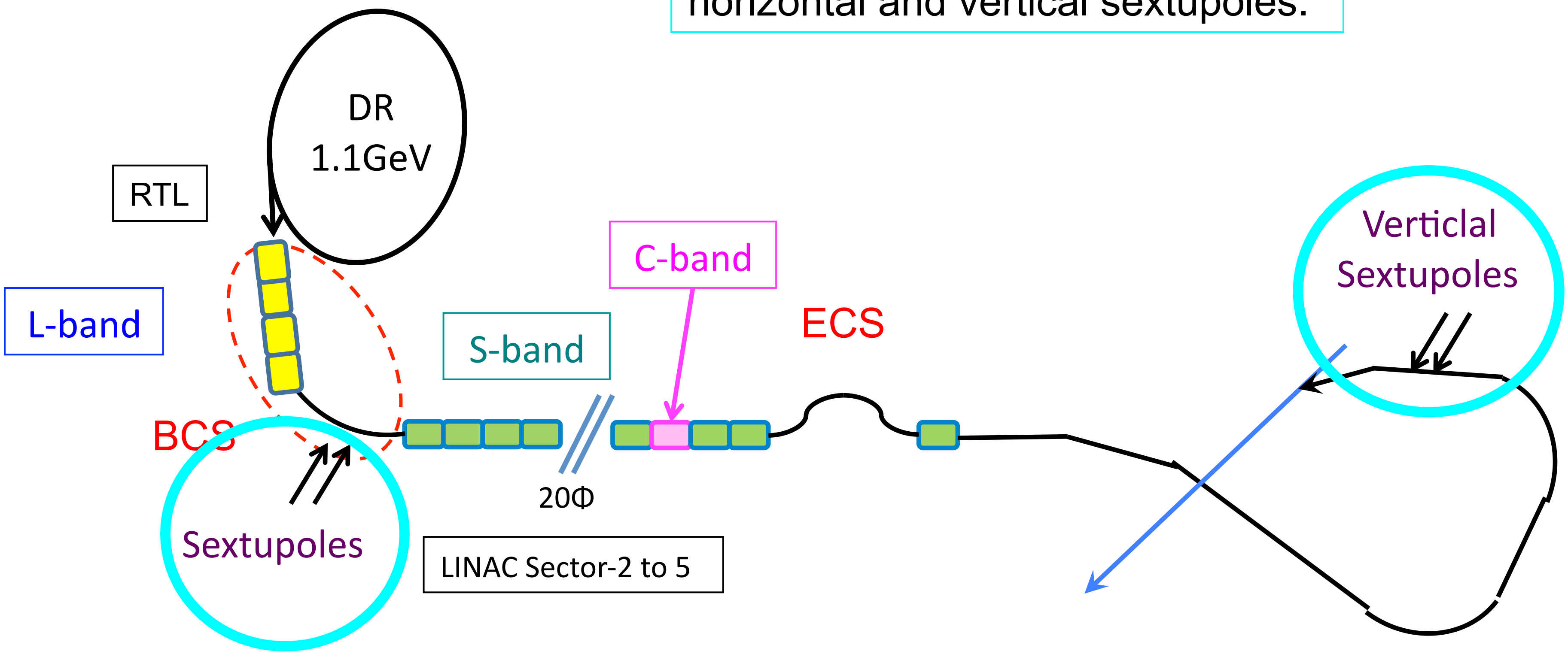
L. Zang, M.Yoshida



Transverse Emittance growth

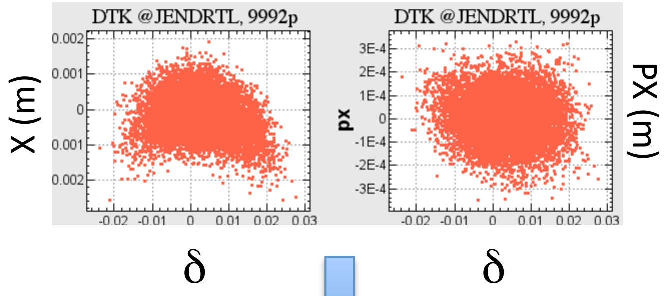
2. Caused by the second order dispersion

We install the two pairs of horizontal and vertical sextupoles.



Corrections of Second-Order Dispersion using Sextupoles

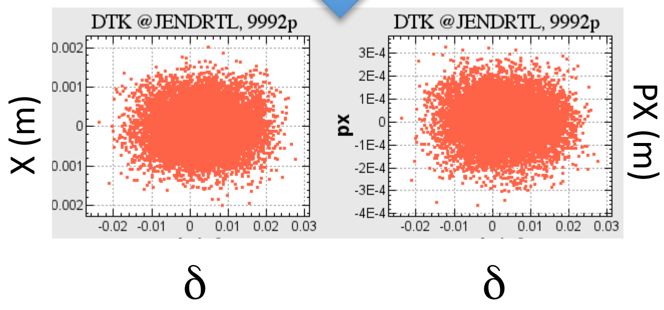
(a) w/o Sextupoles



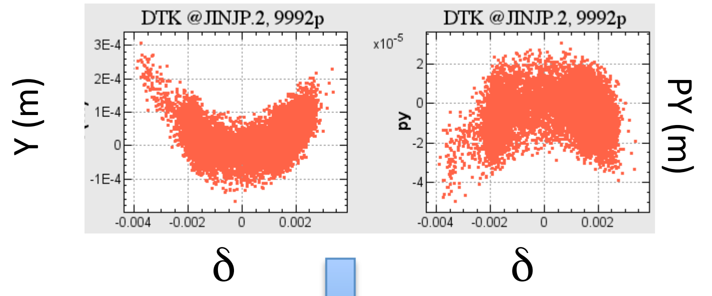
Correction of second order dispersion by sextupoles

Sextupoles

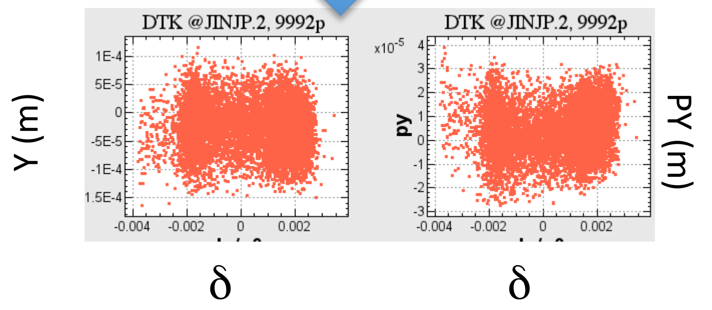
(b) w Sextupoles



1.1 GeV	ε@Sector-3 w/o Sext	ε@Sector-3 w Sext
x(nm)	45.9 →	40.2
y (nm)	0.901	0.903



Vertical sextupoles



4 GeV	ε@INJP w/o Sext	ε@INJP w Sext
x(nm)	12.5	12.5
y (nm)	0.351 →	0.269

Emittance growth is suppressed by sextupoles.

Transverse Emittance growth

Transverse emittance growth

3. due to

Emission of Synchrotron Radiation (SR)

in the beam transport line

LER	w/o SR	w SR	Growth factor
εx (nm)	10.8	12.2	1.13
εy (nm)	0.247	0.256	1.04

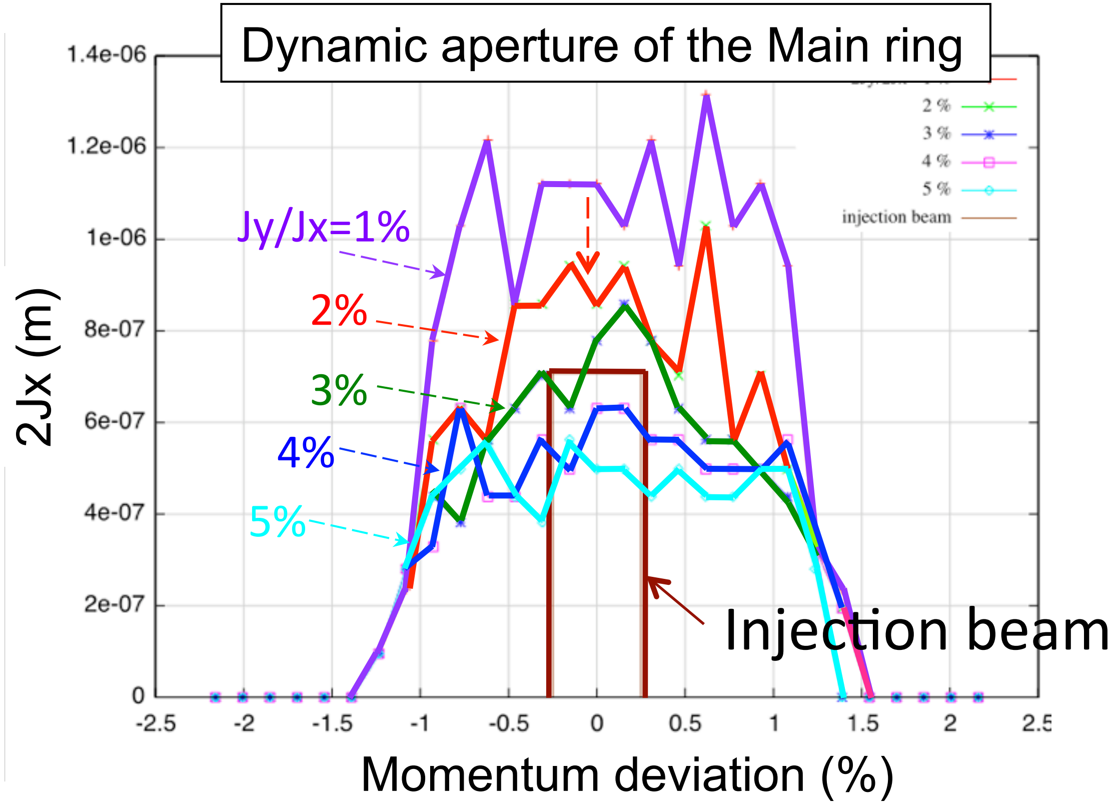
The growth factor is not so large.

Injection into the Main ring (LER)

Y. Ohnishi

For larger vertical amplitude of the injected beam, the dynamic aperture shrinks.

Jy/Jx: Ratio of the vertical to horizontal amplitude of the injected beam.



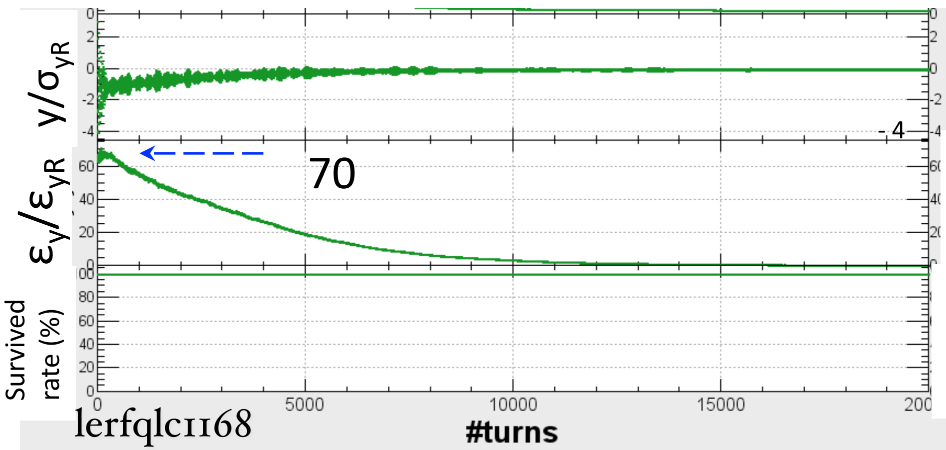
If Jy/Jx < 2%, the beam is safely injected in the Main ring.
In this case, ε_y of injected beam is 2.3 nm.
ε_y from DR assuming no-coupling is 0.25 nm.
-> enough margin

4. ε_y growth due to Beam-Beam effect after the injection

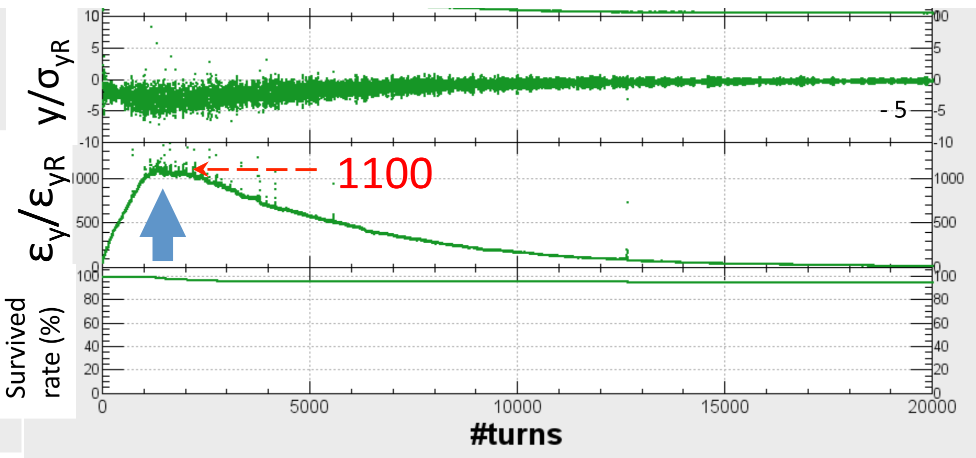
Y.Ohnishi

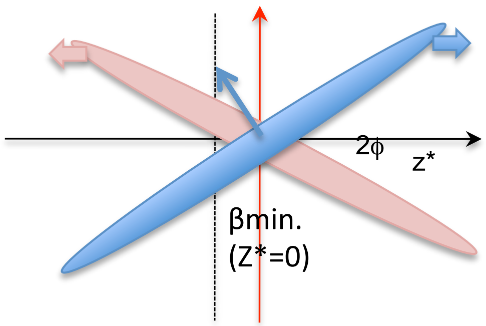
Strong(Stored beam) – Weak(Injected beam) model

w/o Beam-Beam



w/ Beam-Beam





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

This is especially strong in the nano-beam scheme which is very small waist at the IP.

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 particles are lost.

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

Summary

1. From e+ target to Damping ring
   - Beam loss mitigated by
     - choosing proper accelerations in capture section

2. Damping ring
   - Microwave Instabilities due to CSR mitigated by
     - narrower beam pipes
     - larger momentum compaction factor
     - higher synchrotron tune.

3. From Damping ring to Main ring
   - Emittance growth mitigated by
     - adjusting RF-phase
     - offset the initial position of the beam
     - positioning of sextupoles.

The performance of LINAC and beam transport are very important for the next generation B-factories.

I believe proper tunings and patient effort will surely lead us to success !

Gracias por su atención