Emittance and Background of Injection beam in SuperKEKB

EIC Workshop
Oct 9th, 2020
Naoko Iida
SuperKEKB Injector LINAC

Contents

Luminosity & lifetime

The luminosity can be written in terms of *specific luminosity* as:

$$\mathcal{L} = e^2 N_b N_+ N_- f_0^2 \mathcal{L}_{\rm sp} \ , \tag{1}$$

where $N_\pm$, N_b, f_0 are the particles/bunch, bunches/ring, and the revolution frequency, respectively. At the equilibrium, $N_\pm$ must balance with the injector currents $I_{\pm\rm inj}$ as:

$$eN_\pm N_b f_0 = I_{\pm\rm inj}\varepsilon_\pm \tau_\pm \ , \tag{2}$$

where $\tau_\pm$ and $\varepsilon_\pm$ are the lifetimes and the injection efficiencies of $e^\pm$ beams. Then the luminosity is expressed as

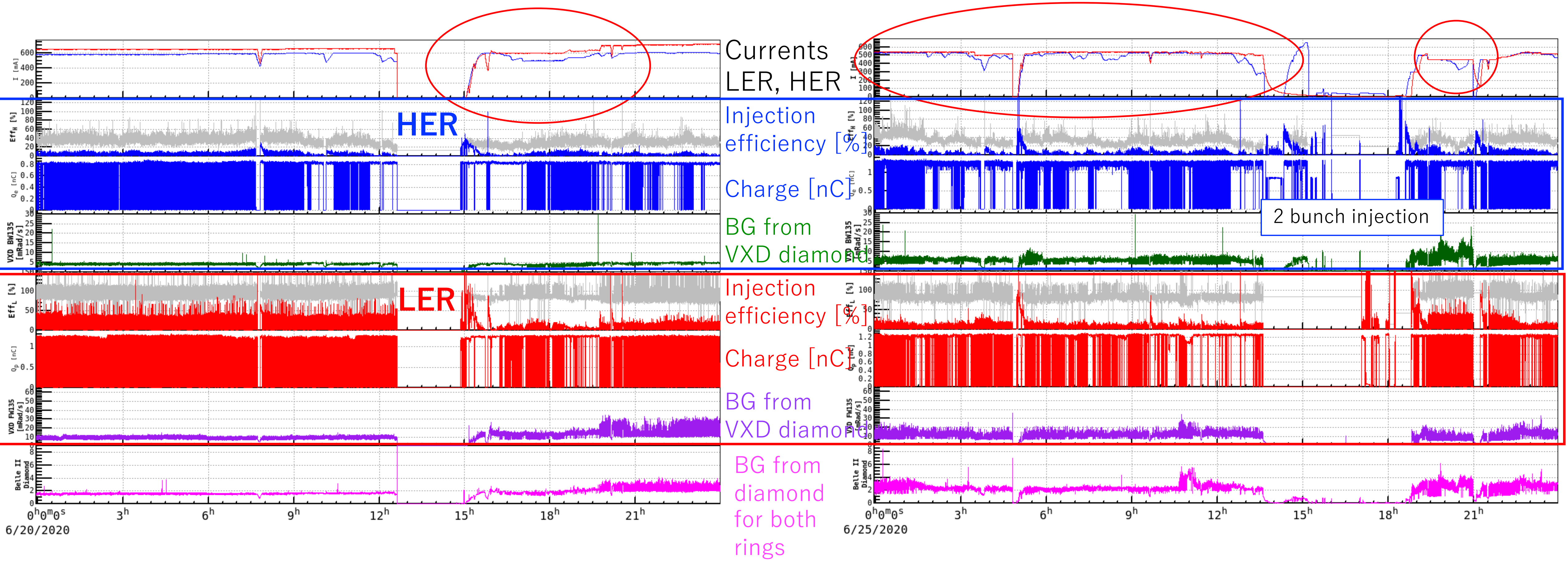
$$\mathcal{L} = I_{+\rm inj}\varepsilon_+ I_{-\rm inj}\varepsilon_- \frac{\tau_+\tau_-}{N_b}\mathcal{L}_{\rm sp} \ . \tag{3}$$

Date 2020	β_y^* mm	N_b	τ_+ sec	τ_- sec	$\mathcal{L}_{\rm sp}$ $1/\mu$bs/mA^2	$\frac{\tau_+\tau_-}{N_b}\mathcal{L}_{\rm sp}$ s/nb/mA^2
6/21	1	978	588	1500	53.4	48.2
6/25	0.8	978	588	1122	66.8	45.1
6/29	0.8	395	588	1068	58.5	93.0
6/29	0.8	789	588	1320	65.0	63.9
6/30	0.8	1565	660	1860	76.4	53.1

A) Charge, lifetime, and luminosity

Poor injection rates for the short lifetimes

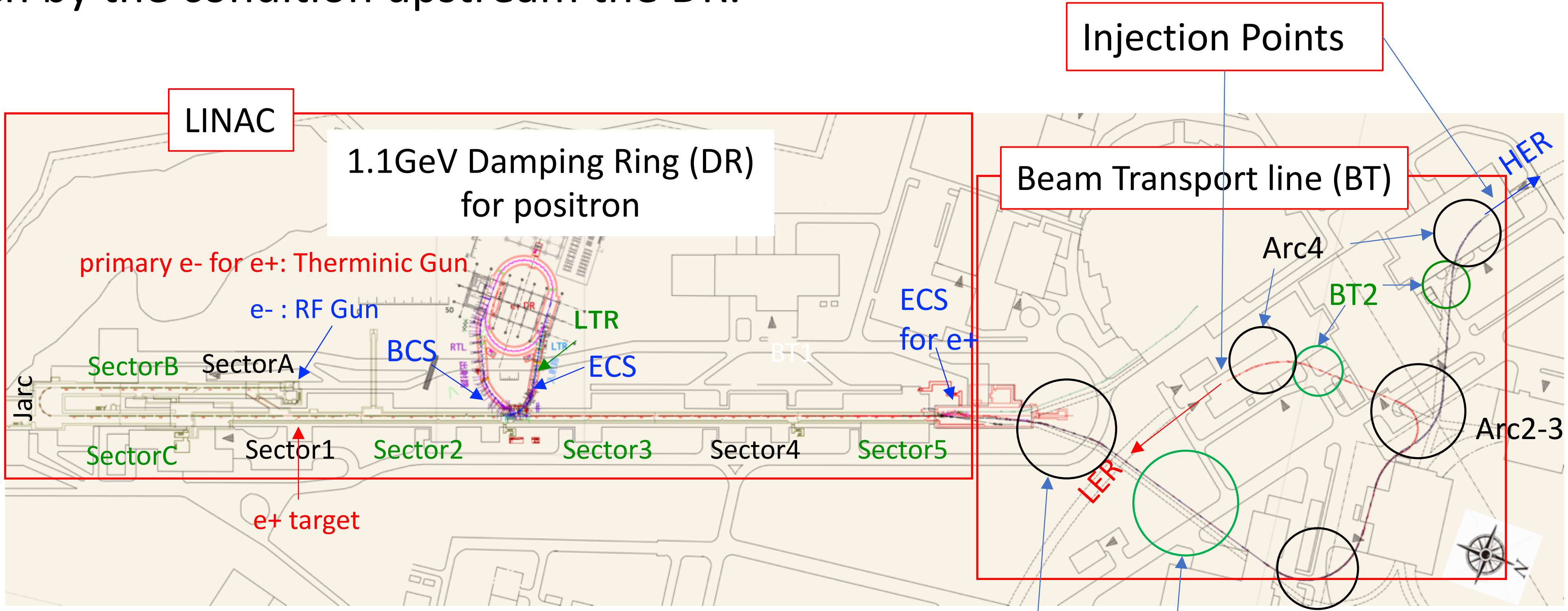
Especially for HER, once injected up to high current, the HER injection could not catch up after LER current becomes higher.



B) Layout of LINAC, BT, Injection to MR

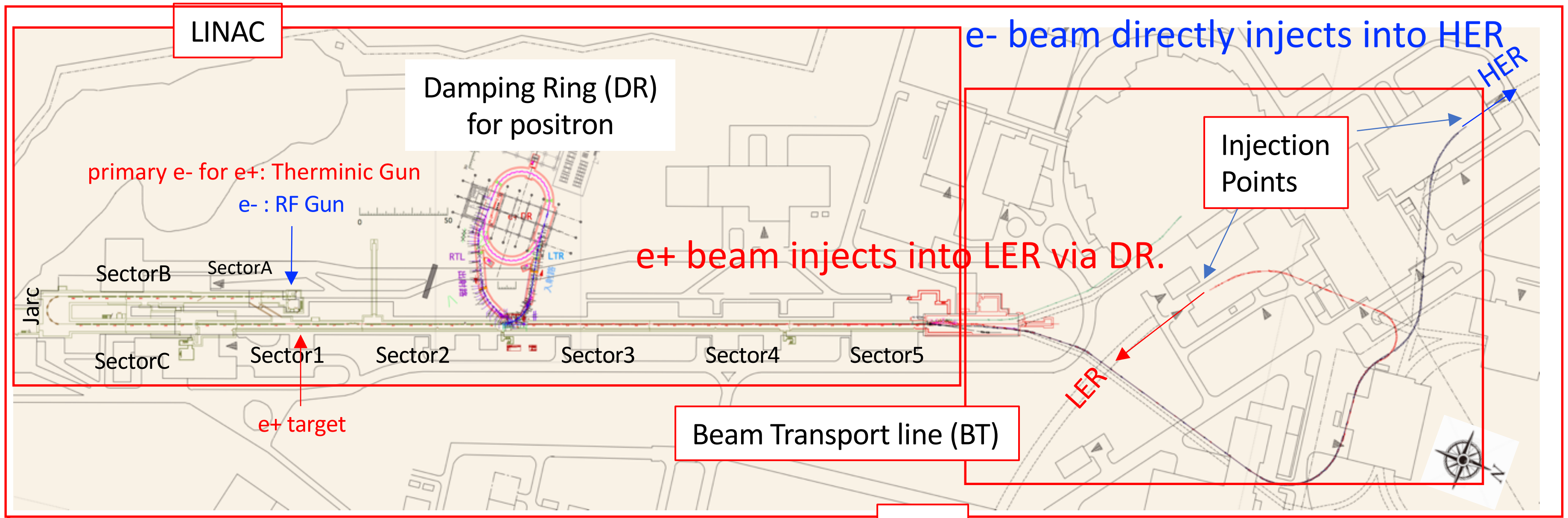
e+ beam injects into LER via DR:
The injection BG is not affected very much by the condition upstream the DR.

e- beam directly injects into HER:
The injeciton BG is directly affected by the condition of RF-gun, LINAC, and BT.

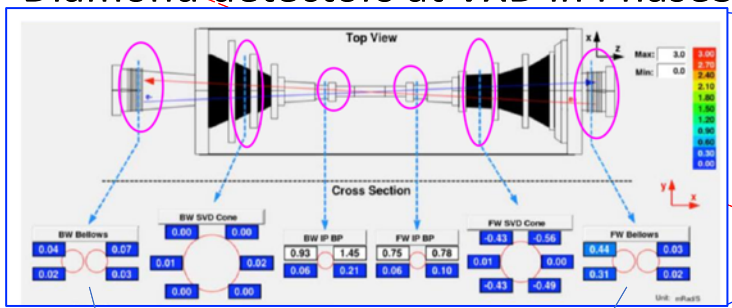


Green: Emittance measured with wire scanners(WS)
BCS: Bunch Compression System
ECS: Energy Compression System

Layout of LINAC, BT, and SuperKEKB



Diamond detectors at VXD in Phase3

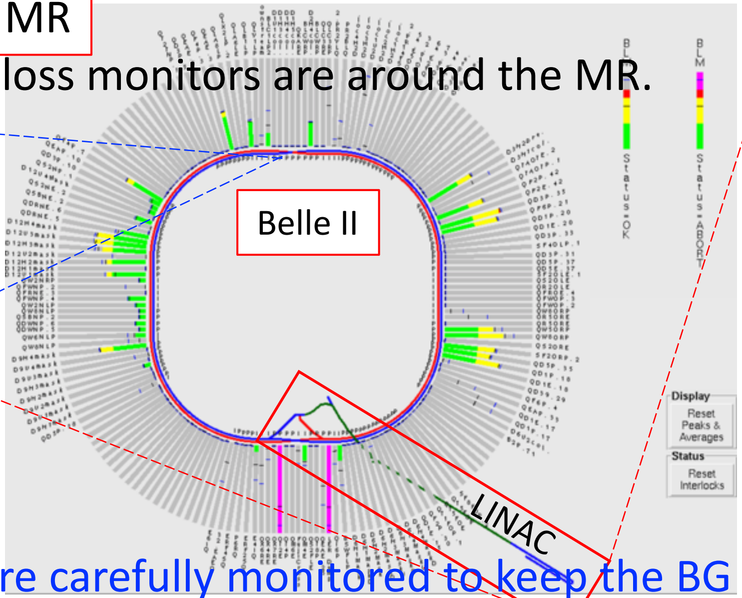


HER:
VXD(Diamond) BW135

LER:
VXD(Diamond) FW135

Most sensitive to the Background (BG) on Belle2.

Many loss monitors are around the MR.



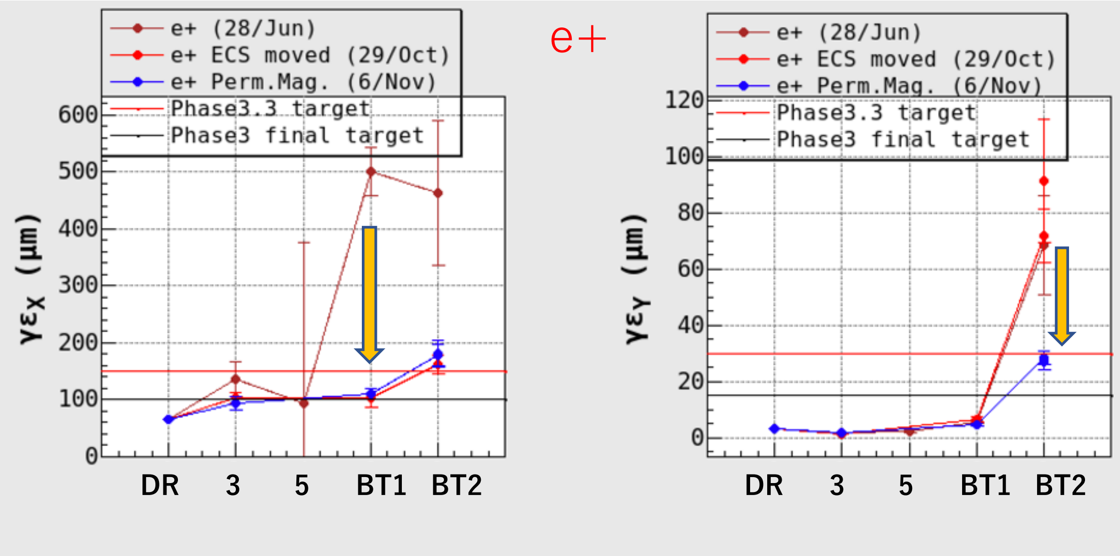
The signals from the Diamonds and the loss monitors are carefully monitored to keep the BG low.

Some aborts are avoided by stopping injection when the signals are high.

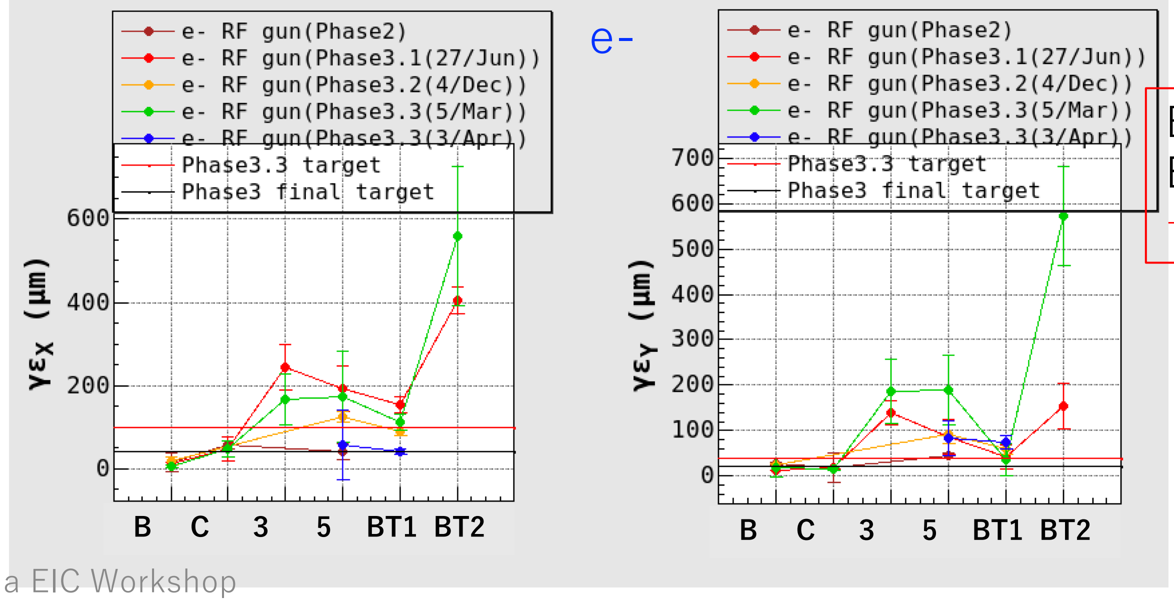
2. Quality of Injection beam

A) Measured emittance and Injection
B) Injection efficiency and background(BG)
C) Emittance explosion in e- BT
D) Improvements of e+ BT and injection
   1. Horizontal emittance
   2. Vertical emittance
   3. Tuning of energy spread
   4. Correction of X-Y coupling between two injection kickers

Measured Emittance



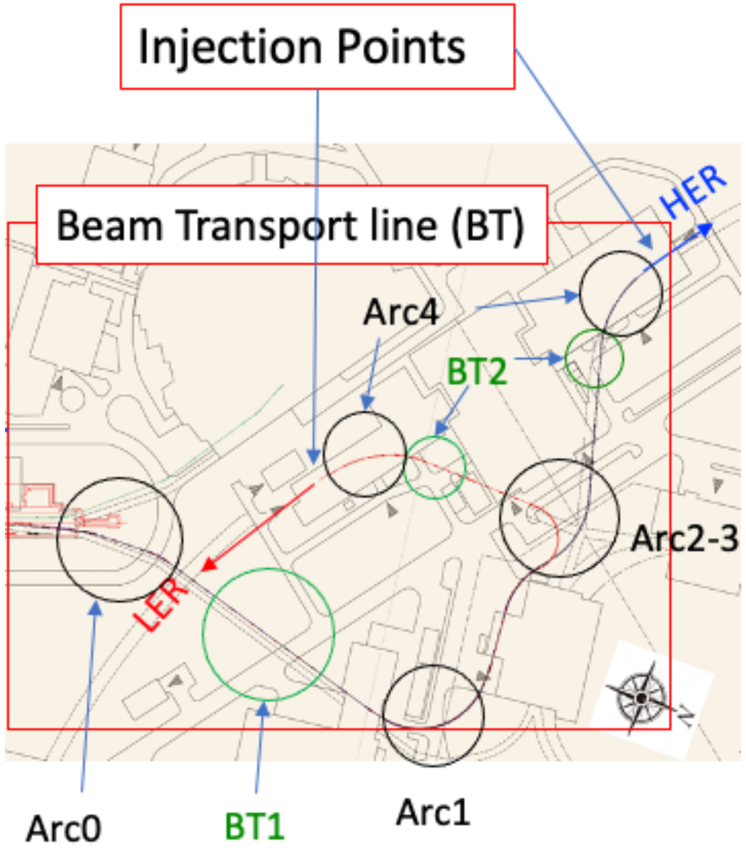
DR → Sector 3、
BT1 → BT2、
Emittances increase
→Need study



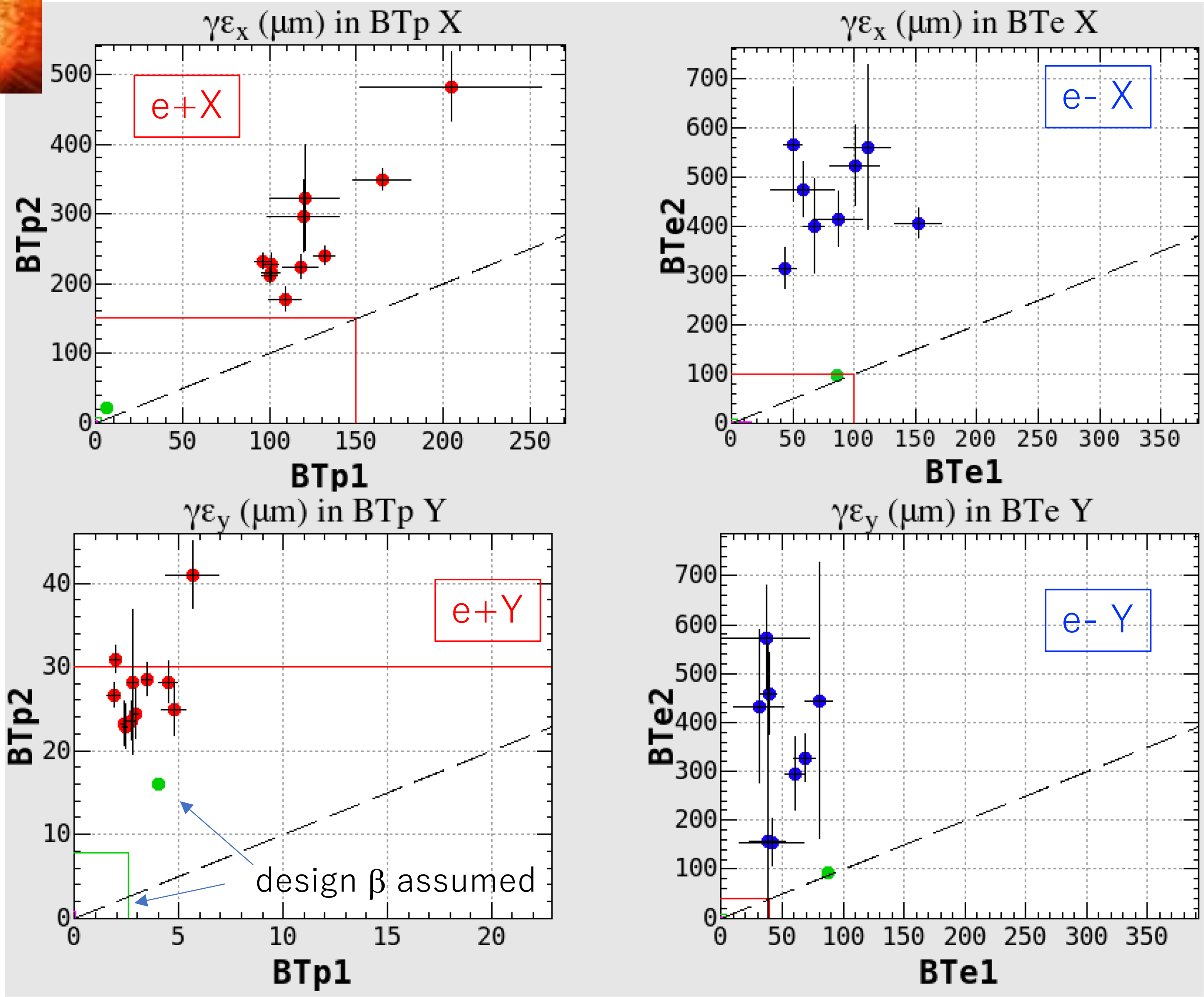
BT1→BT2、
Emittances explosion
→**Need study**

Requirements from MR

Phase3.3	e+	e-
$\gamma\varepsilon_x$ [μm]	150	100
$\gamma\varepsilon_y$ [μm]	30	40
σ_δ [%]	0.16(1σ)	0.1(1σ)



Emittance explosion in BT



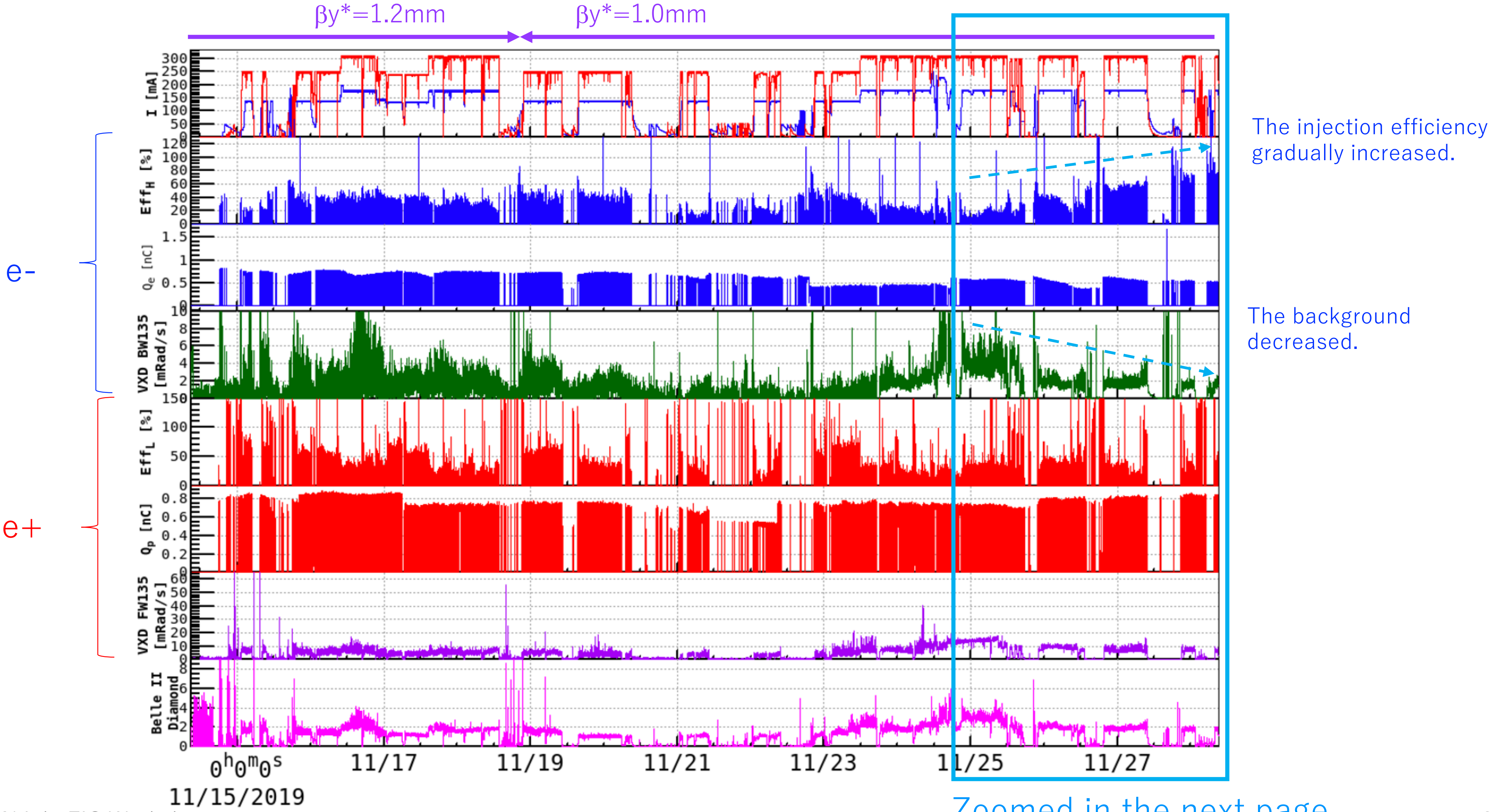
- Measured by WS
- Emittance due to Jitter
- Emittance due to BPM res.
- Emittance due to σ_δ (invisibly small)

Same emittance line of BT2 as BT1

Required emittance from LER/HER

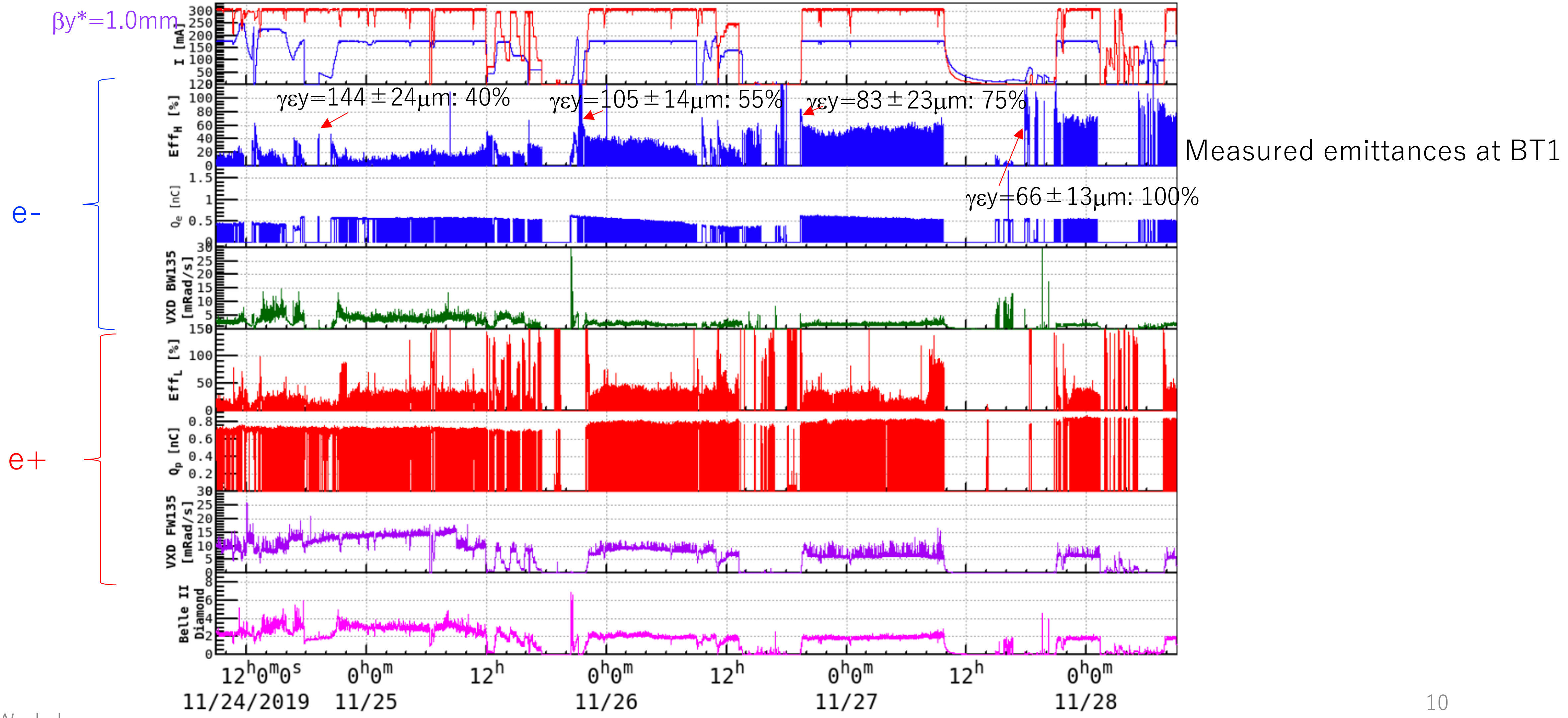
- The horizontal orbit jitter in the e+ is negligibly small.
- The other jitter emittances at BT1 is comparable as measured emittance.
- But in BT2, all measured emittances are larger than the jitter emittances.

B) The injection efficiency and the background



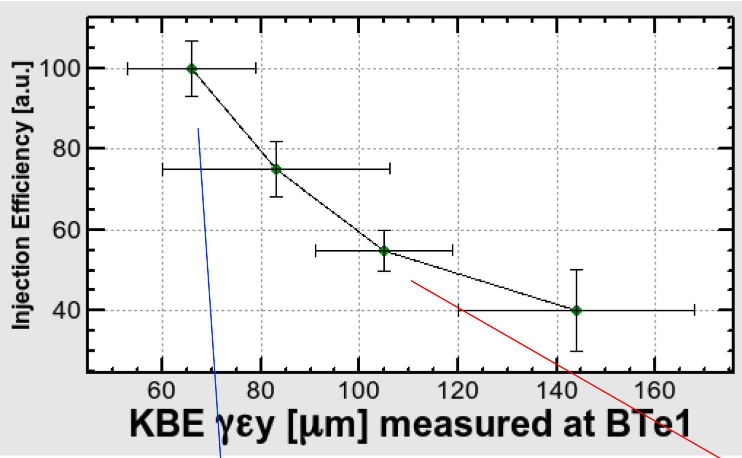
The injection efficiency increased as the emittance decreased by tuning.

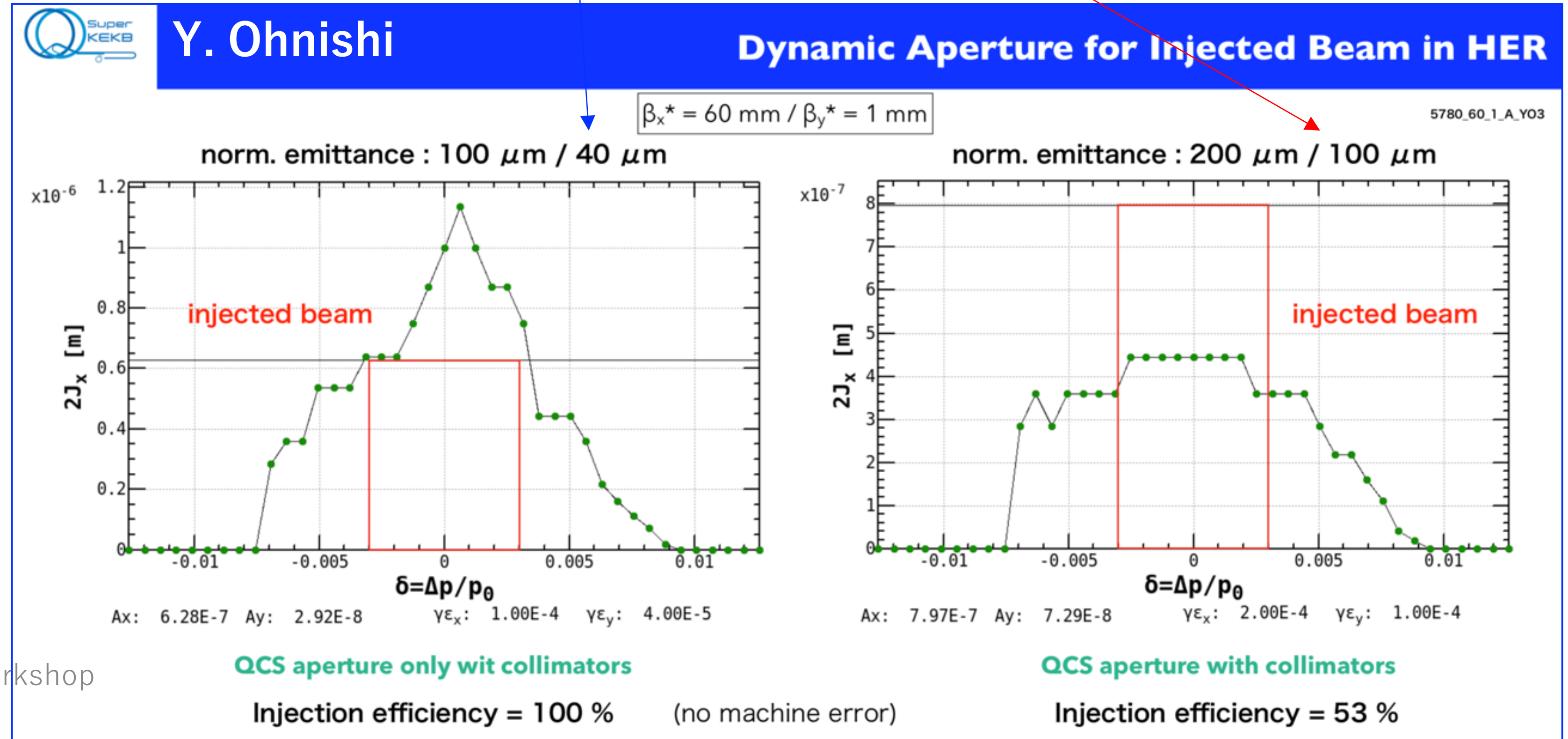
These efficiencies are the values at the low current beam in the HER.
→ The effect of lifetime can be neglected.



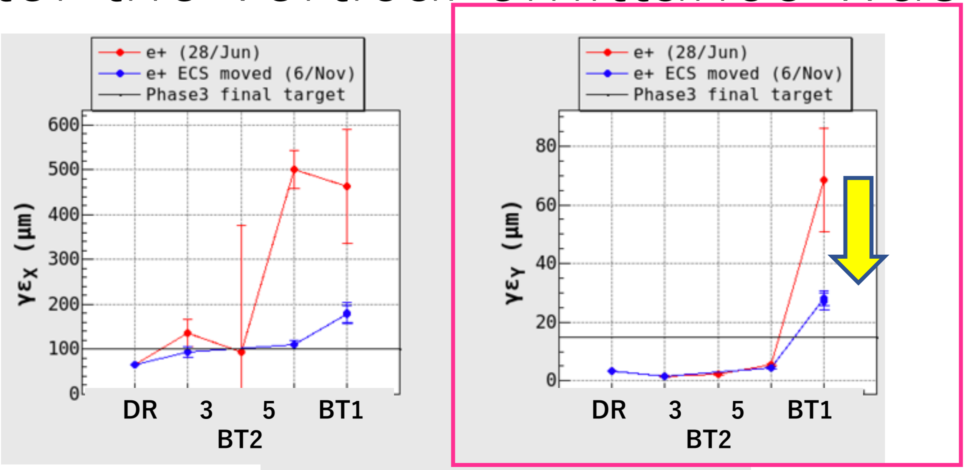
Vertical emittance vs. HER Injection efficiency

This injection efficiency is an arbitrary unit.



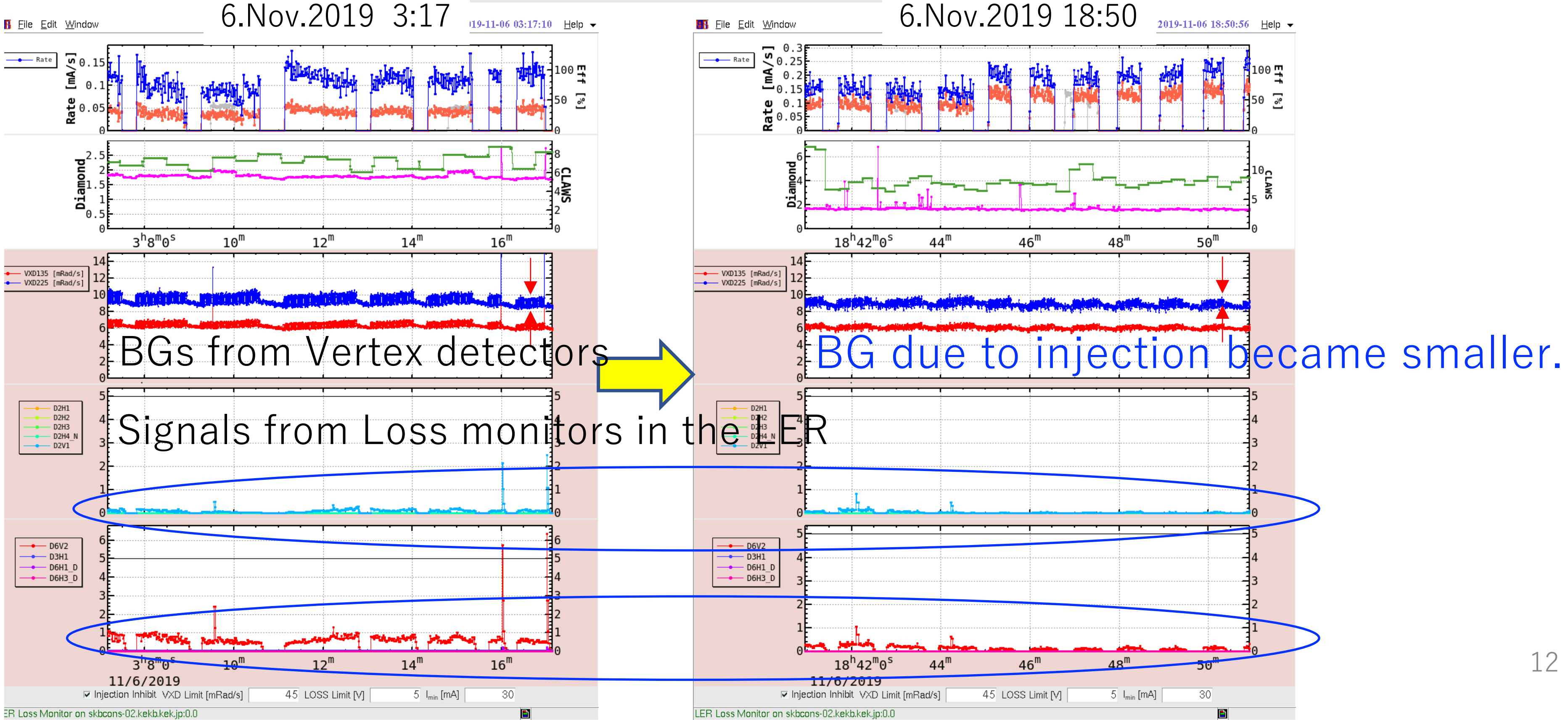


・LER　After the vertical emittance was improved,

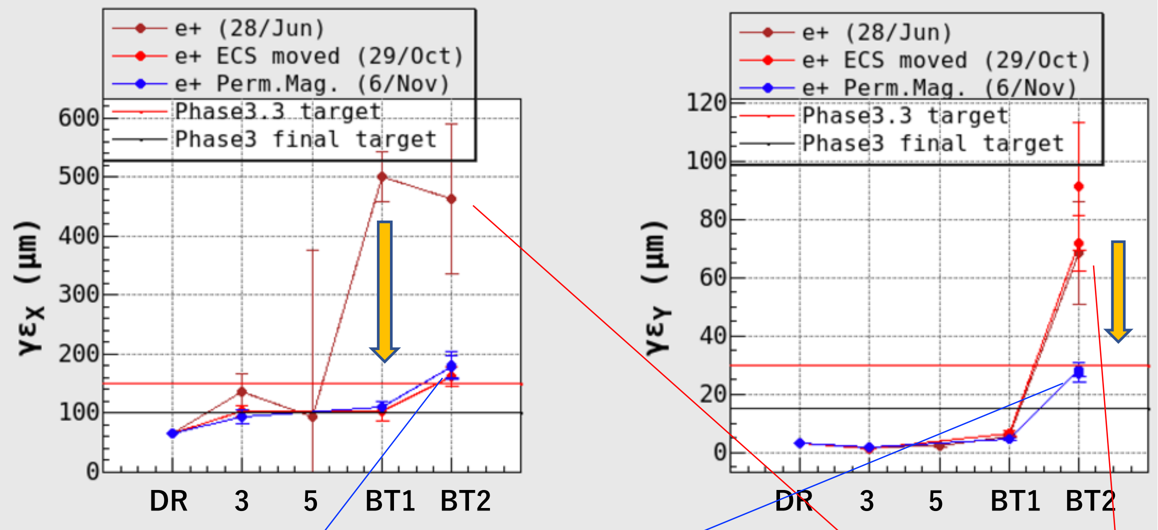


6.Nov.2019 3:17

6.Nov.2019 18:50



- LER



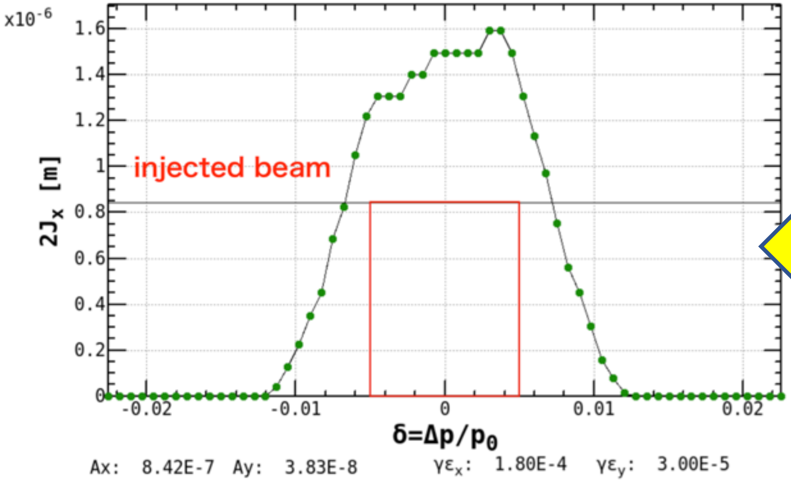
Y. Ohnishi — **Dynamic Aperture for Injected Beam in LER**

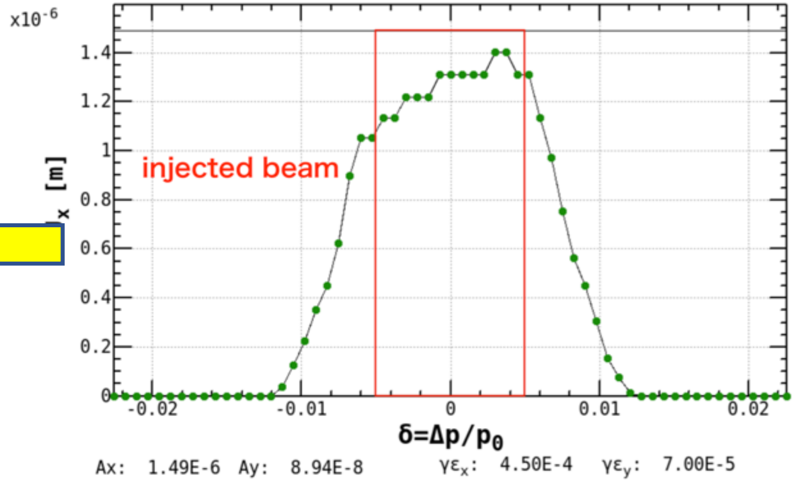
$\beta_x^* = 80$ mm / $\beta_y^* = 1$ mm

1704_80_1_A_YO4

norm. emittance : 180 μm / 30 μm

norm. emittance : 450 μm / 70 μm





QCS aperture with collimators

Injection efficiency = 100 % (no machine error)

(6/Nov/2019)

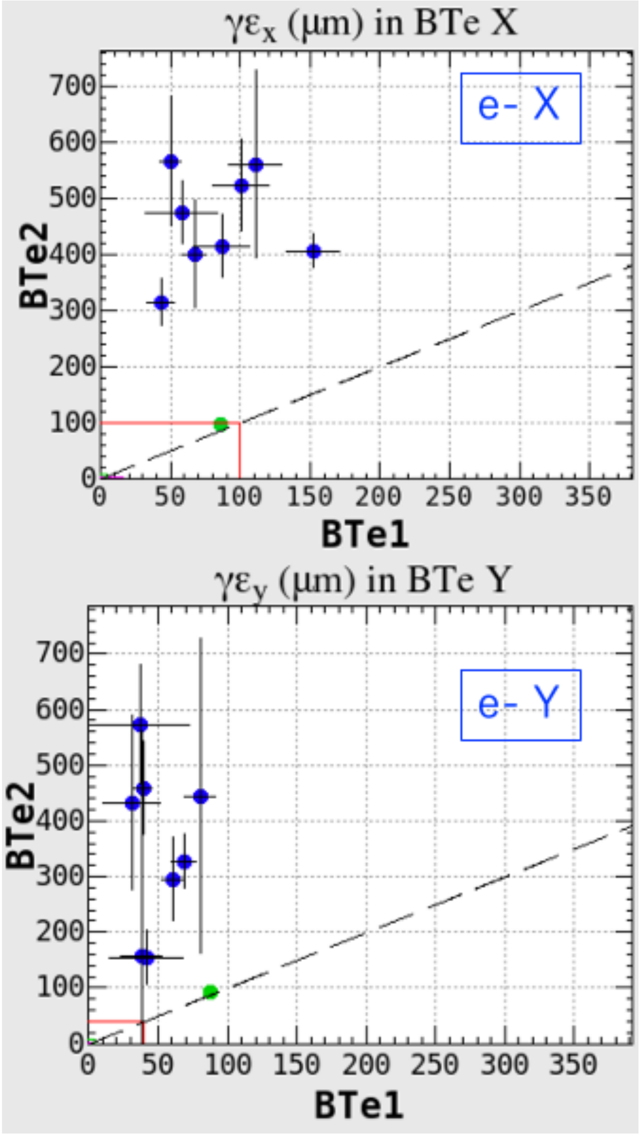
QCS aperture with collimators

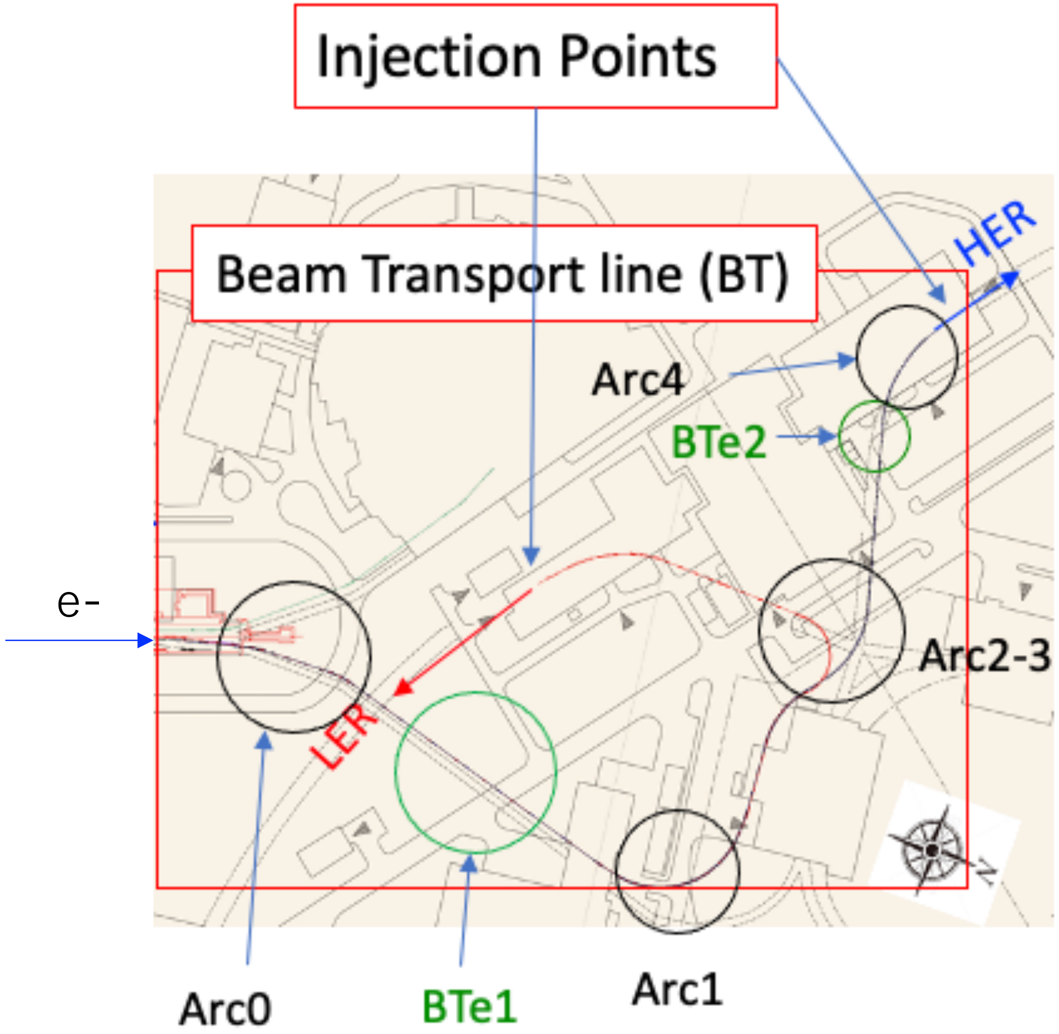
Injection efficiency = 86 %

(28/Jun/2019)

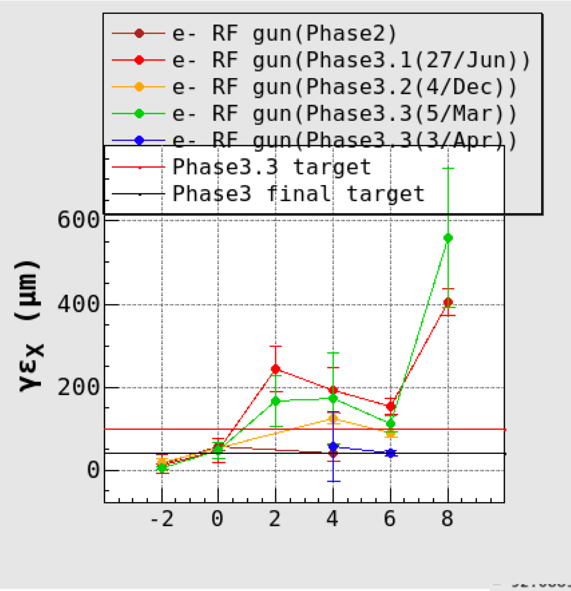
Before modification of ECS / BTp

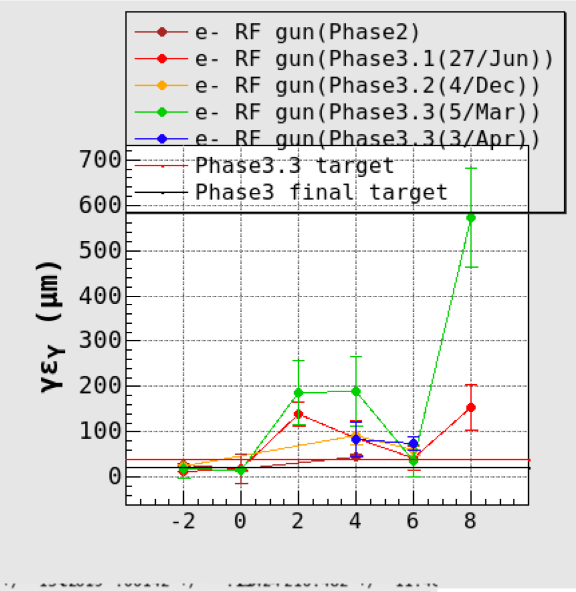
C) Emittance explosion in e- BT line



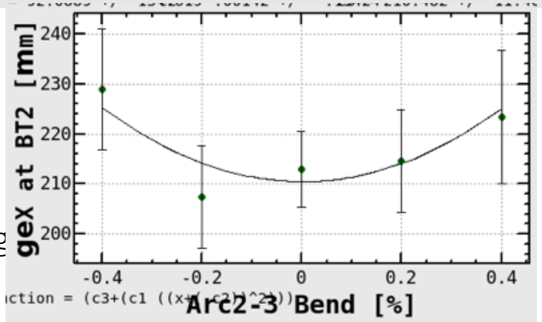


C) Emittance explosion in e- BT line



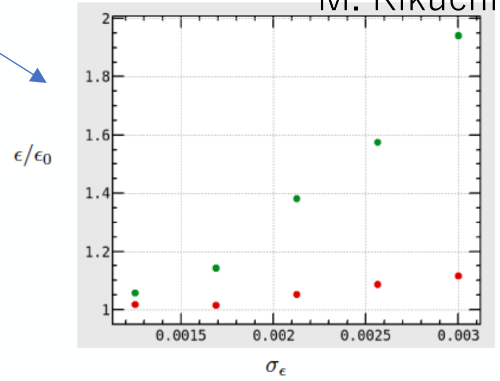


1. Dispersion and orbit jitter emittance:
   - Measurements have been performed.
   - Jitter of power supplies ?
2. Intensity dependence:
   - Not yet done.
   - Small for e+ (10%for 0.9/1.2nC, T. Mori).
3. Multipole components of bends:
   - Not yet done.
   - For e+ changing orbit in the bends did not affect the emittance.
4. Multipole components of quads ?
   - A simulation with multipole components tells that the horizontal emittance is doubled with energ spread of 0.3%. However only 15% increase in vertical.
   - Measurements are to be done.
5. Abnormal quads in the line ?
   - We will check by making bumps to find out the quads.
6. Abnormal obstacles in the line?
   - Examined the inside of the vacuum chamber, but nothing particular has been found, so far.
7. Machine errors and synchrotron radiation are the next candidate(K. Oide).
8. **The source of emittance explosion is still mystery.**



- Emittance v.s. energy spread

M. Kikuchi



Emittance explosion in BTe due to lattice errors +Synchrotron Radiation

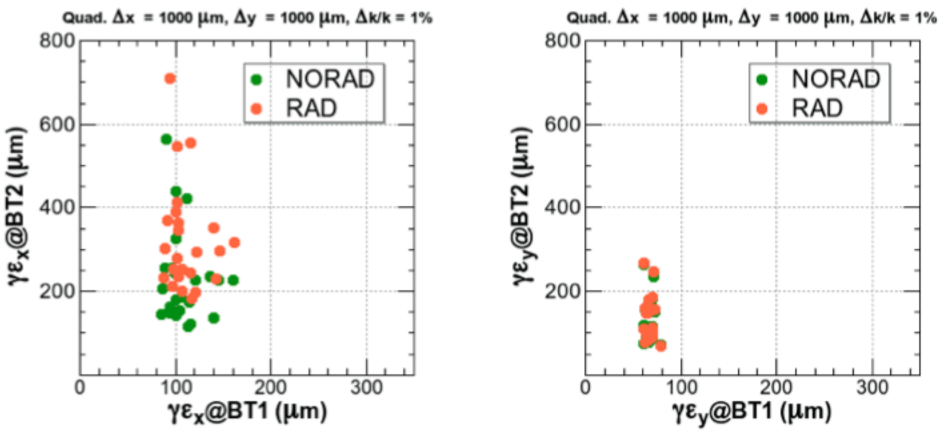
K. Oide

24 samples

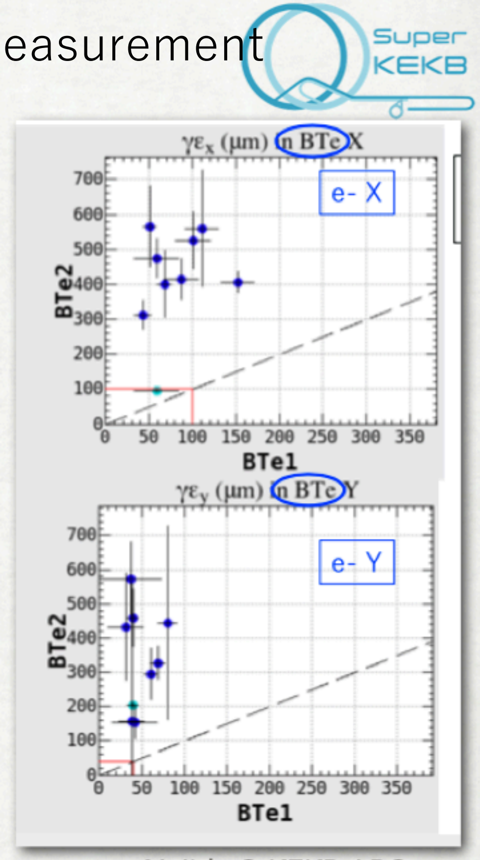
Simulation

A quick result

Measurement



$\gamma\varepsilon_{x,\mathrm{inj}}$	μm	80	$\gamma\varepsilon_{y,\mathrm{inj}}$	μm	60
$\sigma_{z,\mathrm{inj}}$	mm	1	$\sigma_{z,\mathrm{incoh.}}$	%	0.0143
Q/bunch	nC	1.0	φ_{RF}	deg	3.3
Δx_{quad}	mm	1.0 (rms)	Δy_{quad}	mm	1.0 (rms)
Δx_{inj}	mm	1.0 (rms)	Δy_{inj}	mm	2.0 (rms)
$\Delta k/k_{\mathrm{quad}}$	%	1.0 (rms)	GCUT		2.5

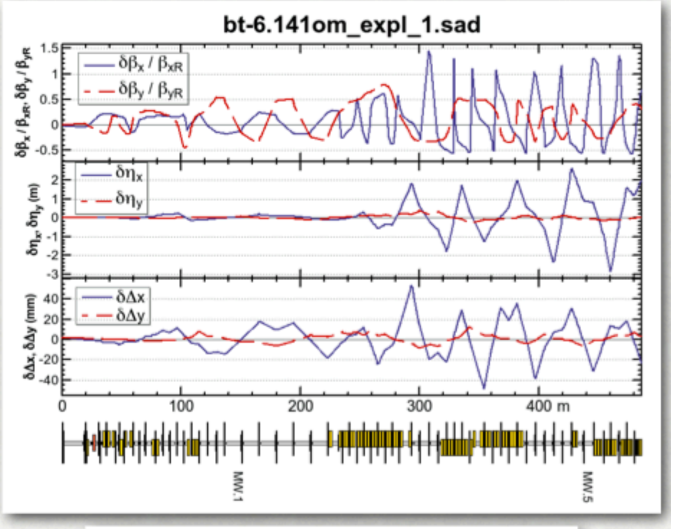


N. Iida @ KEKB ARC

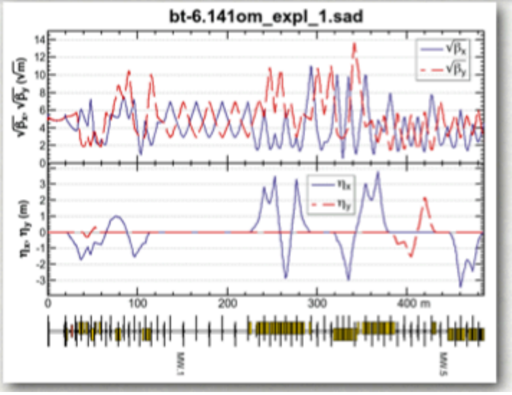
- The parameters above results in an explosion in x, somewhat similar to the observation (right).
- The vertical explosion is smaller than the observation.

Oct. 8, 2020 K. Oide

Biggest explosion among 24 (710 μm)



design optics

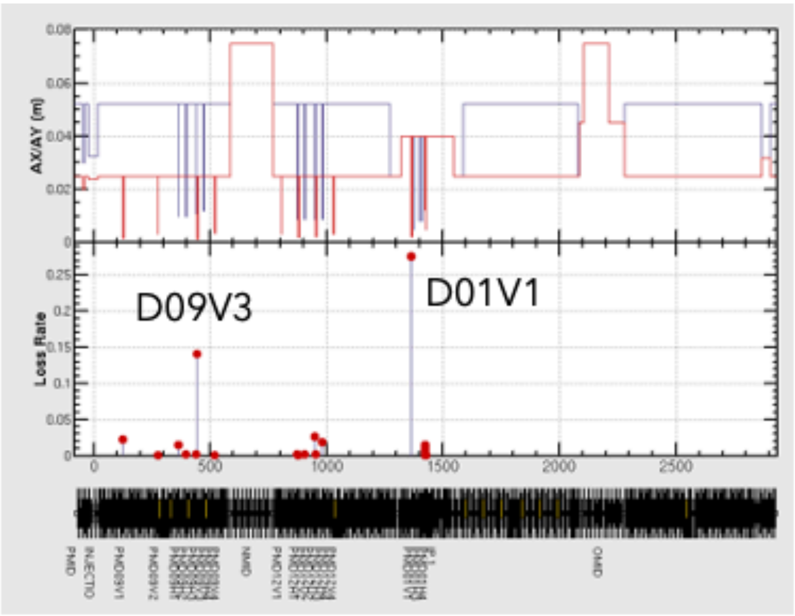


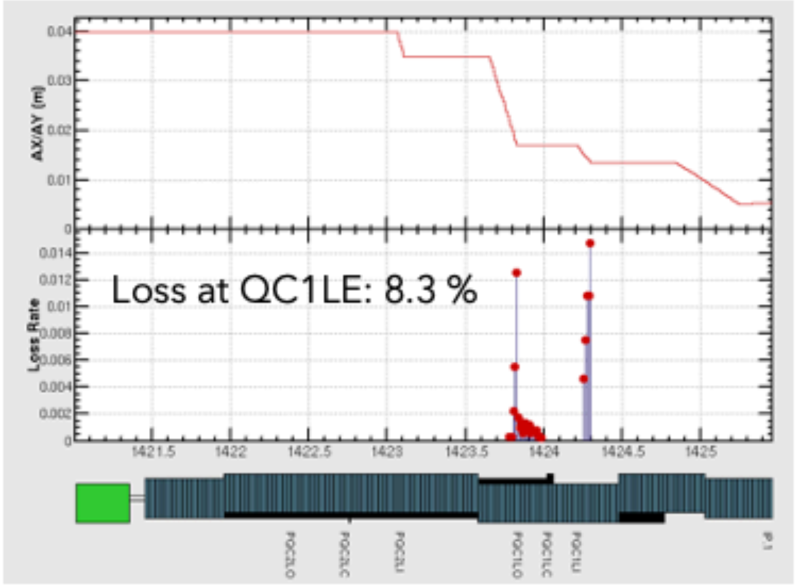
By looking above, a speculation is that the explosion is mainly caused by the dispersion leak due to the quad strength errors.

HER Injection

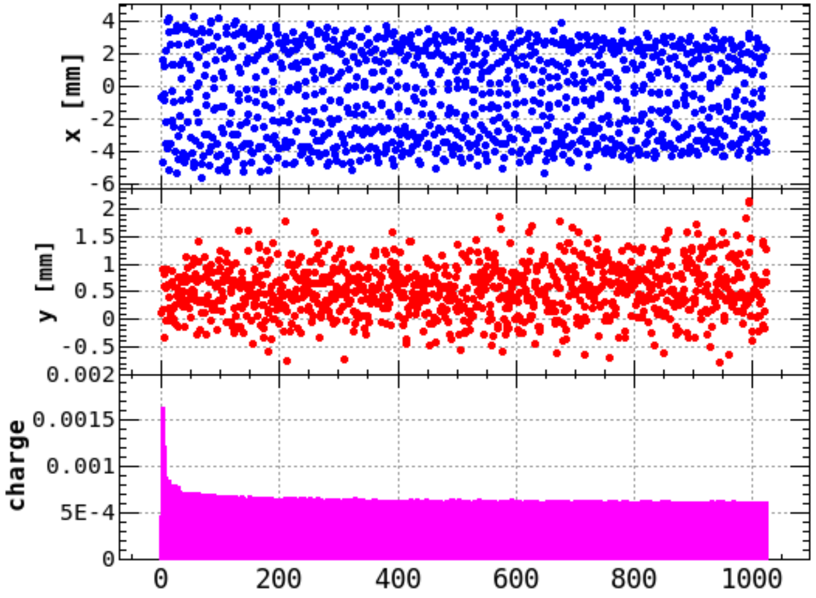
Y. Ohnishi

Simulation of Loss rate at the collimators in HER





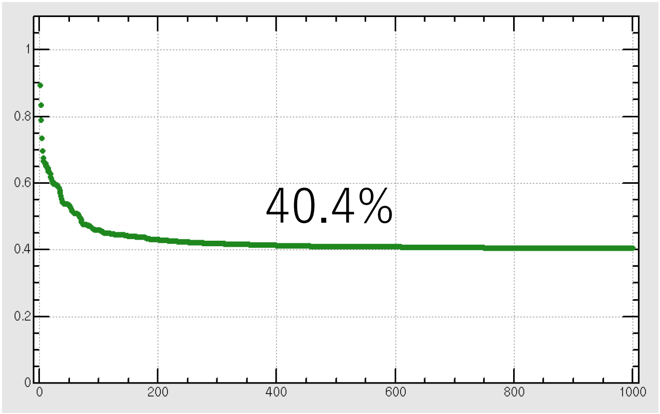
Real charge of injection beam measured by a turn-by-turn BPM



$\beta_x^*/\beta_y^* = 60\ mm/0.8\ mm$

tune : 45.531 / 43.574

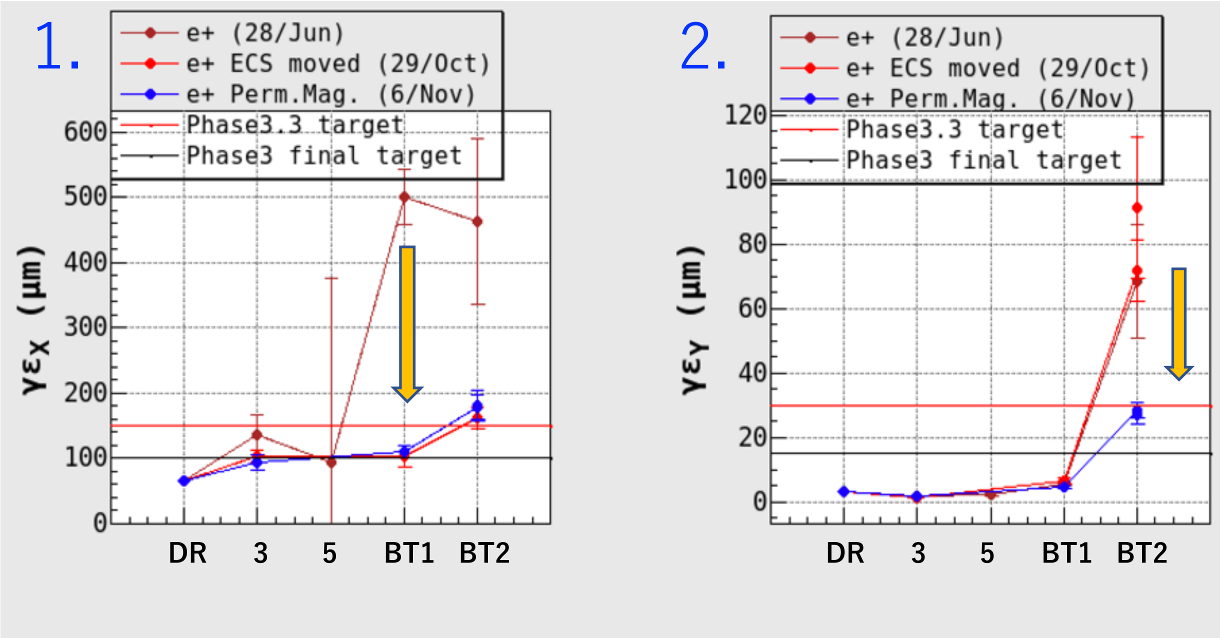
Tracking simulation with no Beam-beam



$\gamma\varepsilon x = \gamma\varepsilon y = 400 \mu m$

D) Improvements of emittance growth in e+ BT

1. Horizontal emittance
   - Residual dispersion at the acceleration for the ECS
2. Vertical emittance
   - Abnormal skew magnetic field from bends
3. Tuning of energy spread and emittance
4. Correction of X-Y coupling between two injection kickers



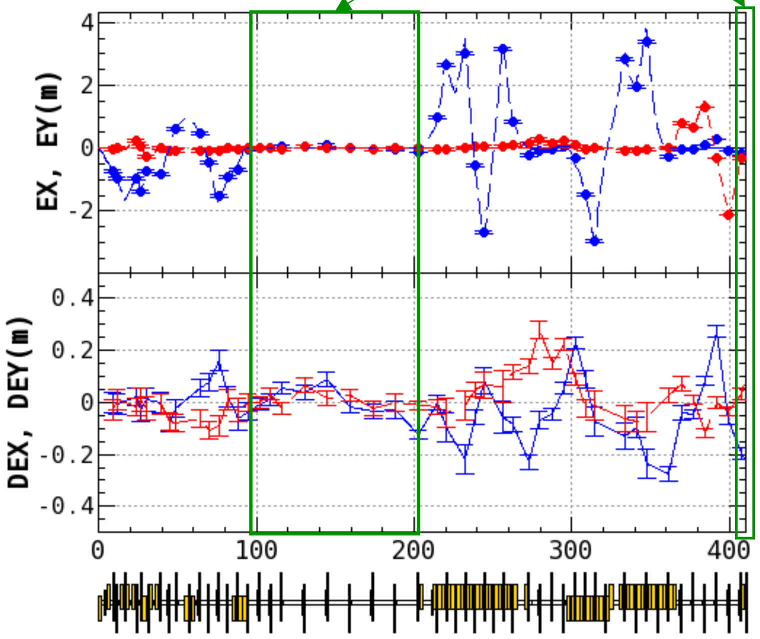
Residual Dispersion in the BT line

Y. Seimiya

- One of the causes of increased emittance is dispersion leakages.
- The dispersions have been corrected for each BT arc one by one.
- After that the dispersion of the BTs overall were measured by changing the beam energy.
- For e- line, the dispersion leak is almost good.
- Non-negligible residual dispersion is still observed especially in e+ BT.

Straight line (BT1)

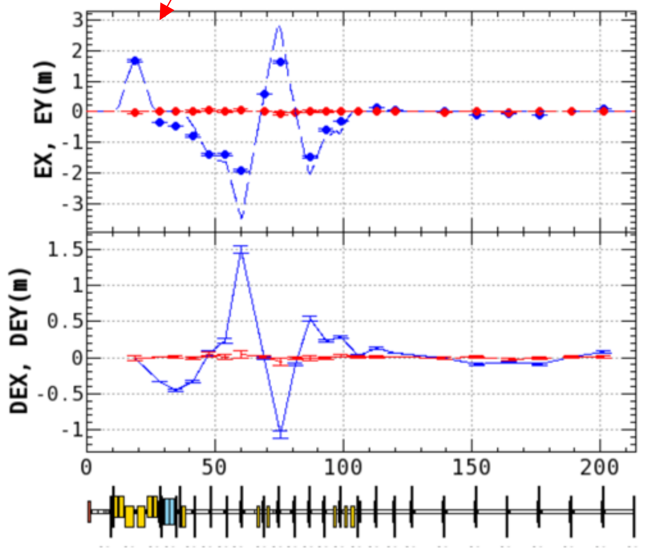
Straight line (BT2)



BT for e- → almost good

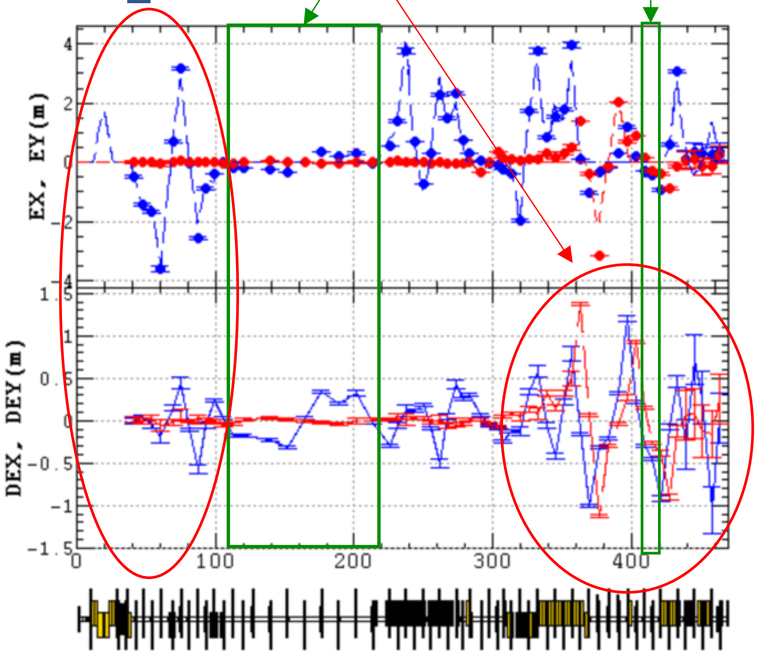
1. Horizontal emittance

ECS



Straight line (BT1)

Straight line (BT2)



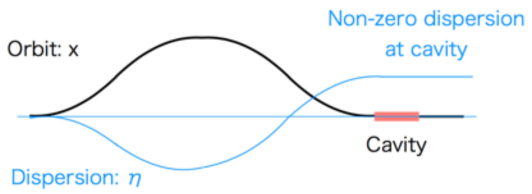
BT for e+

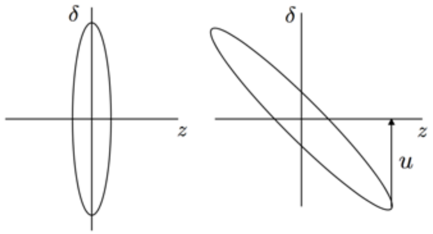
2. Vertical emittance

Residual dispersion at the acceleration structure for a compression system induces emittance growth

- When the beam with dispersion is accelerated by RF cavity, $\eta\delta$ converts to betatron oscillation and causes emittance growth.

M. Kikuchi





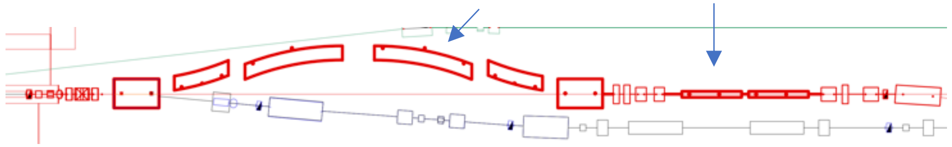
If the cavity has non-zero dispersion, a beam, gaining its energy depending on z, has net growth in the projected-emittance.
This is an analogue of the synchro-beta excitation at the cavity with non-zero dispersion in the ring.

$$\bar{\epsilon}^2 = \epsilon_0^2 + \epsilon_0 \left(\beta\eta'^2 + 2\alpha\eta\eta' + \gamma\eta^2\right) \langle u^2 \rangle$$

$$u = -vz \qquad v = \frac{eV}{E_0}\frac{\omega_{rf}}{c}$$

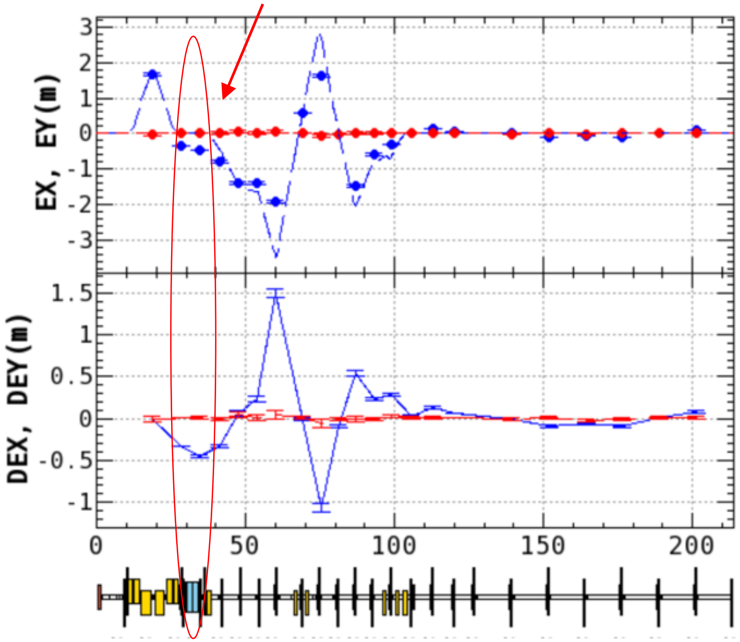
Simulation result: $\frac{\epsilon}{\epsilon_0} \sim 2$

ECS: chicane + acceleration tube



Measured dispersion at the end of LINAC

The dispersion leaks at the ECS cavity.

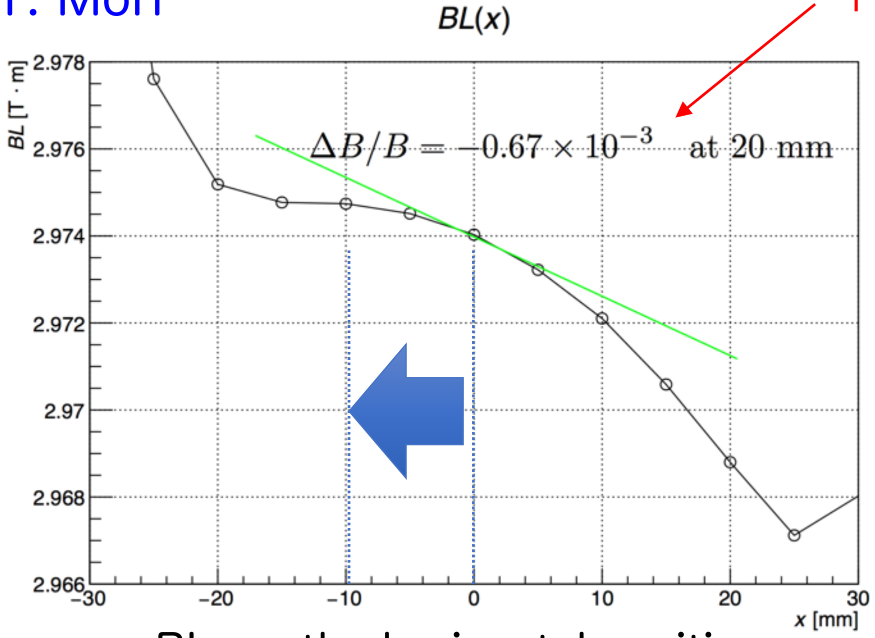


Residual dispersion at the acceleration structure for a compression system induces emittance growth

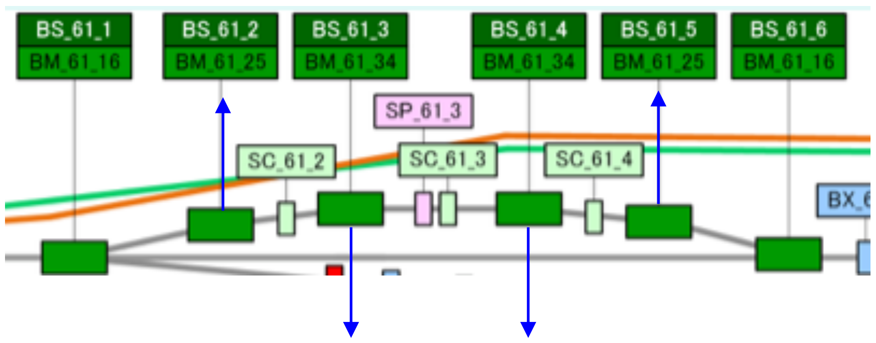
- The bending magnets used in the ECS have multipole components by the measurements in the figure below.
  - Passing through the design orbit in the bends, the beam feels B' field, which results in dispersion leakage.
- By moving the bends about 10mm, the small area of B' can be passed.

T. Mori

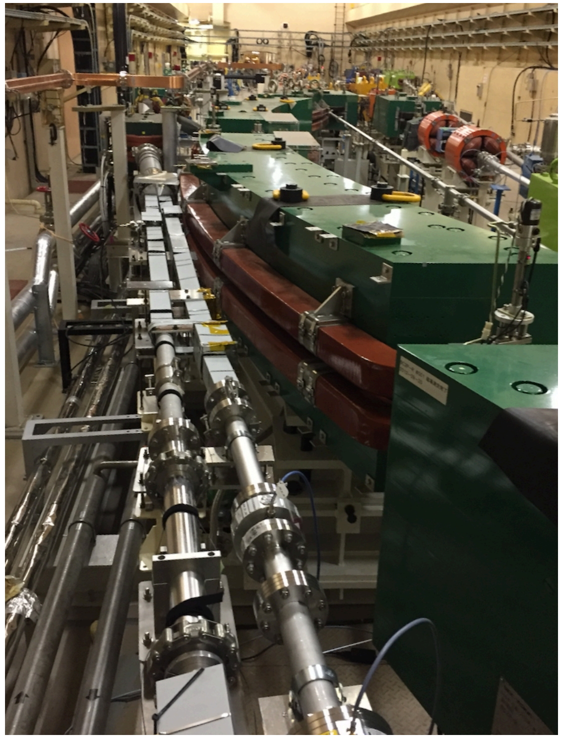
This can explain the measured dispersion leak.



BL vs. the horizontal position



moved 4 bends by ~10 mm



1. Horizontal emittance

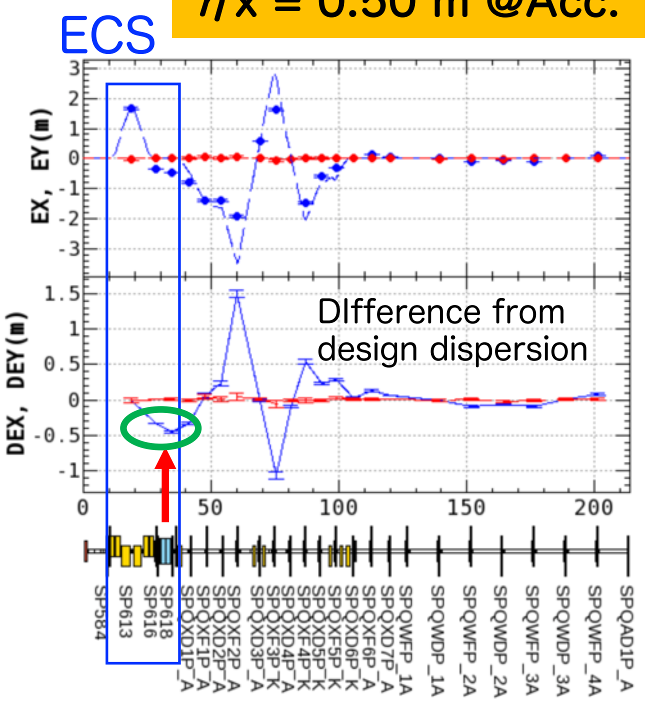
Before moving

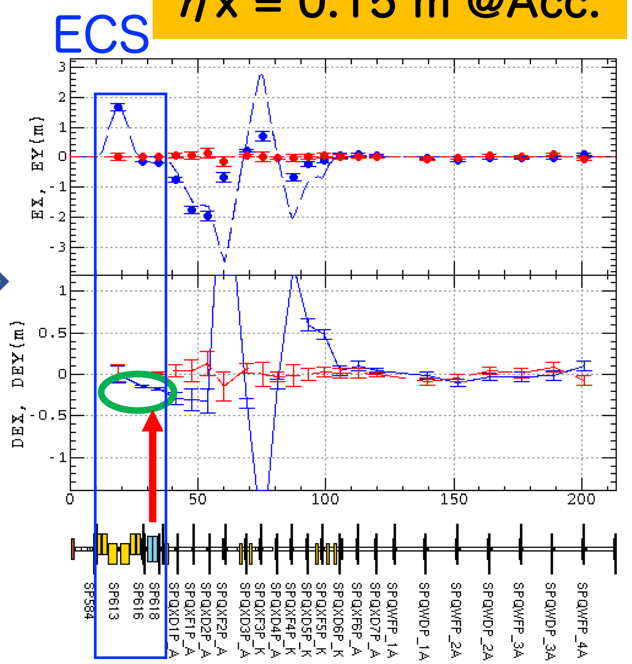
ηx = 0.50 m @Acc.

After moving

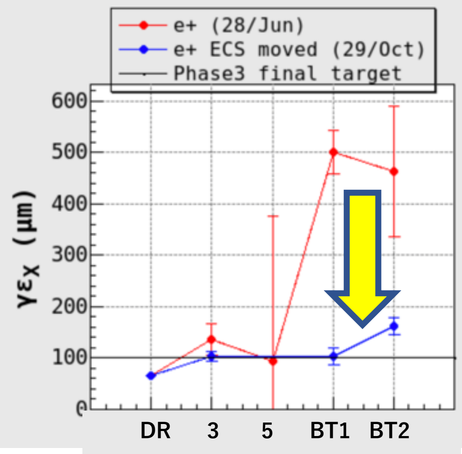
ηx = 0.15 m @Acc.

Y. Seimiya

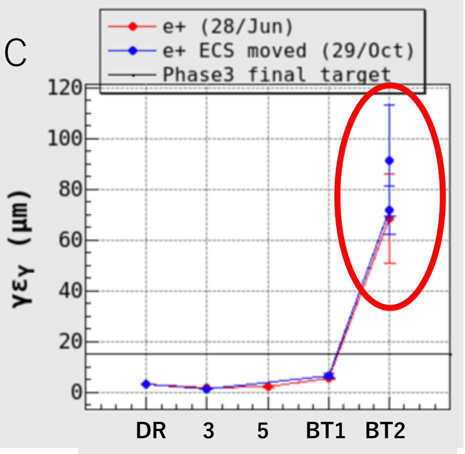




The horizontal dispersion has been improved by moving ECS bends.



1nC

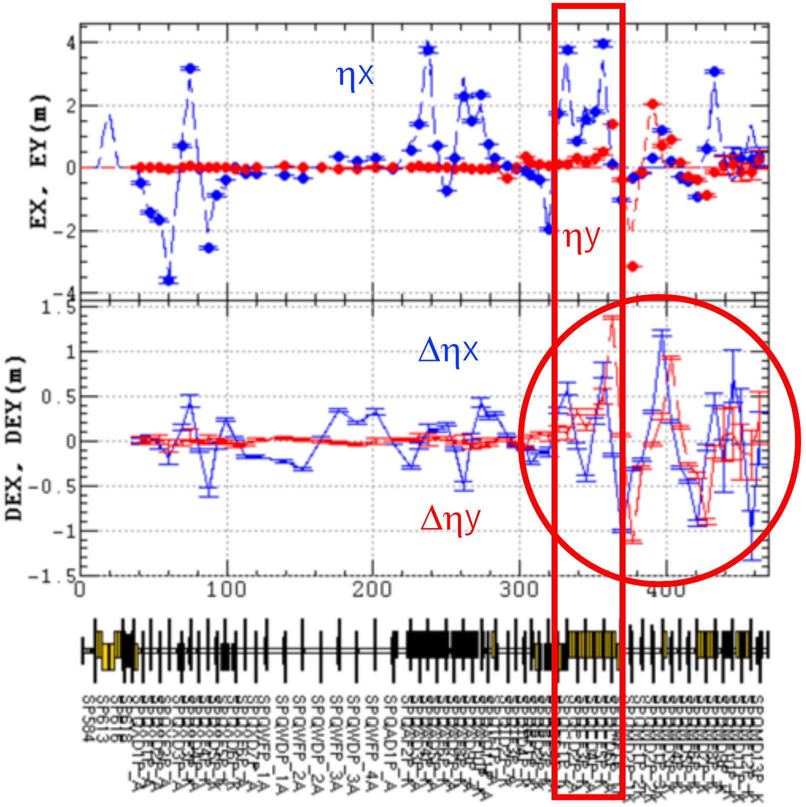


Remained big problem is a large vertical emittance. This is considered to come from abnormal vertical dispersions (M. Kikuchi).

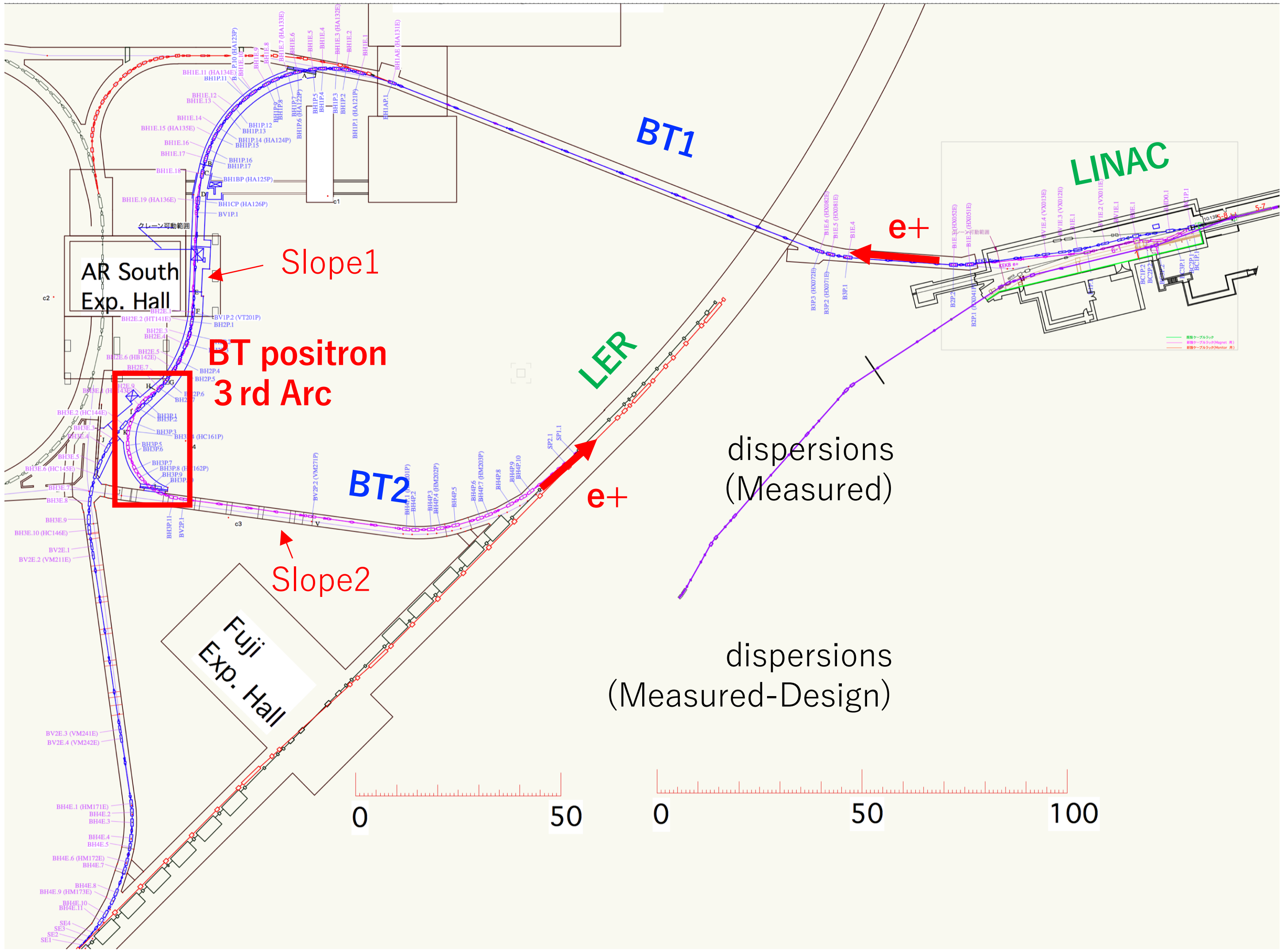
Abnormal skew magnetic field from bends

Measured dispersion in the BT

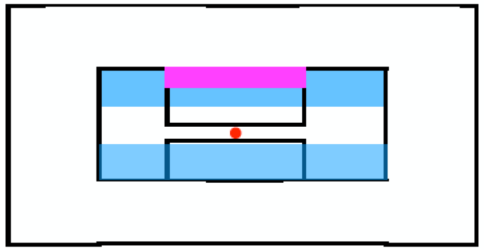
Y. Seimiya



BT positron
3rd Arc



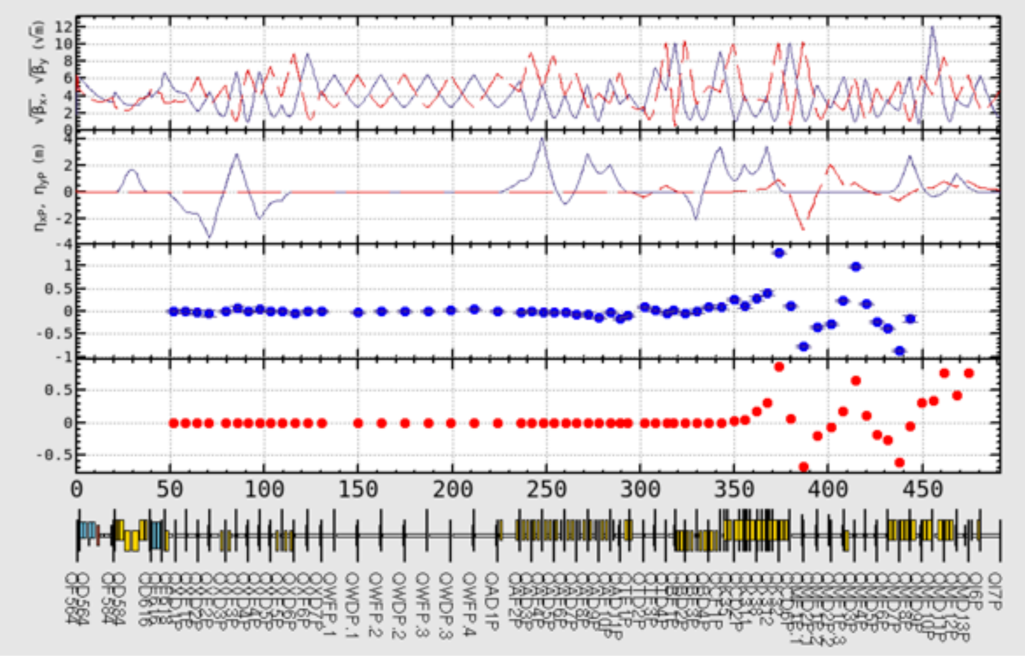
Simulation



The energy of the e+ beam has increased to from 3.5GeV in KEKB to 4 GeV in SuperKEKB.
The gap of bends in the Arc3 had been narrowed asymmetrically.
This created an unusual skew component in bends.
However, this can only explain about one-third of the measured skew quad components.
Anyway, tried to correct it.

M. Kikuchi

e+ BT line



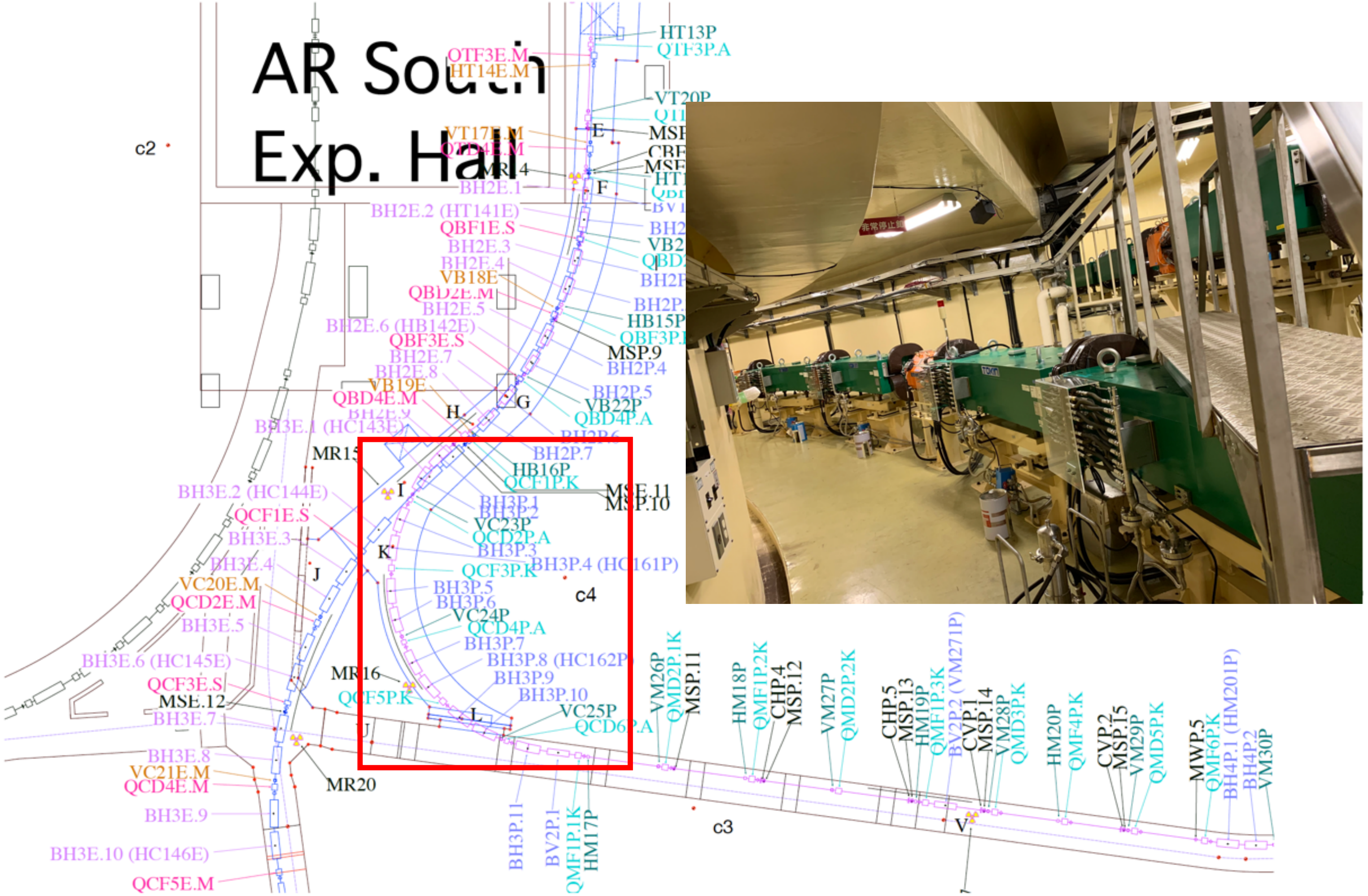
Measured vertical dispersion

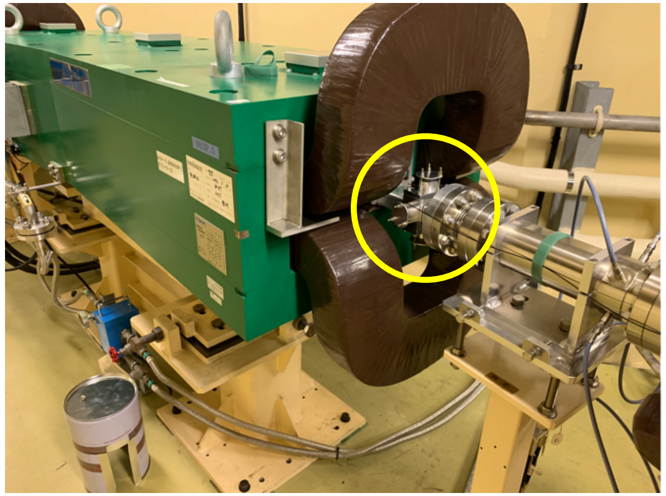
Calculated vertical dispersion by the skew quads

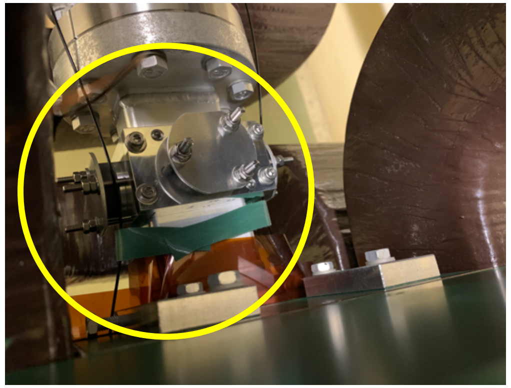
The measurement and calculation are good agreement !

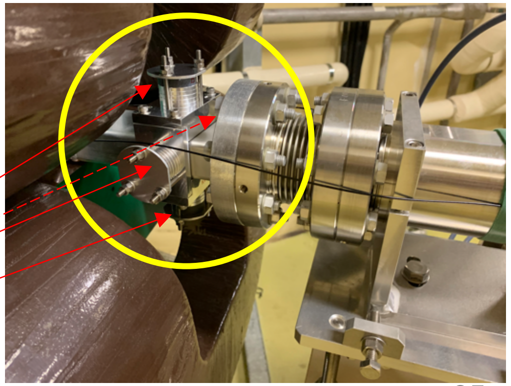
The vertical dispersion could be corrected with the skew quads with permanent magnets.

2. Vertical emittance









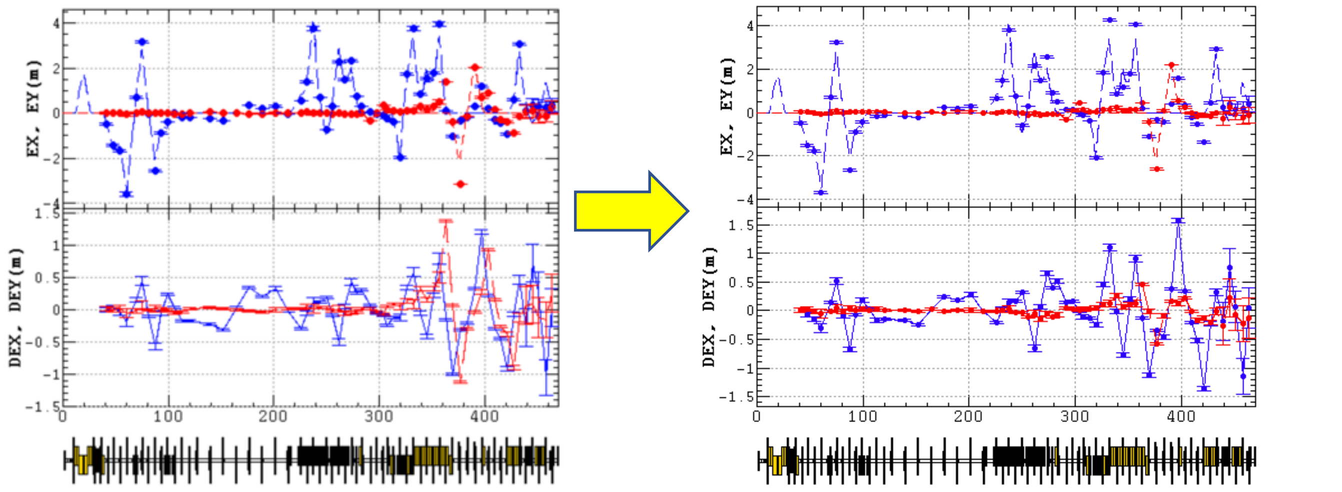
11 of 16 skew quads were installed.

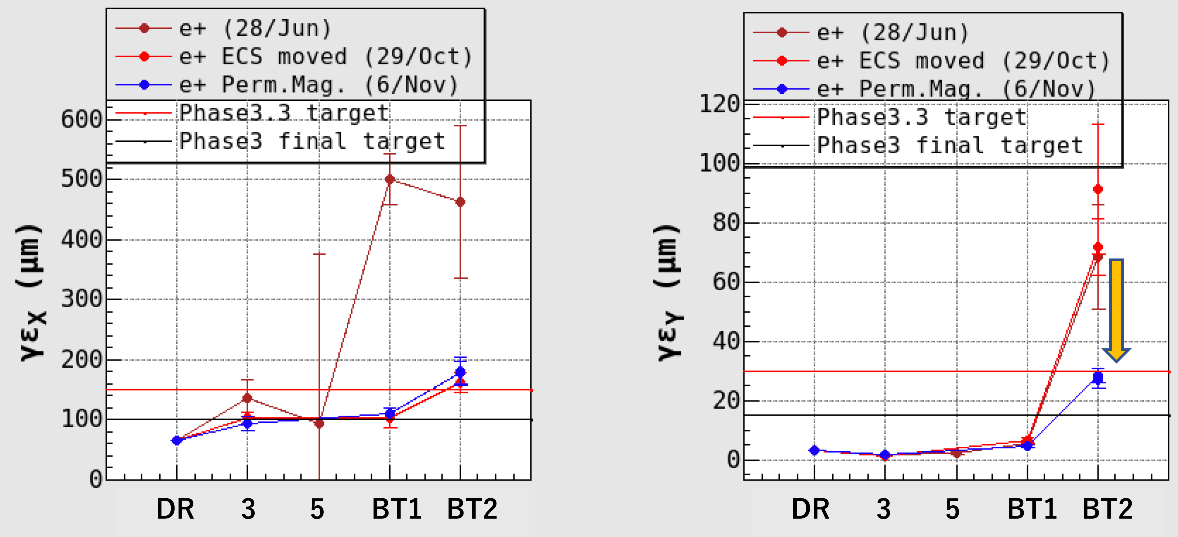
permanent magnets
(Black blocks)

Measured Dispersion

Y. Seimiya

① Before installation of skew quads ② After installation of skew quads

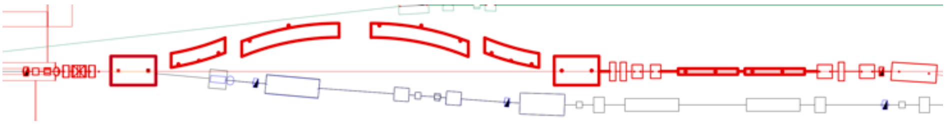




Remaining skew quads will improve the vertical emittance further.

Belle BG depends on the situation of the LER.

ECS: Chicane+Acc

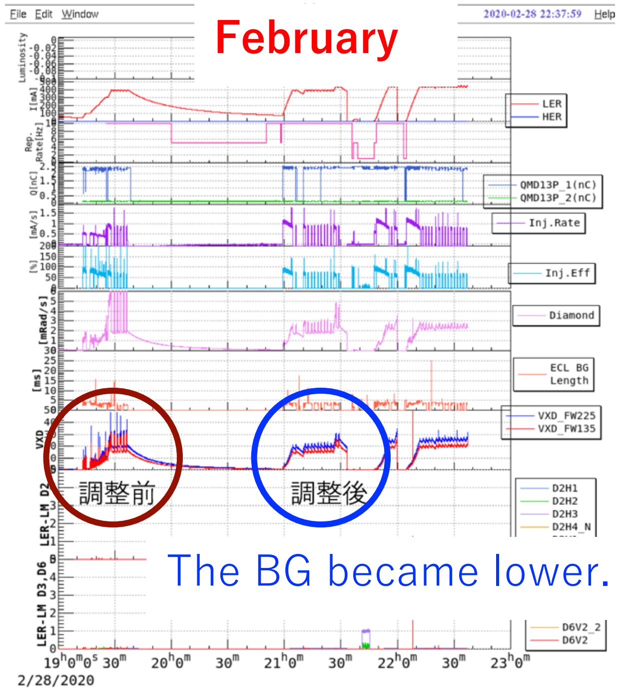


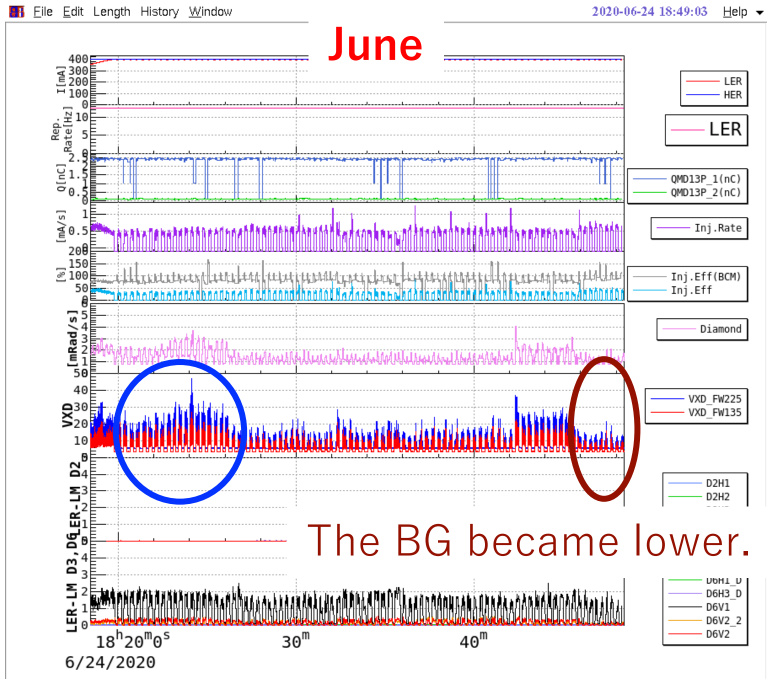
The emittances in the BT becomes large when the energy spread is large in the ECS.
It may be caused by the residual dispersion leak from the chicane which should be closed.

Phase of LINAC	+9 deg	0 deg
σδ in Chicane of ECS	Large	Small
σδ of Injection beam	Small	Large
Emittances	Large	Small

This should be small !

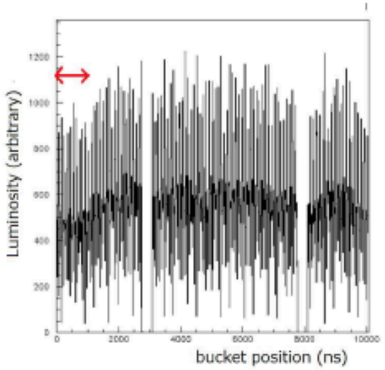
Belle BG monitor

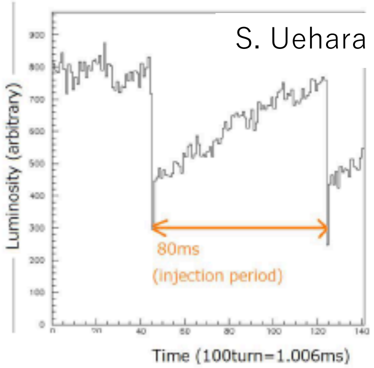




4. Correction of X-Y coupling between injection kickers in the LER

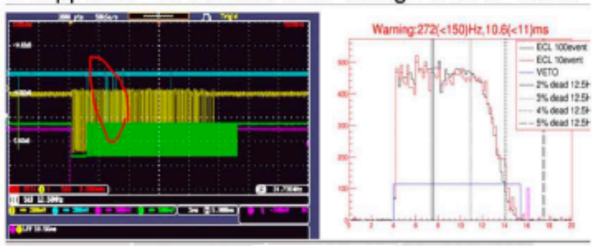
There was a vertical oscillation in the LER just after injection, causing luminosity reduction and the BG.





-June 2nd: BG timing is changed. Outside of injection veto.

It happened ~30 minutes after change 12.5Hz->23hz.



T. Koga

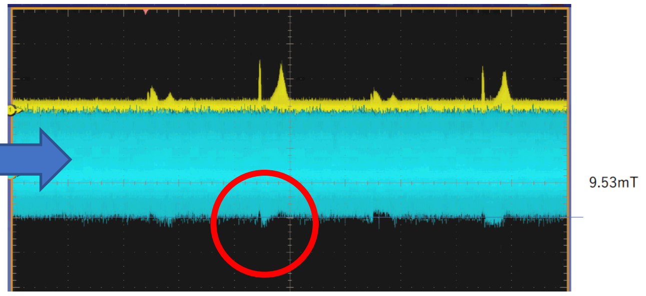
S. Terui,
T. Mimashi, et al.

The detail will be talked by Morita-san.

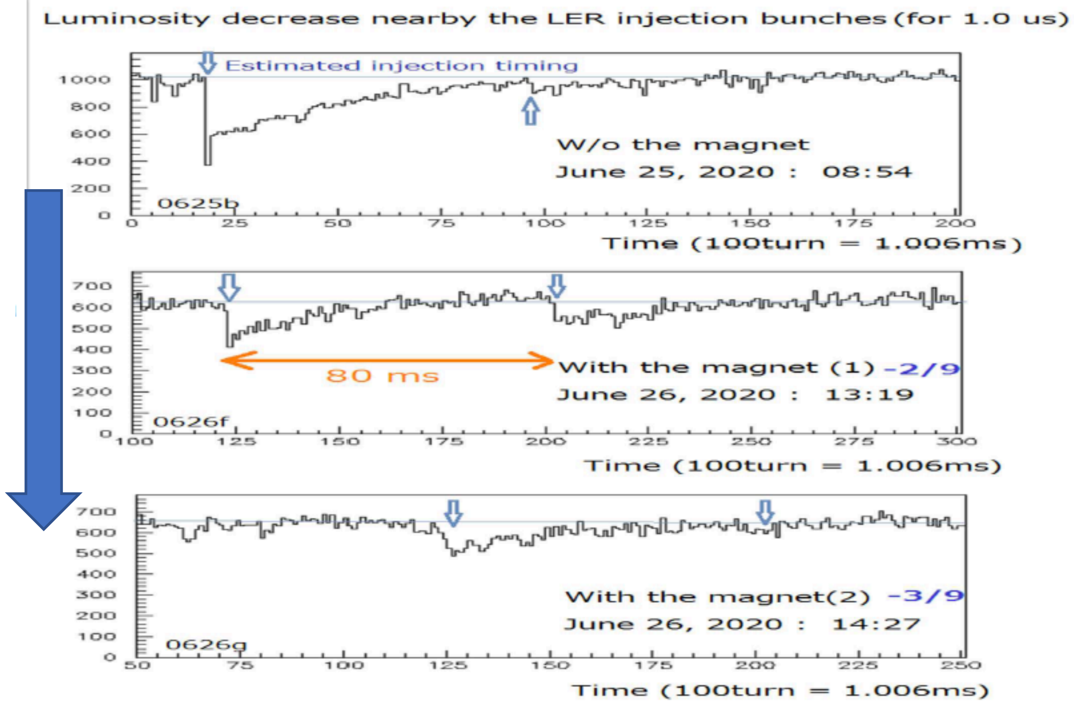
- The vertical oscillation around the injected bunch has been observed with a bunch oscillation recorder(BOR) (S. Terui, M. Tobiyama).
- If there is a vertical offset at the interaction point due to X-Y coupling in the injection π bump,
- the skew quadrupole component k1 is 1.41 x 10^{-4} ($2\sigma_y$, M. Kikuchi).
- A skew quadrupole made of permanent magnets is installed near the injection point.(S. Terui, et al.)
- The skew quadrupole consists of doublet quads whose strength is adjusted by rotating opposite direction to change the skew quad component but not to affect the quad.(K. Oide)

Doublet quads

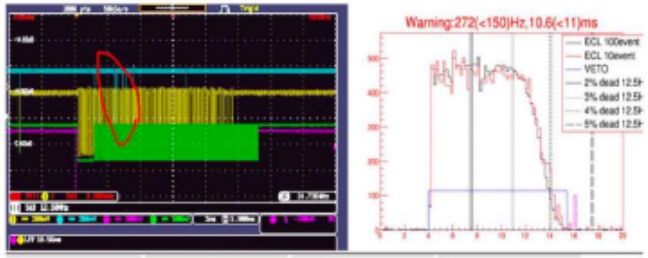
T. Mimashi



S. Uehara

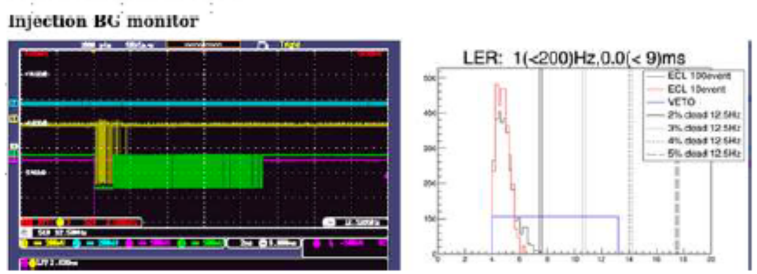


-June 2nd: BG timing is changed. Outside of injection veto.
It happened ~30 minutes after change 12.5Hz->23hz.



T. Koga

skewQ -32mm



- The vertical oscillation became smaller.
- The dead time of luminosity can be shorter.
  (LER: 3.5→2.0%, HER: 1.5%)
- The residue is suspected to be an electric field of the kicker.(K. Oide)

B’L=0.043T(max)
(The permanent magnet: B’L=0.021T)

In this summer shutdown, an electromagnetic skew quad will be installed instead of the permanent magnet. (M. Masuzawa, et al.)

3. Summary

- The injection beam with lower emittance and higher charge is essential for higher luminosity.
- The **explosion of e- emittance** is the biggest problem.
  - Orbit jitters do not explain the explosion.
- The e+ emittance has a room to improve.
  - Close the dispersion at the exit of the ECS chicane