SuperKEKB Injector and Injection (status, issue, and progress)

Everything entangles!

4.Mar.2025

eeFACT2025, @EPOCHAL, Tsukuba, Japan

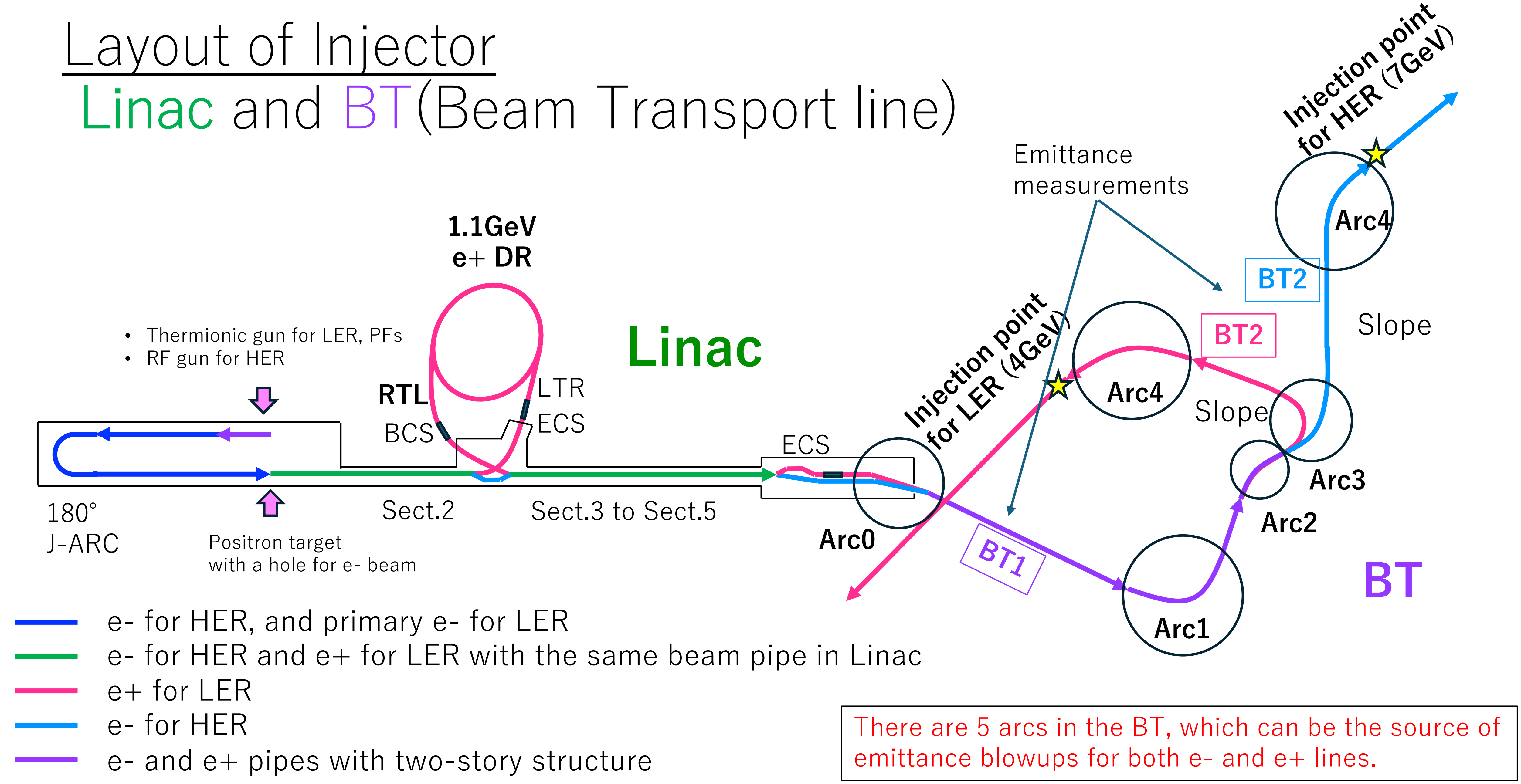
N. Iida (KEK)

Many thanks to, Y. Funakoshi, M. Kikuchi, H. Kaji, M. Kurata, M. Li, T. Miura, F. Miyahara, T. Mori, T. Natsui, Y. Ohnishi, K. Oide, D. Oumbare, M. Satoh, Y. Seimiya, H. Sugimoto, M. Takao, M. Tawada, Y. Yamamoto, M. Yoshida, T. Yoshimoto, X. Zhou, and all members of ICG (Injection Commissioning Group) and SuperKEKB (Linac/Ring)

Contents

Layout of Injector

Linac and BT(Beam Transport line)



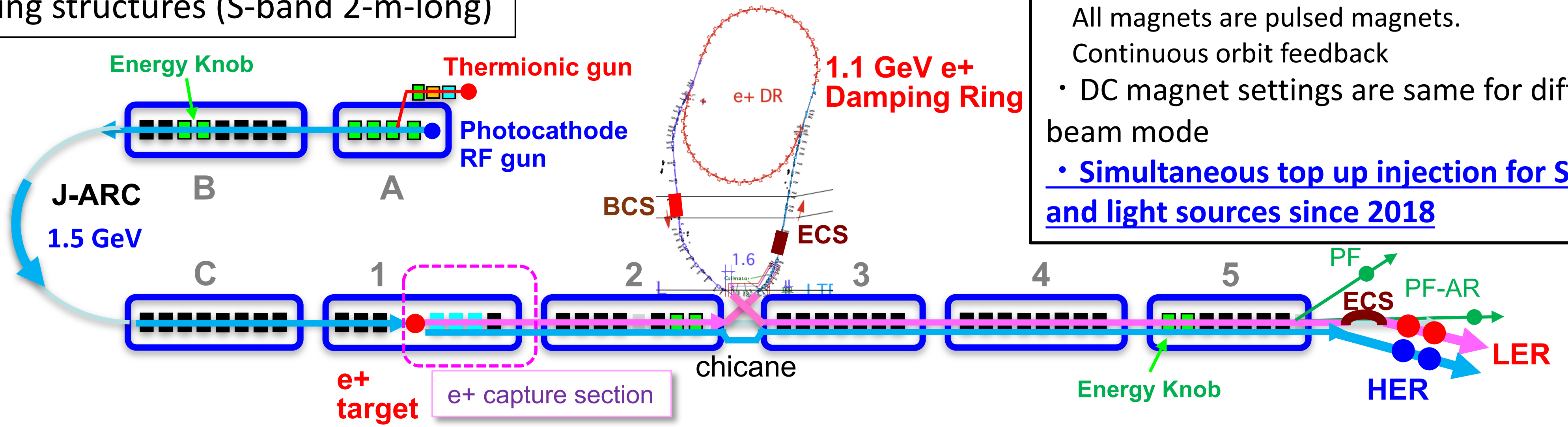
There are 5 arcs in the BT, which can be the source of emittance blowups for both e- and e+ lines.

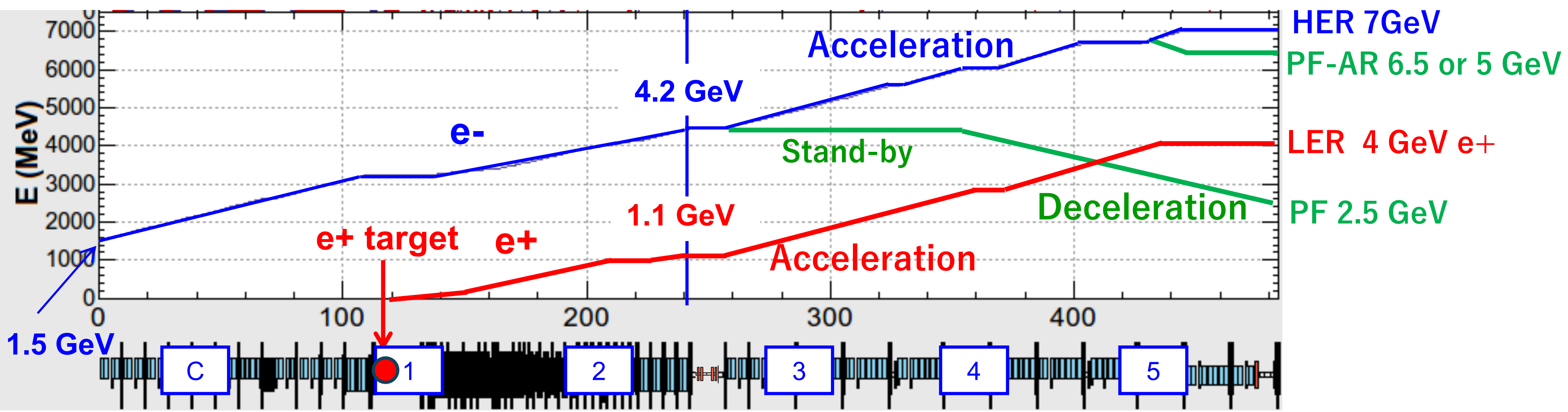
Linac Layout

M .Satoh

Four rings share 50 Hz beam from injector
60 klystron units
240 accelerating structures (S-band 2-m-long)

- Two electron sources:
  - RF gun: HER injection
  - Thermionic DC gun: LER, PF, PF-AR
- Sector 3-5:
  - All magnets are pulsed magnets.
  - Continuous orbit feedback
- DC magnet settings are same for different beam mode
- **Simultaneous top up injection for SuperKEKB and light sources since 2018**





Beam energy variation for each beam mode along the beam line after J-ARC

4

Injection limits luminosity

BEAM INJECTION ISSUES AT SuperKEKB

N. Iida*, Y. Funakoshi, T. Kamitani, M. Kikuchi, T. Mori, T. Natsui, Y. Ohnishi, K. Oide[1],
M. Satoh, Y. Seimiya, and T. Yoshimoto, KEK, Ibaraki, Japan
[1] also at University of Geneva, Geneva, Switzerland

Table 1: Beam Parameters for a Luminosity of $1\times10^{35}/cm^2s$;
* denotes the values at the interaction point.

Parameters	LER	HER	LER	HER
bunches/ring	2345+1		2345+1	
Luminosity [$/cm^2s$]	1×10^{35}		1×10^{35}	
I_{total} [A]	2.08	1.48	2.78	1.65
β_y^* [mm]	0.8	0.8	1	1
σ_z [mm]	6.49	6.35	7.26	6.51
τ_{beam} [min.]	3.4	14.8	4.7	16.9
ϵ_{inj} ^{a} [%]	68	17	66	16
$Q_e^{inj}\times n_{bi}$ ^{a} [nC]	3×2	2×2	3×2	2×2
r_{inj} ^{a} [nC/pulse]	4.1	0.68	4.0	0.64
r_{inj} ^{b} [nC/pulse]			3.0	1.2

←required
←achieved (L=0.51x10^{35})

^{a} Requirement for injection for 25 Hz, $r_{inj}\equiv\epsilon_{inj}Q_e n_{bi}$.
^{b} Parameters when maximum luminosity was achieved in 2024 autumn run.

Even achieved value looks higher than the required,
the ε_{inj} at 1x10^{35} can be degraded due to higher current, higher bunch current, higher collimation, stronger beam-beam.
We can not relax.

IPAC2023, N. Iida et. al., MOPL120

An injection efficiency is expressed by,

$$\epsilon_{inj} = \frac{R_{inj}+R_{loss}}{Q_e f_{rep} f_{rev}\, n_{bi}},$$

where R_{inj}, R_{loss}, Q_e, f_{rep}, f_{rev}, and n_{bi} denote the injection rate [A/s], loss rate [A/s], bunch charge of the injected beam [C], repetition rate of the injection [Hz], revolution frequency of the ring (~100 kHz), and number of bunches per a pulse of the LINAC (2 bunches in maximum). The R_{inj}/R_{loss} are measured with a DCCT every second during the injection/decay time. Table1 summarizes required parameters to achieve the target luminosity. Table 1 also shows the maximum injection rates when the new luminosity record was achieved. For the LER, $r_{inj}{}^b$=2.3 nC/pulse was much lower than the requirement, $r_{inj}{}^a$=4.0 nC/pulse. For the HER, $r_{inj}{}^b$=0.65 nC/pulse was achieved, which satisfies the requirement of $r_{inj}{}^a$=0.64 nC/pulse, but it may drop $r_{inj}{}^b$=0.34 nC/pulse due to unstableness in a few days or hours. This can be recovered by tuning, but it is difficult to maintain the maximum efficiency. This section discusses

Two-bunch operation(two bunches in one linac pulse) has been done at LER in 2024 autumn run.

Injection status in 2024 autumn run

LER(e+) e+ Measured emittance in BT, Bunch charge, Injection efficiency, and parameters in LER

Measured emittance

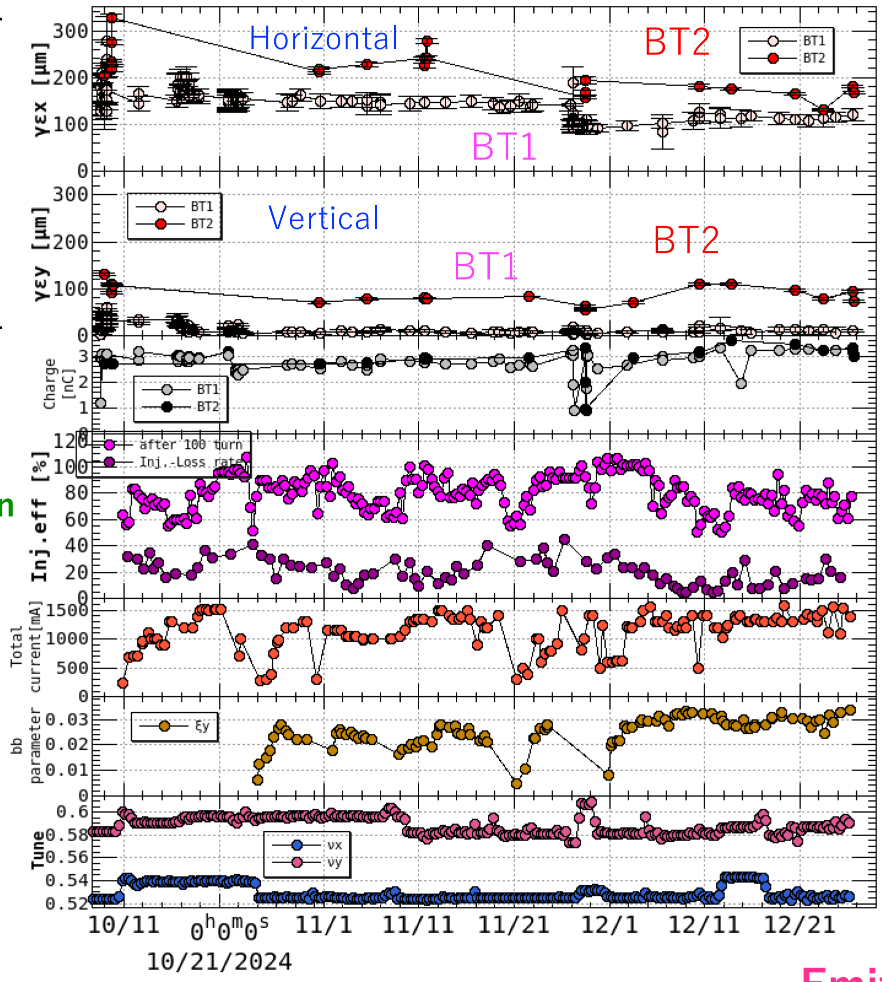
Bunch charge

Injection eff.
- **after 100 turn**
- ΔQring/ΔQinj

Total current

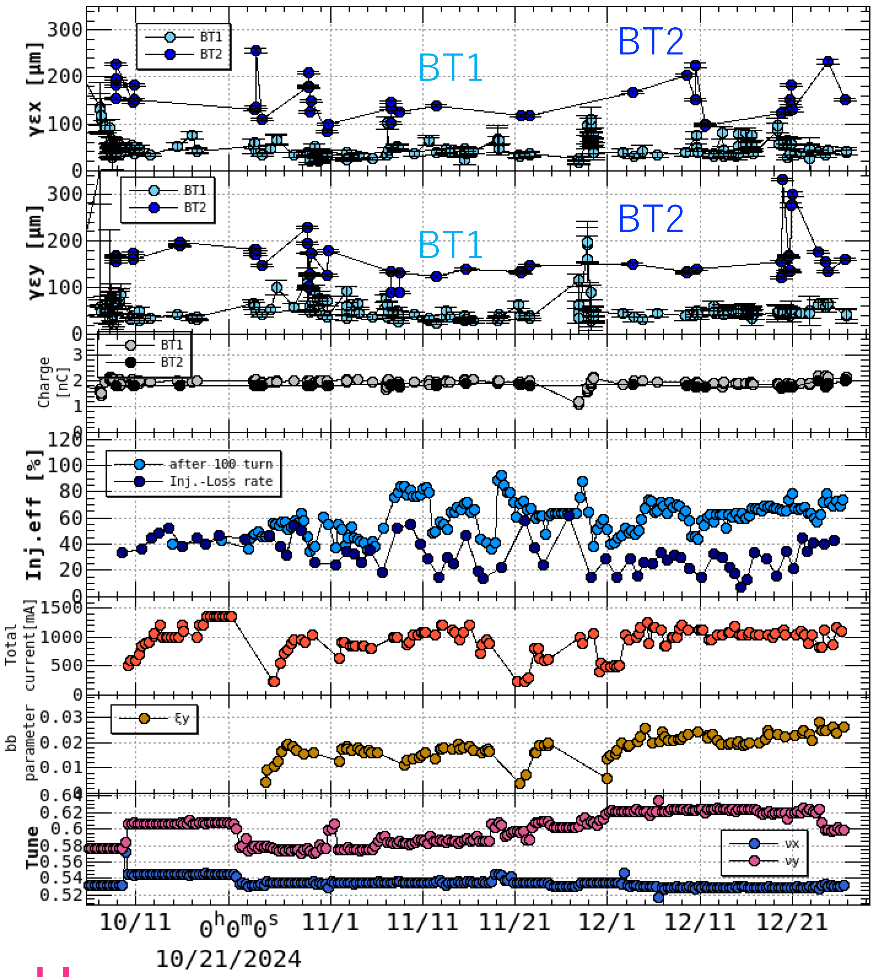
Beam beam parameter

Tune



HER(e-) e- Measured emittance in BT, Bunch charge, Injection efficiency, and parameters in HER

Everything entangles!

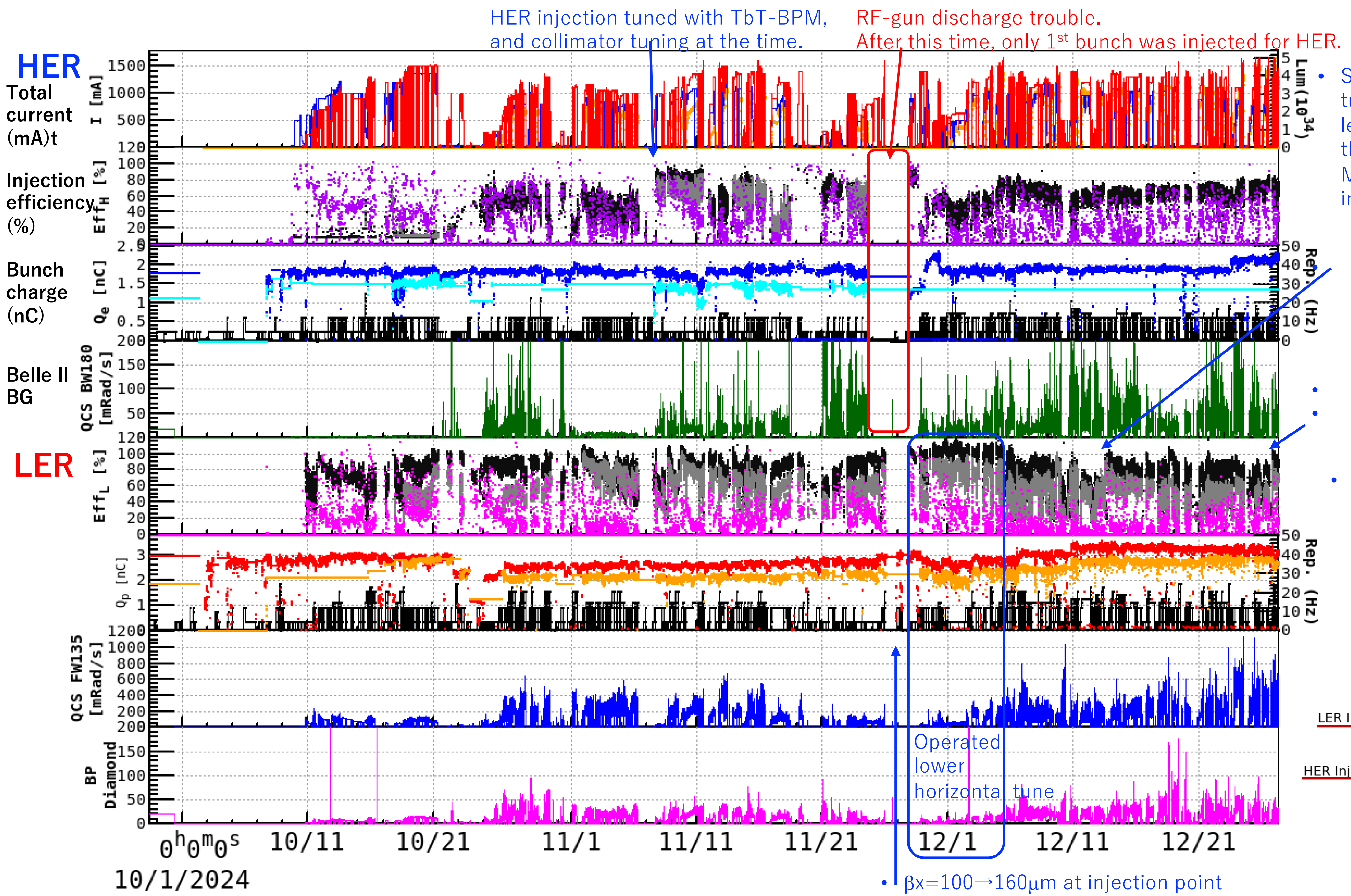


Long. damping time: 2900/2300 turns (HER /LER)

Emittance blowup

e+	BT1	BT2
γεx[μm]	110	170
γεy[μm]	5	90

e-	BT1	BT2
γεx[μm]	45	150
γεy[μm]	45	150



- Sometimes, the automatic tunings(ATs) by machine learning(ML) were done for the e- emittance tuning (by M. Kurata) and HER injection tuning (by S. Katoh).

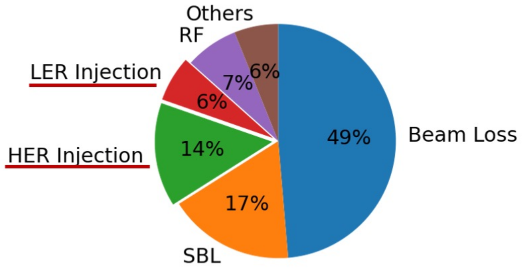
Because εx of LER didn't get bigger due to higher horizontal tune, the kicker height was able to be 2.5mm higher.

- Optics matching at BT end
- bx*=80→70→60mm

- Stable 2-bunch injection was done in LER.

- βx=100→160μm at injection point
- Dispersion correction in RTL (by T. Yoshimoto)

Abort source



2. Injection issues

A) **Emittance growth of the injection beam through the BT**
   - **e-**
   - **e+**
   - **Action of the injected beam and the ring acceptance**

B) Injection efficiency dependence
   - on the charge of the injected beam
   - on the bunch current of the stored beam
   - Injection efficiency decreases due to the beam-beam effect

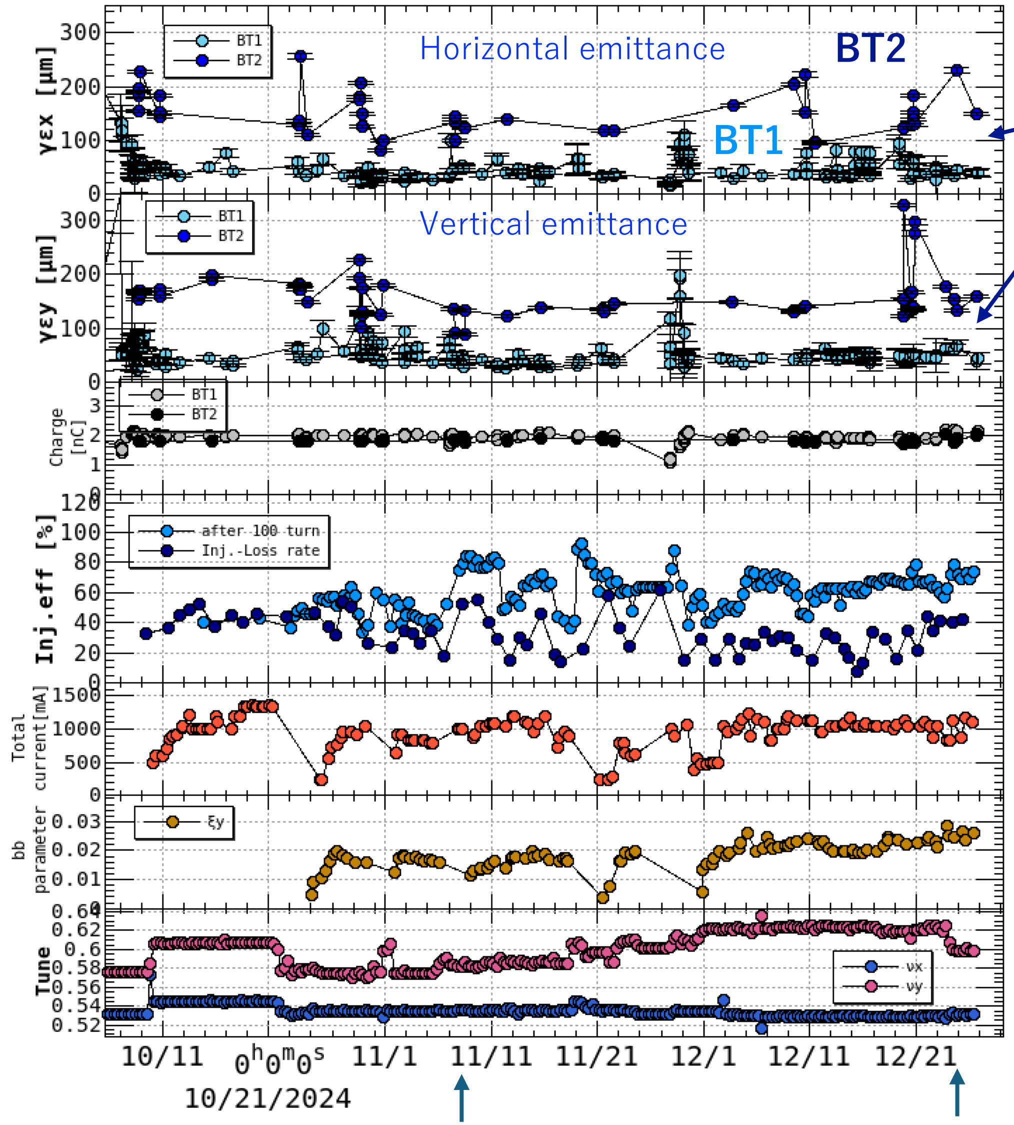
C) Error in “QCS cancel coil”

D) Stability of the beam

2. A) emittance growth

HER

e- Measured emittance in BT, Bunch charge, Injection efficiency, and parameters in HER



Inj. tuning w TbT BPM, and Collimator tuning

βx*=80mm to 60mm

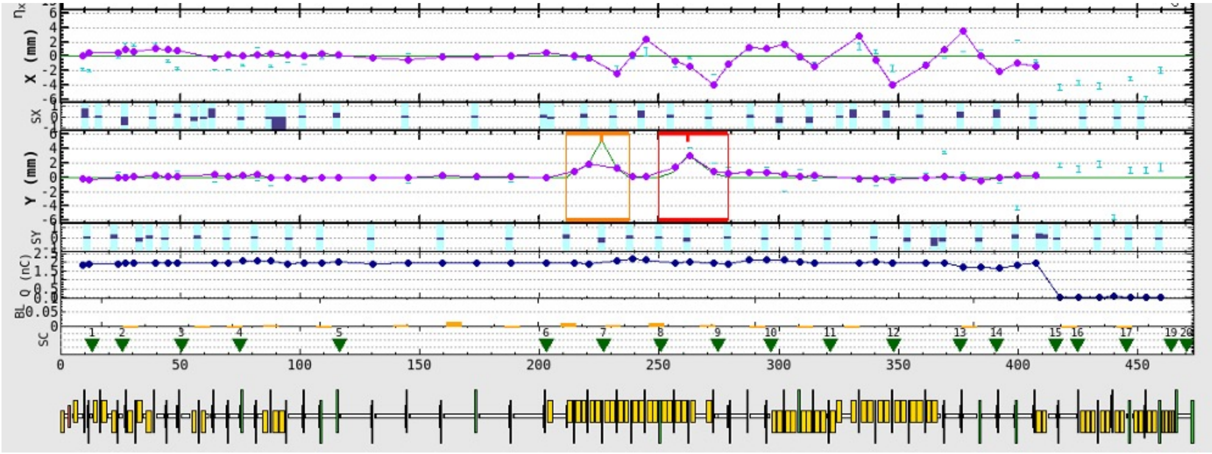
e-	BT1	BT2
γεx[μm]	45	150
γεy[μm]	45	150

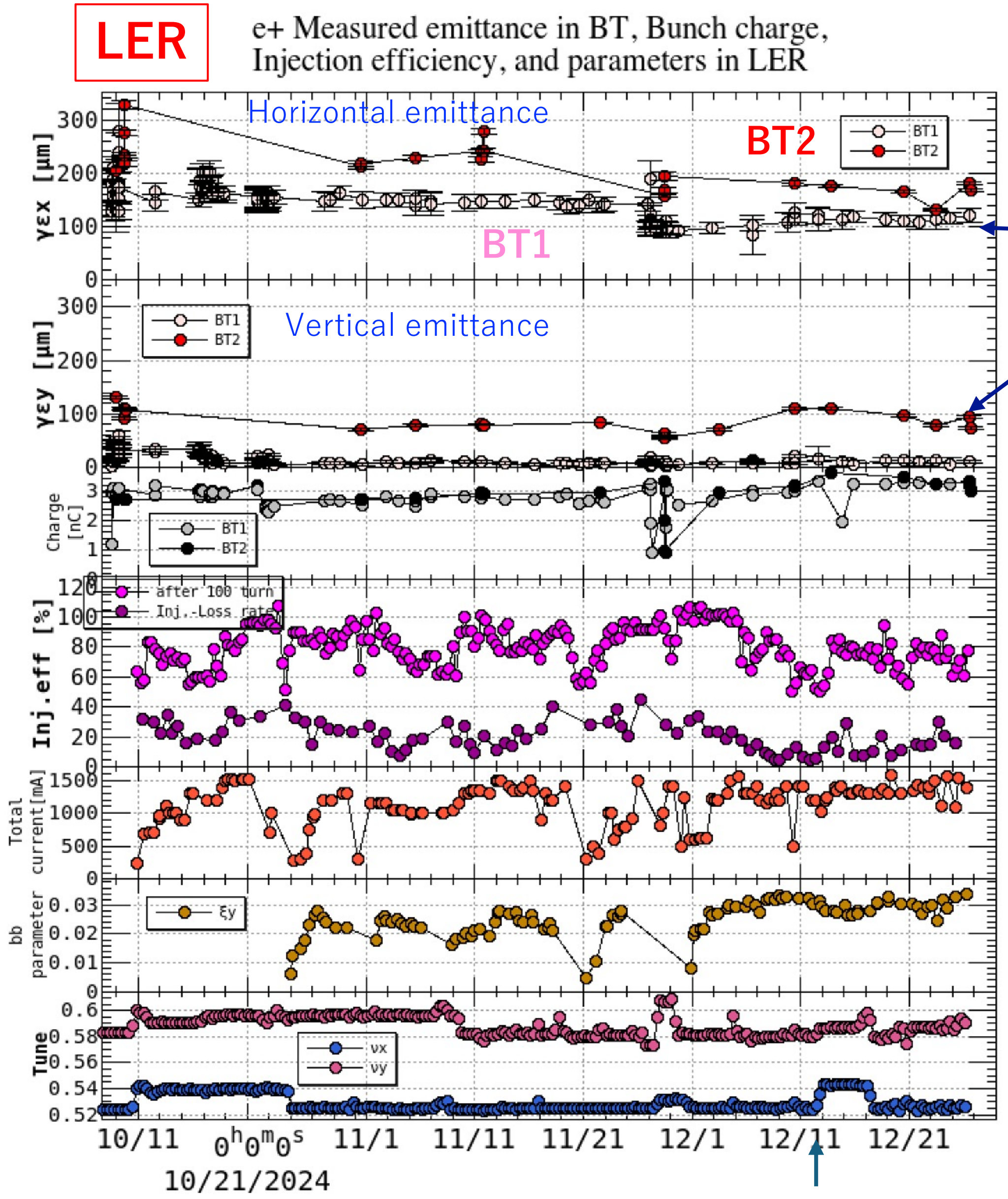
- There are large emittance growth through the BT line in the horizontal and vertical planes.
  - The sources of horizontal emittance blowup in BT are estimated as:
    1. ISR(Incoherent Synchrotron Radiation): ~30μm
    2. CSR(Coherent Synchrotron Radiation): ~60μm(2 nC)
  - γεx = 45μm(BT1) to 135μm(BT2) can be understood.
  - The vertical blowup has been still mystery.
    - Unexpected multipole magnetic fields exist, which might be the blowup source. (The vertical bump orbit makes the horizontal orbit in the Arc of e- BT.)

Δx [mm]

Δy [mm]

Q [nC]

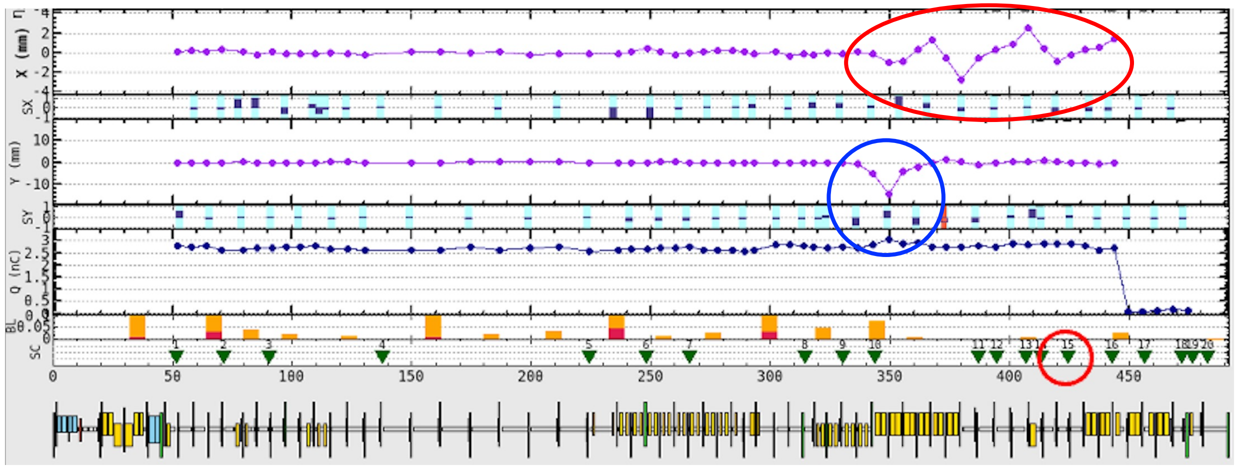




βx=100 m
to 160 m
@inj. point

e+	BT1	BT2
γεx[μm]	110	170
γεy[μm]	5	90

- There are large emittance growths in the e+ BT line for both horizontal and vertical planes.
  - One of the sources of blowups has been recently understood.
  - Unexpected multipole magnetic fields exist in Arc3.
    (Inspired by an observation that a vertical bump orbit generates the horizontal orbit.)



K. Oide

By the multipole of the BH3P tracking through the BT line shows the blowup of the emittances like the lower left plot.
If we reform the BH3P, the blowup will be mitigated like the lower right plot.

Reformed multipoles on BH3P (M. Tawada, M. Kikuchi)

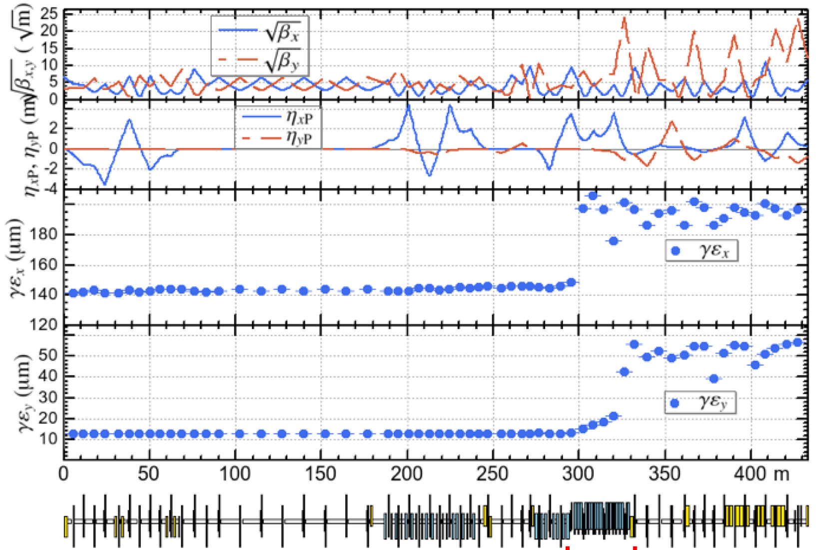
Arc3

- **Tracking by SAD includes:**
  - **multipoles in BH1P/2P/3P, reform of BH3P (Tawada, Kikuchi, ver-3-6 from-median-plane)**
  - **vertical offset of BH1P (Iida)**
  - **measured rotation/pitch errors of quads in ARC3 (Tawada)**
  - **perm. skew quads for dispersion correction (Kikuchi)**
  - **measured emittances at BT1 (Yoshimoto) scaled on particles @ linac exit (Iida)**
  - **additional sextupole at BH3P.1 based on bump meas. (Yamaguchi, Iida)**
  - **refined bend model**
  - **synchrotron radiation in all elements**

K. Oide, Feb. 25, 2025
Multipole calculation, quad roll: M. Tawada + M. Kikuchi including reformed BH3P (250225).
Perm. skew Q: M. Kikuchi
Emittance meas. @BT1 T. Yoshimoto
Sext. meas., Lattice, initial particles, etc.: N. Iida, Y. Seimiya, T. Yamaguchi

	Meas.	Simulation	
BH2P/3P		present	reformed
K2, 1/m^2	0.65		
$\gamma\varepsilon x$@BT2 [μm]	170	195	157
$\gamma\varepsilon y$@BT2 [μm]	90	55	15

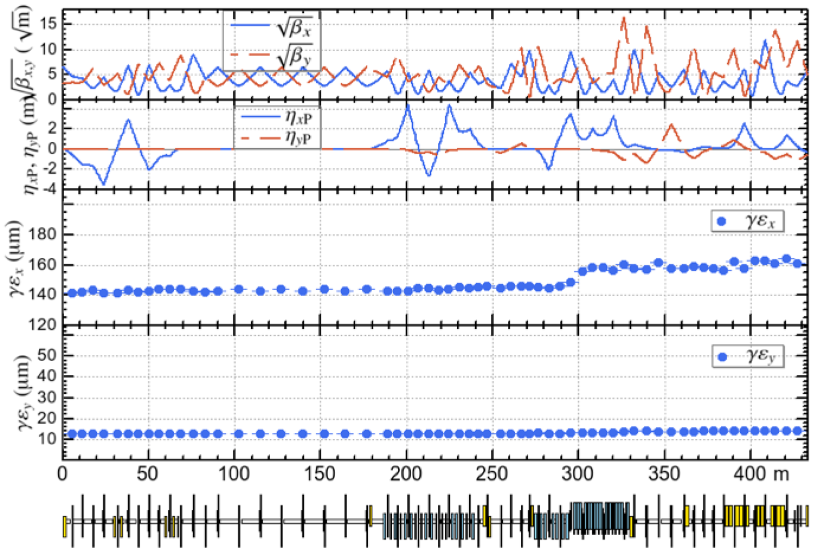
linac-btp_BH1P_MULT_APERT_AveMeasMag3_20231202.sad
$K2_{SKBH3P} = .64935\ /m^2,\ K1_{SKBH3P} = 0\ /m$



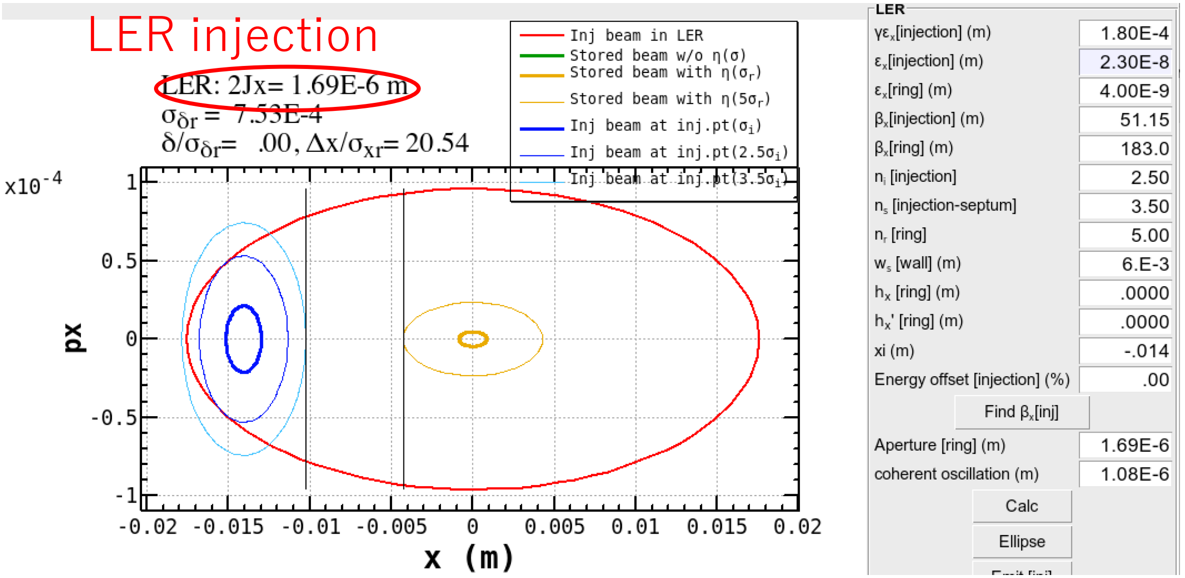
11xBH3P in Arc3

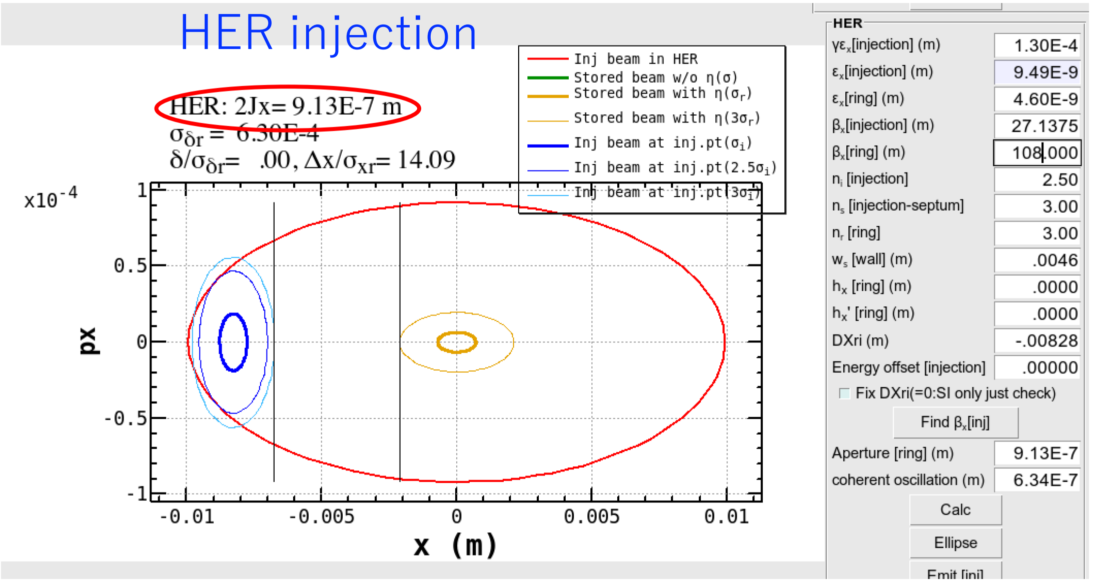
Reformed BH3P

linac-btp_BH1P_MULT_APERT_AveMeasMag3_20231202.sad
BH3P multipole: ver-3-6, from-median-plane
$K2_{SKBH3P} = .64935\ /m^2,\ K1_{SKBH3P} = 0\ /m$



Aperture of the Injection Beam and Ring Acceptance





LER	Injection beam	Ring(meas.)[1]
2Jx [μm]	1.70	1.4
2Jy [μm]	0.069 (6εy)	>0.02
δα [%]	0.32(95% Incl.)	1.03

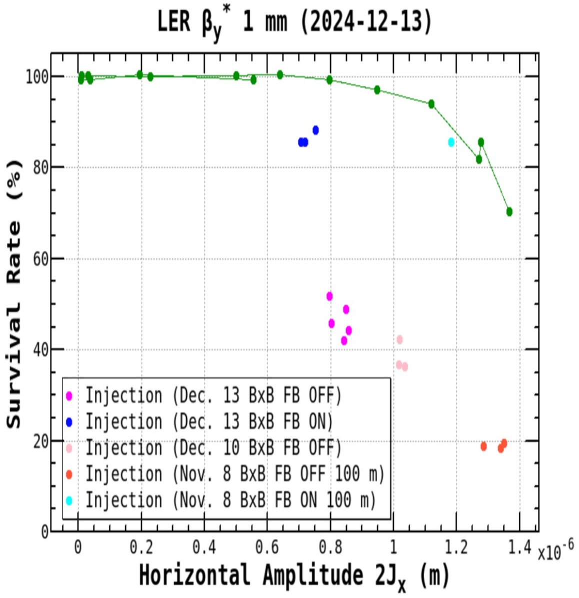
HER	Injection beam	Ring(meas.)[1]
2Jx [μm]	0.91	0.90
2Jy [μm]	0.066 (6εy)	> 0.04
δa [%]	0.31(95% Incl.)	0.56

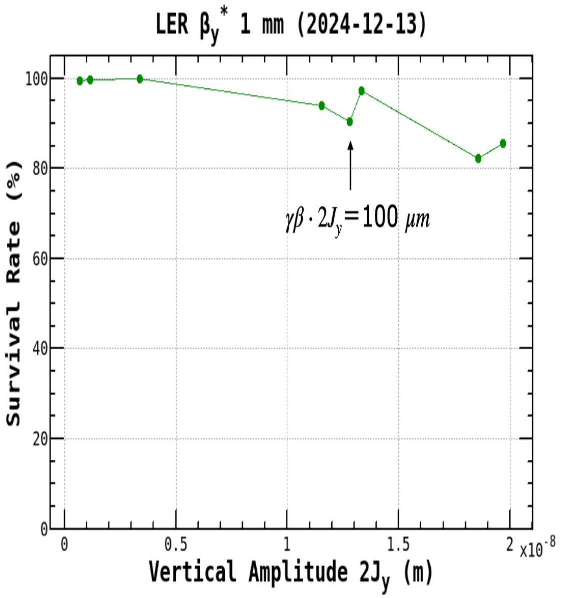
[1] Y. Ohnishi, https://kds.kek.jp/event/54174/attachments/187807/253831/SuperKEKB_eeFACT2025.pdf P.17, 19

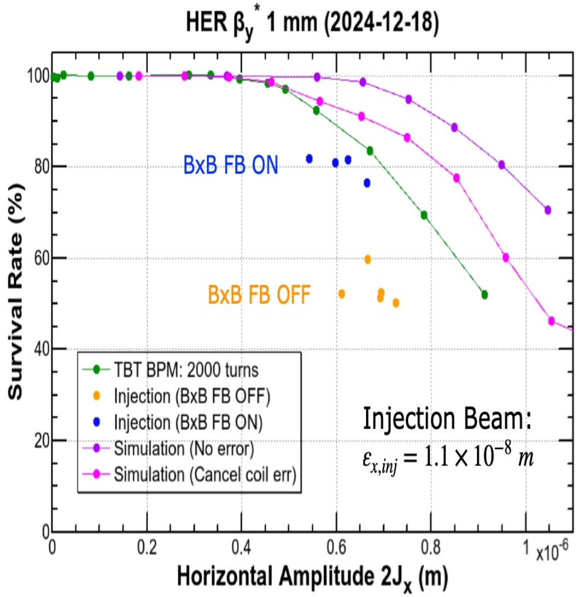
[1] Y. Ohnishi,
https://kds.kek.jp/event/54174/attachments/187807/253831/SuperKEKB_eeFACT2025.pdf P.17, 19

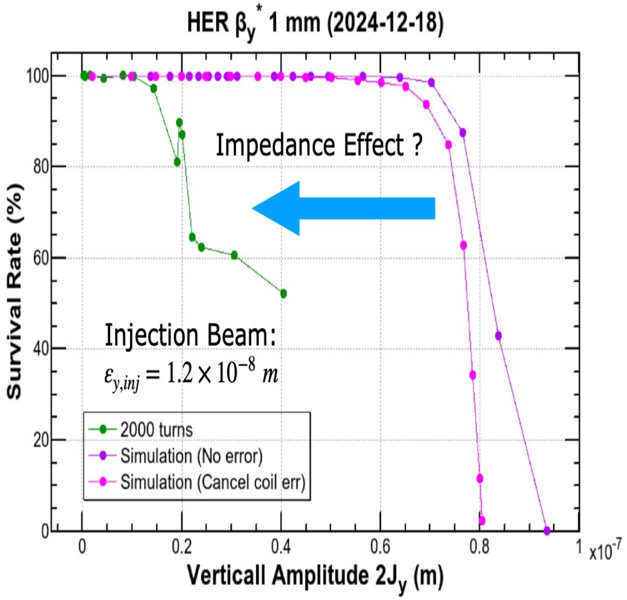
Measurement: 13.Dec.2025

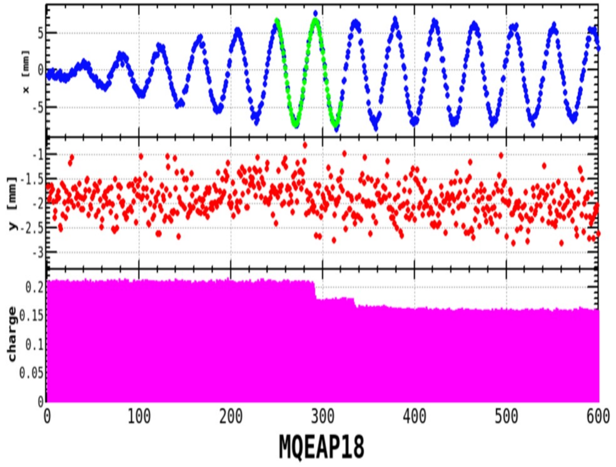
$\beta_x^* = 60\ mm\ /\ \beta_y^* = 1\ mm$





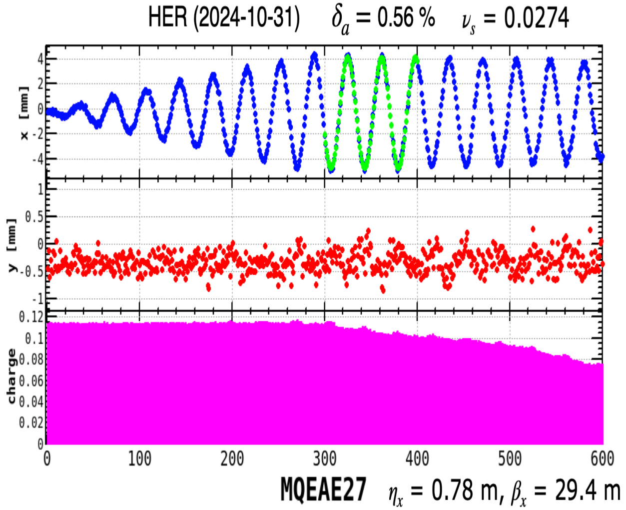






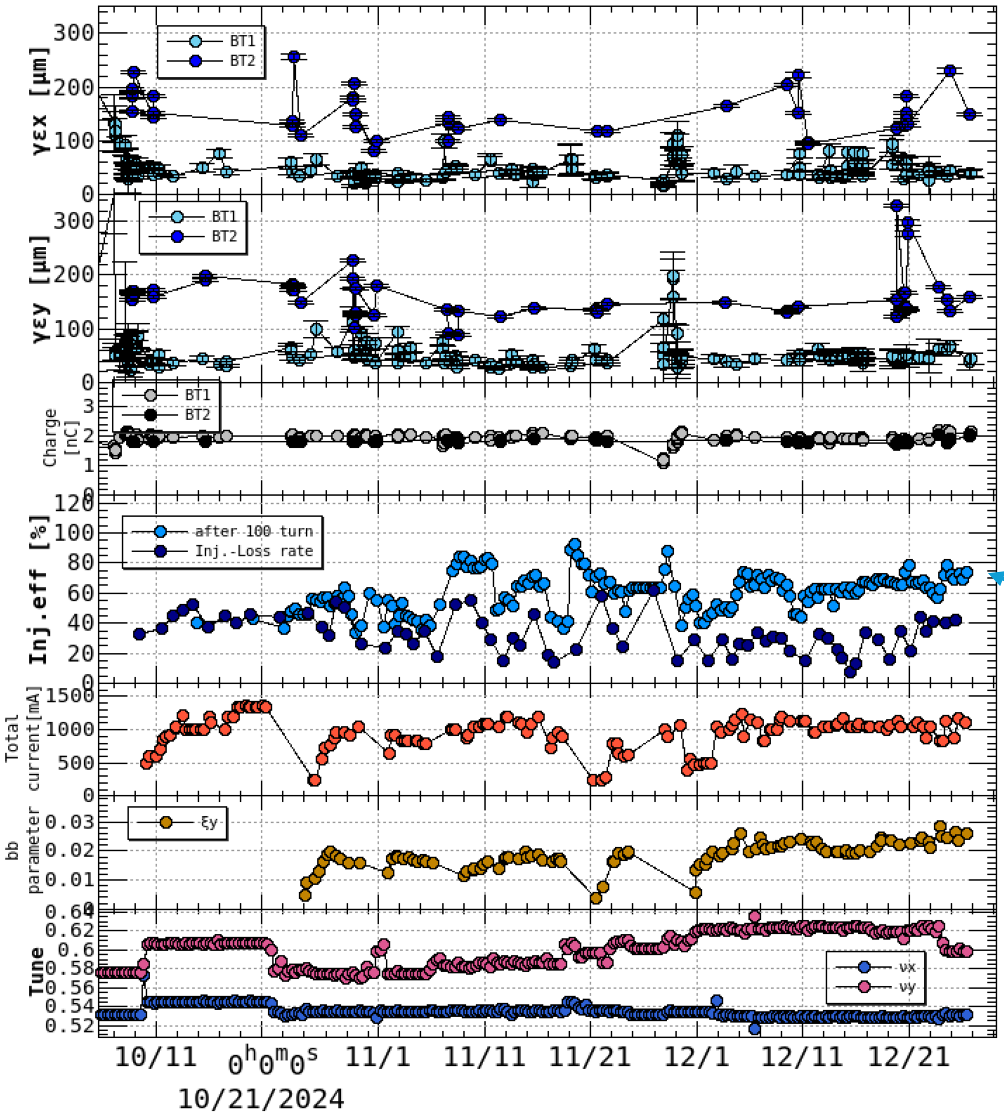
δ_{max} = 1.03 %

13.9 σ_δ



HER

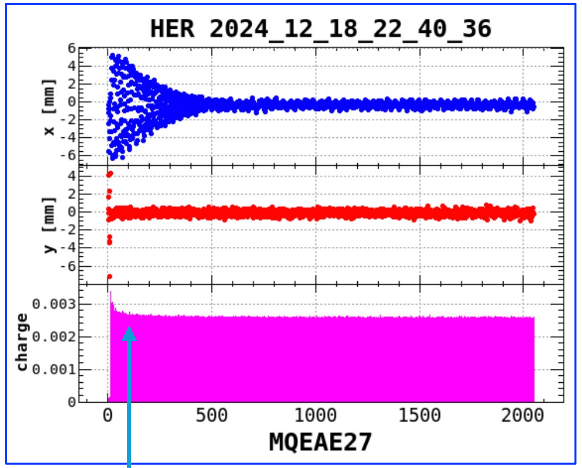
e- Measured emittance in BT, Bunch charge, Injection efficiency, and parameters in HER



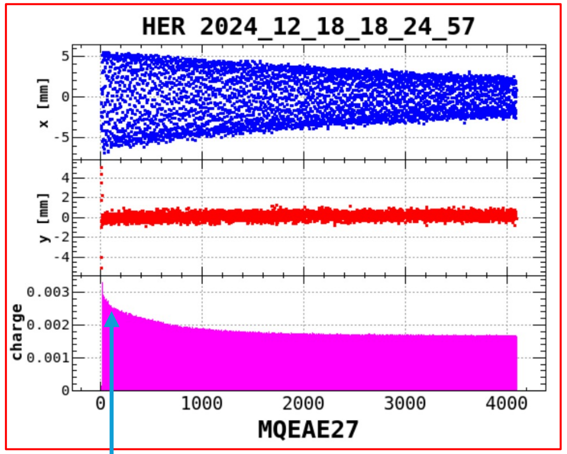
TbT-BPM: Turn-by-turn BPM
BxB FB: Bunch-by-bunch feedback

Measurements of the oscillation of injection beam with TbT-BPM

BxB FB ON



BxB FB OFF



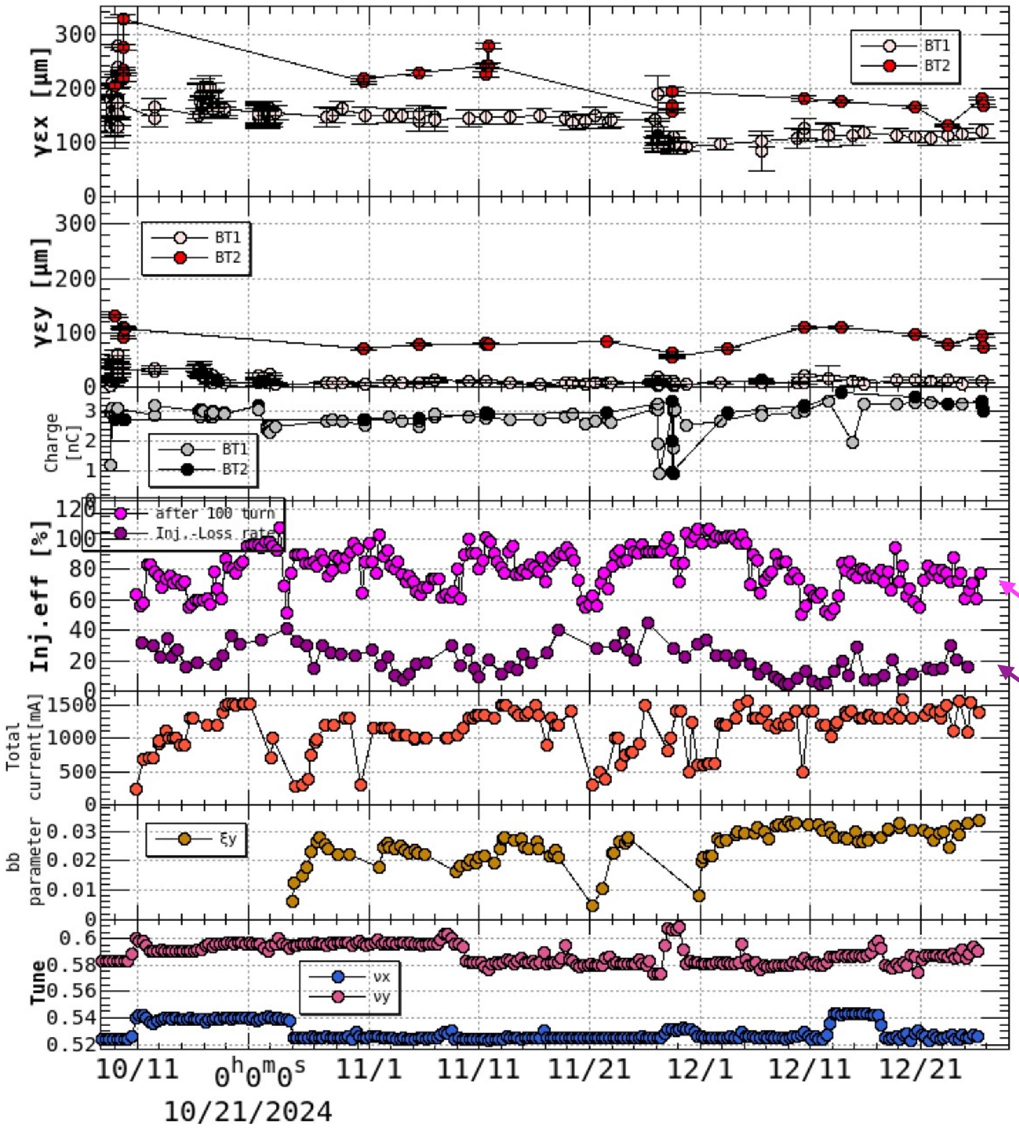
Injection efficiency at 100th turn after injection

<u>BxB FB effect gets weaker at high stored current</u>

- The injection efficiency becomes worse at the higher stored bunch current. It is considered that just after the injection, the center of mass of the charge in the bucket oscillates horizontally. That is to be suppressed by the BxB FB.
- However, at the high current, the CoM gets close to the stored bunch, the injection oscillation is less suppressed by BxB FB.
  - High current: 0.537mA / 0.2 mA stored/injected bunch

LER

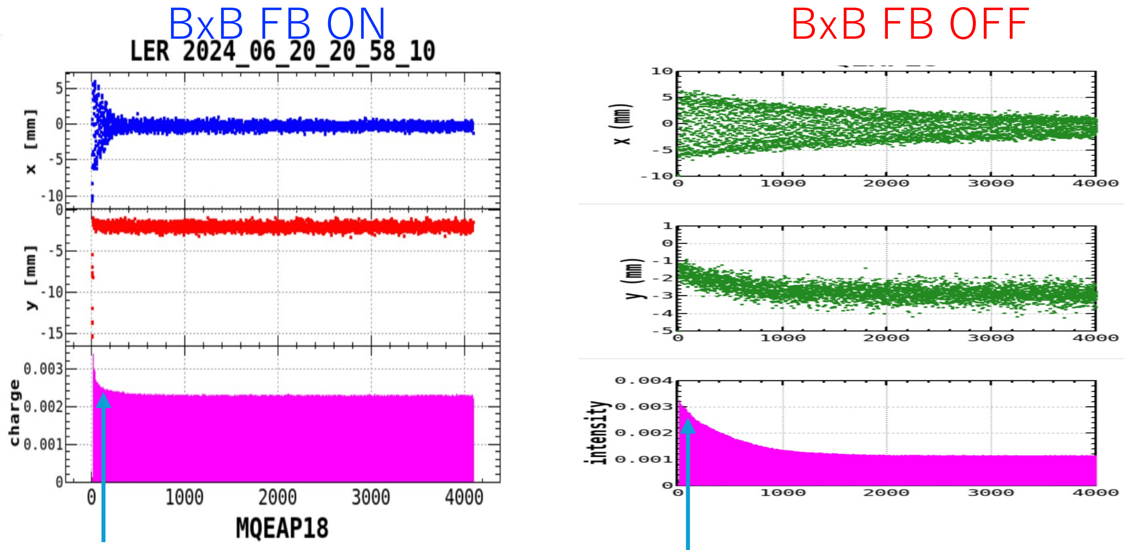
e+ Measured emittance in BT, Bunch charge, Injection efficiency, and parameters in LER



This tendency is more pronounced in the LER.

TbT-BPM: Turn by turn BPM
BxB FB: Bunch by bunch feedback

Measurements of the oscillation of injection beam with TbT-BPM



Injection efficiency of 100turn after injection
Injection efficiency – Loss rate due to beam lifetime

BxB FB effect gets weaker at high stored current

- High current: 0.696mA/0.3 mA stored/injected bunch

Already presented by Y. Ohnishi.

[1] Y. Ohnishi, https://kds.kek.jp/event/54174/attachments/187807/253831/SuperKEKB_eeFACT2025.pdf P.17

B) Injection efficiency dependence on the charge of the injected beam

Vertical aperture is too small. $\leftarrow A_y \simeq 1.3\,\sigma_{y,inj}$ Less than $3\sigma_{y,inj}$

Survival rate depends on intensity.

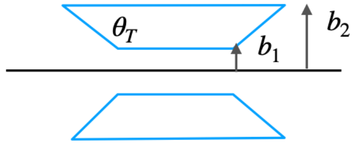
Transverse wakefield in collimators

$$y' = \frac{\Delta y_0 Q}{E}\kappa$$

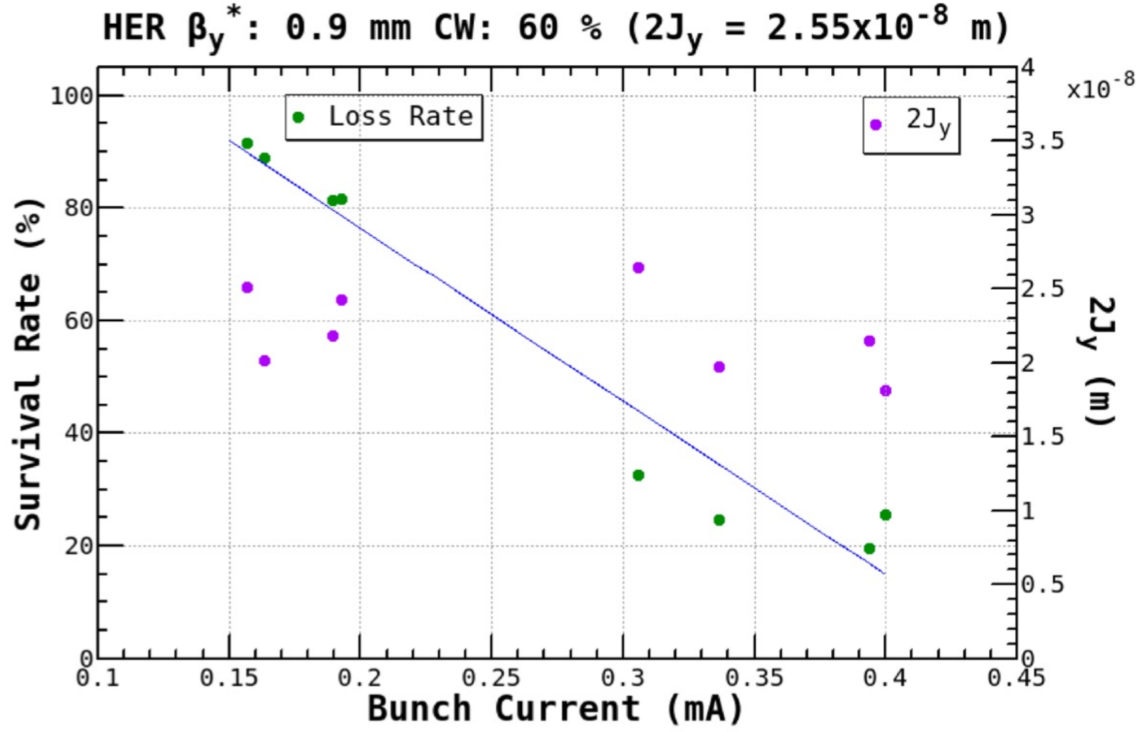
κ : Kick Factor

$\alpha = \theta_T b_1/\sigma_Z$

Inductive (α<<1)



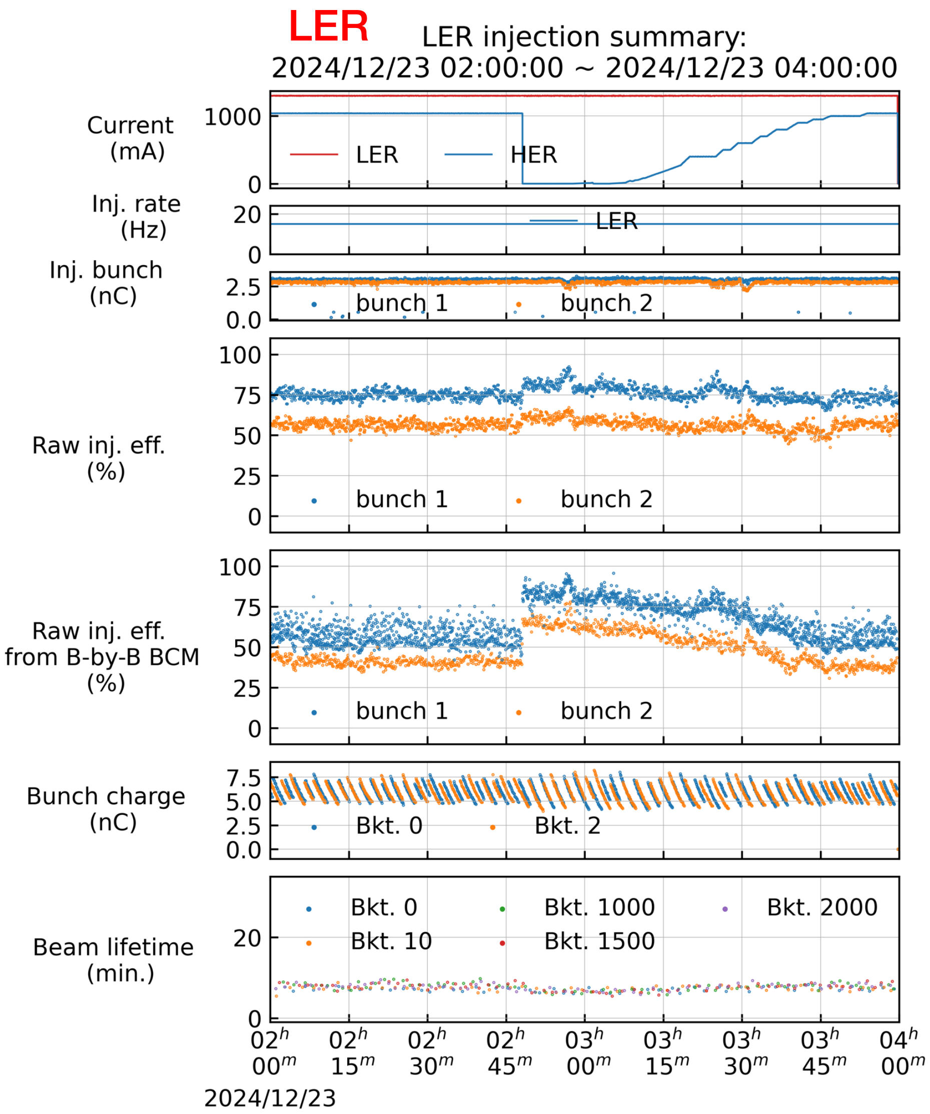
Impedance in the whole ring should be considered.



Beam-Beam effects on Beam Injection Efficiencies

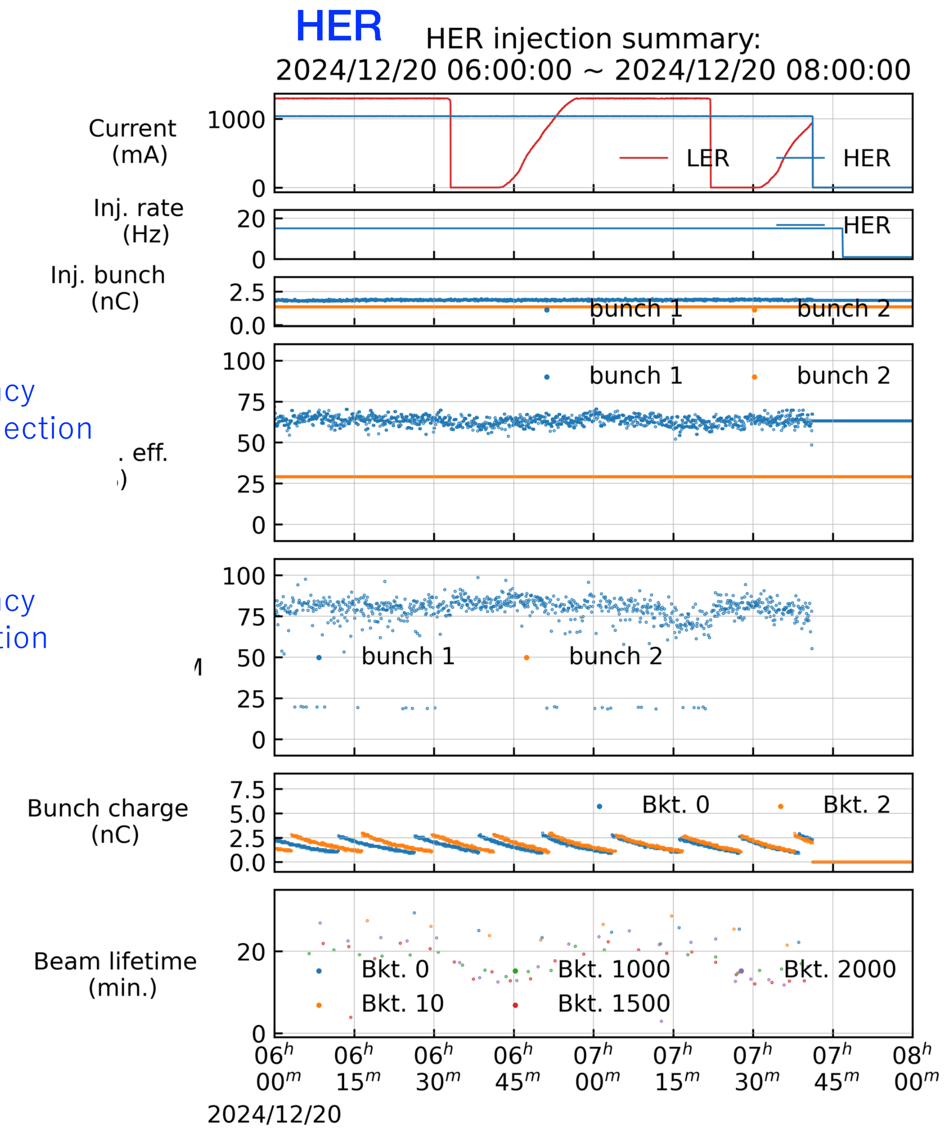
T. Yoshimoto, H. Kaji

- LER raw injection efficiency was reduced by the presence of the HER beam due to the beam-beam effect, whereas HER efficiency was not affected by the LER beam.



Injection efficiency 100 turn after injection (%)

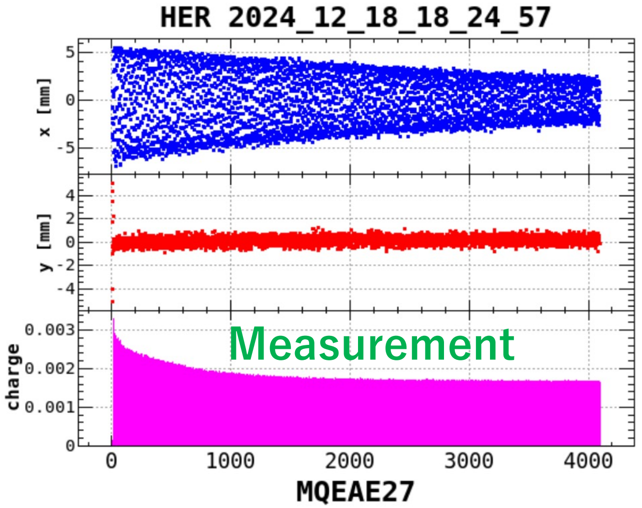
Injection efficiency 5 sec after injection (%)

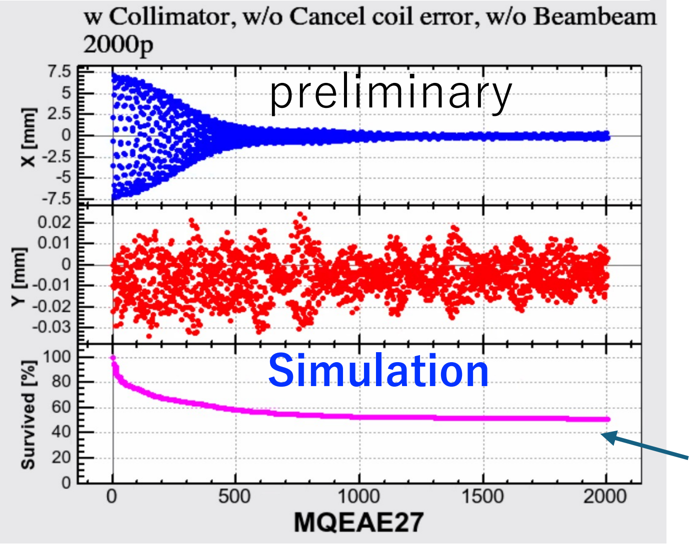


HER injection

Listen to M. Li's talk(TUA14) this late afternoon.

BxB FB OFF





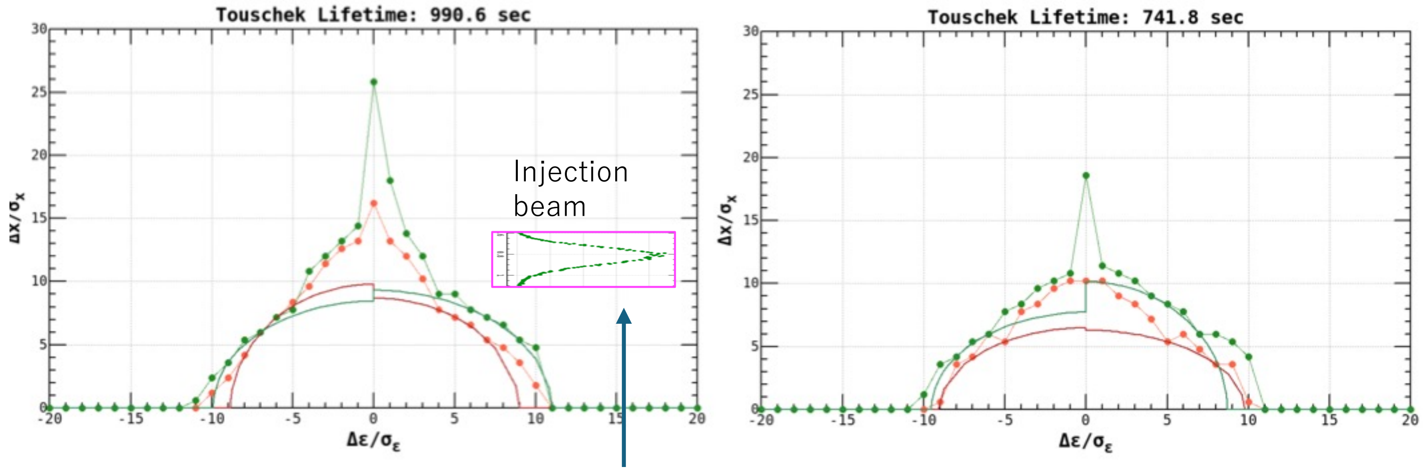
This simulation is just starting.

[1] Y. Ohnishi, https://kds.kek.jp/event/54174/attachments/187807/253831/SuperKEKB_eeFACT2025.pdf P.16

- Simulation(SAD) of injection is on going including the error in "QCS cancel coil" and Beam-beam effect.

H. Sugimoto

w/o cancel coil error | w cancel coil error



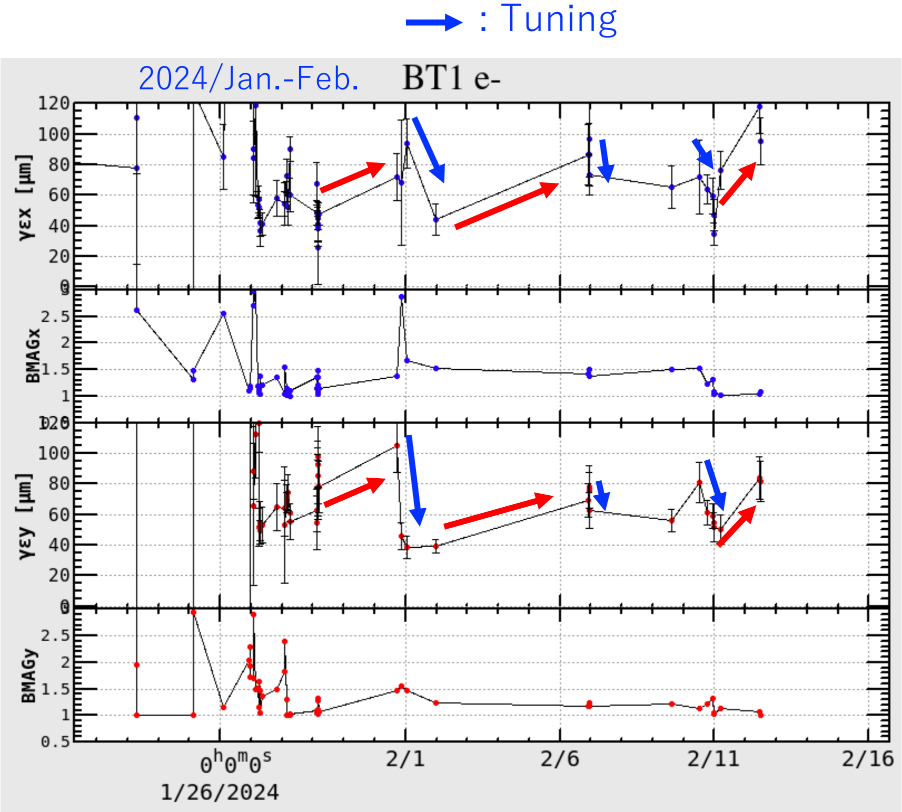
- The injected beam might be affected by the cancel coil error.
- The degradation can be suppressed to some extent by using the nonlinear correction windings of QCS or a sextupole around the ring (H. Sugimoto).

More precise simulations are also done by M. Takao, and Y. Yamamoto.

Stability of the beam

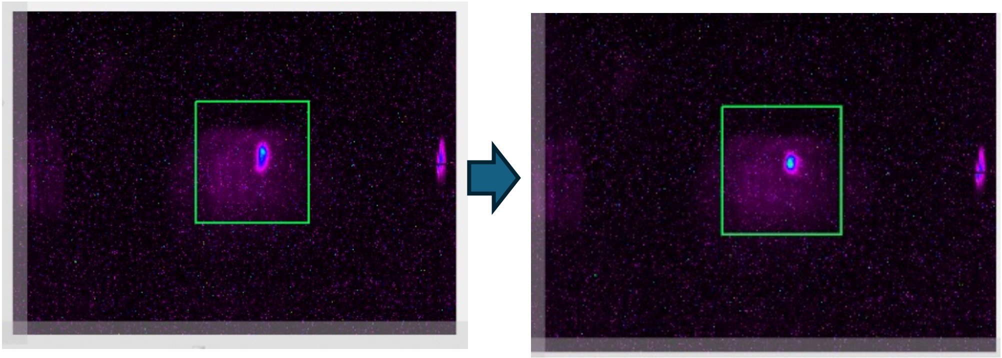
e-

Measured emittances



Beam tuning in LINAC improves the emittance, but keeps it only a few days.

SRM



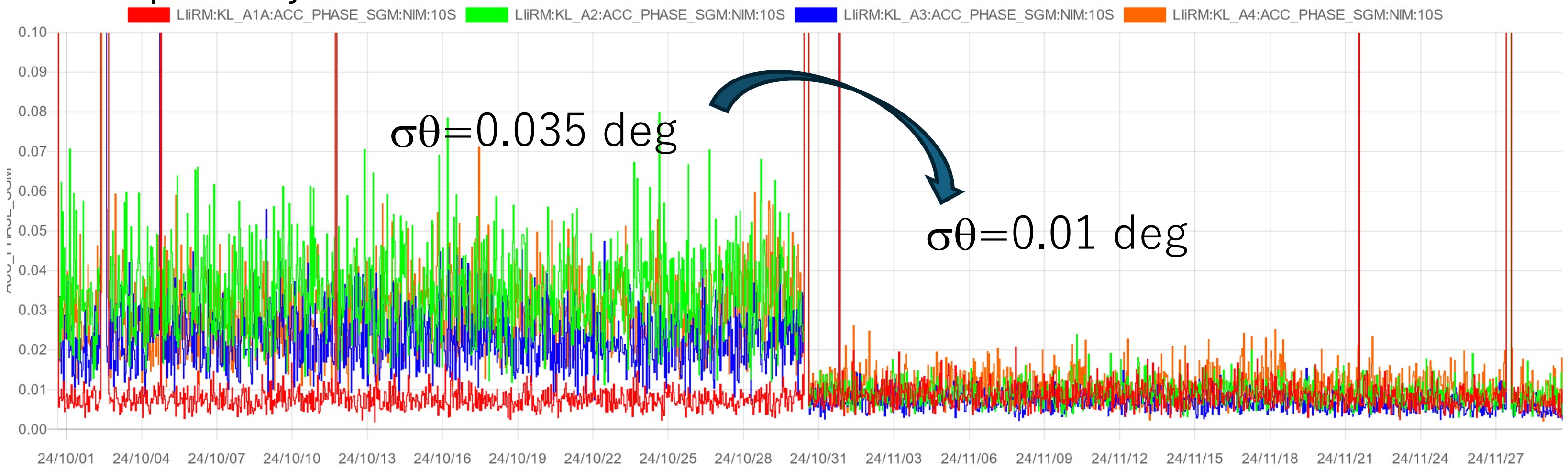
- It doesn't stay in good condition for more than a few days
- However, in the latter half of 2024 winter-spring run, when the beam became larger at the SRM in BT, the operator tuned the pulsed steering upstream, and the situation recovered.
- In the next operation, this will be replaced with automatic tuning(→P. 23).

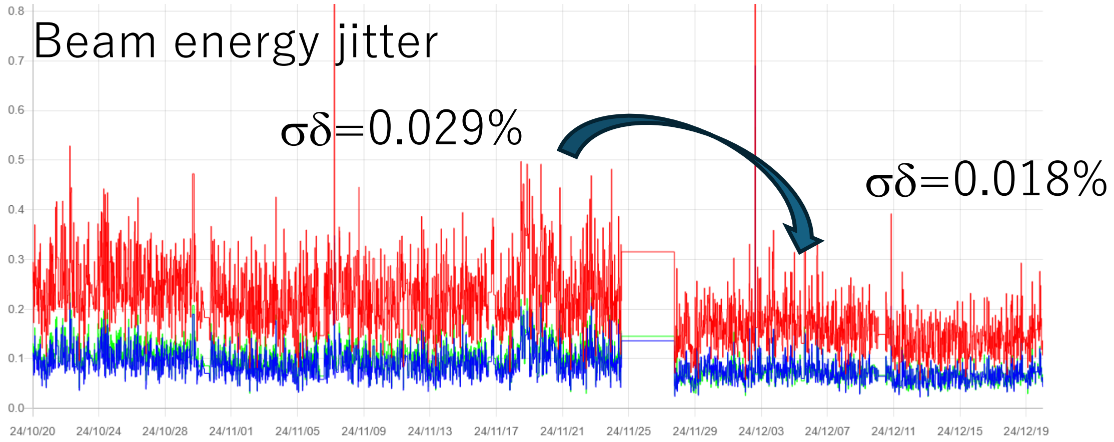
T. Miura, et.al.

Stability of the Klystron

For the klystron power supply, we used to set the voltage analogically,
but we changed it to digital transmission to stabilize the power supply voltage.

RF phase jitter





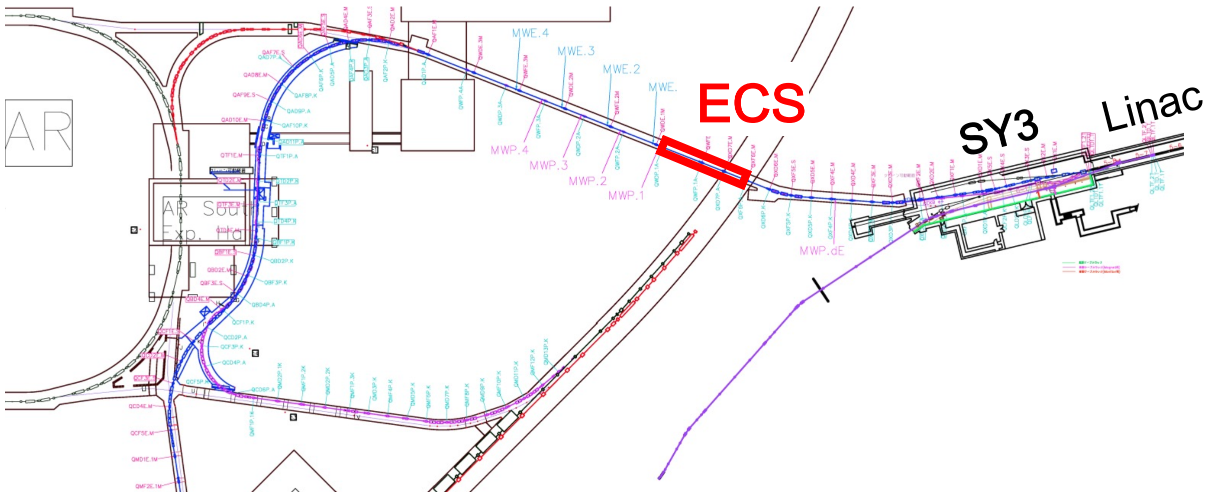
- In addition, an update to the air conditioning temperature control in the klystron gallery will be implemented starting this week.

HER BT Energy Compression System (ECS)

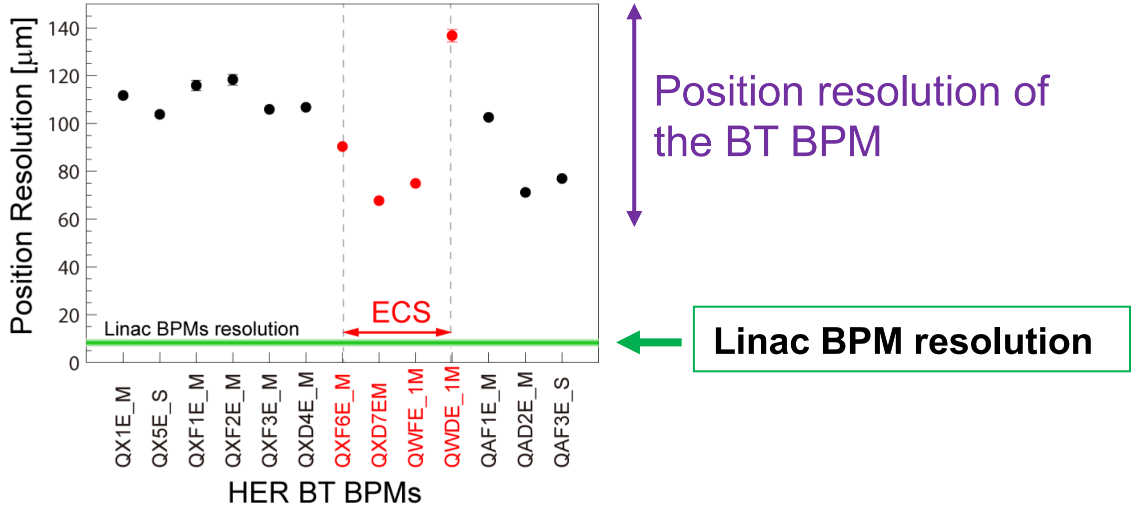
F. Miyahara

Background of HER BT ECS introduction

1. As the bunch charge increases (current: 2 nC → 4 nC) , emittance growth due to short-range transverse wakefields will become a significant issue.
2. Bunch compression at Linac J-Arc is effective in suppressing the short-range transverse wakefields.
   ➔ However, bunch compression increases the energy spread due to longitudinal wakefields.
3. This energy spread will be reduced using the Energy Compression System (ECS) in the HER BT.



The ECS, consisting of four accelerating structures, has been introduced (currently under construction).



- To suppress emittance growth due to wakefields in the accelerating structures, the beam must pass through the center of the accelerating structures.
- Since the position resolution of the BT beam position monitors is not sufficient, the readout system of the Linac position monitors will be used.

3. Plan of the Injection Improvement

A) Stability of the injection beam

B) Automatic tuning with machine learning
   - e- emittance
   - Injection tuning

C) Two-bunch tuning using the fast kicker for the 2nd bunch

D) e- ECS and the future plan of new straight BT line

Listen to G. Mitsuka's talk (FRB04)

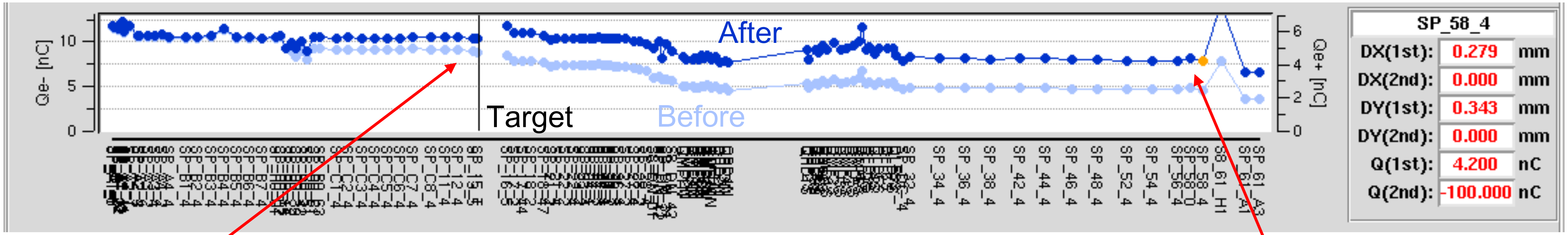
F. Miyahara

2. Maximization of e+ beam transmission rate from Linac to DR

The performance of the injector has significantly improved through various automated adjustments using machine learning (Bayesian optimization). (+ downhill simplex)

1. Maximization of positron beam transmission rate from Linac to DR

4.2 nC was achieved at the Linac end



T. Natsui

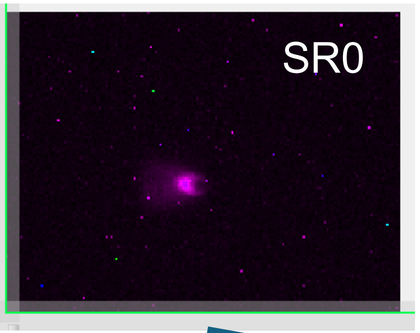
Increase in the beam charge irradiating the target.

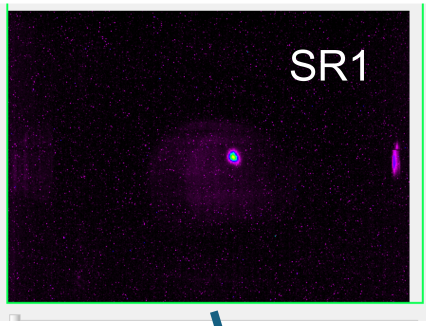
Significant improvement in the transmission efficiency of the generated positron beam.

2. Minimization of e- beam emittance at HER BT

Adjusting the beam orbit to reduce the beam sizes observed by the SR monitors leads to a reduction in emittance

1st bunch	$\gamma\varepsilon_x$ [μm]	$\gamma\varepsilon_y$ [μm]
Before ML	64.9±8.6	45.6±11.0
After ML	29.2±5.1	46.9±13.0





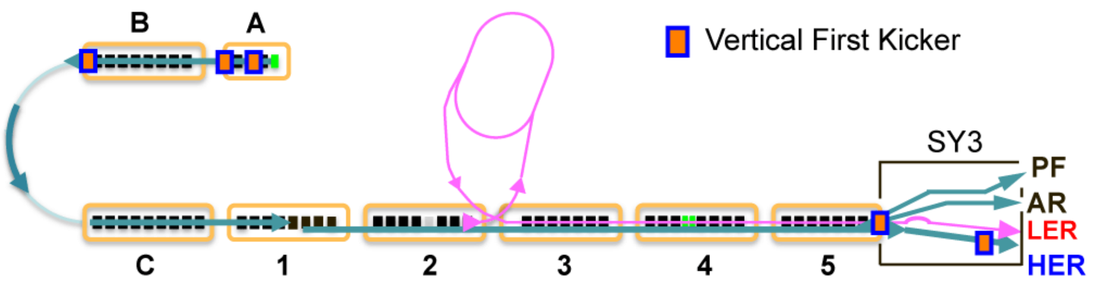
M. Kurata

Electron BT beam line

F. Miyahara

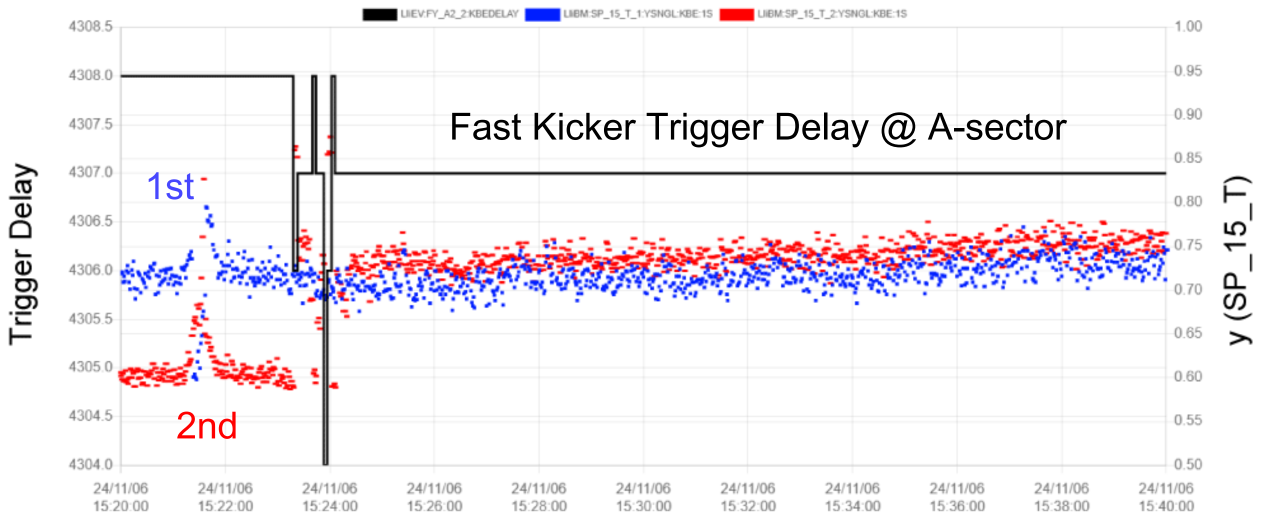
Fast Vertical Kickers in the Linac

Five fast kickers capable of kicking only the 2nd bunch in the y-direction have been installed.



1) Orbit correction for the 2nd bunch

By using the Fast Kicker, the y-orbits of the 1st bunch and the 2nd bunch can now be aligned.



Trigger Delay and vertical e- beam (HER) position before the target

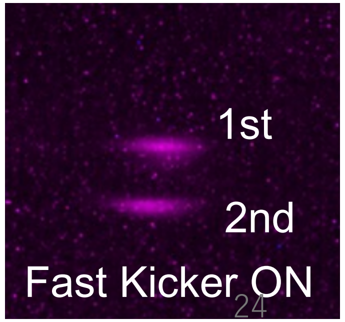
2) Beam diagnostics with separated two bunches

- The beam profiles of the first and second bunches can be measured simultaneously.

⇩

- The emittance and energy spread of the first and second bunches can be evaluated.

e- beam profile at BT

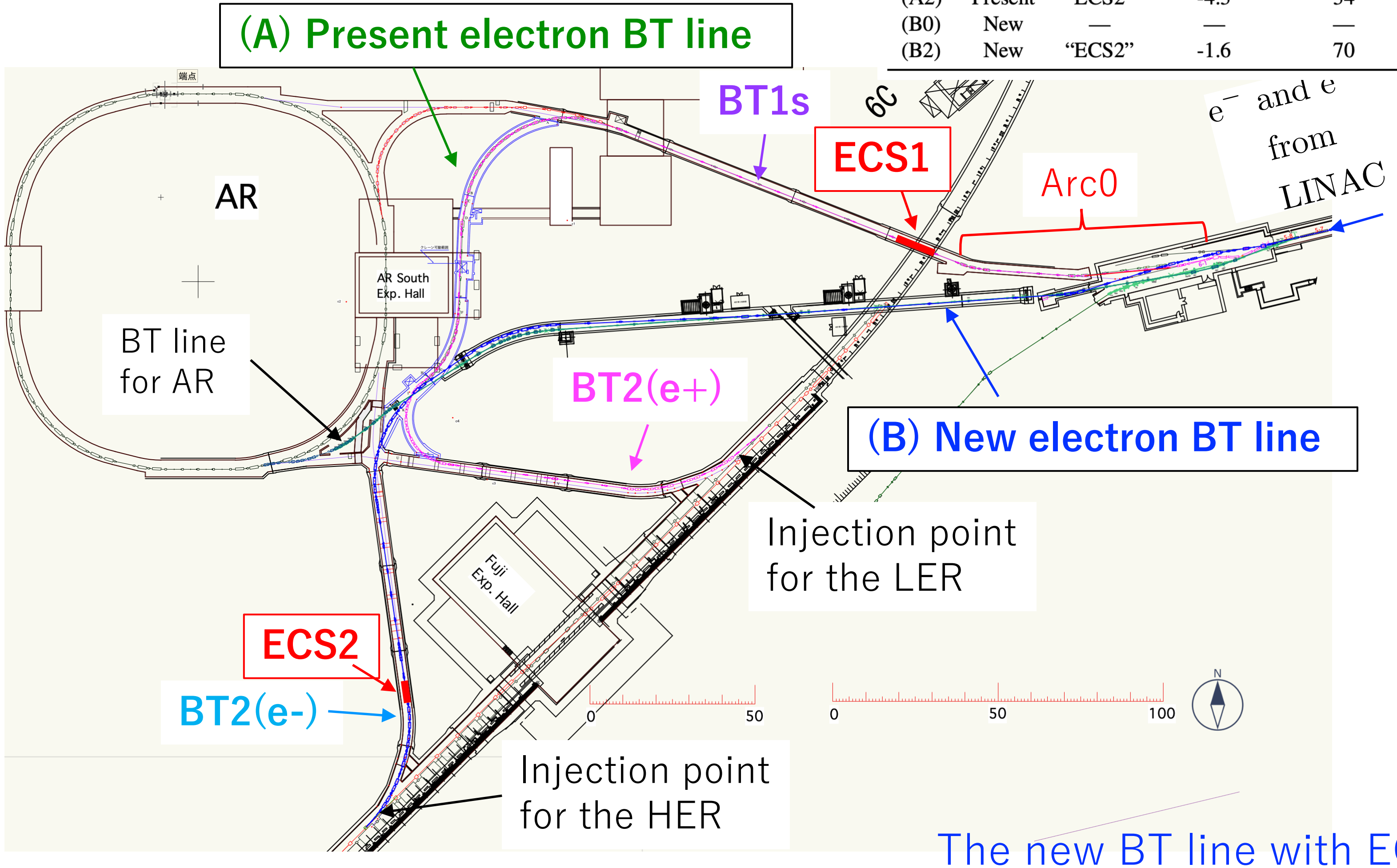


e- beam profile at BT

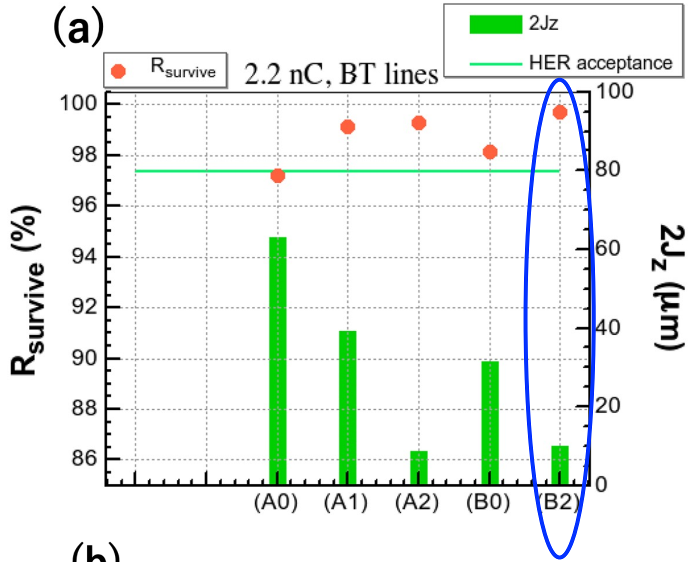
Proposal of the new straight e- BT line and The energy compression system (ECS) for e- beam

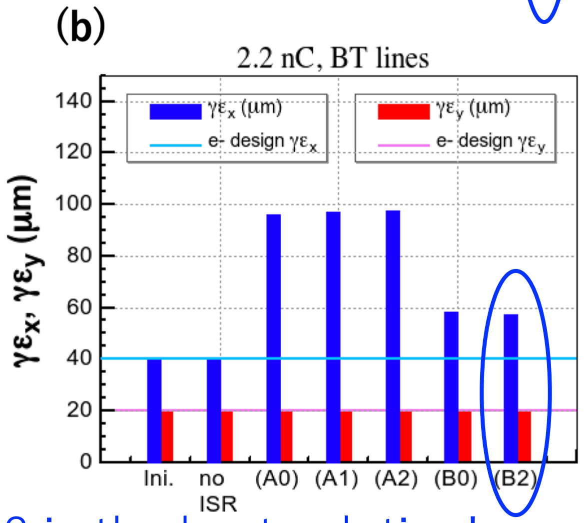
Table 2: The ECS Parameters in the BT Lines

	BT line	ECS	R_{56} [m]	V_c^{Total} [MV]
(A0)	Present	—	-0.11(Arc0)	—
(A1)	Present	"ECS1"	-1.0(Arc0)	72
(A2)	Present	"ECS2"	-4.3	34
(B0)	New	—	—	—
(B2)	New	"ECS2"	-1.6	70



Tracking by SAD, **no CSR**





The new BT line with ECS2 is the best solution!

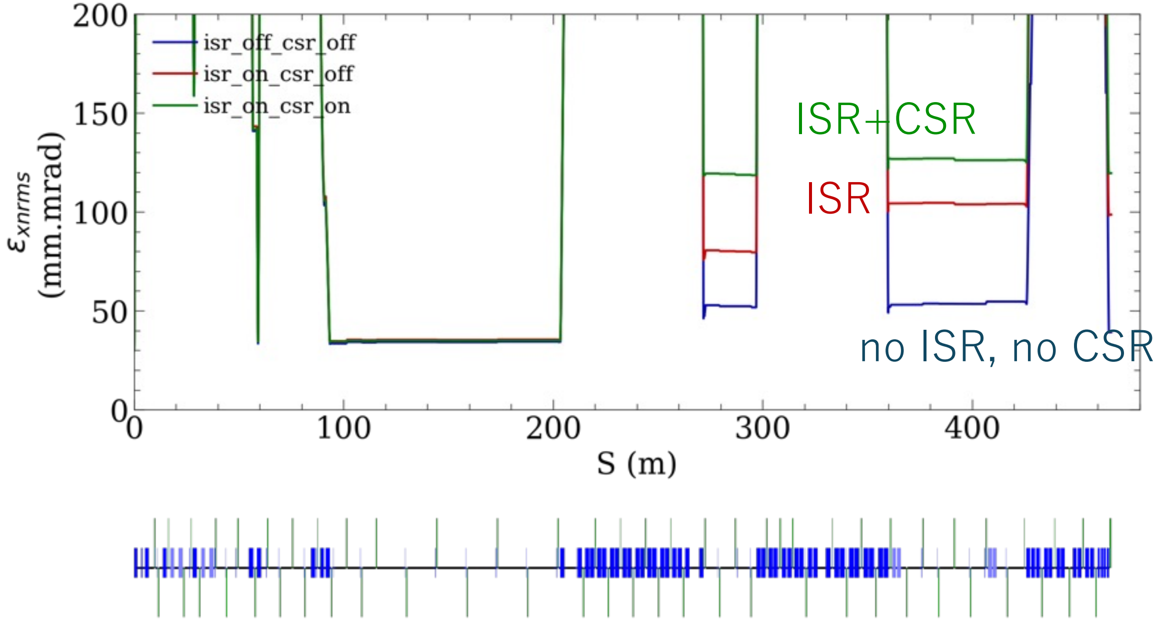
But we are already installing ECS1 in the e- BT!!

Present and straight BT line

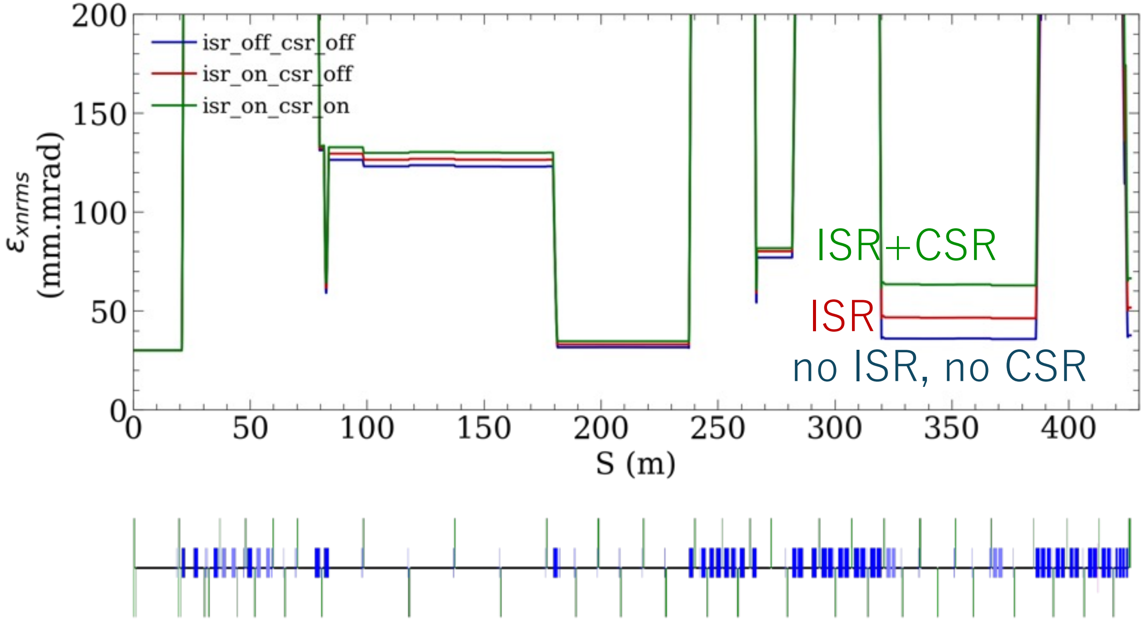
- x/y nemit: 30 um.rad
- Bunch charge: 2.2 nC

T. Yoshimoto

Current beam transport



straight beam transport (design)



- New straight beam transport line can effectively suppress CSR and ISR effects thanks to fewer and weaker bending magnets, as expected.
- Bending ducts with a full height of 30 mm cannot completely suppreess CSR.

Simulation		γεx [μm] at the end of BT	
ISR	CSR	present BT	new BT
Off	Off	53	36
On	Off	104	46
On	On	126	63

Summary

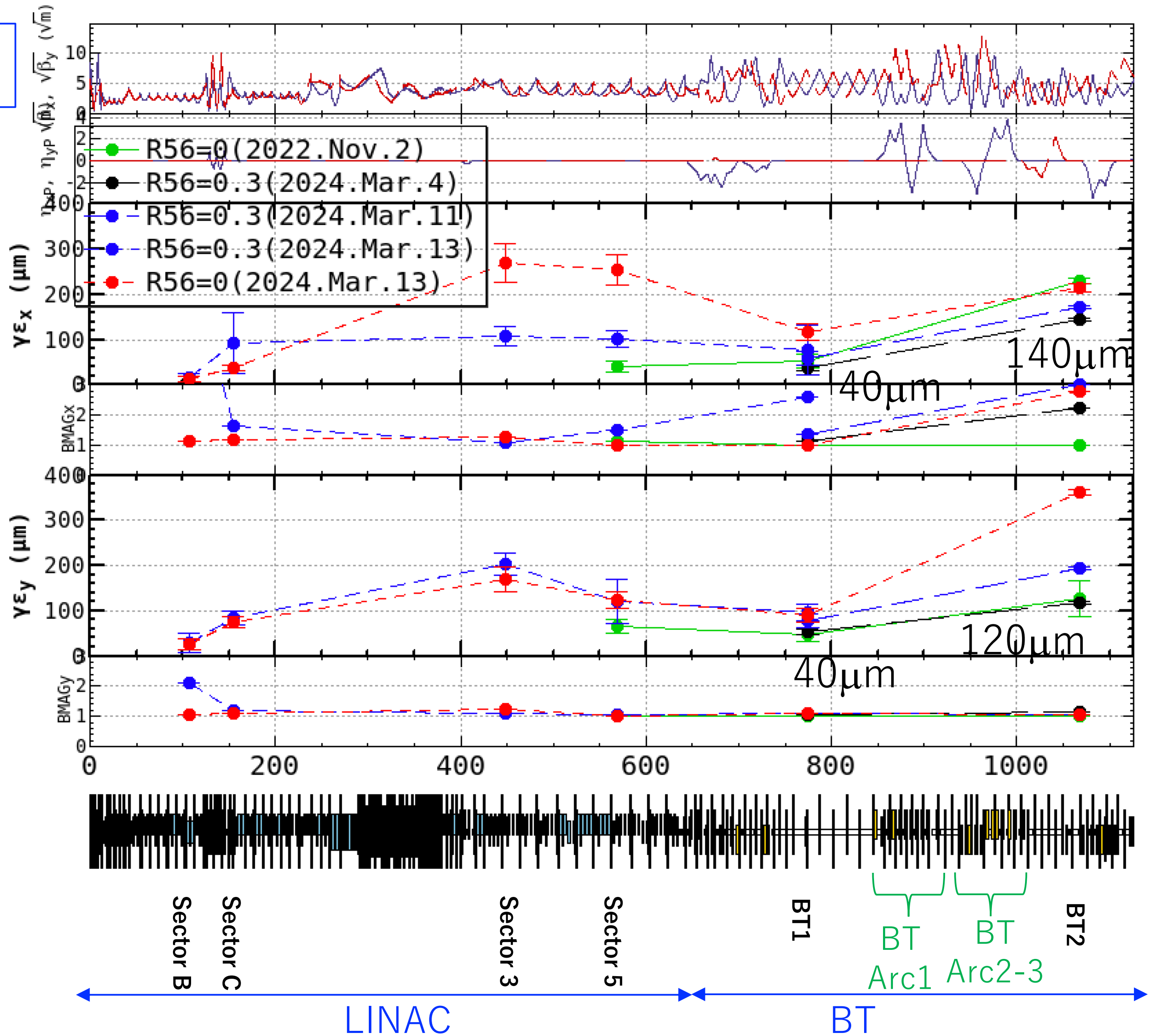
- SuperKEKB Injection status
  - The current injection performance is not sufficient for the luminosity of $1x10^{35}$ /cm^2/s.
  - Everything is entangled with injection.
    - The beam emittances (6D), stability, bunch charge, stored bunch current, total current, collimator setting, beam-beam strength, dynamic aperture…
- Improvement plans
  - Emittnace growth
    - e+: reform of the dipole magnets in Arc3 of BT
    - e-: rebuilding the BT line to the straight path (future plan)
    - The vertical blowups are still mystery.
  - Automatic tuning with machine learning for tuning of emittance, injection, etc
  - Stabilization in Linac is on going.

Backup

e-

BT

2 nC



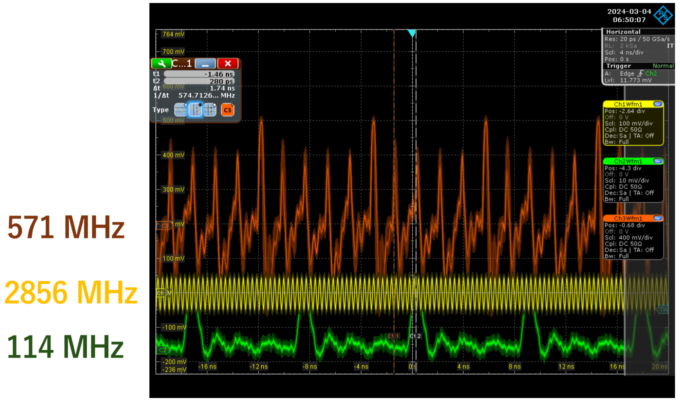
R56=0(2022.Nov.2)
R56=0.3(2024.Mar.4)
R56=0.3(2024.Mar.11)
R56=0.3(2024.Mar.13)
R56=0(2024.Mar.13)
γεx (μm)
γεy (μm)
BMAGx
BMAGy
140μm
40μm
120μm
40μm
0
200
400
600
800
1000
Sector B
Sector C
Sector 3
Sector 5
BT1
BT Arc1
BT Arc2-3
BT2
LINAC
BT

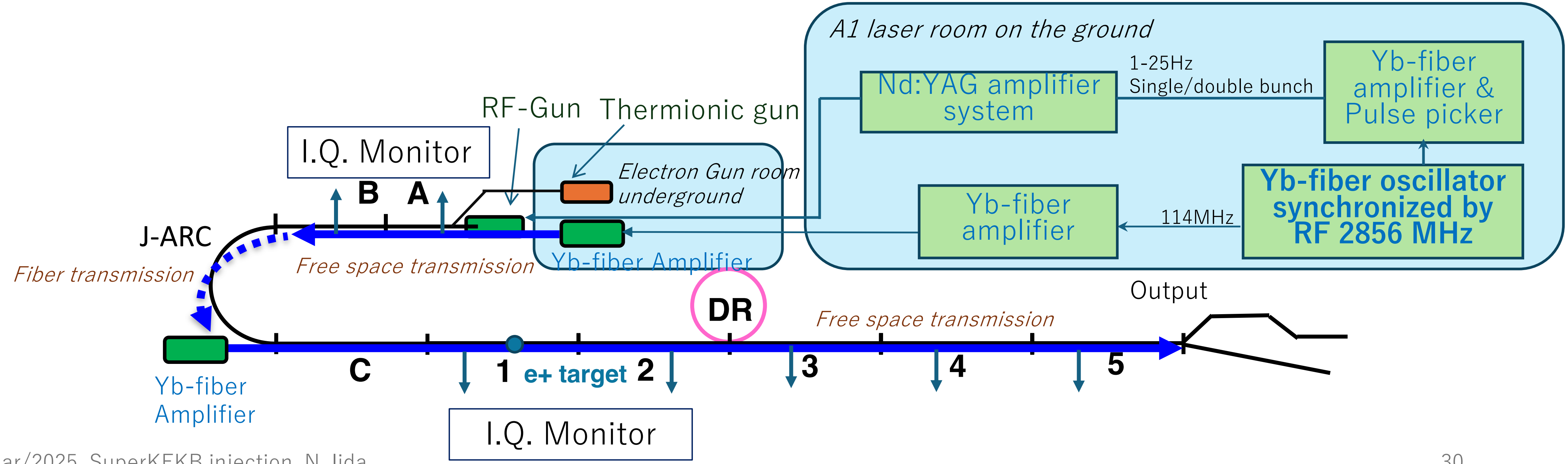
X. Zhou

RF Stabilization using all Optical Synchronization

- To improve synchronization accuracy and support the future development of linear accelerators, a new synchronization system based on laser pulse light signals instead of electronic radio frequency signals was developed.
- The RF signal generated by the RF gun's laser source is not affected by temperature fluctuations or klystron interference.
- The laser signal has the capacity to cover the entire Linac.

Laser signal





Utilization of the optimization program

F. Miyahara

The performance of the injector has significantly improved through various automated adjustments using machine learning (Bayesian optimization).

Typical use cases for machine learning programs

Purpose	Execution time	Execution interval or execution count
Maximization of positron yield at positron capture section exit	A few minute (When slightly deviating from the optimal conditions)	A few times in a day (**Automatically execute when the yield decrease**)
Maximization of the e+ beam transmission rate from positron capture section exit to SY2 (End of 2-sector)	~a few days (~160 params. Execute the beamline in multiple parts)	Only once
Maximization of the e+ beam transmission rate from Linac (SY2) to Damping Ring	~20 min	Several times a day after Linac startup
Align the vertical orbit of the electron 2nd bunch with that of the 1st bunch using fast kicker	A few minute	A few (Because each beam was stable before the gun problem)
Minimization of emittance in the HER BT through beam orbit adjustments in the Linac	~30 min	A few times a month
Increase the beam transmission rate for both the 1st and 2nd bunches in the Linac	~20 min	Several times a day after Linac startup