First synchrotron injection attempt into the SuperKEKB HER

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Many thanks to the all members of SuperKEKB (Linac/Ring) and MELSC operators.

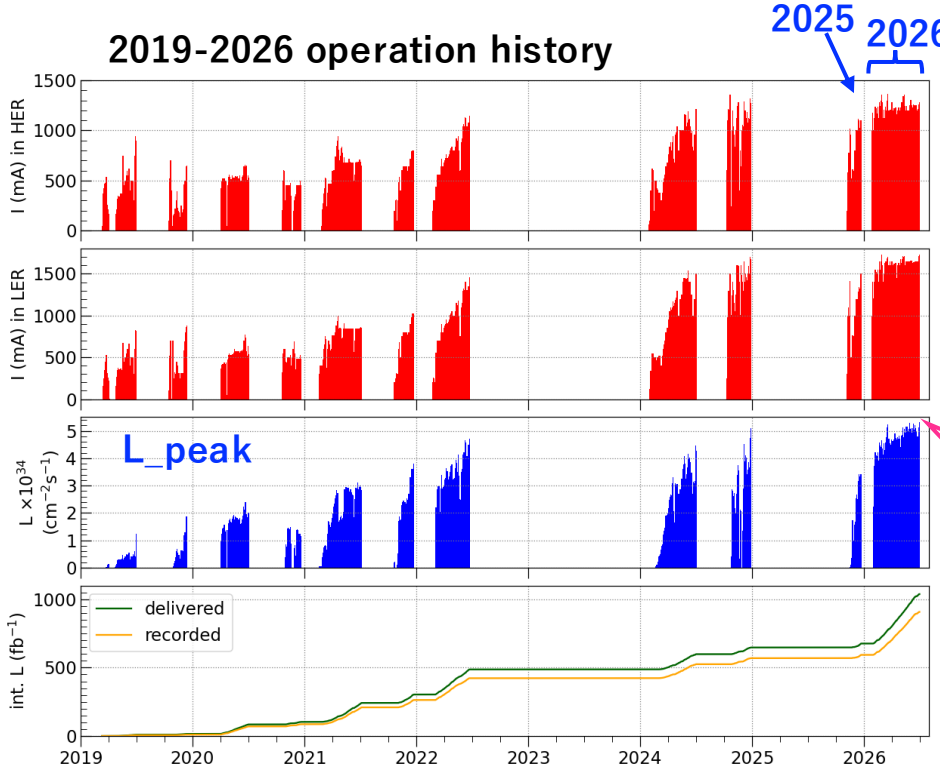
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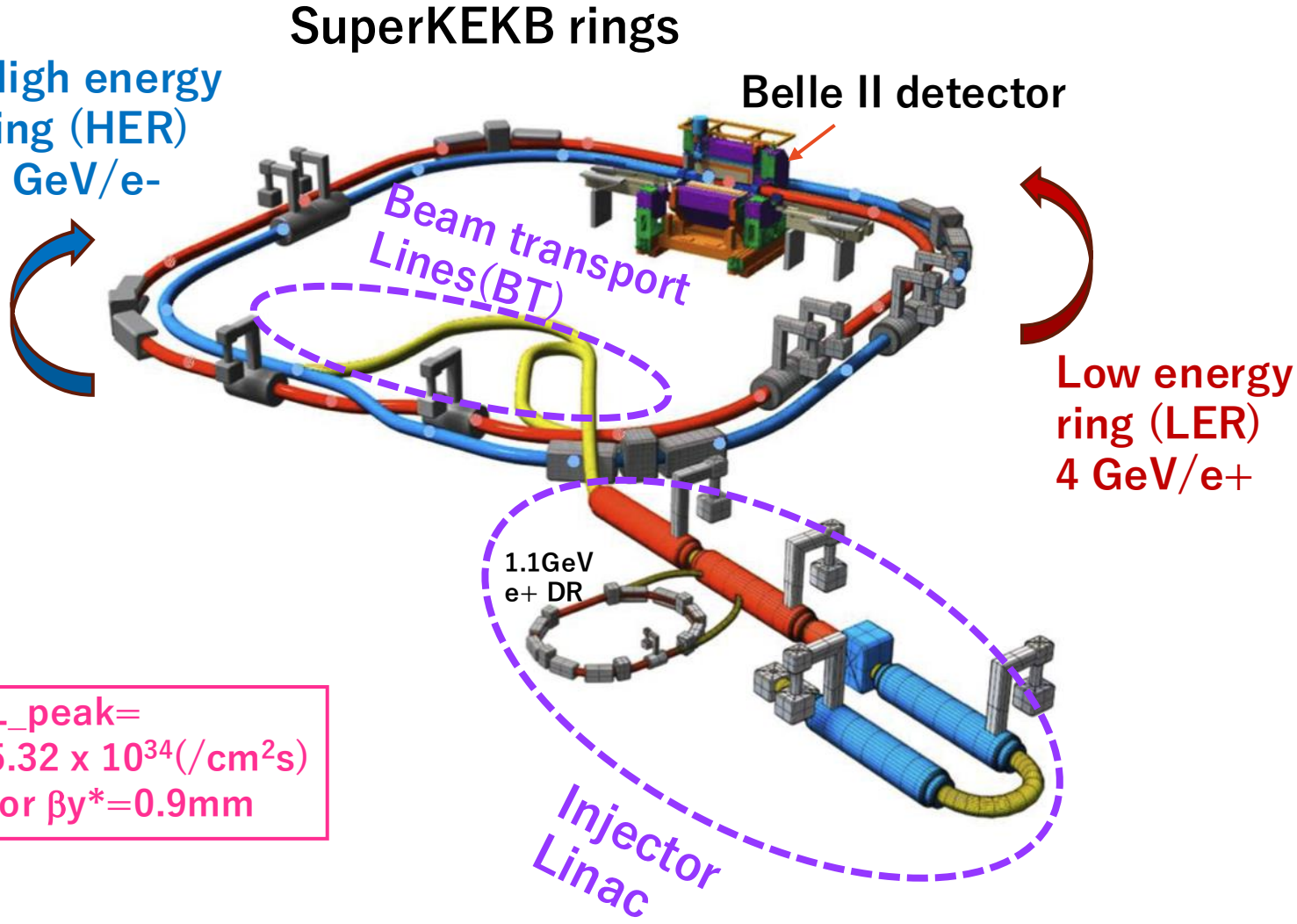
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SuperKEKB collider

- SuperKEKB is an e-/e+ collider which aims to produce a large number of bb_{bar} pairs from the Upsilon-4S.
- The **β*(x,y) = (60,1)mm** in this talk.



L_peak=
5.32 x 10^{34}(/cm^2s)
for βy*=0.9mm



At the beginning of **2025 operation**, we tried the **synchrotron injection** in the **HER for the first time.**

Parameters of SuperKEKB for the synchrotron injection study

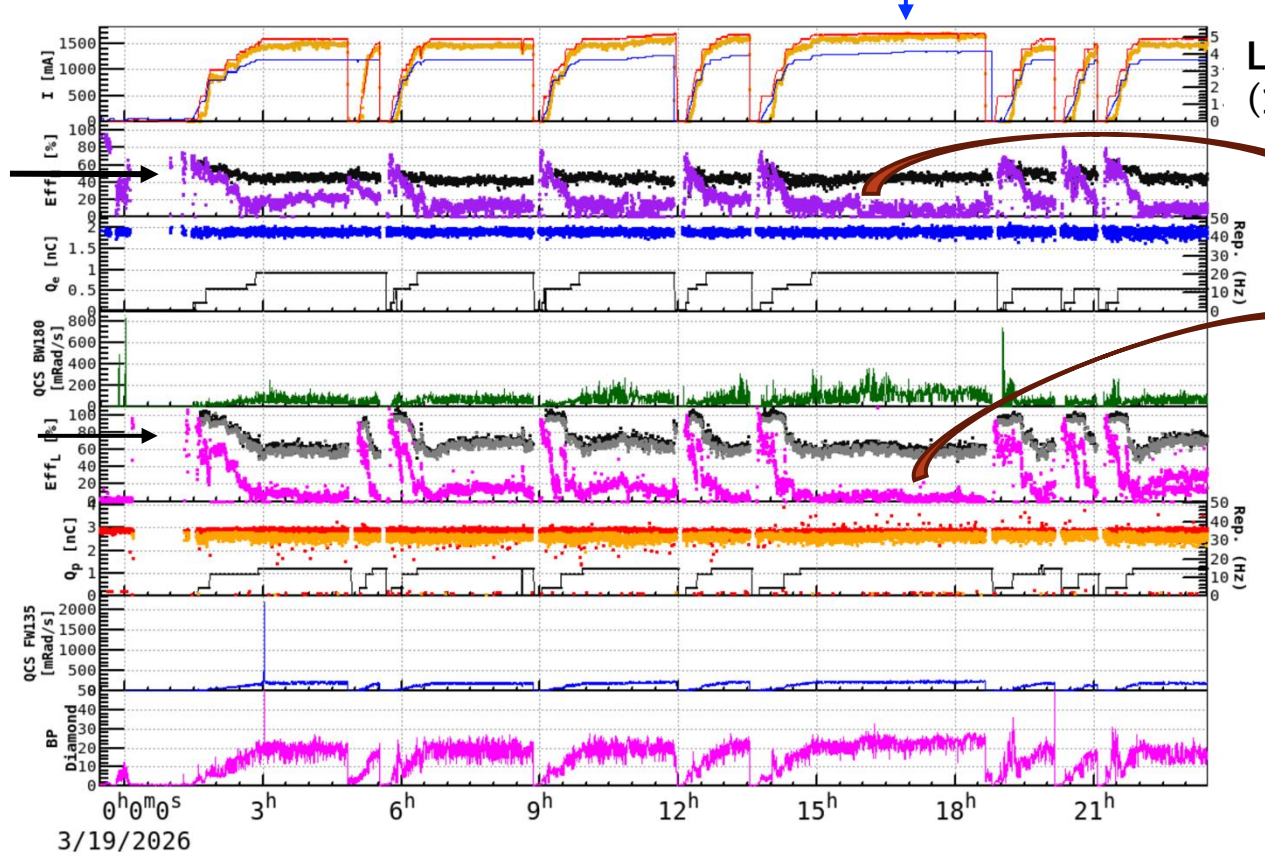
TABLE I. Parameters of SuperKEKB collider rings.

Ring		HER (e^-)		LER (e^+)
Injection mode		BI	SI	BI
Beam energy	[GeV]	7.0		4.0
Circumference	[m]	3016.315		
Energy loss / turn	[MeV]	2.41		1.51
Bunch current	[mA]	0.55		0.68
Colliding bunch population	[10^{10}]	2.5		4.3
Emittances at collision $\varepsilon_{x,y}$	[nm]	4.5 / 0.04		4.3 / 0.04
Momentum compaction α_p	[10^{-4}]	4.54		3.07
$\beta^*_{x/y}$	[mm]	60 / 1		
Transverse tunes $\nu_{x/y}$		45.531 / 43.575		44.535 / 46.588
Chromaticities, meas. $\nu'_{x/y}$		0.03 / 1.73	+0.92 / +2.30	+1.4 / +1.9
Energy spread σ_δ	[%]	0.063		0.074
Bunch length σ_z	[mm]	5.1		6.0
RF voltage	[MV]	14.2		9.1
Synchrotron tune ν_s		0.027		0.024
Long. damping time	[turns]	2910		2650
RF acceptance	[%]	2.0		2.6
Half crossing angle at IP θ_x	[mrad]	±41.5		
Crab waist ratio	[%]	60		80
Beam-beam ξ_x/ξ_y [a]		0.0013 / 0.0289		0.0026 / 0.0475
Piwinski angle $(\theta_x\sigma_z)/\sigma^*_x$		12.9		15.5
Luminosity / bunch /10^{31}	[/cm^{2}s]	2.4		

[a] incl. hourglass.

Injection limits the luminosity

The injection status at **the new peak luminosity record (5.24 x 10^{34}) for βy*=1mm** as of March 2026



The injection and loss ratio are balanced, so no further injections into the both rings were possible.

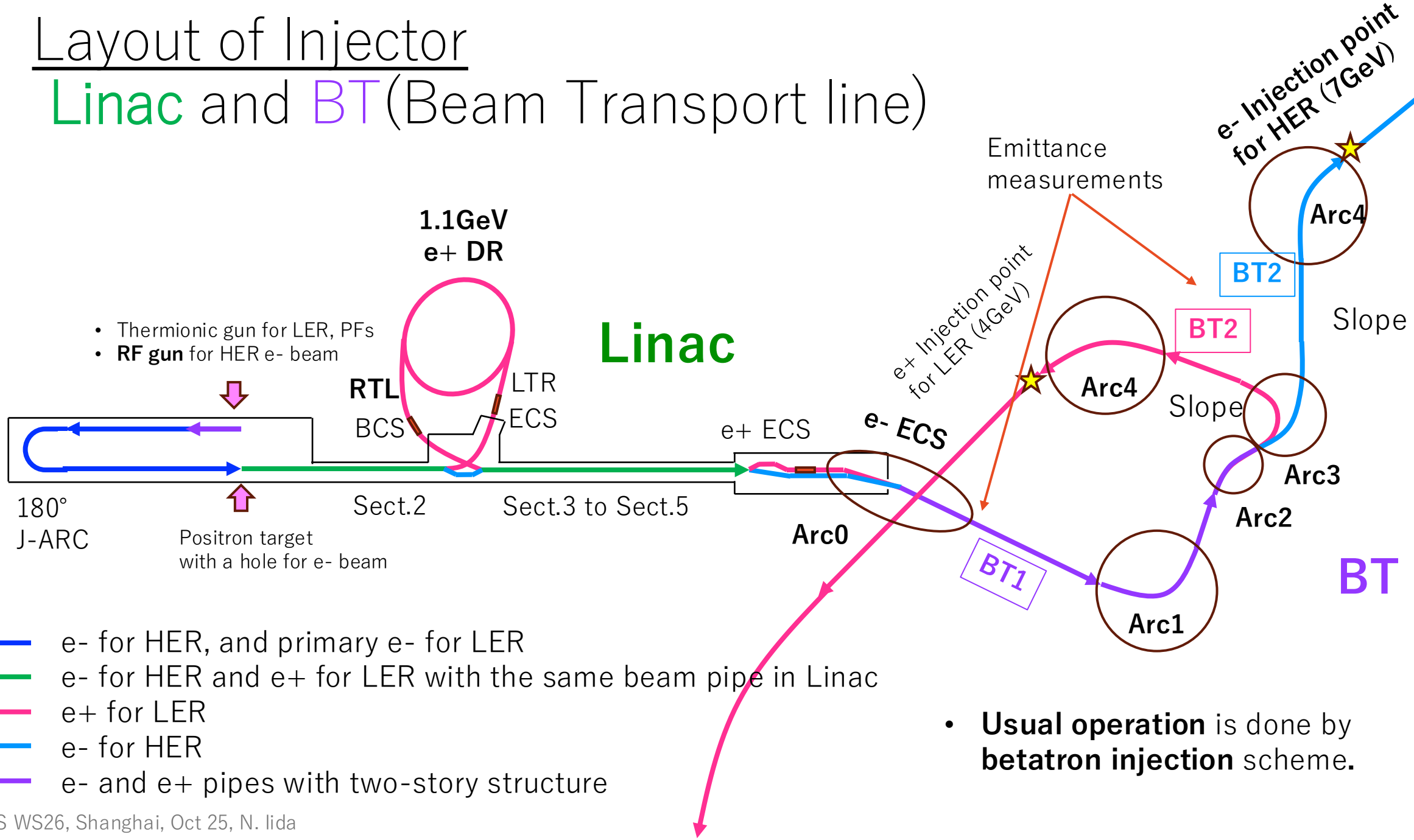
The stored current of HER was limited by,

- Linac bunch charge (1.8nC/pulse)
- Repetition rate (21Hz)
- Injection efficiency (~50%) at high current
- Beam lifetime (~12 min)

←Each parameter must be improved for higher luminosity!

Layout of Injector

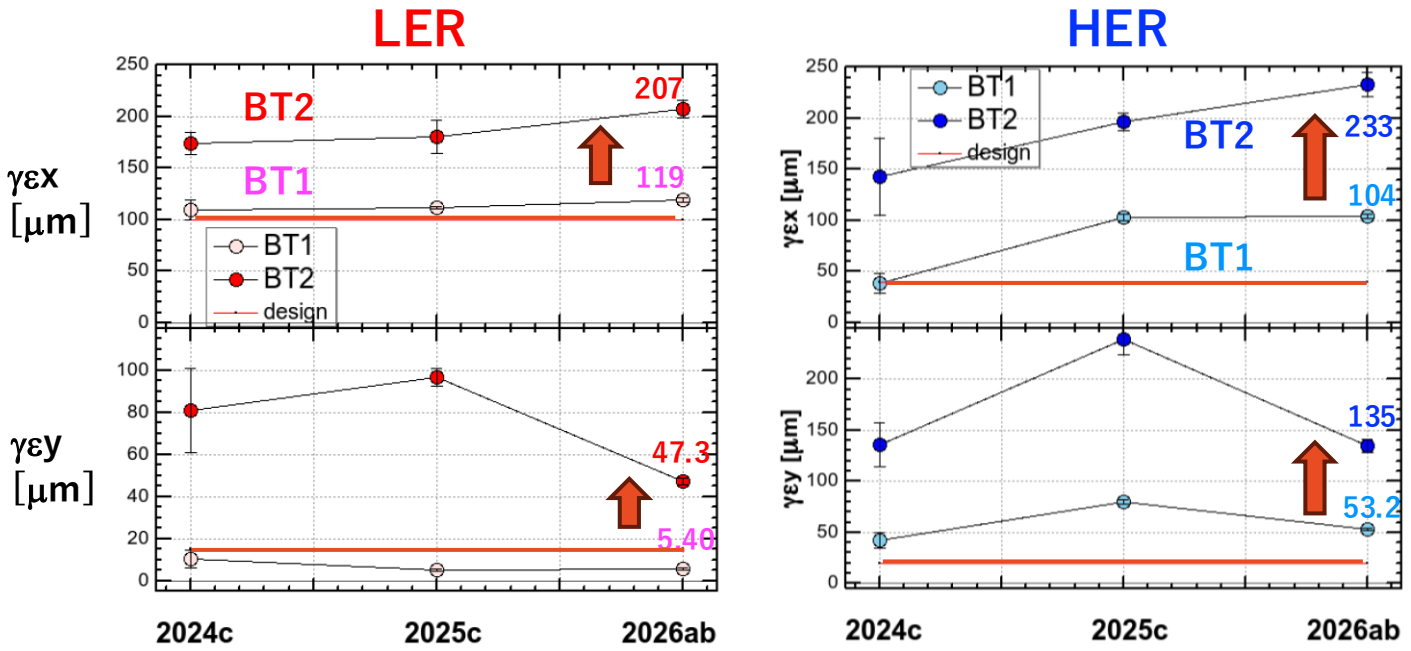
Linac and BT(Beam Transport line)

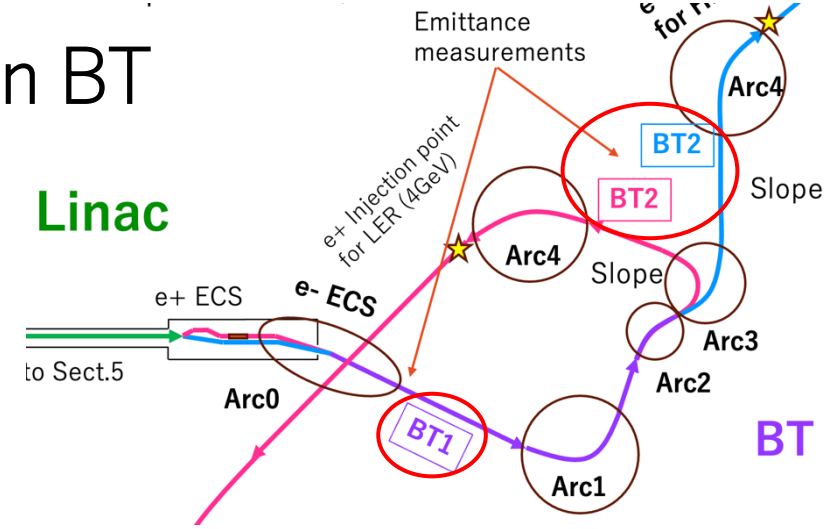


- e- for HER, and primary e- for LER
- e- for HER and e+ for LER with the same beam pipe in Linac
- e+ for LER
- e- for HER
- e- and e+ pipes with two-story structure

- **Usual operation** is done by **betatron injection** scheme.

Unusual emittance growth of the injection beam in BT





— Requred emittance from the SuperKEKB ring

Table 2: The Courant-Snyder invariants of the injected beam and the measured acceptance of the ring

	CSI	Injected beam		Ring acc.
HER	$2J_x$ [μm]	1.01	<	1.4
	$2J_y$ [μm]	0.059 ($6\varepsilon_y$)	≫	0.038
LER	$2J_x$ [μm]	1.48	≫	1.15
	$2J_y$ [μm]	0.036 ($6\varepsilon_y$)	<	0.044

Injection efficiency [%]

~60

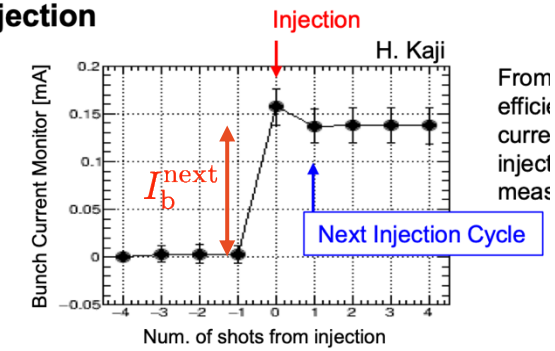
~90

$$\epsilon_{\rm inj} \equiv \frac{I_{\rm b}^{\rm next} T_0}{Q_{\rm inj}}$$

T_0 : rev. period

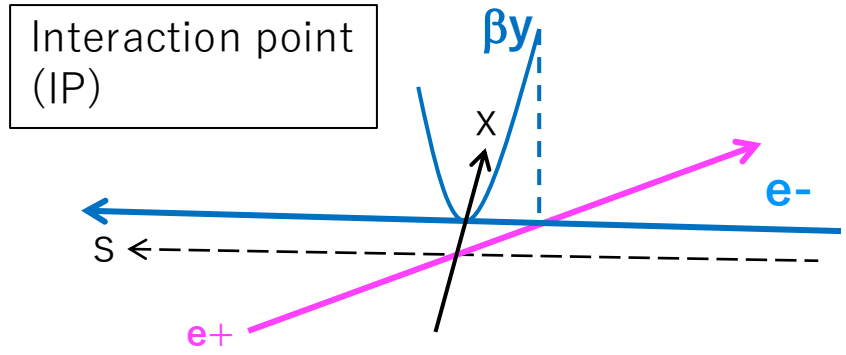
$Q_{\rm inj}$: inj. charge

Injection efficiency at the next injection



- **The large emittance growth in the BT** is one of the major causes of the low injection efficiency for both rings.

- **The poor injection efficiency depends not only on the high emittance of the injection beam, but also on the conditions of the ring.**
- **One of them are due to the horizontal oscillation of the injection beam.**



Why synchrotron injection (SI) ?

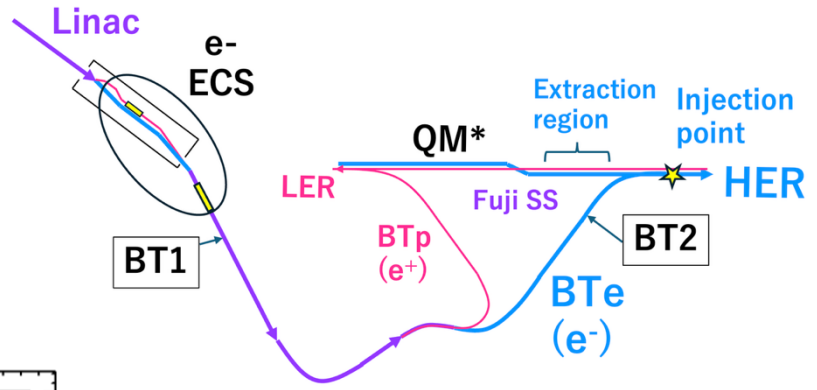
In SI, the injection oscillation is converted from the horizontal to the longitudinal.

- The horizontal orbit oscillation in the non-dispersive region becomes almost eliminated.
- A number of effects are expected naively such as …

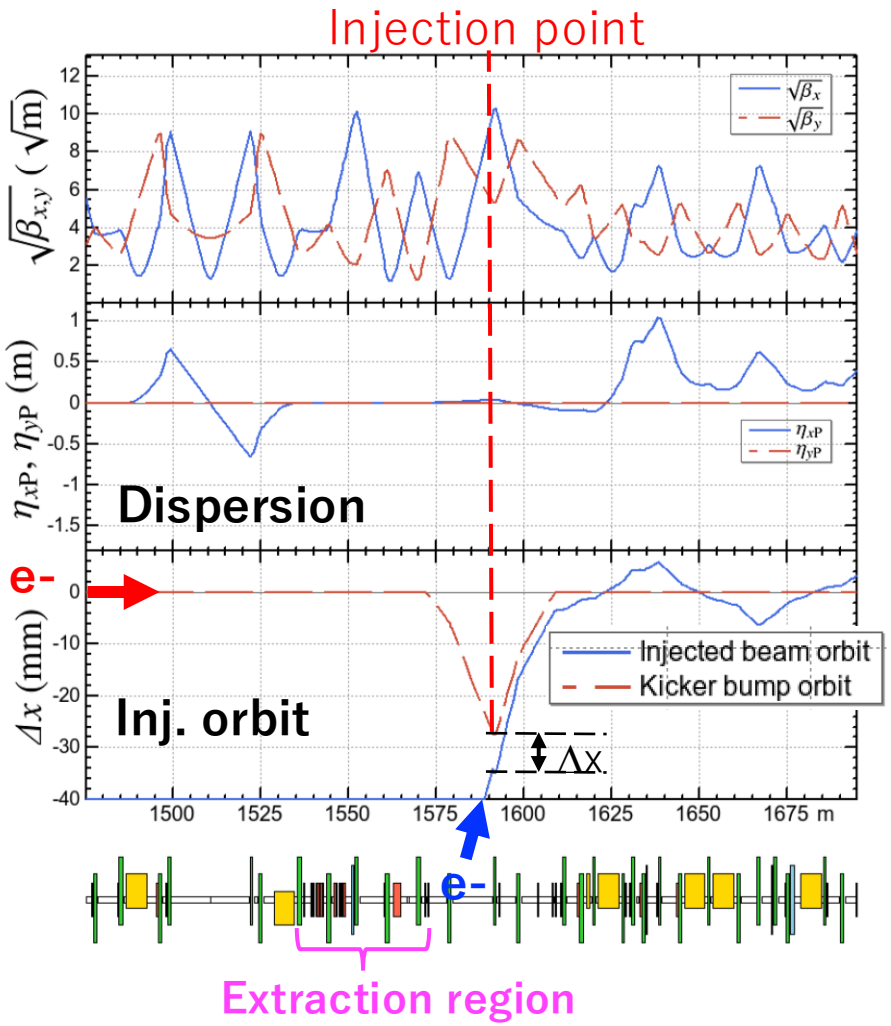
	BI	SI
Beam-beam kick at IP	Large H. oscillation	No H. oscillation
Beam-beam with nano-beam	H. osci. causes shift of s→large βy	(Coll. at s~10σz)
Dynamic aperture (DA)	Large H. osci. decreases V. DA	No H. osci.
SR to the IP beam pipe	Larger due to H. osci.	No H. osci.
Damping time	58 ms (Horizontal)	29 ms (Longitudinal)
Sensitivity to b-b/sext. misalignment/tune	More sensitive	Less sensitive

- First of all, the horizontal oscillation disturbed by the b-b effect.
- In the case of SuperKEKB which has nano beam scheme, with large crossing angle, this b-b effect, another special effect due to shift of the IP he collision happens at the larger betay.

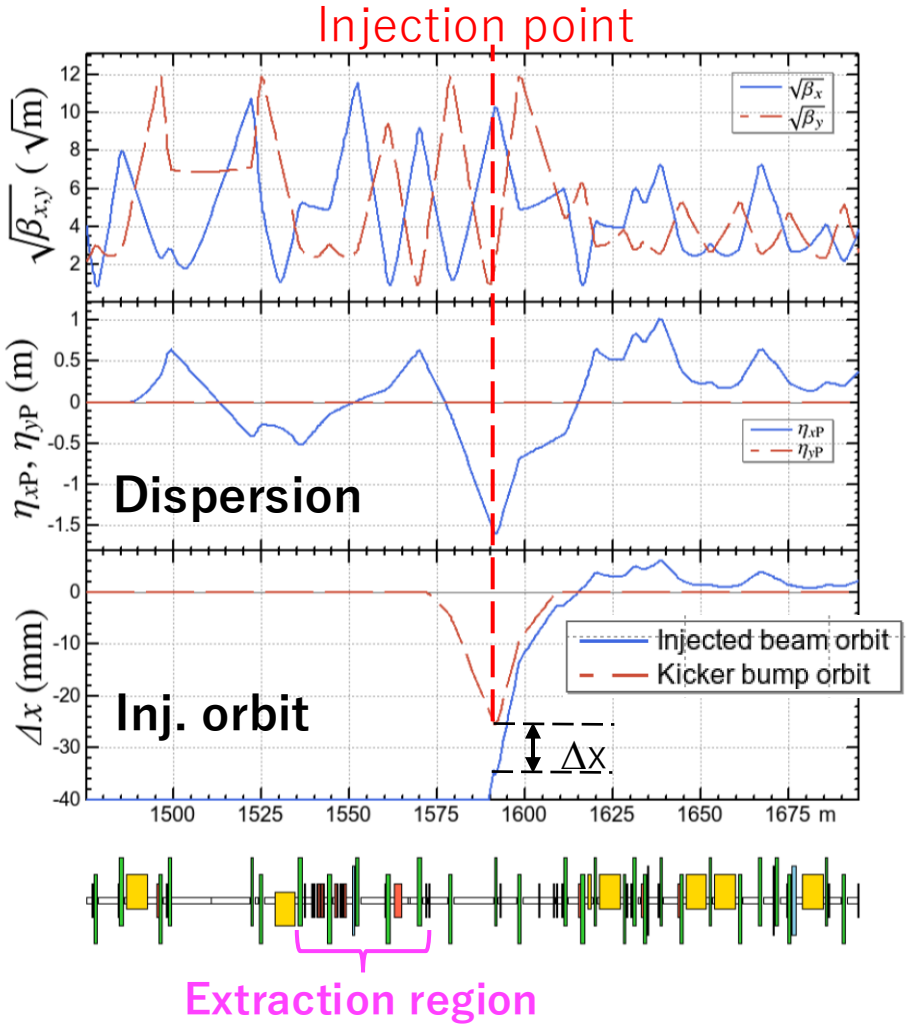
Ring optics for injection



Betatrotron injection (BI)
Off axis, on momentum



Synchrotron injection (SI)
On axis, off momentum

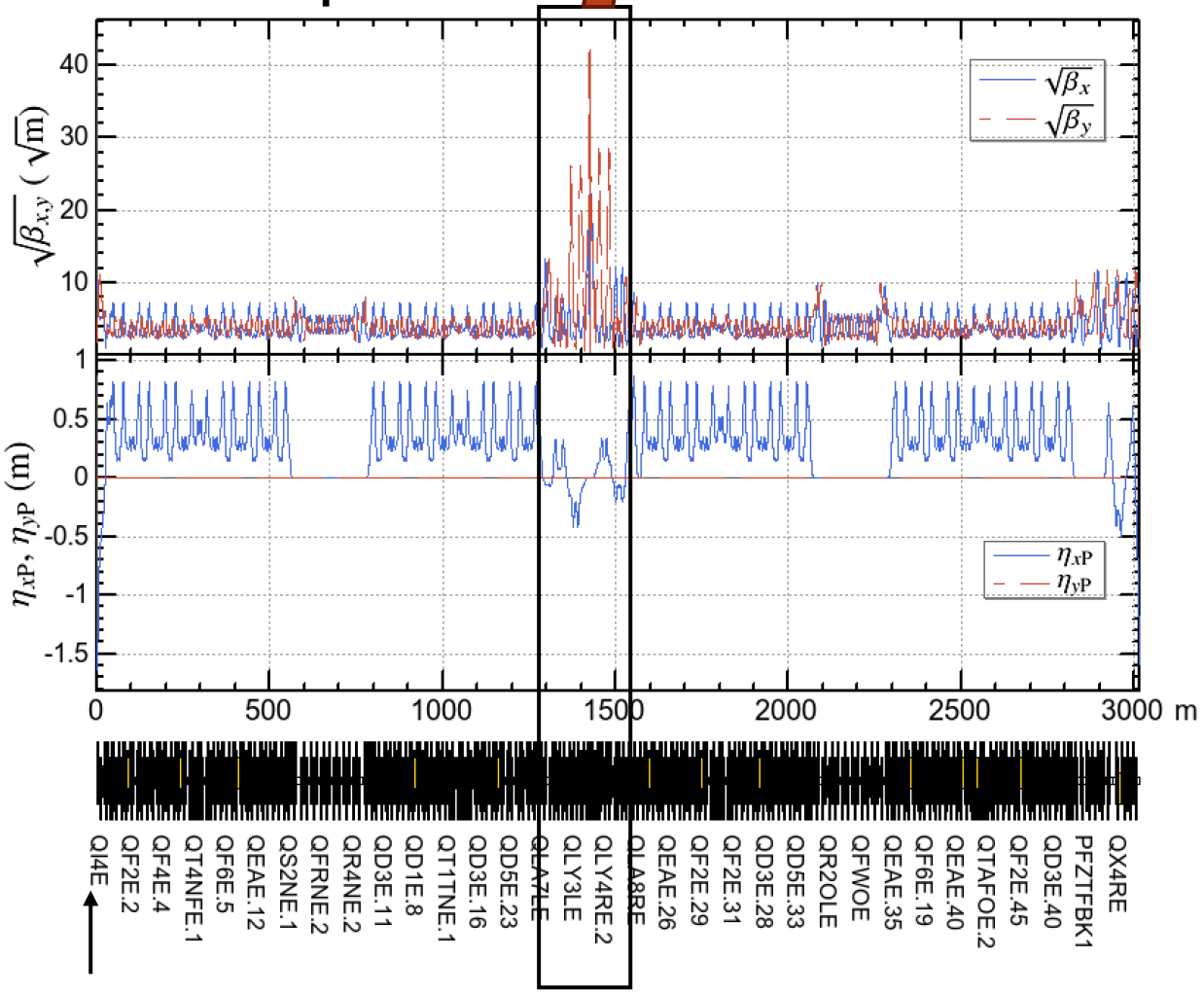


- $\eta x = \Delta X/\delta$: horizontal dispersion
  =orbits of the beam with offset energy (δ)
- **In SI**, the **energy of injection beam** is made **0.6% higher** = The injection beam's orbit makes the dispersion orbit.
- In the non-dispersive region.
  → **$\Delta X=0$ at the interaction region.**
  → However, although it oscillates in the longitudinal direction, its impact on collisions is small.

BI: $\Delta X=\Delta X_\beta$
SI: $\Delta X=\eta_x\delta$

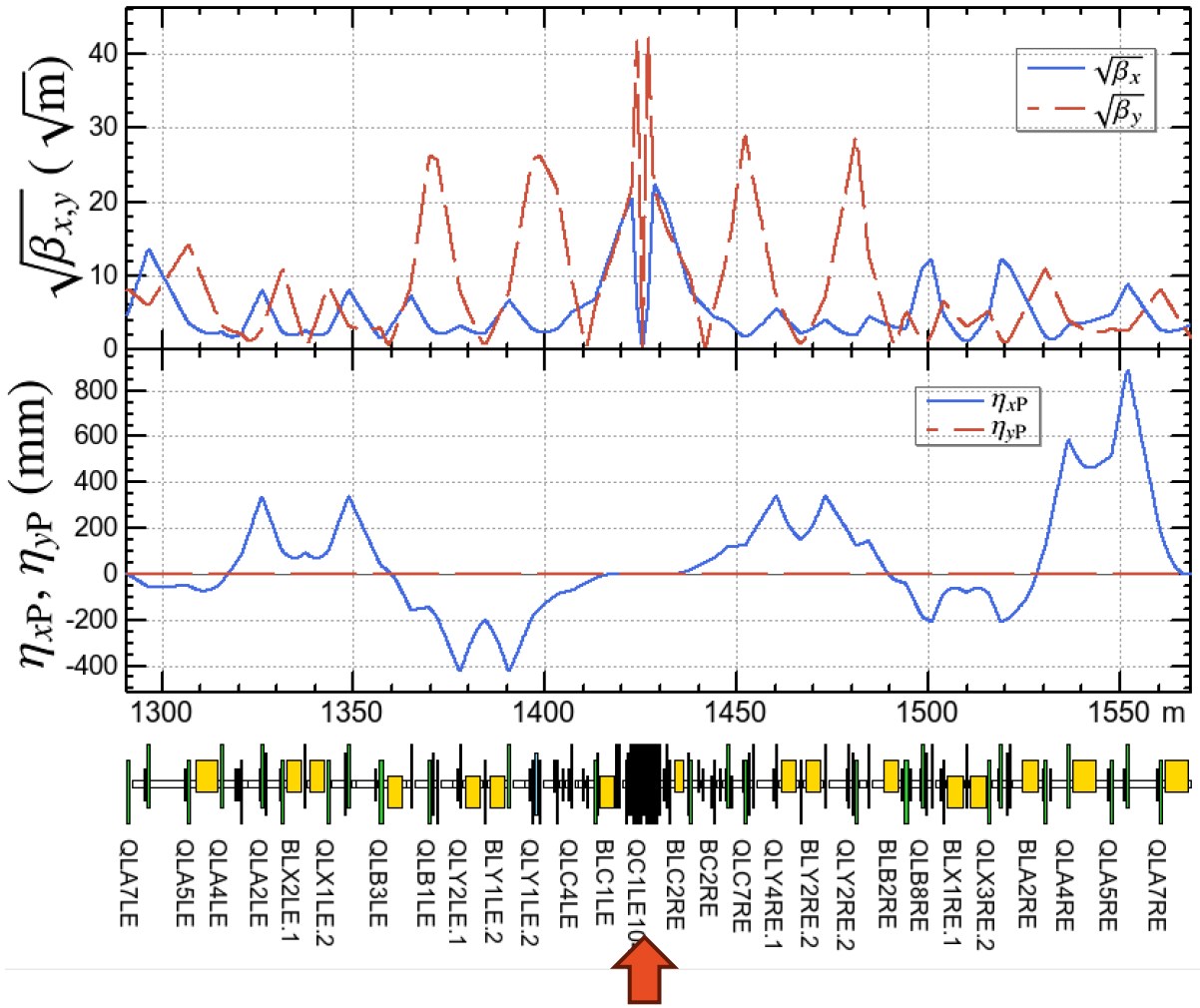
Interaction region (IP)

HER optics



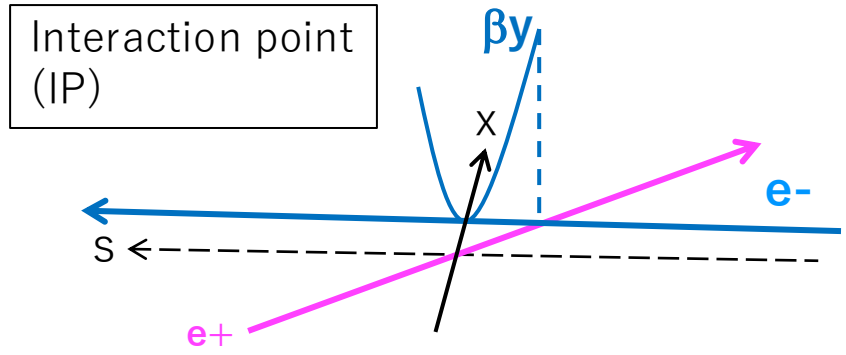
Injection point

Interaction region



At the interaction region, there is no dispersion by design.
→ No oscillation of injected beam

- **The poor injection efficiency depends not only on the high emittance of the injection beam, but also on the conditions of the ring.**
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Why synchrotron injection (SI) ?

In SI, the injection oscillation is converted from the horizontal to the longitudinal.

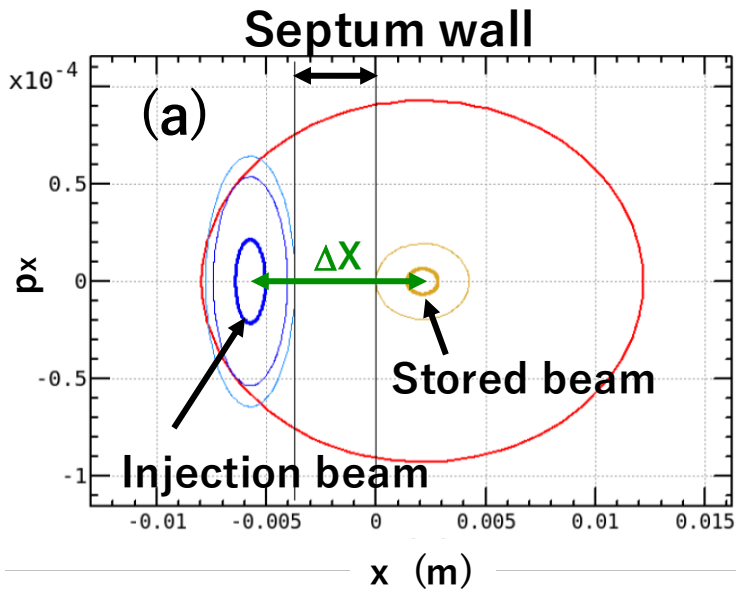
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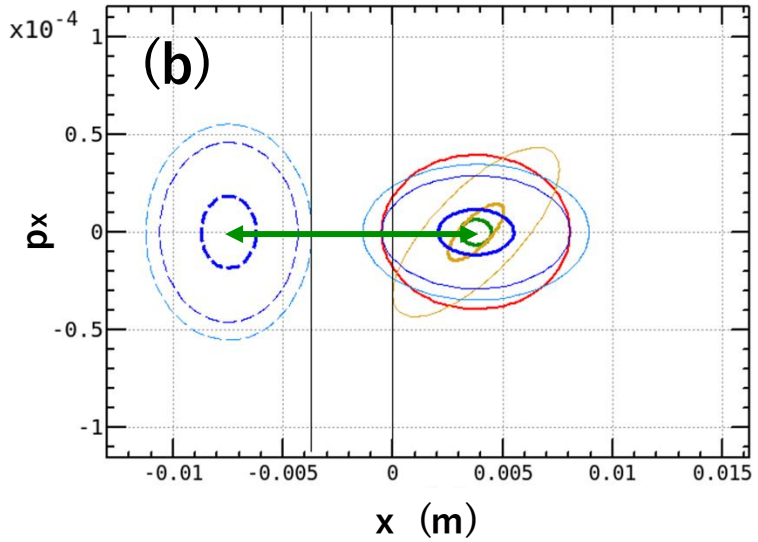
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Horizontal action of the beams at the injection point

Betatron injection (BI)



Synchrotron injection (SI)



The injection beam moves within the region of this red circle.

	BI	SI
ε_x [nm]	4.6 / 14.6	
σ_δ [%]	0.063 / 0.18[a]	
$\beta_{x,\mathrm{inj}}$ [m]	108.4 / 31.6	108.4 / 108.4
$\alpha_{x,\mathrm{inj}}$	0 / 0	0 / 0
$\eta_{x,\mathrm{inj}}$ [m]	0 / 0	-1.66 / 0
$\eta_{p_x,\mathrm{inj}}$	0 / 0	-0.02/-0.02
ΔX [mm]	-7.86	-11.26
ΔX_β [mm]	-7.86	0.0
$\Delta p/p_0$ [%]	0.0	+0.68
$2J_x$ [μm]	0.935	0.169

[a] full width

- ←Injection Parameters. The subscript “inj” denotes the values of ring / injection beams at the virtual injection point PINJAX0 where the αx is zero.
- The betatron component of the injection oscillation and the initial momentum offset are shown as ΔX_β and $\Delta p/p_0$, respectively.

- **SI is tested this time.**
- The sextupoles used in the simulation for BI are different from those used in the real beam operation:they were newly optimized using a method similar to that applied for the SI.

Commissioning of the SI

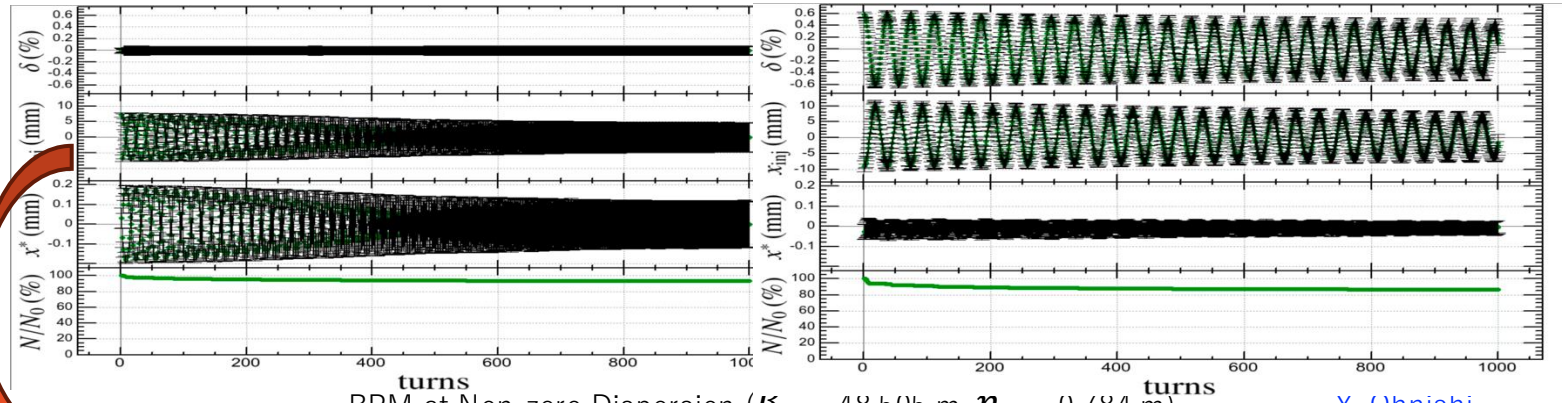
- Synchrotron injection was tried for SuperKEKB-HER.
  - Nov 6~20, at the beginning of 2025 operation
    - $\beta^*_{x,y}$
      - (400, 81) mm, “detuned optics” for **four days** for vacuum scrubbing
      - (200, 8) mm for **two days** for measurement and extraction orbit tuning.
      - (100, 3) mm for **two hours**
      - (60, 1) mm for **14.5 hours collision tuning** and going to the **physics run** with **top-up injection**
  - Nov 20 10:00, 2025
    - The injection scheme was switched back to the betatron injection, because the test period was over.
      - At the SI, the injection became worse for the higher repetition rate, 12.5 Hz than 5 Hz.
      - However, this phenomenon often occurs even with BI, so **it doesn't seem to be unique to SI.**

Oscillation of injected beam

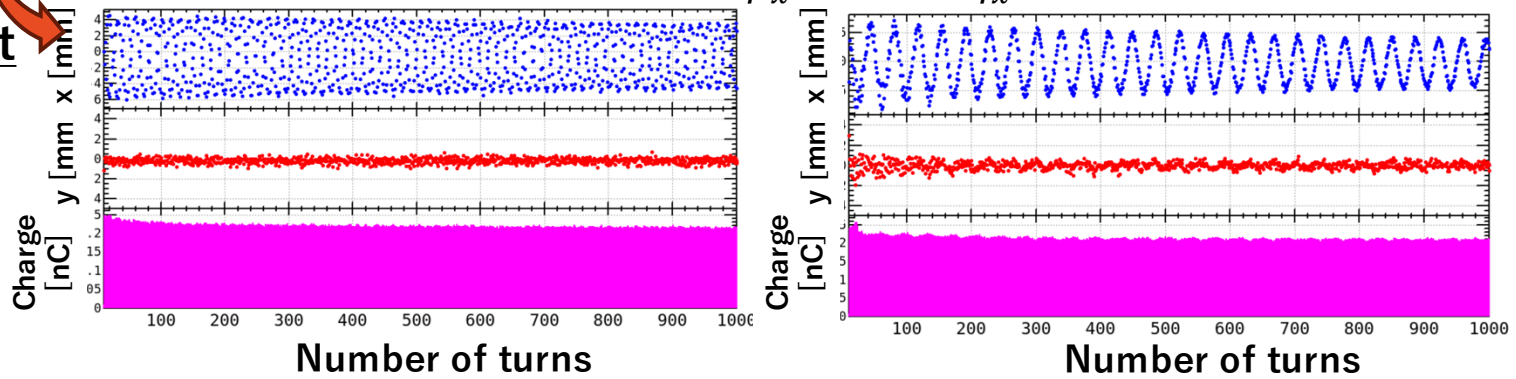
Simulation
K. Oide

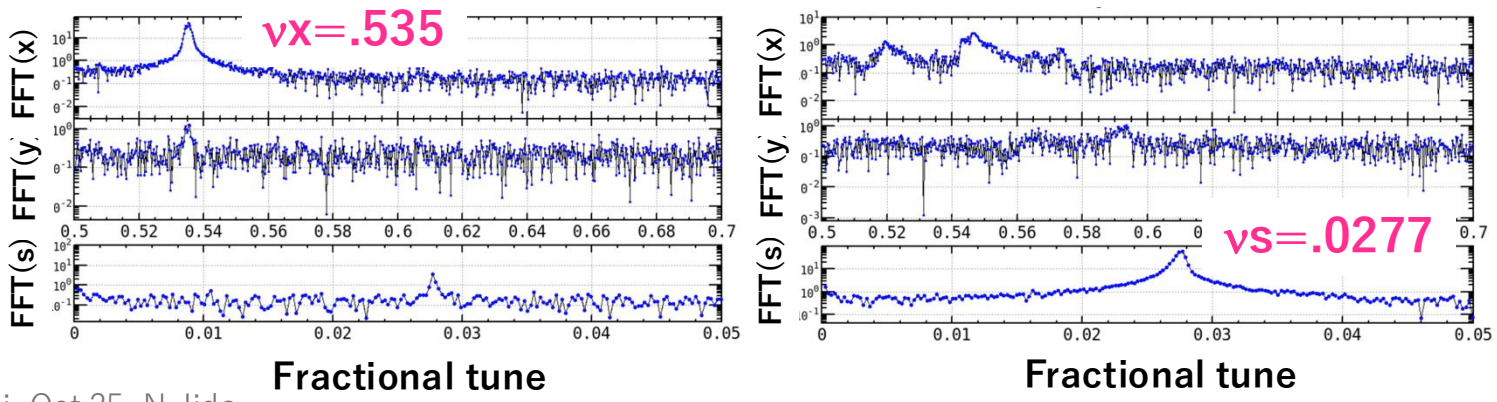
Measurement
by TbT-BPM
βy*=81mm
(detuned optics)

Betatron injection | **Synchrotron injection**



BPM at Non-zero Dispersion (β_x = 48.505 m, η_x = 0.784 m) Y. Ohnishi



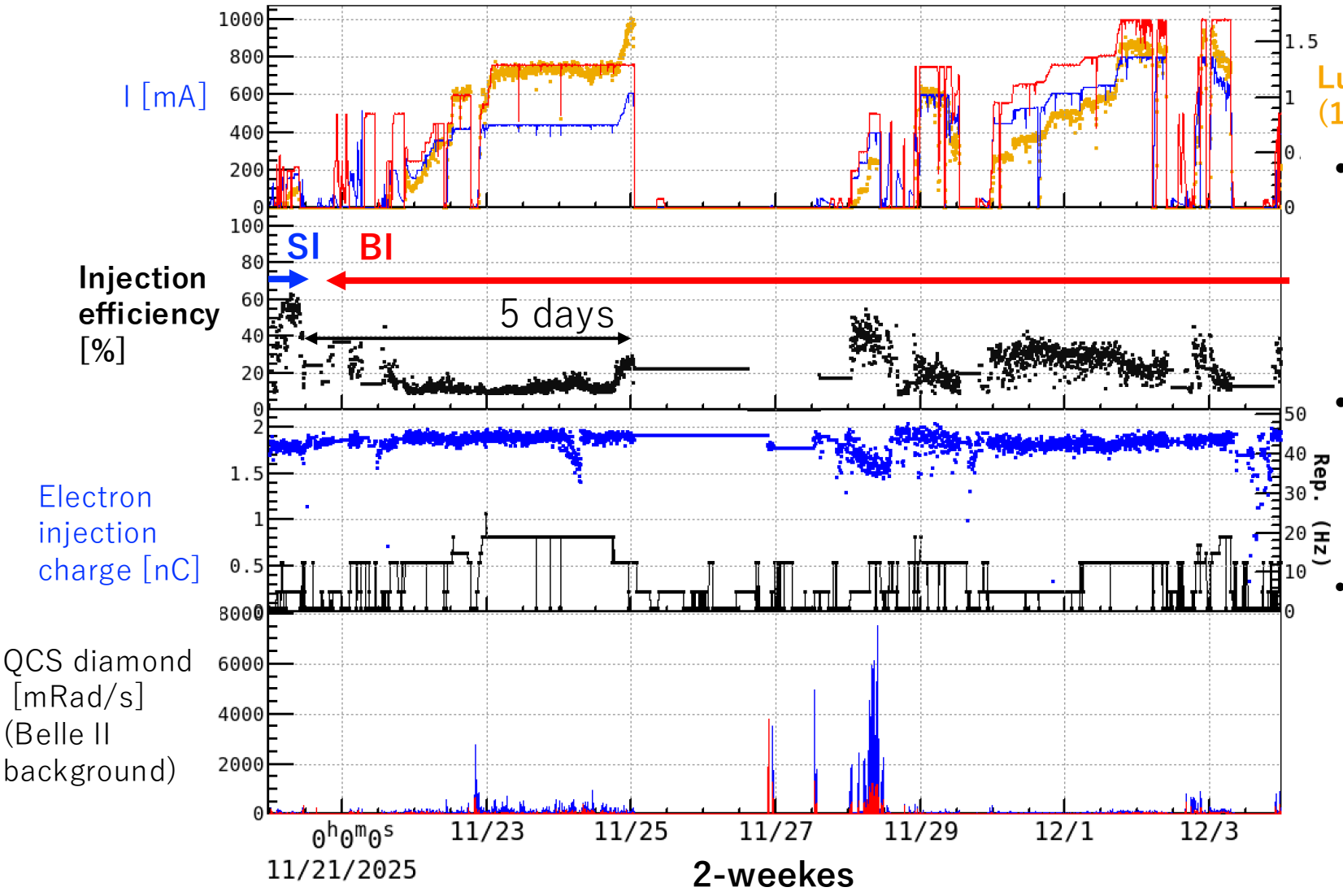


Complete agreement!

- During the detuned optics operation, the oscillations of injected beam were measured with the TbT-BPMs.
- **A significant difference in oscillation frequencies** is observed between BI and SI.
- A peak appears at the horizontal tune in the FFT spectrum of BI, while the synchrotron tune of SI.
- These results indicate a **perfect realization** of the **synchrotron injection!**

Injection history of SI and BI at the beginning of 2025 (βy*=1mm)

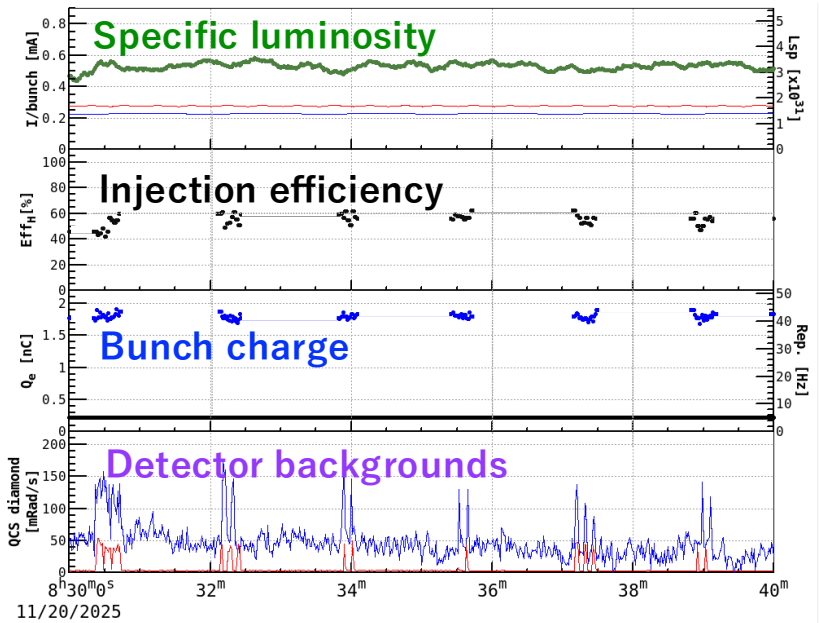
SI: Synchrotron Injection
BI: Betatron Injection



- While the injection efficiency of **SI** was achieved **60 %** only **in 6 hours**, **BI** could not exceed **30%** even **in 5 days**.
- This means that the **injection tunings of SI is much easier than those of BI.**
- In the 2025 run, since the RF gun for HER e- beam was just changed and for the no enough tuning time, the emittances of e- beam were larger than the other runs.

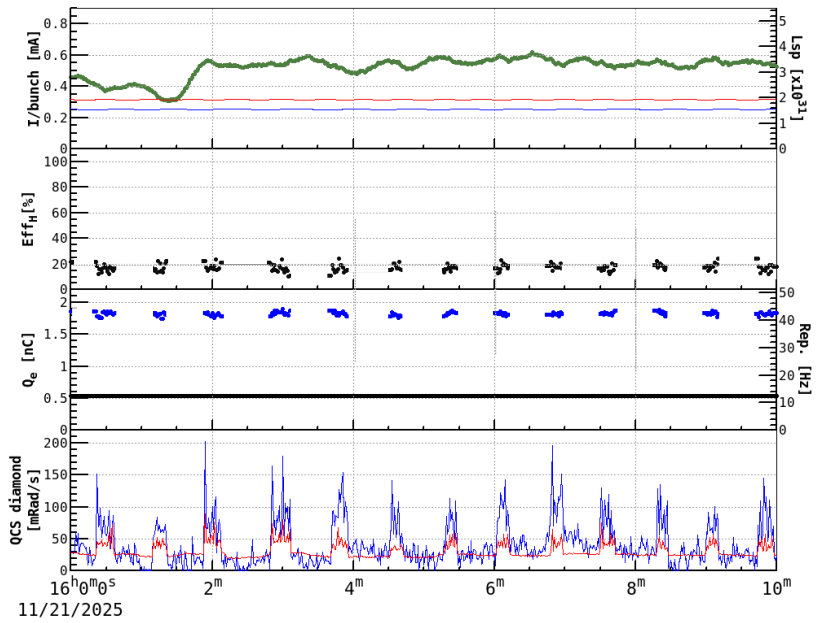
SI: Synchrotron Injection
BI: Betatron Injection

SI(20-Nov-2025)



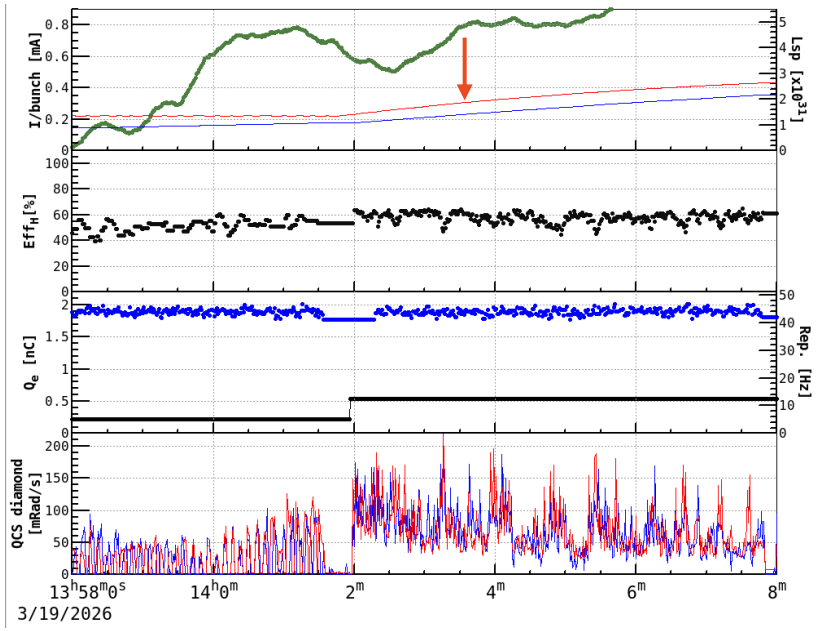
10 min.

BI(21-Nov-2025)



10 min.

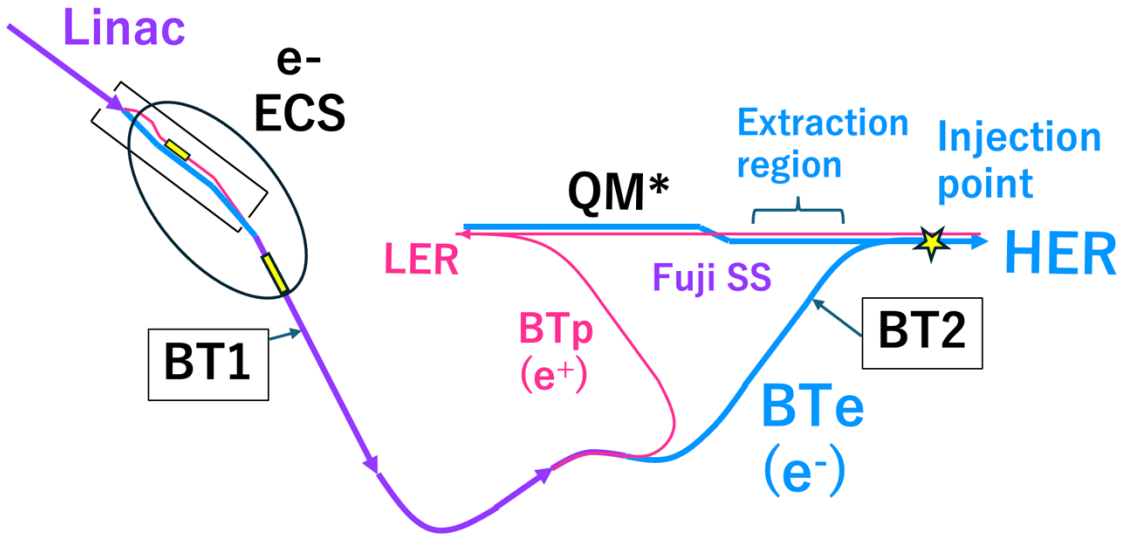
BI(19-Mar-2026)



10 min.

- The Belle II backgrounds were almost same for both injections.
- In the next run in 2026, after the emittance tuning of the e- beam and the injection tunings were done well, the injection efficiency of BI recovered 60%.

Tracking Simulations



- Injection beam
  - Linac (by SAD)
    - Longitudinal short-range wake
  - BTe (by elegant)
    - Energy compression system (ECS)
    - CSR and ISR
- Optics matching from BTe to HER
  - Artificial matching
    - Match particles from BTe to HER's off-momentum phase space
  - Emittance scaling
    - Emittance blowup from BT1 to BT2(~x3) has not been understood.
    - An artificial scaling was necessary.
- HER (by SAD)
  - Full 6D tracking with crab-waist optics.
  - Optional weak-strong beam-beam effects
  - No unknown machine errors
  - 1000 to 20000 particles and 1000 to 8000 turns

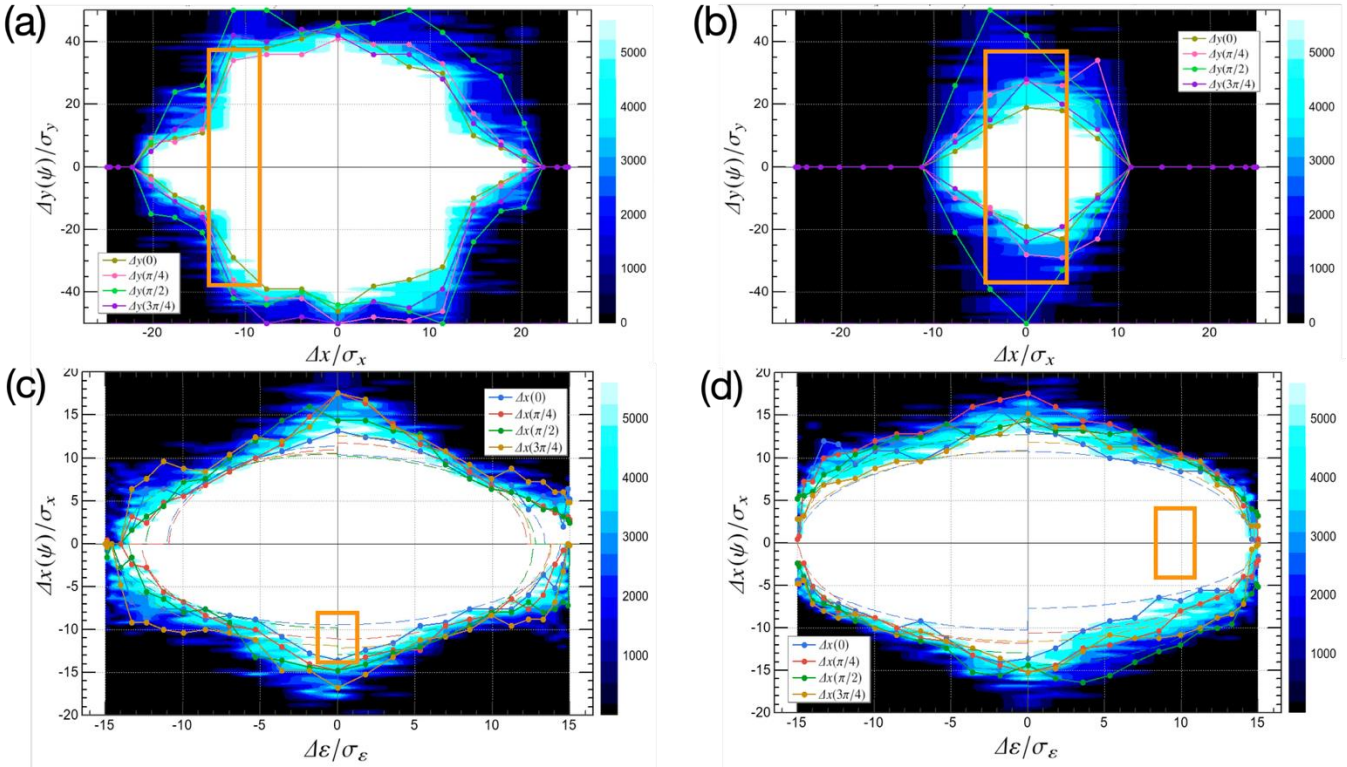
Dynamic Aperture by Simulations

BI SI

: Injected beam

x-y

z-xy

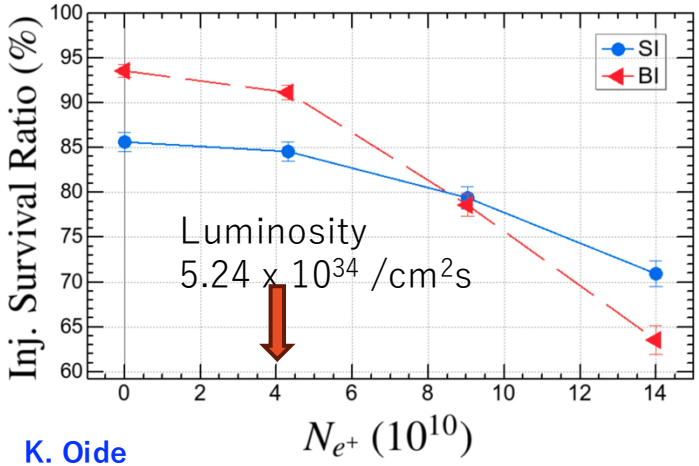


K. Oide

- (a), (b): The transverse dynamic aperture. **The orange square indicates ~ ±2.5 σ of the injected beam**. As for SI(b), the tracking starts with an initial momentum offset $\Delta p/p0 = 0.6$ %, and perform a synchrotron motion.
- (c), (d): The dynamic momentum acceptance are plotted in (c) BI and (d) SI, respectively, where the horizontal axes are the initial momentum offset. **The orange squares show the horizontal size and momentum spread of the injected beams.**
  - In both BI and SI cases, the injection efficiency is not 100%, due to the large vertical emittance of the injected particles.

SI: Synchrotron Injection
BI: Betatron Injection

Simulation with, beam-beam

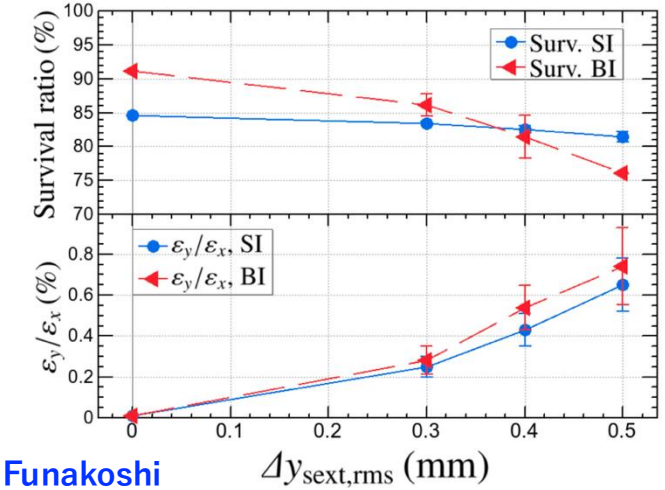


K. Oide

- **The simulated dependence of the injection survival ratio on the bunch population of positrons.**
- Obtained by tracking with 1000 particles after 8000 turns from injection.
- The intensity $Ne+ = 4.3 \times 10^{10}$ corresponds to the highest luminosity record $5.24 \times 10^{34}/\mathrm{cm}^2\mathrm{s}$.

The stronger beam-beam effect will affect the injection **for BI than SI.**

Sextupole mis-alignments



Y. Funakoshi

- The simulated dependence of
  - the survival ratio (upper)
  - the vertical emittance (lower)

  by random vertical misalignments for all sextupole magnets(Δysext,rms) in the HER $Ne^+ = 4.3 \times 10^{10}$.

The effect of x-y coupling on beam injection is more pronounced in BI than SI.

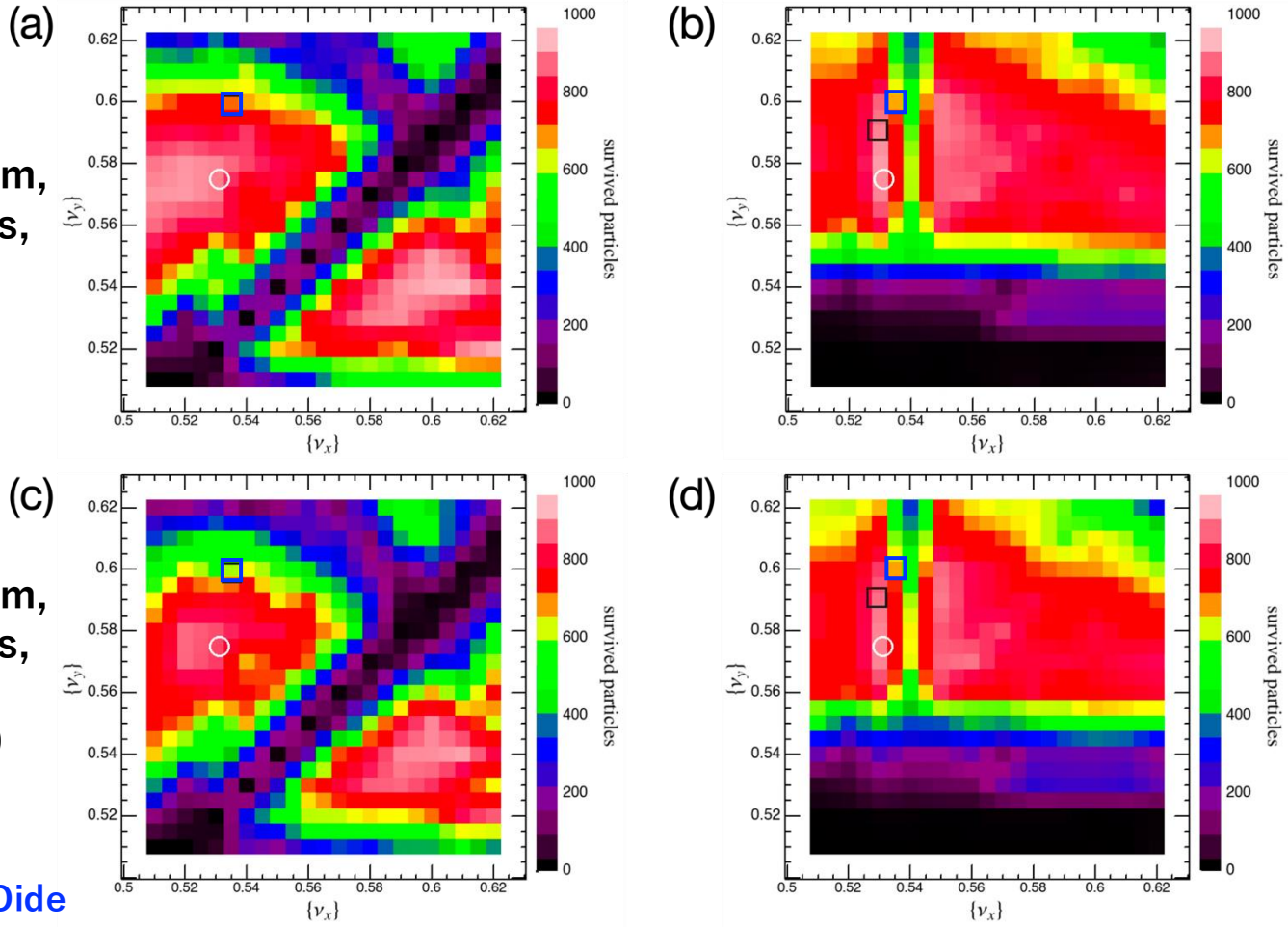
- This result is to be expected, as BI involves larger horizontal betatron oscillations, which may influence beam injection via the x-y coupling, touching the vertical dynamic aperture.
- **SI is more weakly affected by beam–beam interaction and sextupole misalignments than BI.**
- This can be a motivation for SI for higher luminosities.

Simulation of tune scan of injection survival ratio

BI ○ : DA optimized point □ : Operating point in 2026 **SI**

w/o
beam-beam, collimators, knobs, tune

w
beam-beam, collimators, knobs, tune(ope.)



- The dependence of the injection efficiency on betatron tunes. (a,c): BI, (b,d): SI.
- The fractional part of the tunes are set at { ν x,y} = (0.531, 0.575) for (a,b), **(0.535,0.599)** for (c), and (0.529, 0.591) for (d), respectively.
- **For (c,d), the ring collimators, beam-beam, and the IP knobs* are set to the values in the beam operation in November 2025.**
- The sextupoles are optimized for the DA at the tunes indicated by the white circle, and kept unchanged during the scan. The black square shows the operating tune in Nov. 2025 for each mode.
- **Clear resonance lines νx-νy~N** and 5(νx+νy)~N are seen **only for the BI**, which are **strengthened by beam-beam**.
- There are strong dark bands if the tunes get **close to half-integer** ($\{\nu_y\}\rightarrow 0.5$) for SI. The reason for the dark bands is that the optics has **insufficient momentum acceptance** required by SI for $\{\nu_y\}<\sim 0.55$.
- The differences due to such as beam-beam effects are visible in both cases, but **stronger in BI than SI.**

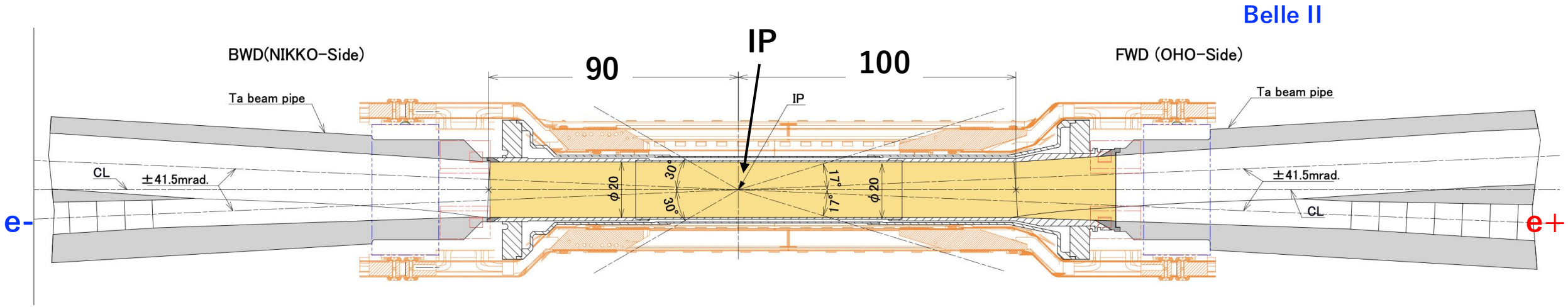
*IP knob: To control X-Y couplings, vertical dispersions at the IP by skew quadrupole windings.

- **Injection efficiency at the operating point in 2026 □ at the peak luminosity**

[%]	BI	SI
w/o	70.0	68.0
w	**60.7**	**68.2**

K. Oide

Photons hitting the IP beam pipe



- The number of primary photons from the injected beam was estimated by tracking for the first 30 turns with 20000 particles.
- The IP beam pipe is located at ±0.1 m from the IP, and has 10 mm inner radius, tilted to the *e*+ beam by the half crossing angle 41.5 mrad.
- For **BI**, the number of photons per 1000 electrons per turn and average photon energy were **1.65 ± 0.045 and 0.37 keV**, respectively.
- For **SI**, those were **0.69 ± 0.029 and 0.39 keV**. **K. Oide**

- Since the Belle II-PXD detector has been turned off due to sudden beam losses, the SR background has not been measured.

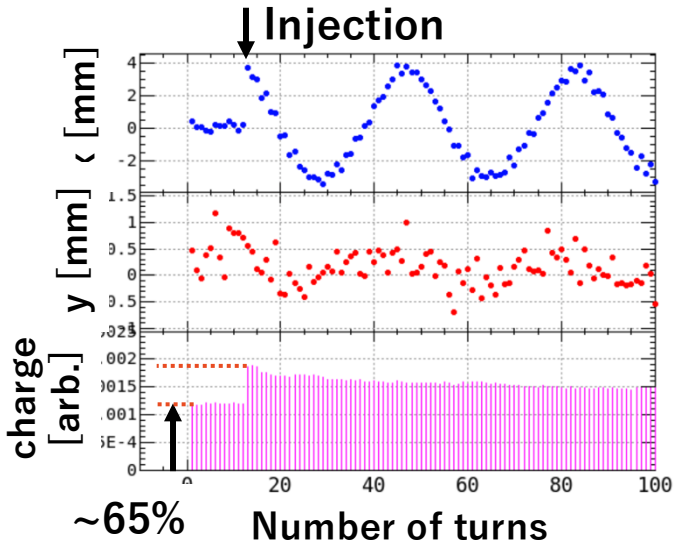
Summary

- **Synchrotron injection (SI) was tested for the first time in the HER of SuperKEKB, with collision and top-up.**
- In the experiment, the injection oscillation was **fully transferred** from the horizontal **to the longitudinal plane as designed**, demonstrating the successful SI operation.
- At $\beta y^*=1$ mm, **injection tuning was simpler than for BI**, and an **injection efficiency of ~60%** was achieved in 6 hours, while BI did not exceed 30% in 5 days.
  - Although the study was terminated due to injection difficulties at high repetition rates, likely not intrinsic to SI, a future reattempt are planned.
- **Simulations** indicated that **SI is insensitive** to collisions, sextupole misalignments, and betatron tunes.

Thank you for your attention!

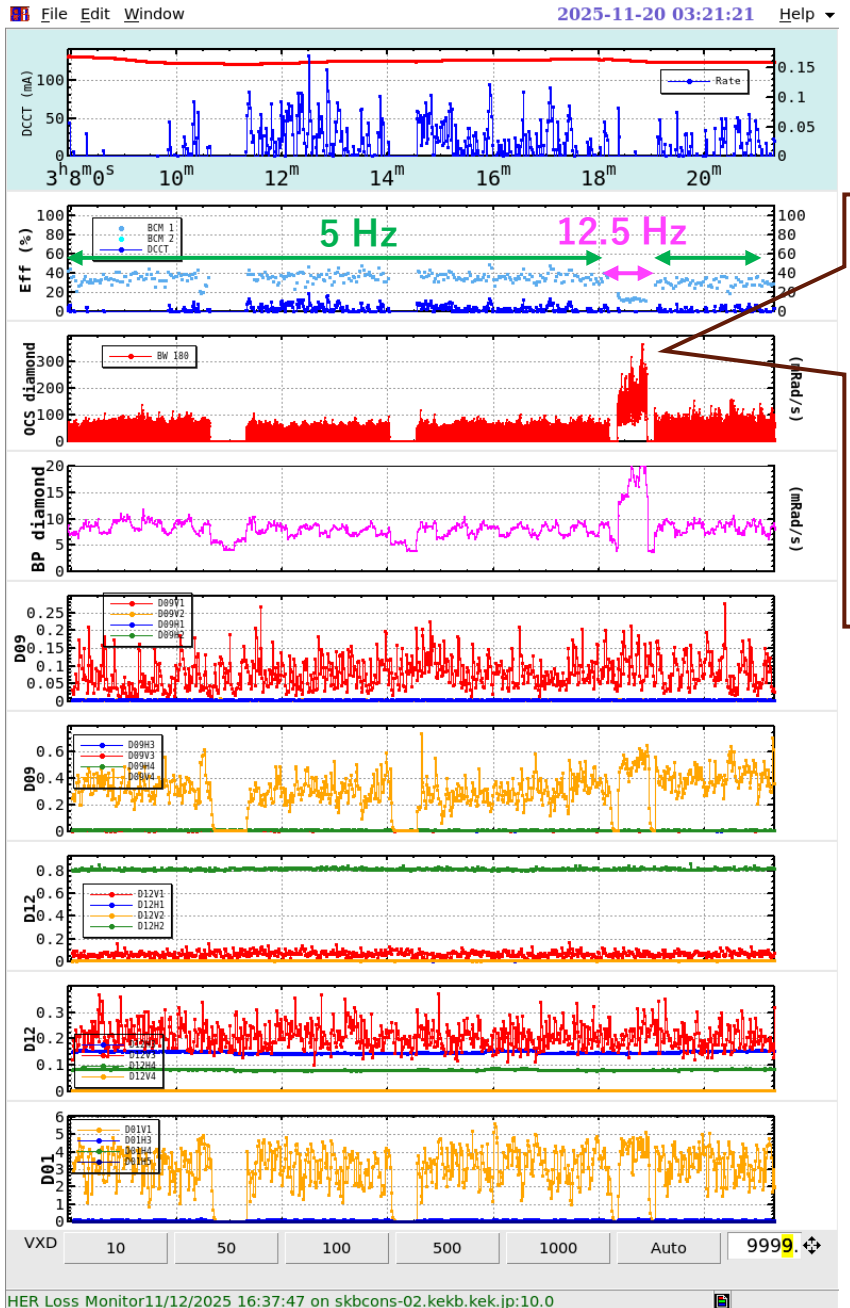
Backup slides

βy*=1mm injection tuning



A TbT-BPM measurement of the injected beam

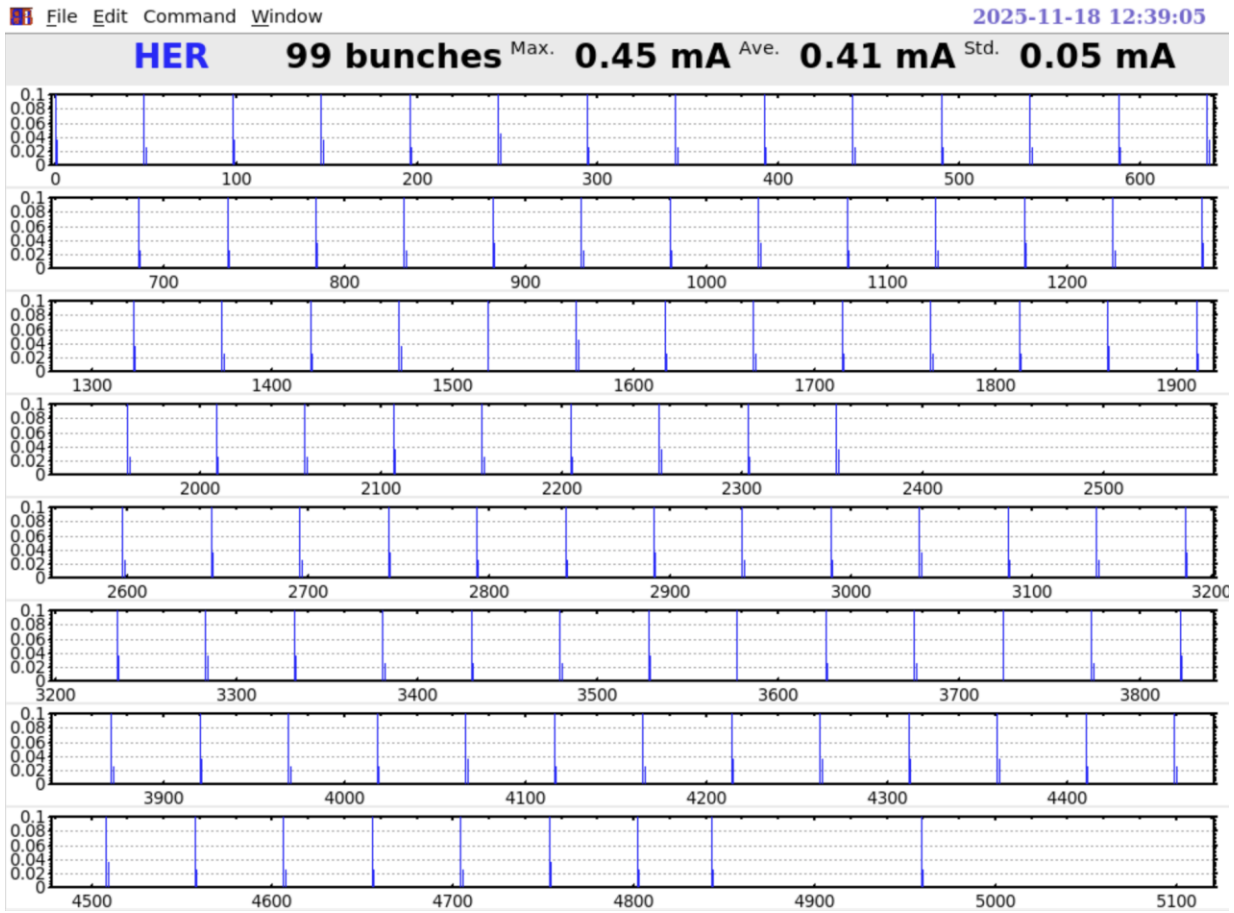
- The horizontal axis shows the turn number, where the injection was performed at the turn #12.
- The points before turn #12 show the previously stored beam, which was kicked out by the injection kickers at turn #12, while the next beam is injected simultaneously.
- The stepwise increase in beam charge indicates that the survival ratio of the previously injected beam was 65%, by assuming the same amount of injected charge.
- **The injection phase was adjusted** so that the horizontal oscillation at a TbT-BPM in a dispersive region is **maximized on the first turn**.
- This ensures that the longitudinal oscillation arises only from the energy difference, i.e., **the phase is properly tuned**.



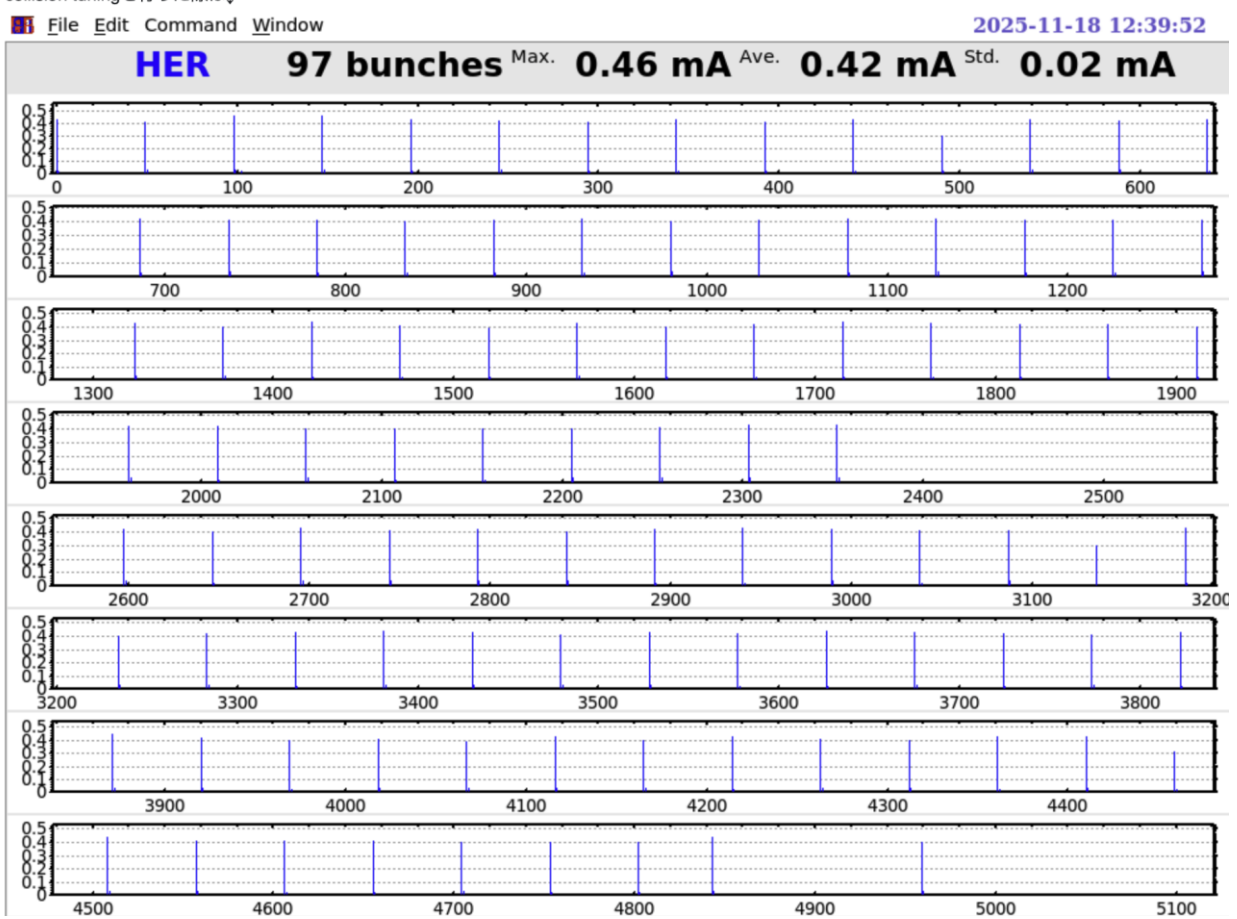
However, for some reason, changing the repetition rate of injection from 5Hz to 12.5Hz reduced the injection efficiency and drastically increased the background (BG) of the Belle II detector.

Although the study was terminated due to injection difficulties at high repetition rates, likely not intrinsic to SI, a future reattempt is necessary.

The beam was accidentally injected on the next bucket.

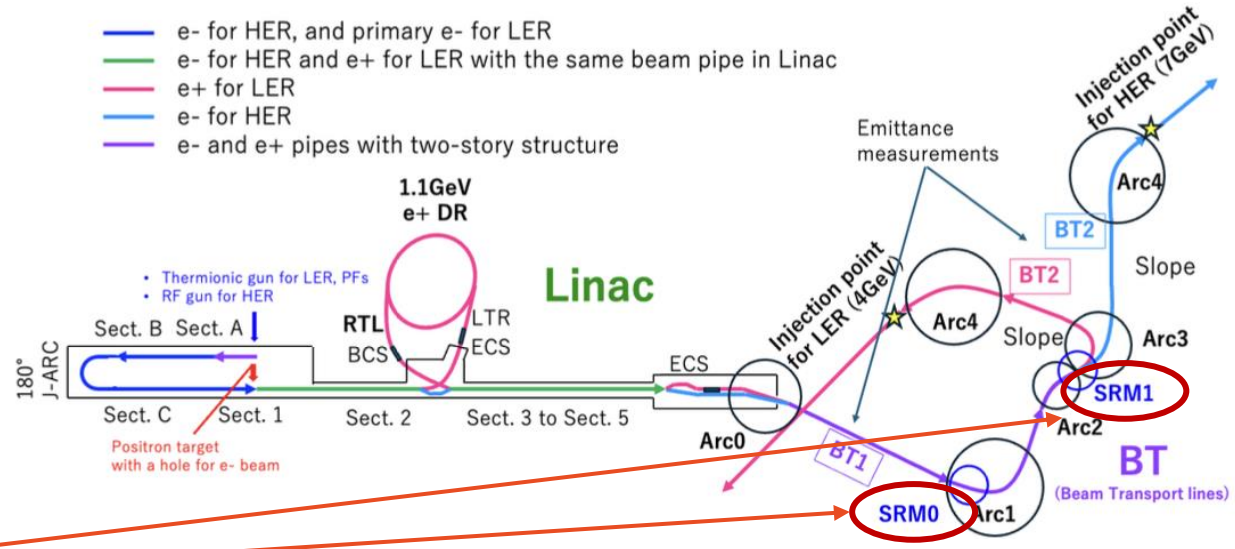


collision tuningを行った際は↓



- 0.41 mA for 96 correct bucket, but ~0.04 mA beams were observed as injected on the next bucket during mainly βy*=8 mm or detuned optics.
- We wanted to confirm whether the beam was injected into adjacent buckets at the same pulse.
  - But unfortunately since only the data every 10 s were archived for 5 Hz, that could not be confirmed.

New Emittance auto tunings(EAT) by Dr. Y. Seimiya



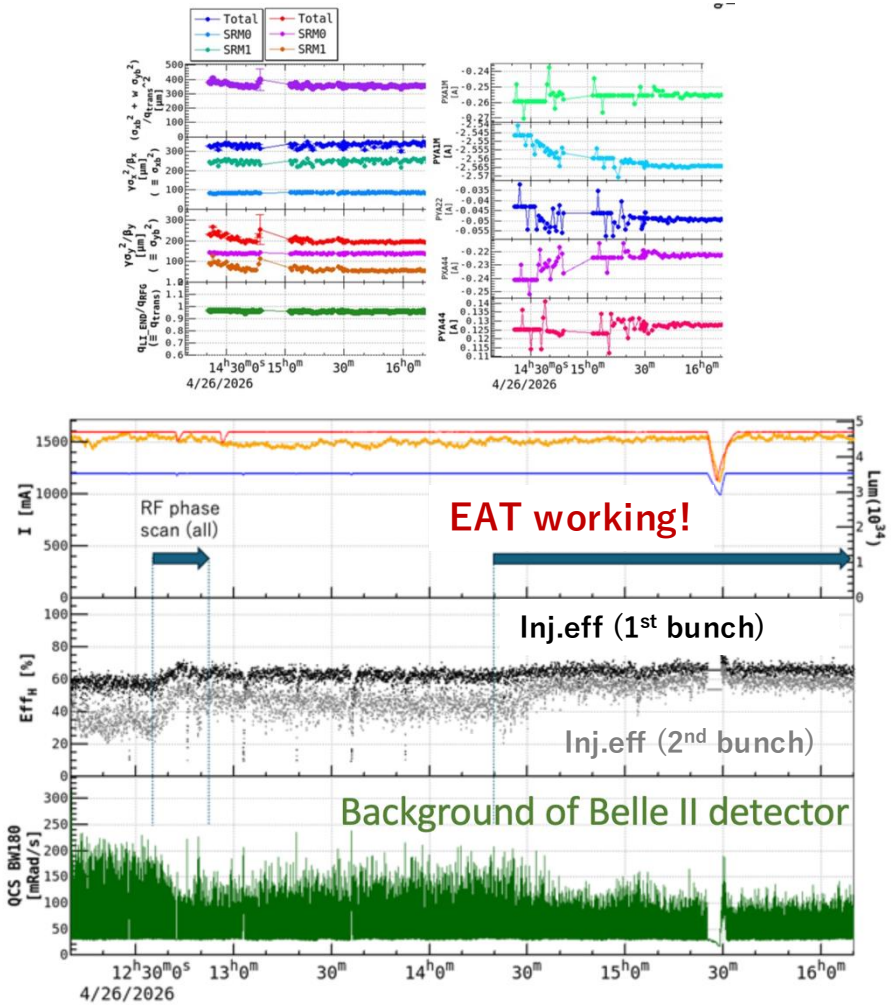
Two effective automatic tunings have been installed in **HER**.

- Looking at two measured beam size monitors(SRMs) in e- BT, the emittance growths can be suppressed by optimizations.
  1. Due to the transverse wakefield through the Linac by making orbit with pulsed steerings (**EAT**).
  2. Tuning of the laser timing relative to the Linac RF phase (“**EAT-II**”).

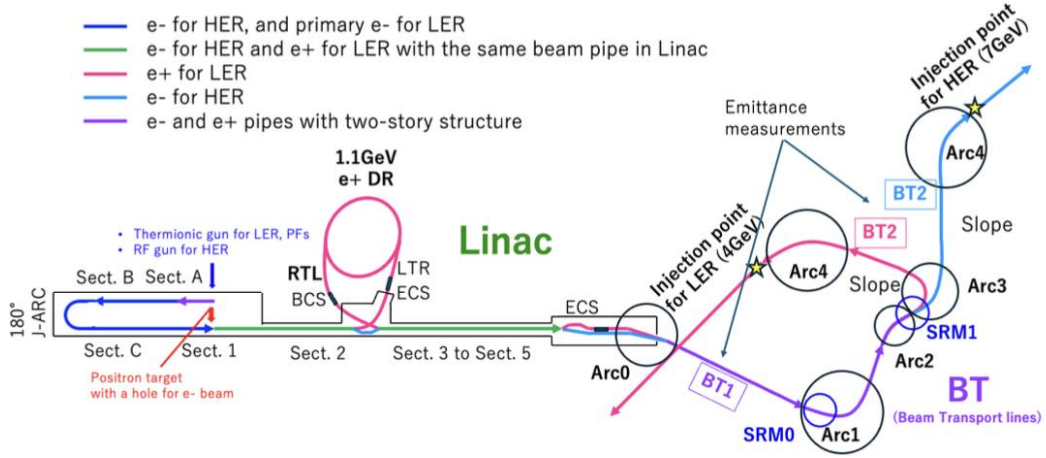
  - The optimization method can be selected Downhill Simplex or Bayesian.

Emittance auto tunings by Y. Seimiya

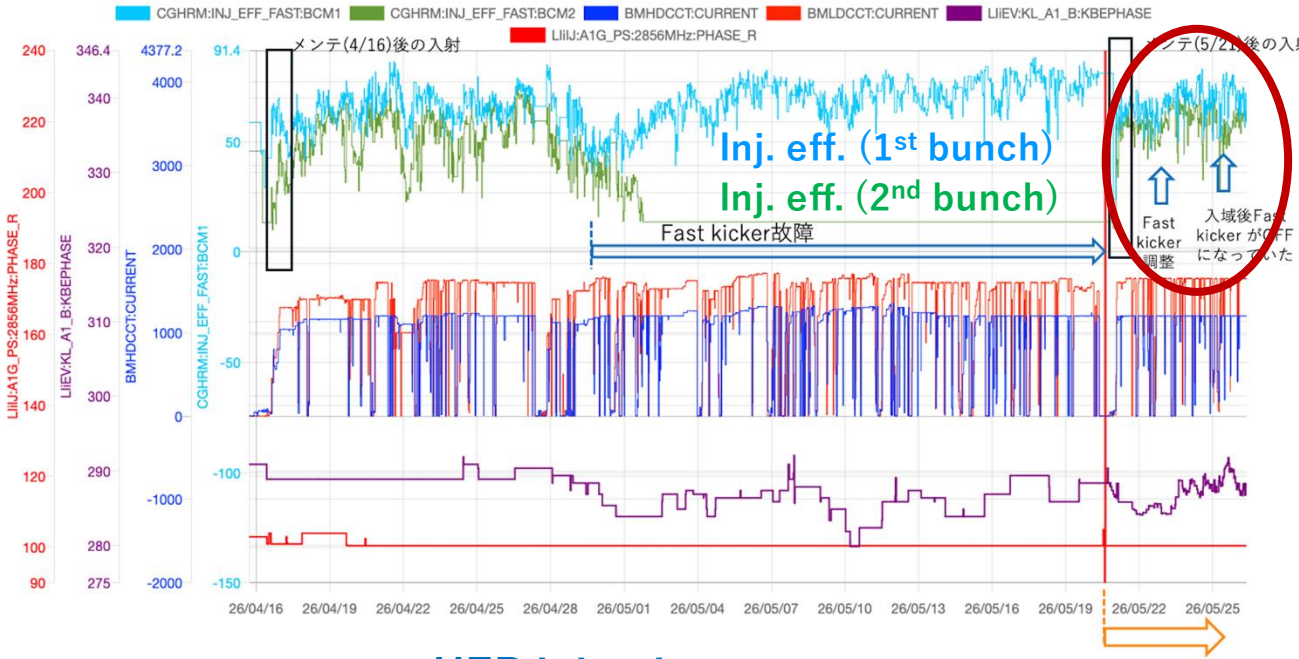
1. Cancellation of the Linac wake (MOP6653)(EAT)



HER injection status



2. Tuning of the laser and linac-RF phase("EAT-II")



HER injection status

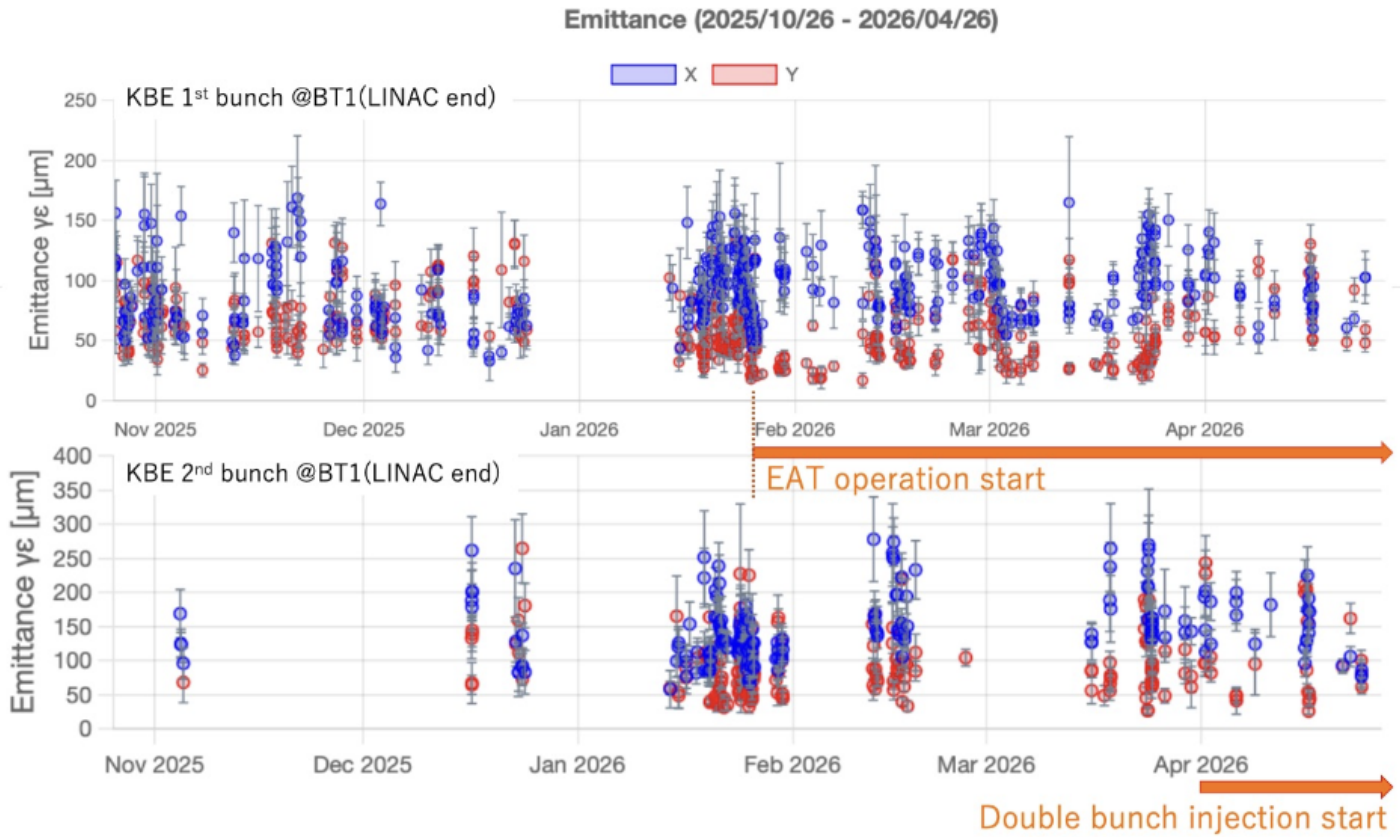
EAT-II working!

The stability of injection efficiencies for both bunches can be more improved!!!

Emittance history at BT1

Y. Seimiya

- In the case of only the 1st bunch operation, i.e., during the period when the 2nd bunch plot is not available, the vertical emittance, which affect injection performance significantly, is large and unstable before EAT operation.
- After the EAT operation, the vertical emittance often stabilizes and improve below 50 μm.
- On the other hand, in the case of double bunch operation, the emittance had not improved as much as expected.
- Possible causes include orbital drift between the first and second orbits and RF phase drift.



- We plan to develop this system to achieve higher injection efficiency and stability by tuning the RF phase (all).

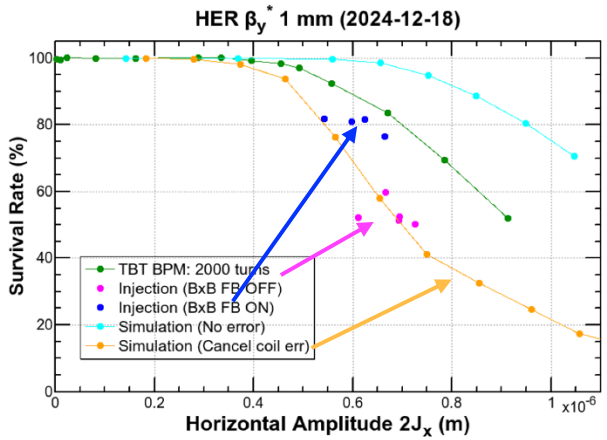
Dynamic aperture measurements

Y. Ohnishi

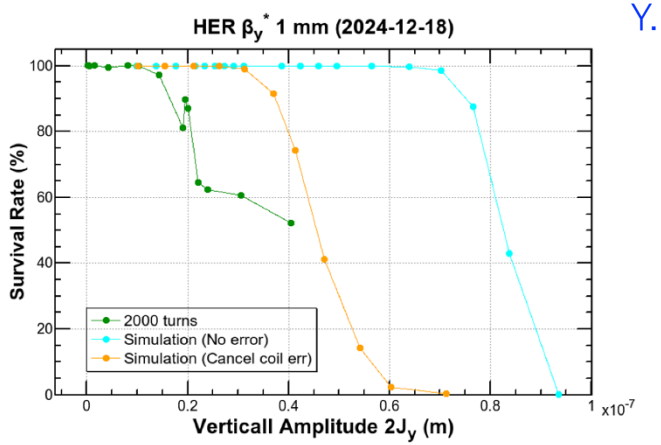
Betatron Injection

Cancel coil error reduces vertical aperture significantly.

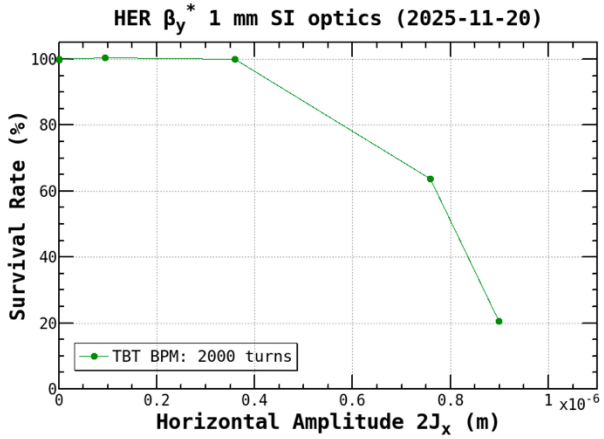
Horizontal amplitude

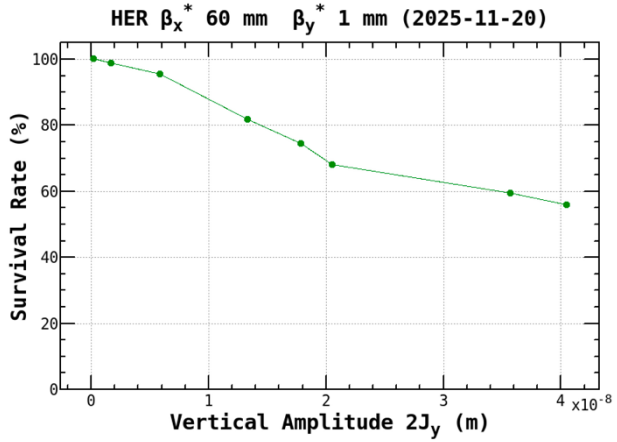


Vertical amplitude

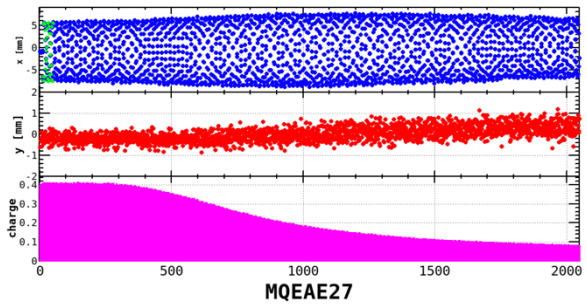


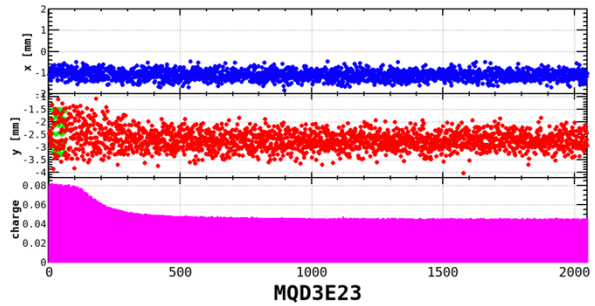
Synchrotron Injection





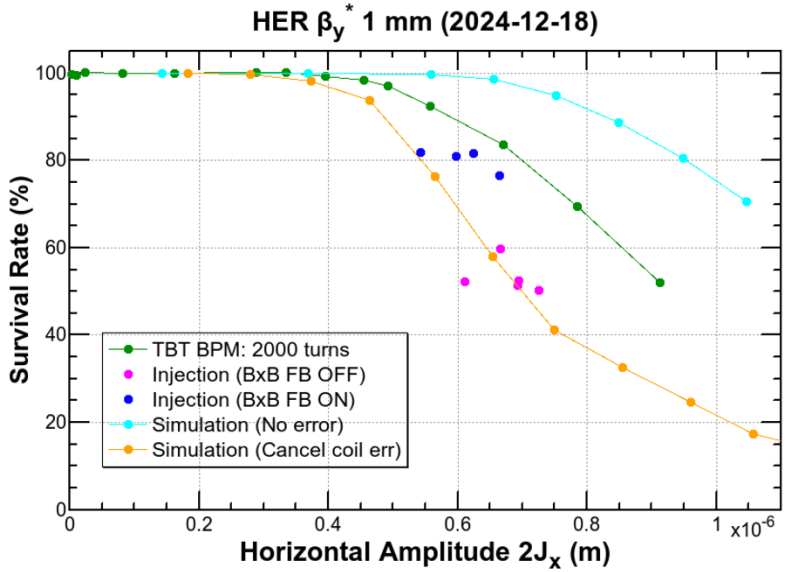
Measured DAs of SI are almost same are those of BI.

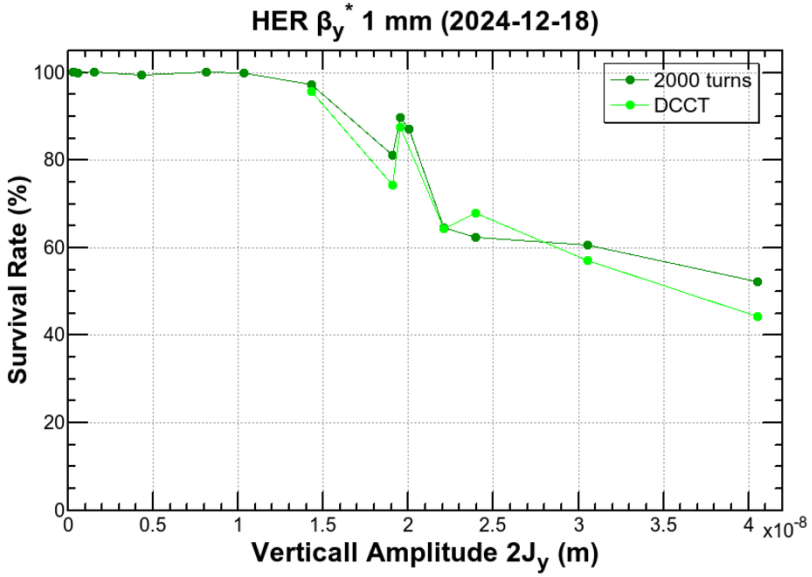


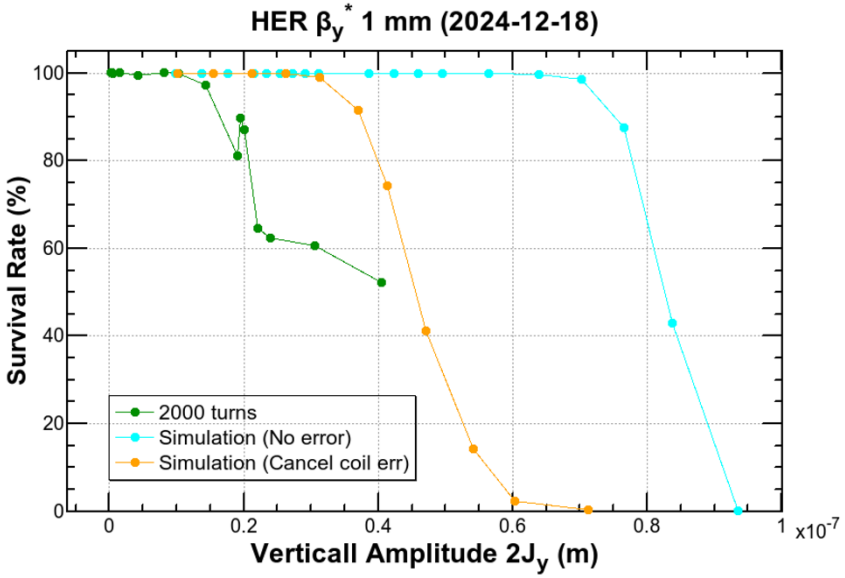


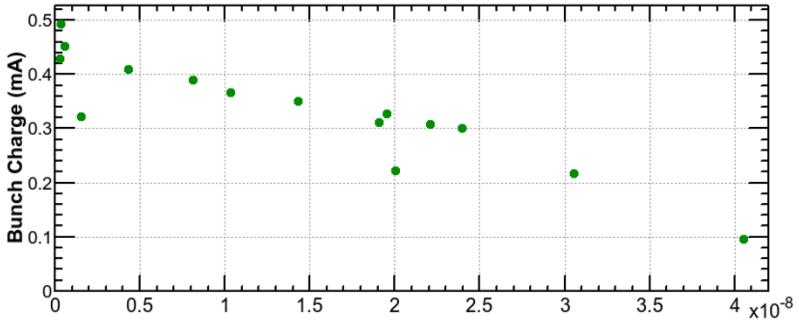
DA of Betatron injection

Y. Ohnishi





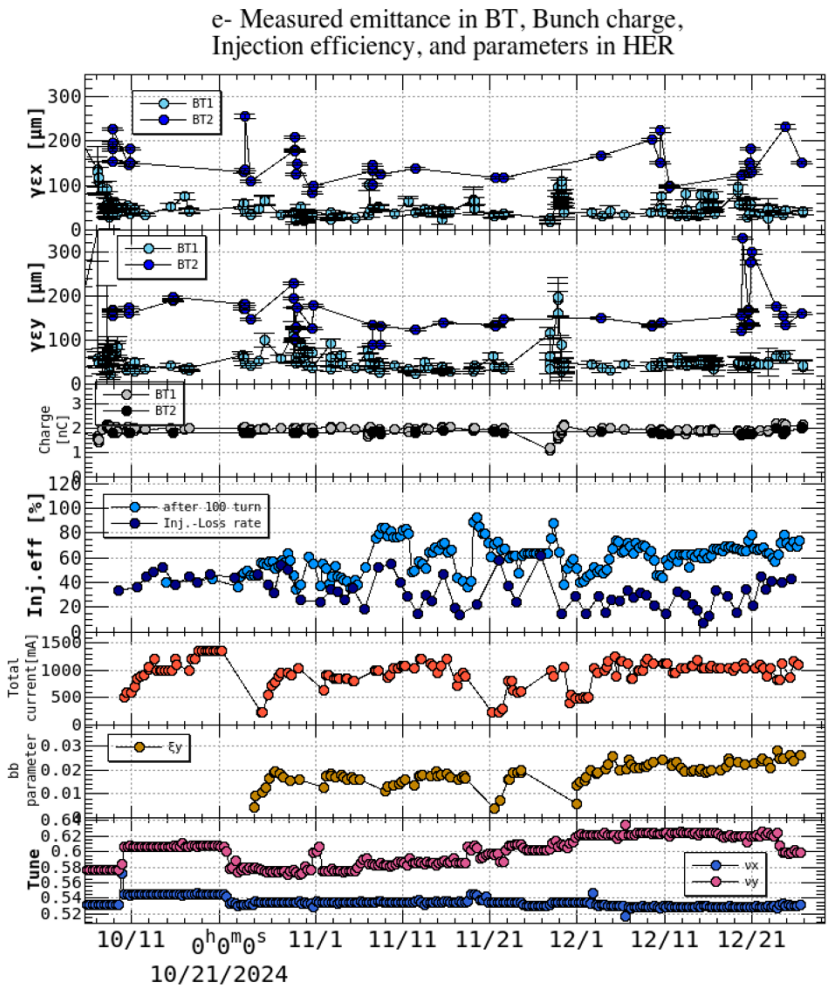




Cancel coil error reduces vertical aperture significantly.

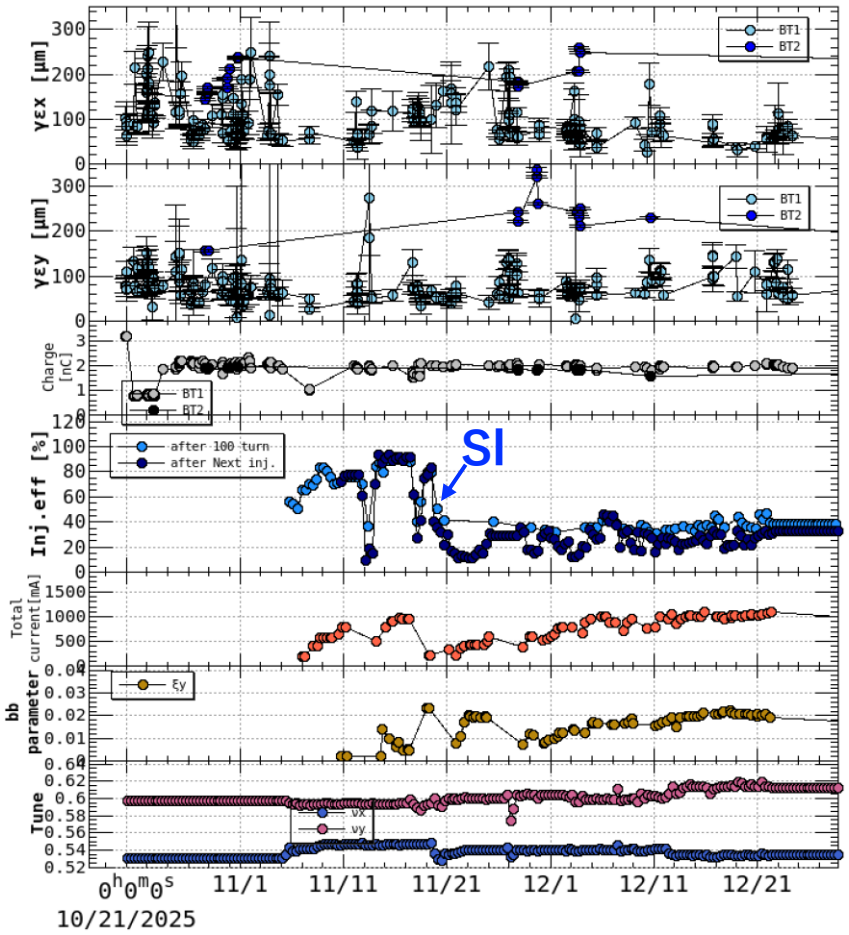
HER emittances

2024c



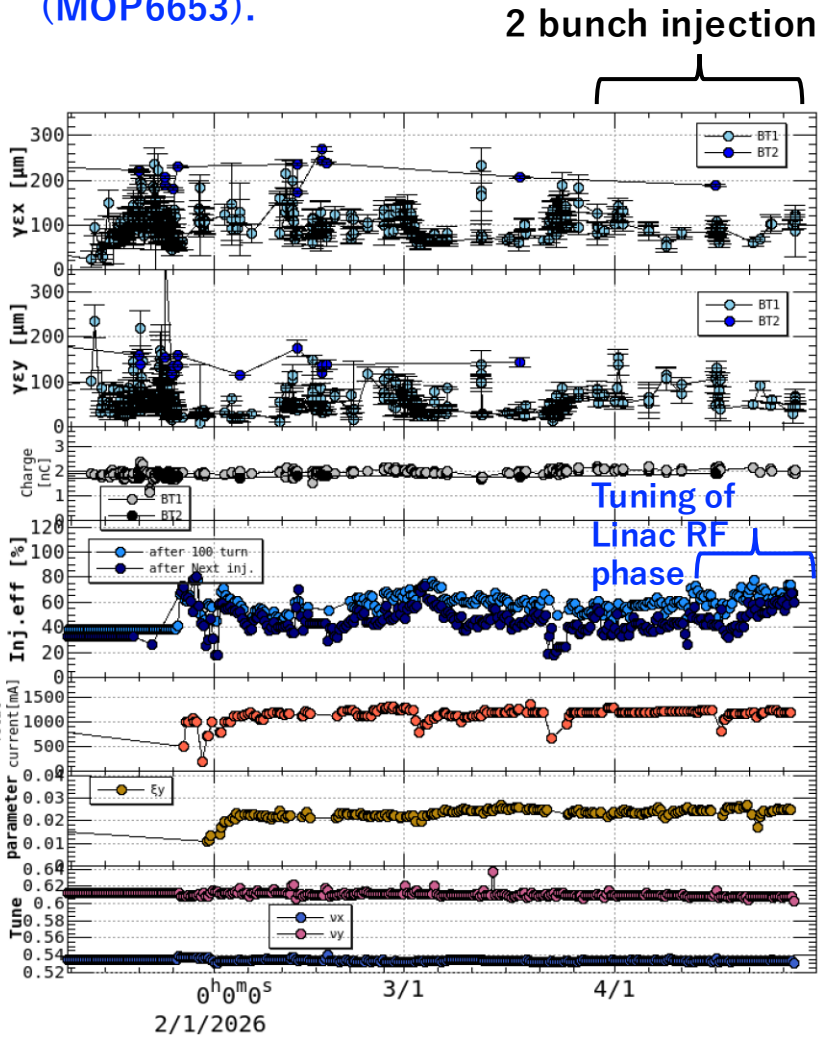
2025c

Due to the limited tuning time after the RF replacement, the emittance could not be sufficiently reduced, resulting in poor injection performance throughout the operation.

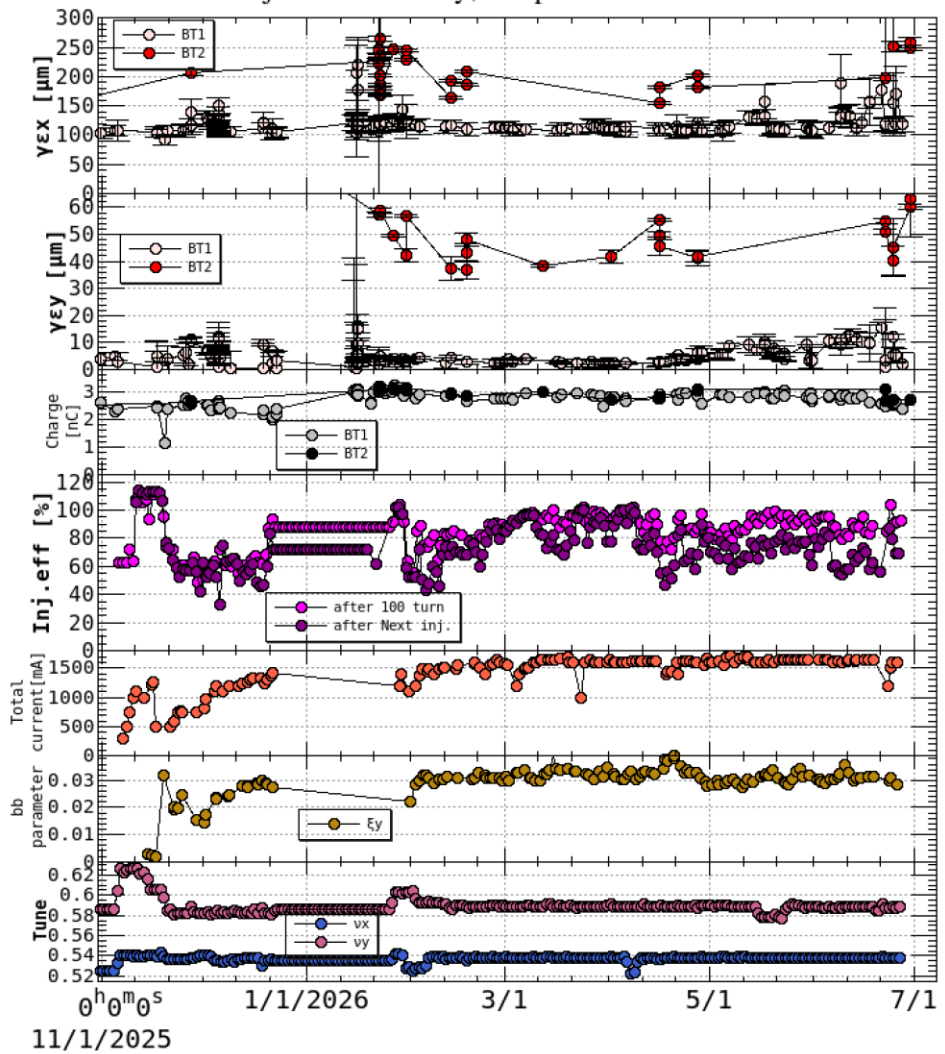


2026ab

γεy has been kept smaller thanks to "EAT" (MOP6653).

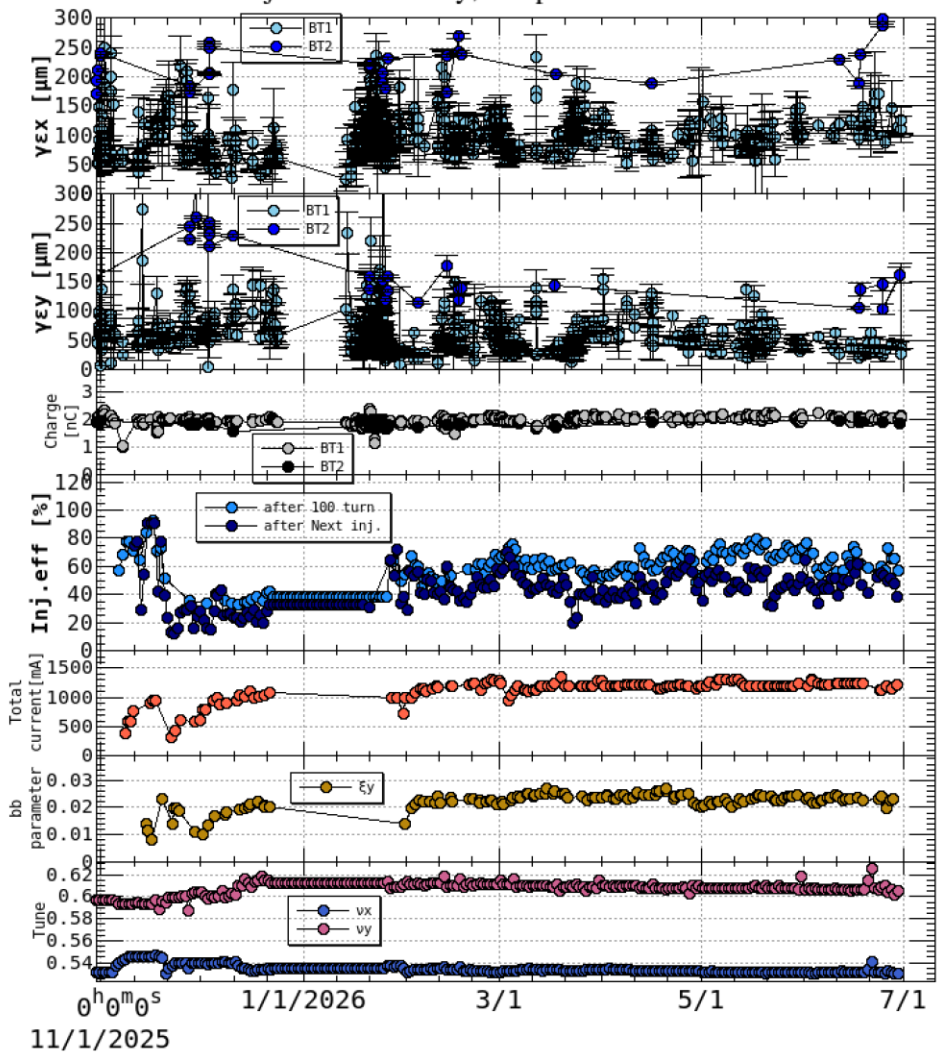


LER



e+ 2026ab	BT1	BT2	Req.
gex [mm]	119.0 ± 2.0	207.2 ± 9.0	100
gey [mm]	5.40 ± 0.39	47.26 ± 1.82	15

HER

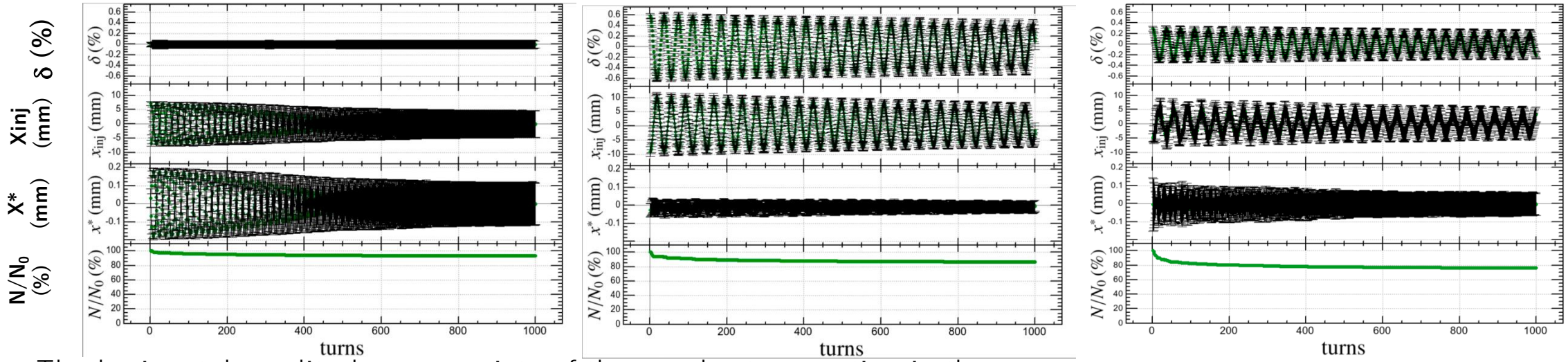


e- 2026ab	BT1	BT2	Req.
gex [mm]	104.0 ± 1.7	233.4 ± 11.4	40
gey [mm]	52.83 ± 1.58	134.6 ± 6.8	20

Tracking simulations of the injection to HER

SI: Synchrotron Injection
BI: Betatron Injection
SBI: Synchro-betatron Inj.

Betatron injection (BI) **Synchrotron injection (SI)** **Synchro-beta injection (SBI)** K. Oide



- The horizontal amplitude x_{inj} consists of the synchrotron motion in the case of SI.
- x_{inj} looks smaller for the BI than for the SI.
  - This is because the separation between the stored and injected beams are smaller for the BI. This horizontal displacement at the injection point mostly consists of the synchrotron motion in the case of SI.
- The horizontal oscillation at the IP, $x*$, reaches an amplitude of approximately ±0.2 mm in BI, whereas it is suppressed to less than ±0.05 mm in SI.
  - This significant reduction in the horizontal injection oscillation suggests that SI provides improved the injection during collision.

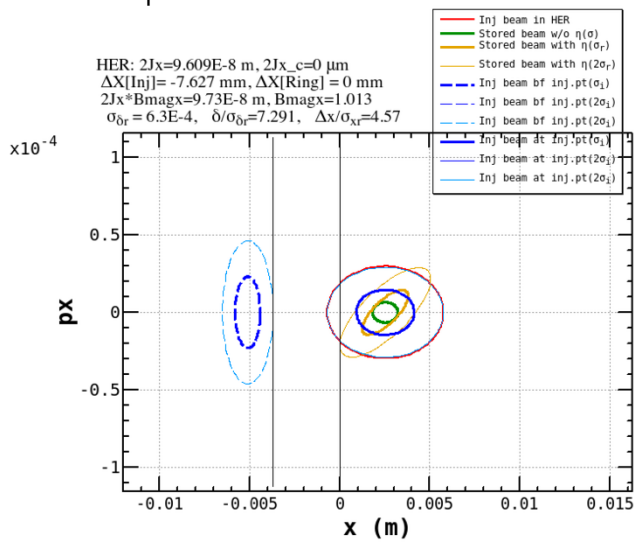
	BI	SI	SBI
w/o bb	93.6±0.8	85.6±1.0	77.6 ± 1.3
w bb	91.2±0.8	84.6±1.1	70.9 ± 1.5

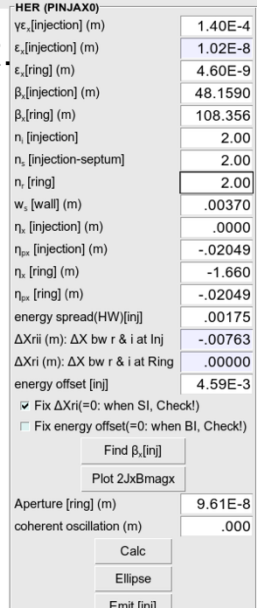
- As we did not test SBI.
- For SI, about 5% loss is seen at the first a few turns because that the momentum acceptance is slightly insufficient.

SI

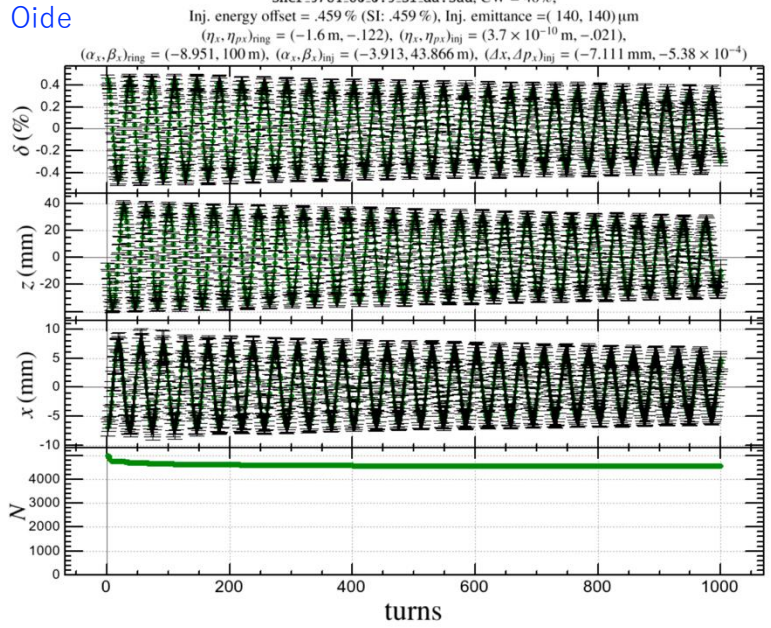
SI βy*=0.9mm, CW40% w/o cancel coil
DX=7.627mm at PINJAX0

[I] ηx=0 at INJECTIO(BT end)
The dispersion is mis-matched to HER.



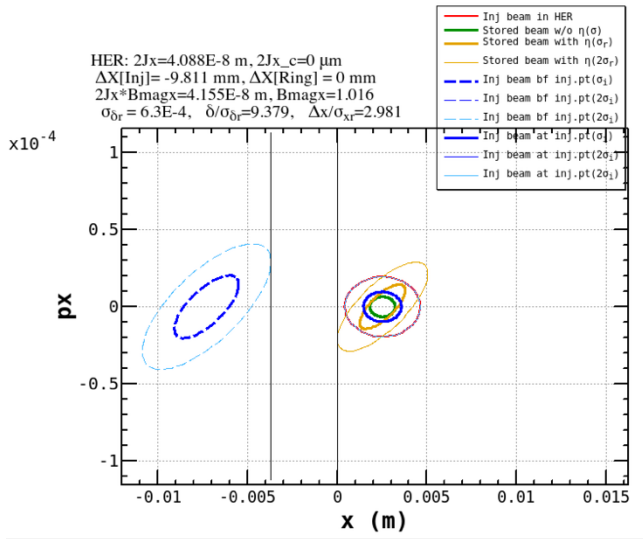


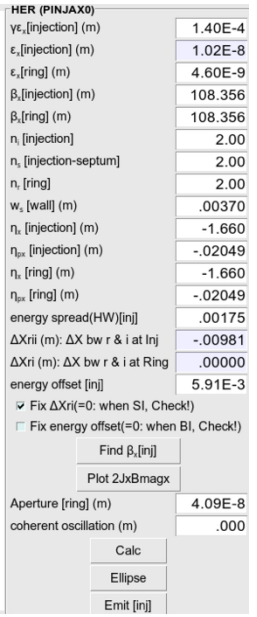
AX	BX	NX	EX	EPX	Element	Length	Value	s(m)	AY	BY	NY	EY	EPY	DetR	#
-3.9132	43.8656	7.90200	3.7E-10	-.02147	INJP	.00000	0	465.254617	.40536	22.2326	5.77424	.00505	1.11E-4	2.E-35	922
4.71E-7	48.1590	7.90462	-.01625	-.02049	-PINJAX0	.00000	0	466.020606	-1.5477	22.5219	5.77976	.00524	5.54E-4	2.E-35	927



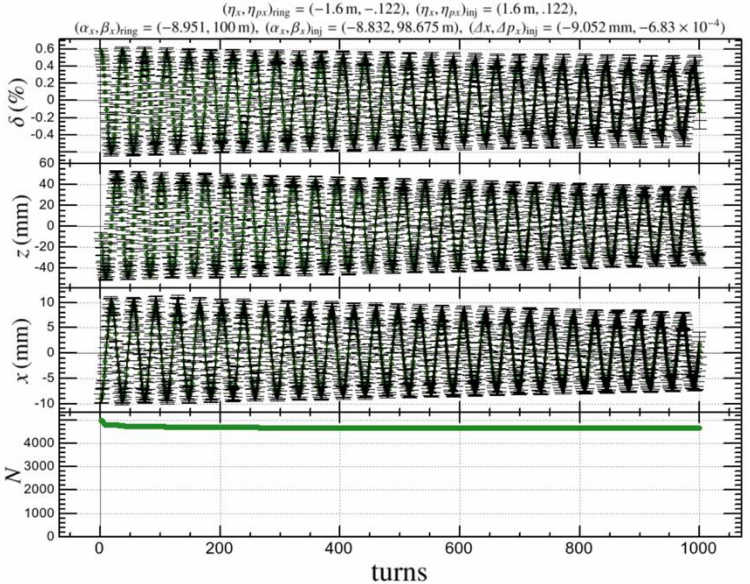
K. Oide

[II] ηx=-1.6 m at INJECTIO(BT end)
The dispersion is matched to HER.



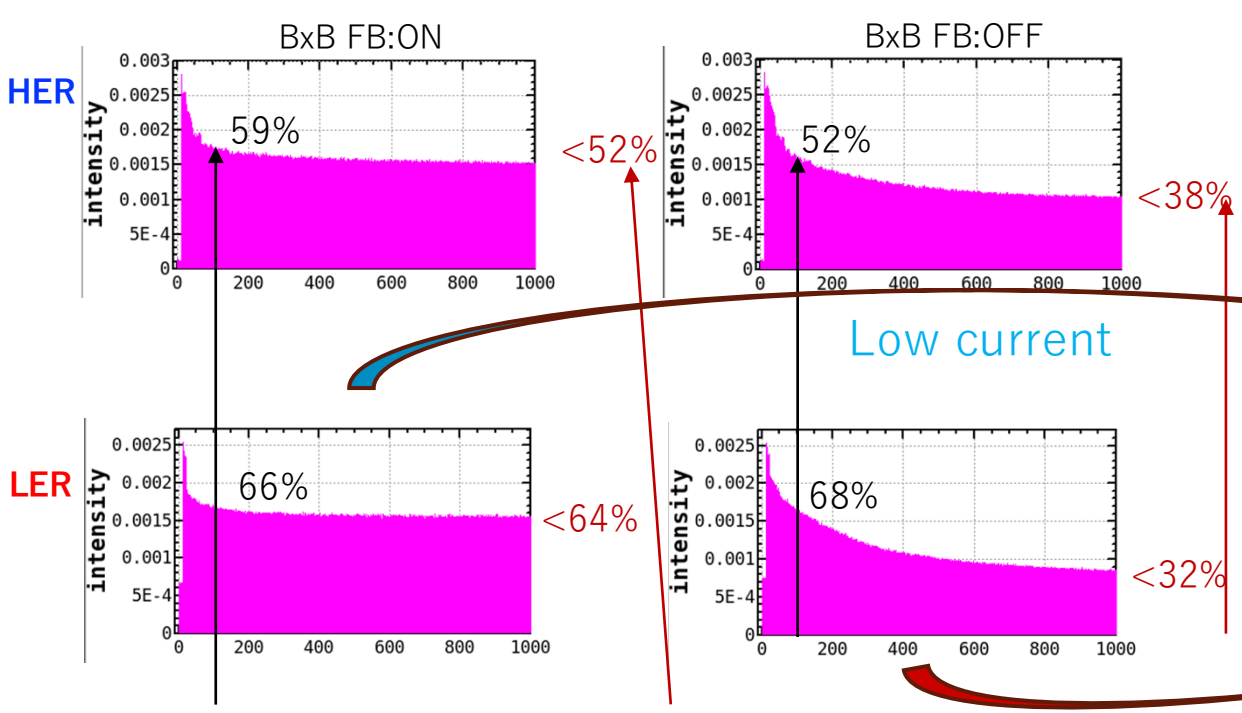


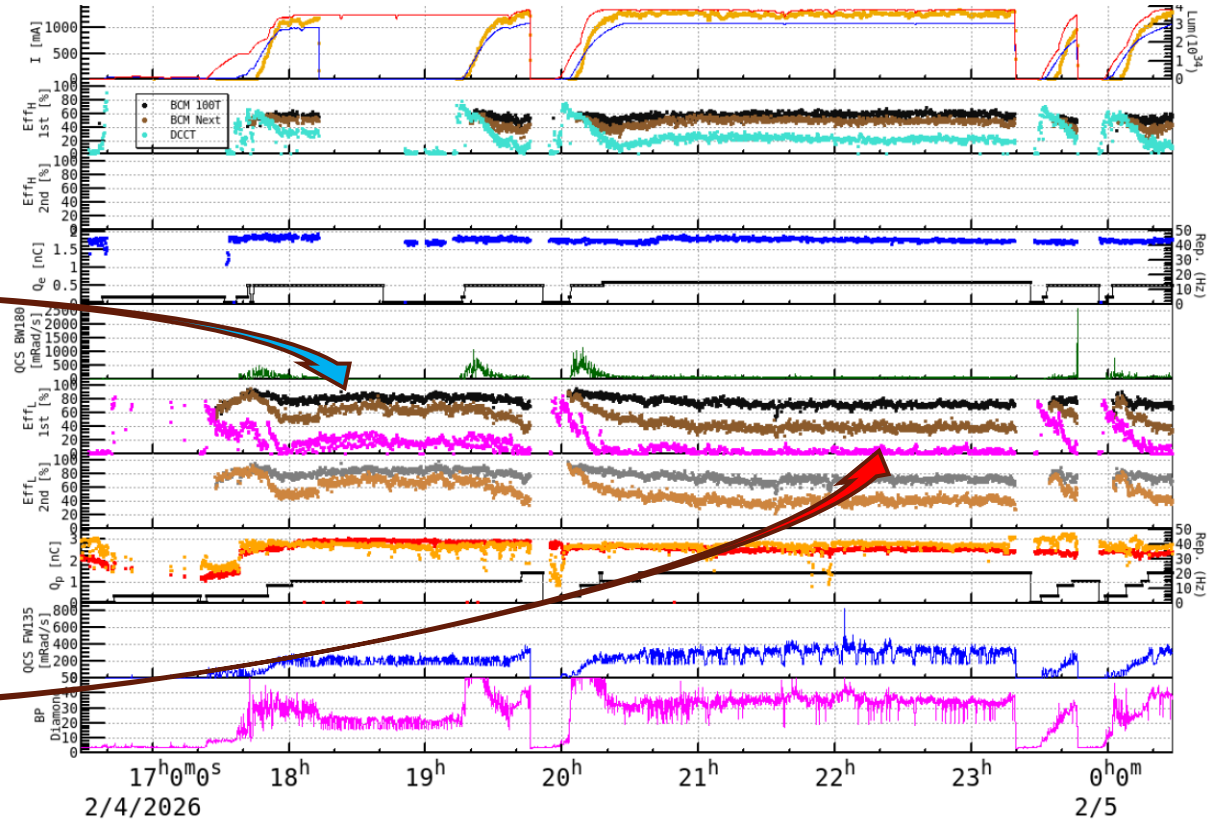
AX	BX	NX	EX	EPX	Element	Length	Value	s(m)	AY	BY	NY	EY	EPY	DetR	#
-8.8324	98.6746	7.90855	1.60000	.12186	INJP	.00000	0	465.254617	.40536	22.2326	5.71179	.00283	2.36E-4	3.E-35	922
-5.5E-9	108.356	7.90971	1.66045	-.02049	-PINJAX0	.00000	0	466.020606	-1.5477	22.5219	5.71731	.00307	4.93E-4	3.E-35	927show



- It is true that the oscillations of both δ and x are smaller when matching is used, and the loss is slightly better when matching is used, but the difference is not significant.
- It is easier to adjust if ηx is closed at the septum exit, so I would like to try SI with both hx=0 and 1.6m.

Injection efficiencies





A) **The injection efficiency** in the **first approximately 100 Turn** is easily affected by the effects of the injection beam (injection adjustment, injection beam emittance, etc.).

B) **From 1000 Turn onwards**, it is easily affected by the effects of the ring (tuning, beam-beam).