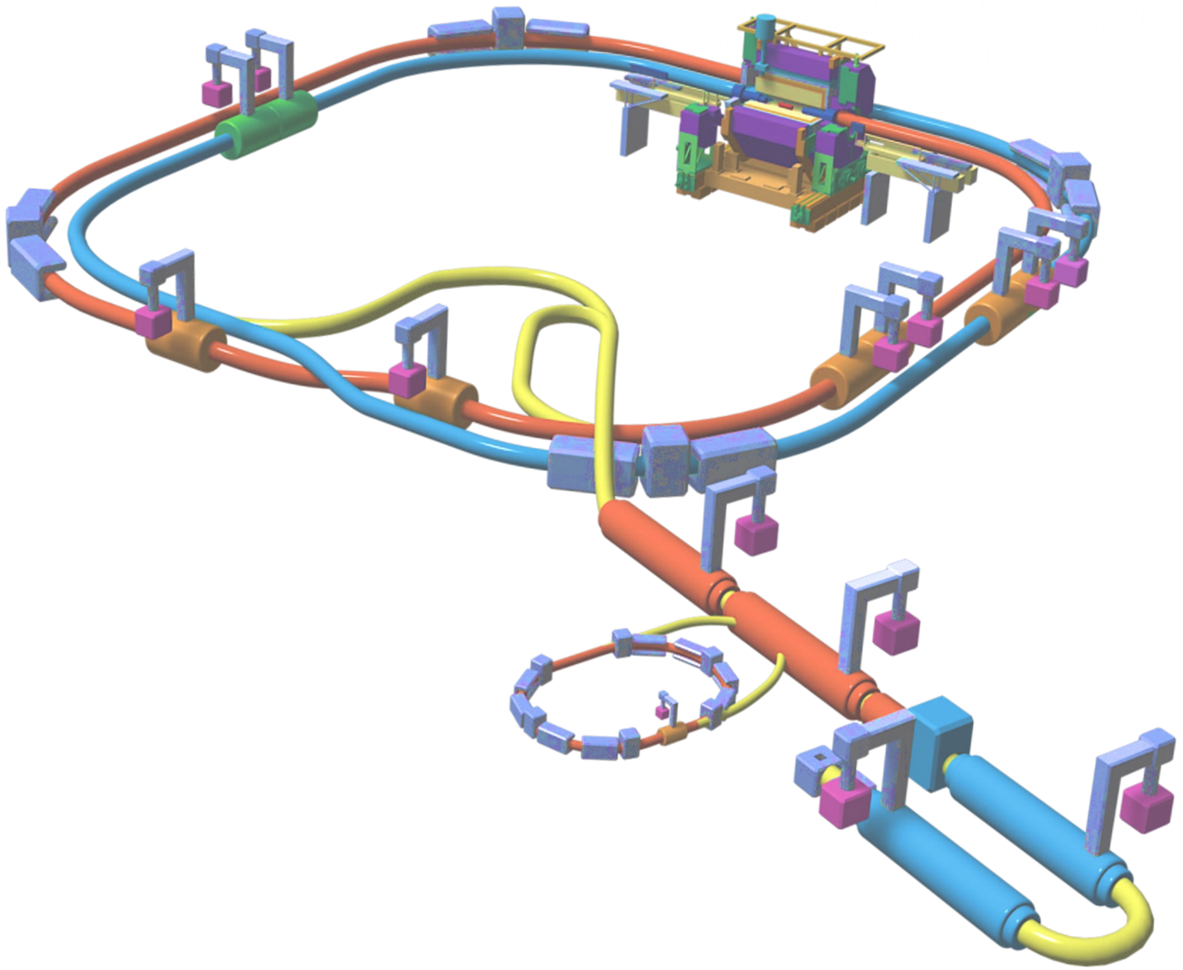
Injection Tuning



T. Yoshimoto

on behalf of LINAC Beam Analysis Group,
Beam Injection Task Force (BITF) from other Acc. Divisions, and Injection Commissioning Group (ICG)

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- **Injection performance**
  - Short-term injection status
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- **Injector status**

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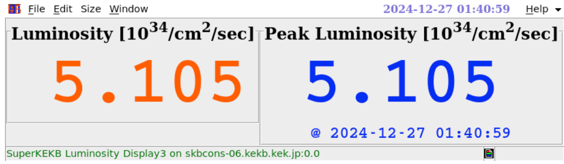
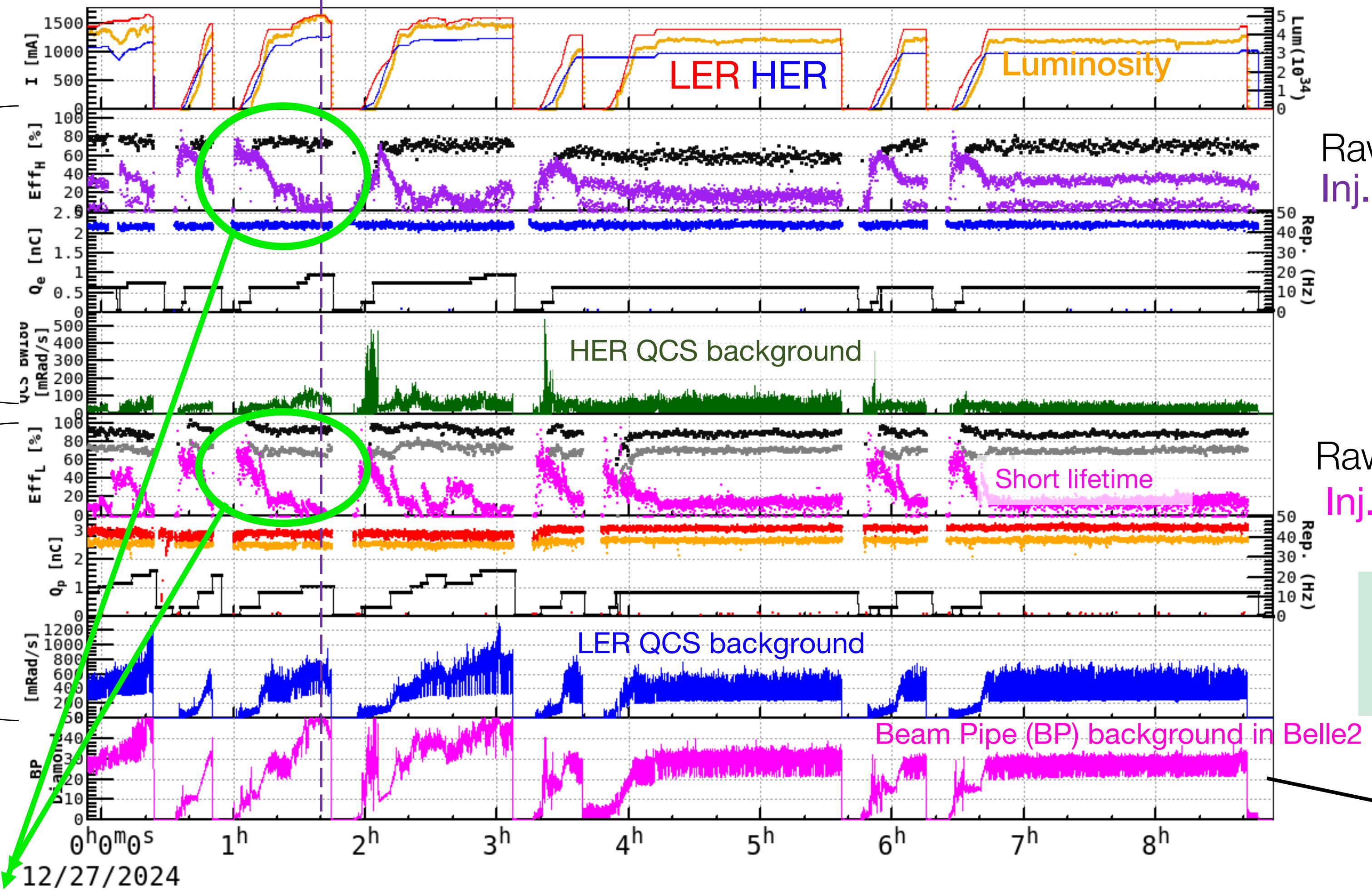
  - β^*_y Dependence of Dynamic Apertures (HER)
  - Acceptance Dependence of Injection Efficiency (HER)
  - Minimum Envelope Injection

- **Summary**

Short-term Injection Status



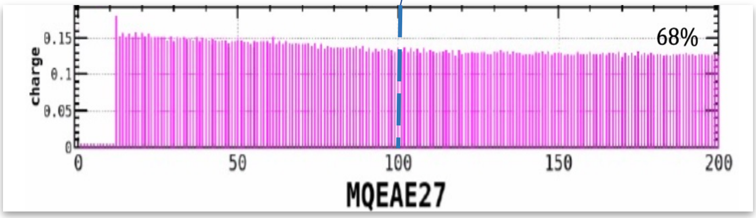
Run 2024c record: the luminosity $\mathcal{L}$ = 5.105 × 10^{34} cm^{-2}s^{-1} at HER / LER: 1270 / 1650 mA.



Def.:
injected charge @100th turn / bunch charge @ injector end

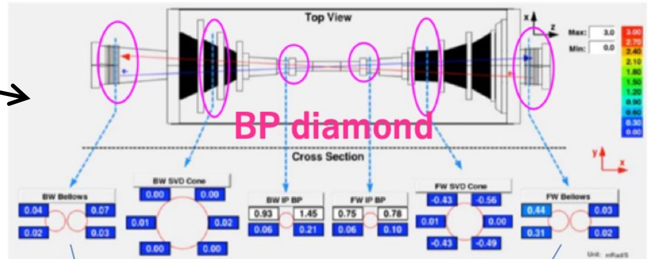
Raw inj. Efficiencies (bunch 1 & bunch 2)
Inj. efficiency margin

TbT BPM data:



Raw inj. Efficiencies (bunch 1 & bunch 2)
Inj. efficiency margin

Def.:
raw inj. eff. – required raw inj. eff.*
*It gives that inj. beam rate = beam loss rate.



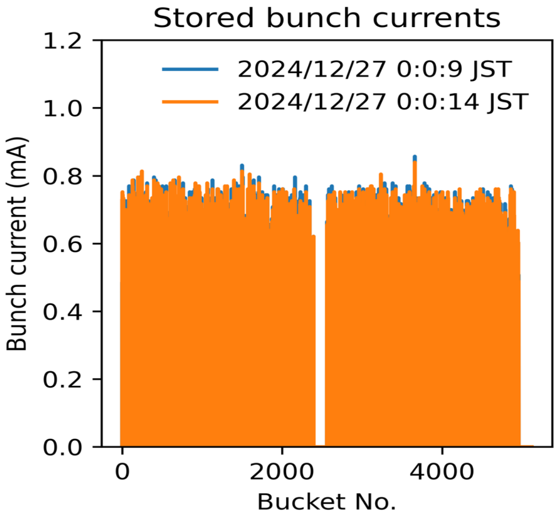
- Why do the injection efficiency margins rapidly drop as currents increase?
- This understanding is one of the keys towards higher luminosity operation.

Shot-by-shot Raw Injection Efficiencies

- Time difference of bunch-by-bunch BCM data achieved every ~5 sec. gives 1) raw injection efficiency 2) beam lifetime, 3) injection stability.

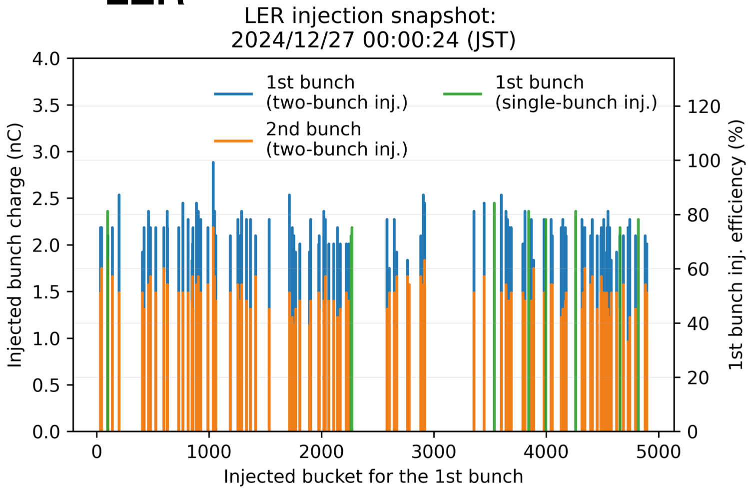
Bunch-by-bunch BCM data:

LER example



Bunch-by-bunch injection snapshots:

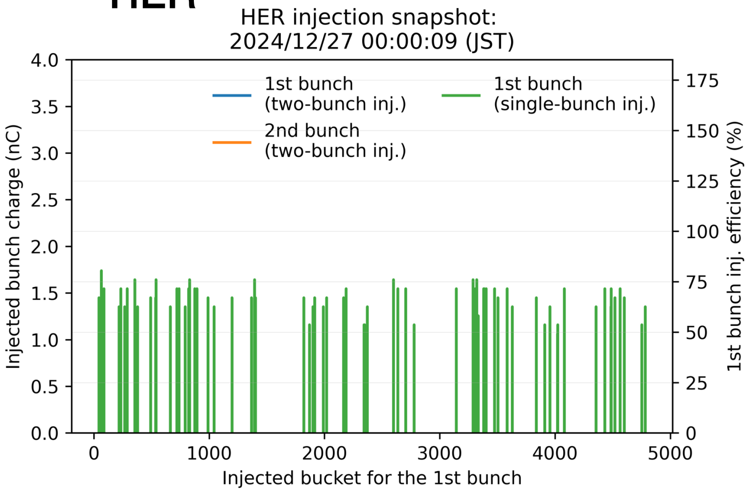
LER



2024-12-27 00:00:24
Number of the injected_buckets (1st, 2nd, single, unidentified):
217 (103, 103, 9, 0)

Injection statistics:
1st bunch current (mA): 0.217±0.020
2nd bunch current (mA): 0.148±0.017
Single bunch current (mA): 0.228±0.010

HER

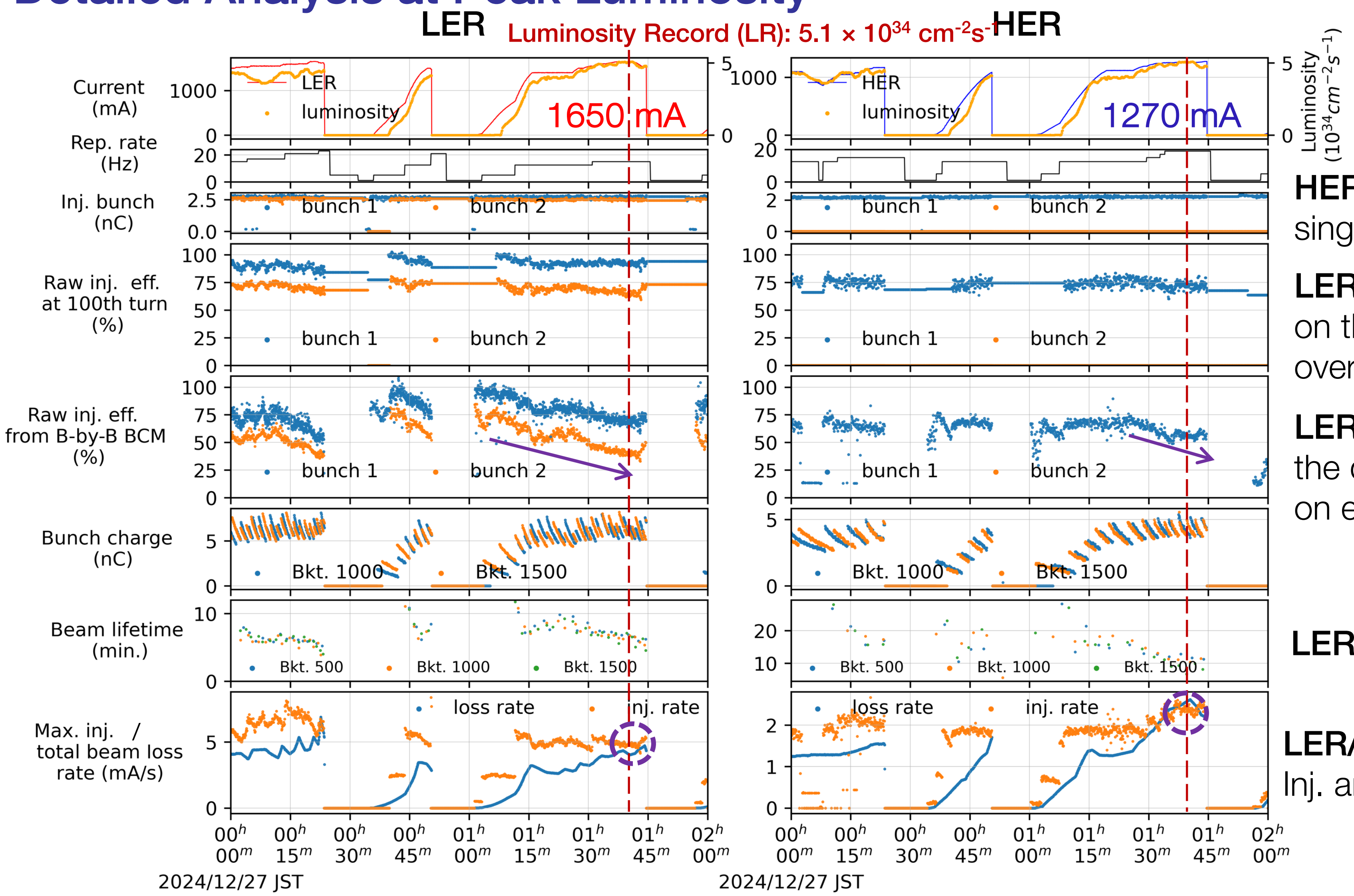


2024-12-27 00:00:09
Number of the injected_buckets (1st, 2nd, single, unidentified):
72 (0, 0, 72, 0)

Injection statistics:
1st bunch current (mA): nan±nan
2nd bunch current (mA): nan±nan
Single bunch current (mA): 0.144±0.014

- LINAC shot-by-shot jitters (in RF phases, beam orbits, beam energies) give ~10% raw injection efficiency jitters in both rings. It is not a serious concern at this moment, excepting beam aborts.

Detailed Analysis at Peak Luminosity



HER:
single-bunch inj. due to the LINAC RF cavity issue.

LER/HER: raw injection efficiency calc. based on the data 1 msec (100 turns) after injection is overestimated.

LER/HER: raw injection efficiencies (based on the data <u>a few seconds after injection</u>) depend on each stored current.

LER/HER lifetimes: ~7/10 min. at LR

LER/HER: Injection power are not sufficient.
Inj. and beam loss rates were even at LR.

Potential solutions for higher inj. power:

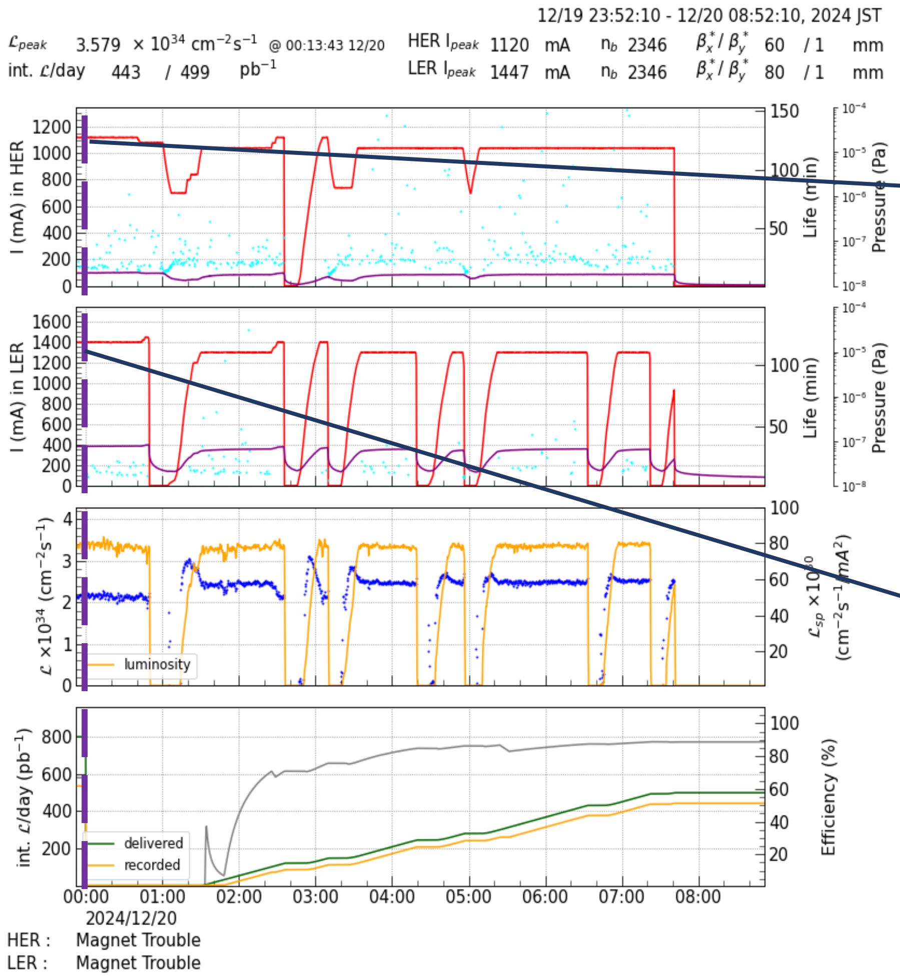
LER: 1) higher raw inj. efficiencies (**Max.: ~1.6x**), 2) higher bunch charge 3 nC -> 4 nC, 3) higher. rep. rate: 15 => 23Hz (**Max.: ~1.53x**)

HER: 1) stable two-bunch injection (**Max.: ~2x**), 2) higher raw inj. efficiency (**Max.: ~1.8x**), 3) higher bunch charge > 2 nC (?)

Bucket-by-Bucket Beam Lifetimes

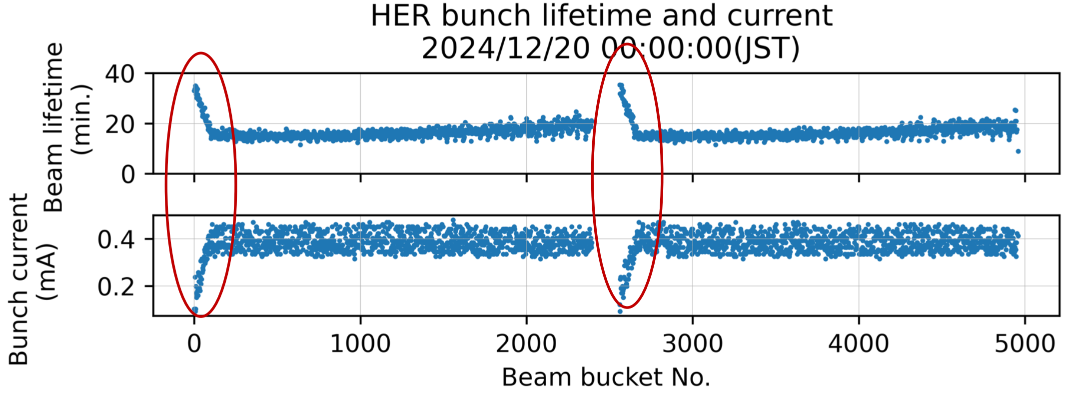
- For HER, heads of two bunch trains have longer beam lifetimes than the following bunches.
- For LER, heads of two bunch trains have shorter beam lifetimes than the following bunches.

⇒ The cause remains unaddressed, although they do not have serious impacts on beam operation. Further study is necessary.

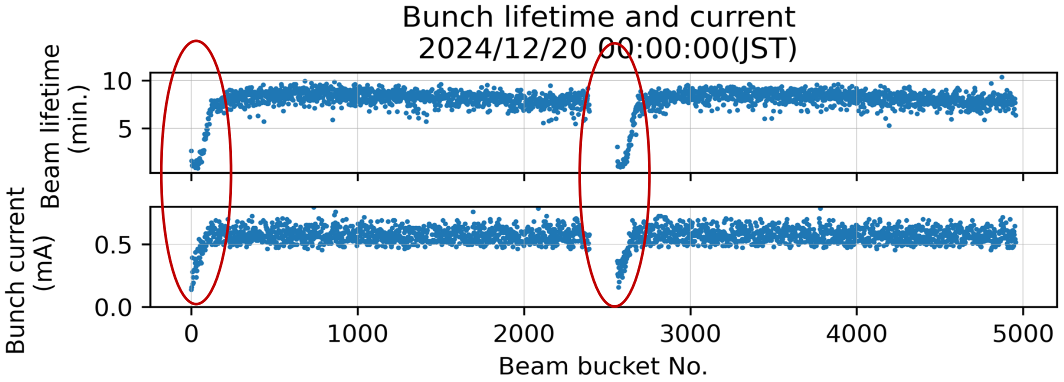


HER

Is that caused by B-by-B FB or long-range wakes?



LER

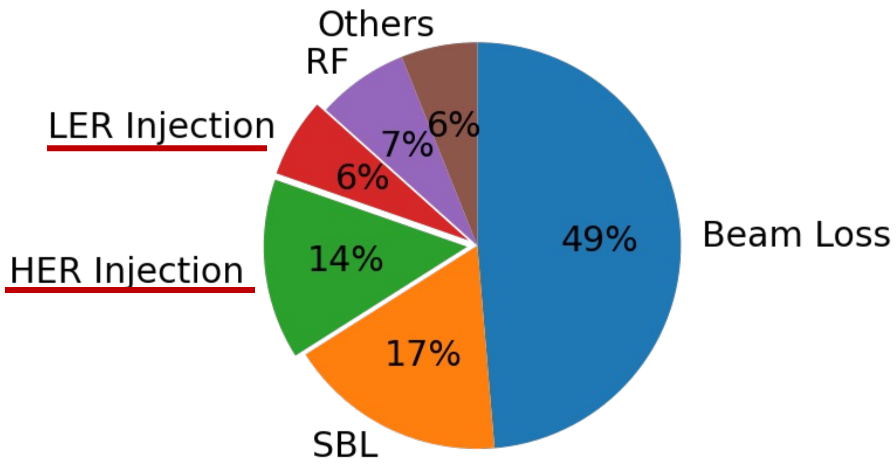


Injection-Triggered Beam Aborts (Apr. 1 ~ Dec. 27)

SBL verification: H. Ikeda
Abort web system: H. Nakayama (Belle)

- The frequencies of LER & HER injection-triggered beam aborts occupied 6% and 14% of all aborts, respectively. They usually caused both-rings aborts, due to spiky beam losses mainly on Belle2 CLAWS/VXD diamond detectors.
- No serious radiation losses on BELLE-II, compared to Sudden Beam Losses (SBLs).

Abort source analysis:

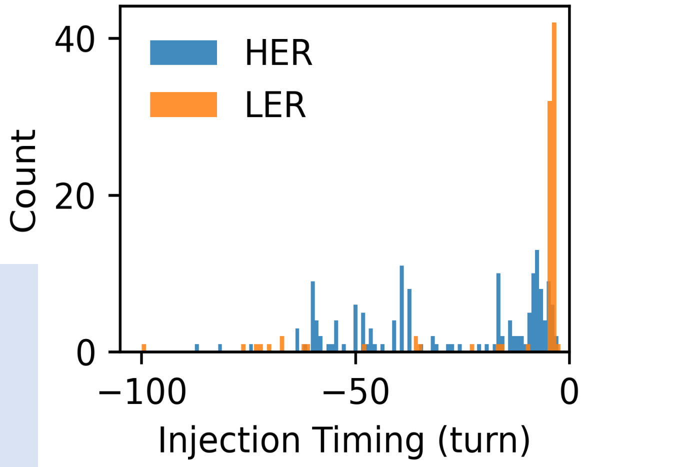


2024-04-01 00:00:00 ~ 2024-12-31 00:00:59

ring	SBL	BeamLoss	Injection	RF	Mag	VA	EQ	Tuning	Others	Manual	Uncategorized	TOTAL
TOTAL	226	634	269	95	6	8	28	1	28	-	8	1303
Both(LER)	170	92	80	3	4	-	-	1	10	-	-	360
Both(HER)	37	173	161	2	1	1	-	-	2	-	1	378
Both	-	-	-	-	1	1	5	-	-	-	3	10
LER	19	278	2	47	-	2	2	-	11	-	-	361
HER	-	91	26	43	-	4	21	-	5	-	4	194

*HER > 50 mA, LER > 50 mA, No manual abort is included.

Injection-triggered abort timings*:

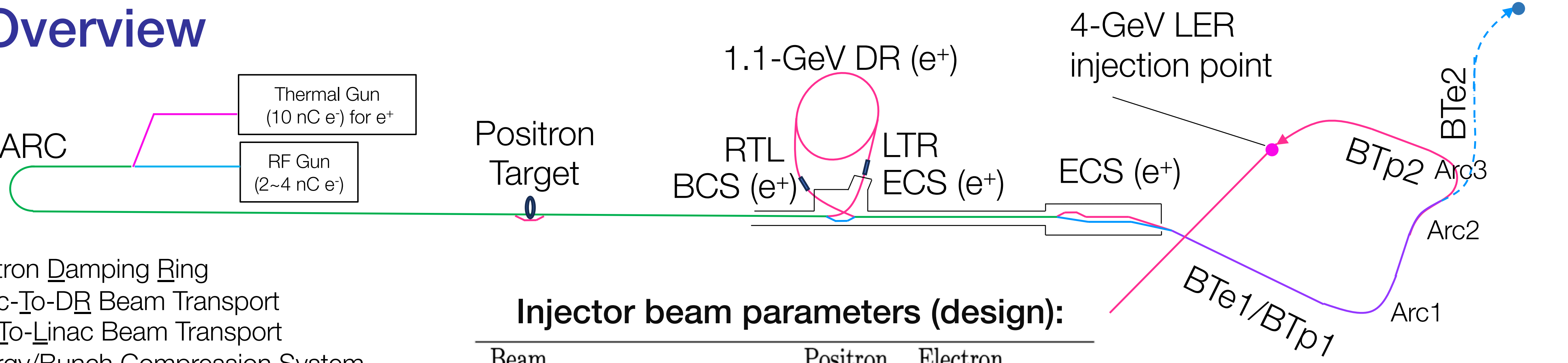


*1 turn = 10 μs

- LER and HER injection-related aborts mostly occurred within ~5 and ~10 turns after injection, respectively.
- Significant reduction of injection-triggered abort frequencies is necessary for stable operation.

http://skb-rf-web.kek.jp/sbl_verification/index.html?from=2024-04-01&from_time=00%3A00&to=2024-12-31&to_time=00%3A00&select_category=on&hide_manual=on&ler_current_cb=on&ler_current=50&her_current_cb=on&her_current=50&pressure_location=

Injector Overview



DR: positron Damping Ring
LTR: Linac-To-DR Beam Transport
RTL: DR-To-Linac Beam Transport
ECS/BCS: Energy/Bunch Compression System
BT: Beam Transport line
LER/HER: Low/High Energy Ring for e+/e-

Injector beam parameters (design):

Beam	Positron	Electron	
Beam energy	4.0	7.007	GeV
Normalized emittance $\gamma\varepsilon_{x/y}$	100/15	40/20	μm
Energy spread	0.16	0.07	%
Bunch charge	4	4	nC
No. of bunches/pulse	2	2	
Repetition rate	50		Hz

* H. Akai, et al., https://arxiv.org/pdf/1809.01958.pdf

Previous findings:

LER-BT

- no CSR/ISR effects[1]
- Undesigned Strong X-Y coupling in BTp-Arc3 => X/Y emittance growths in BTp[1]

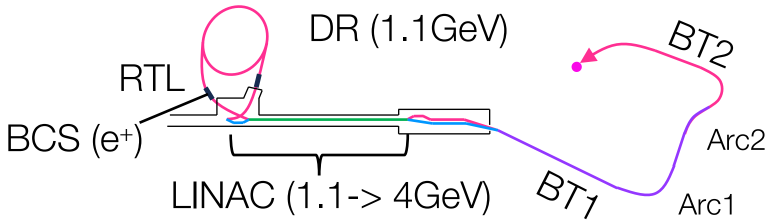
HER-BT

- CSR/ISR effects[2]: $\gamma\varepsilon_x$ = + ~60 /30 μm (for a 2-nC bunch)
- Arc1 nonlinear magnetic effect[3]: $\gamma\varepsilon_x$ =+ ~12 μm

[1] T. Yoshimoto, "Injection", SuperKEB MAC2024 review, https://www-kekb.kek.jp/MAC/2024/
[2] N. Iia, "Beam injection issues in 2022ab", SuperKEB MAC2022 review, https://www-kekb.kek.jp/MAC/2022/Report/Iida.pdf
[3] T. Yoshimoto, "Fringe effect of bending magnets with 3d map", https://kds.kek.jp/event/44594/contributions/227074/attachments/161859/208718/20221124_BAG_meeting_yoshimoto_BTe_fringe_effect.pdf

LER Injector Status

New Findings



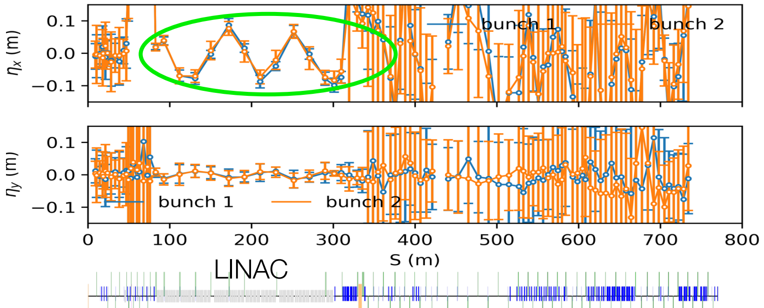
1) LINAC residual dispersions[1]

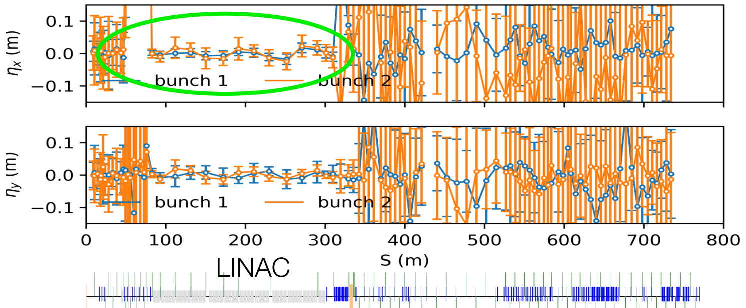
- Dispersions of each bunch downstream can be measured by changing RF phase of BCS in RTL.

=> The measurements reveal hor. emittance blowup (+ ~40 μm) in the LINAC was mainly caused by the hor. residual dispersion (~0.1 m).

- After the suppression, hor. emittances of bunches 1/2 at BT1were significantly reduced from 143/182 to 101/139 μm.

Dispersion suppression:

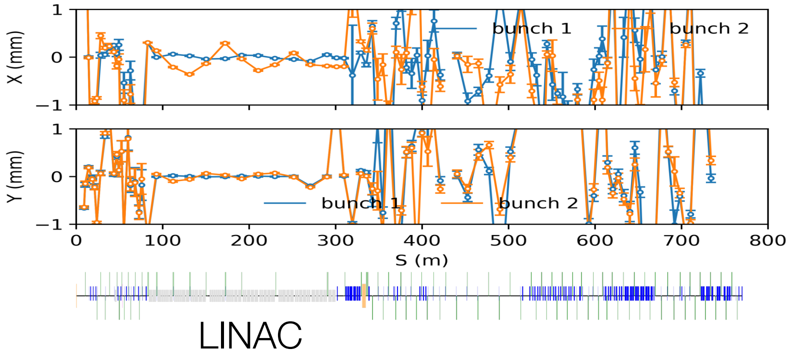




[1] T.Yoshimoto, https://kds.kek.jp/event/53040/contributions/279565/attachments/184780/248325/2024-11-14_RTL_dispersion_leakage_tolerance_yoshimoto_v1.pdf

2) Orbit difference of bunches 1and 2

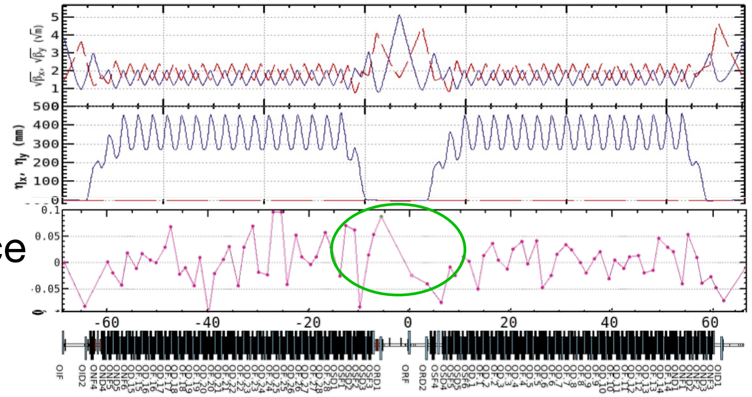
- The possible reason of the hor. emittance difference at BT1 (1st: 101 μm, 2nd: 139 μm) is the LINAC orbit difference, which cannot be corrected with a fast kicker in RTL.
- Horizontal orbit difference between bunches 1 and 2 arise in DR.



Beta functions:

Dispersions:

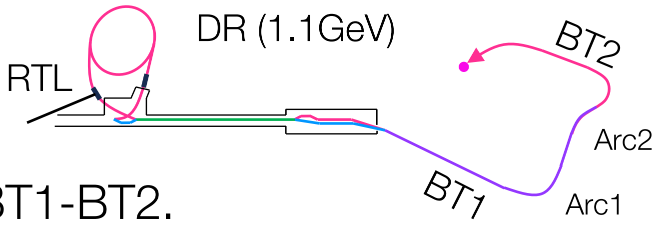
Hor. orbit difference of bunches 1 & 2:



N. Iida

↕ Δx: ~100 μm near the extraction point

LER Injector Emittances and Dynamic Apertures:



1) Injector emittances

- Transverse emittance growths are an issue, due to magnetic X-Y couplings between BT1-BT2.

3-nC , Bunch 1/2	DR (design)	RTL (MSs08)	Sector 3 (WSs)	BT1 (MWP.1-4)	BT2* (MSP.15)	Injection (design), 4-nC
$\gamma\varepsilon_x$ (μm)	65	~79/	111/112	101.2/138.7	180/	<100
$\gamma\varepsilon_y$ (μm)	0.65(k=1%)	0.24/	2.6/1.1	10.2/18.3	84/	<15

N. Iida

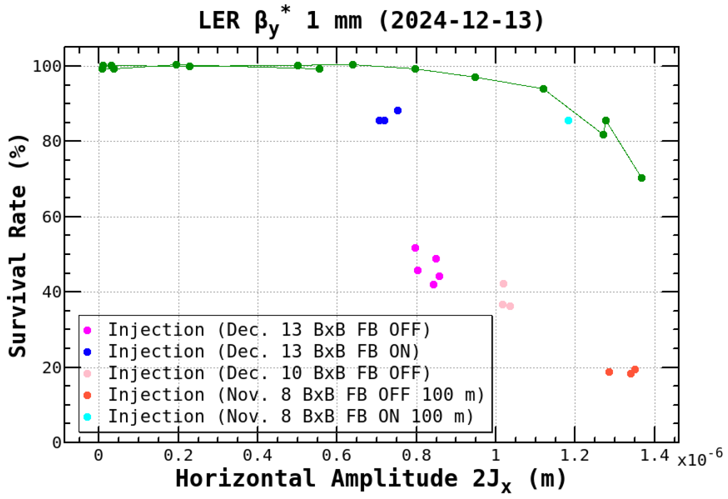
Nominal error: ± < 10 μm

*BT2-OTR was moved a few tens of meters downstream in 2024 to cross-check beam sizes with wire scanners.

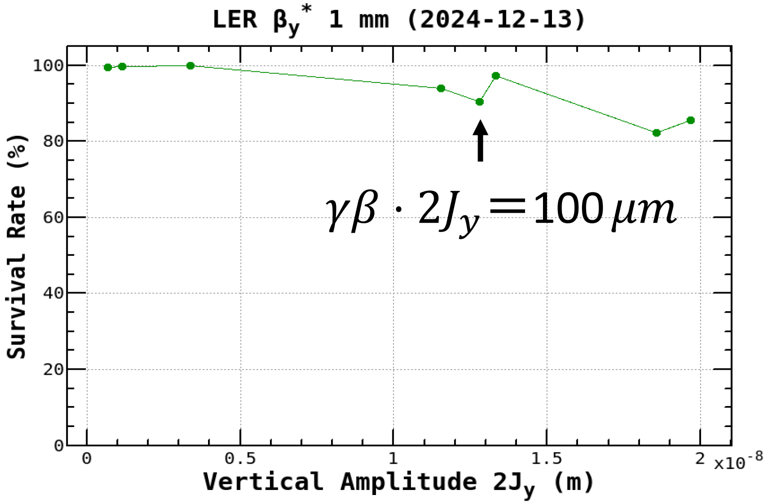
2) Dynamic apertures at β_y^* = 1 mm

Y. Ohnishi, N. Iida, M. Kurata

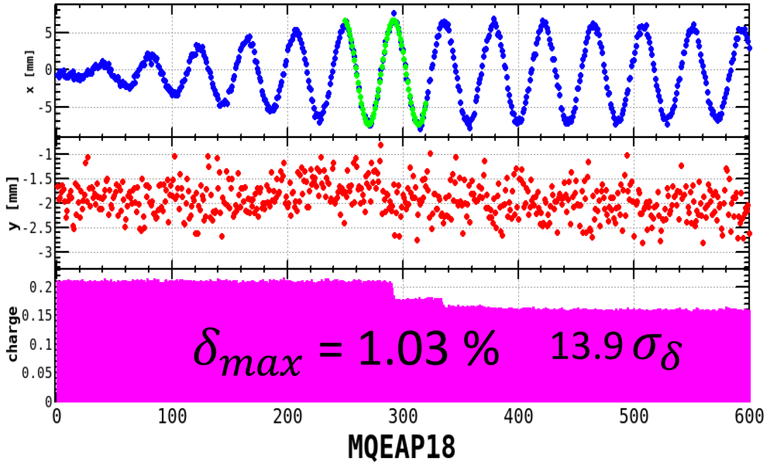
Hor. direction:



Ver. direction:



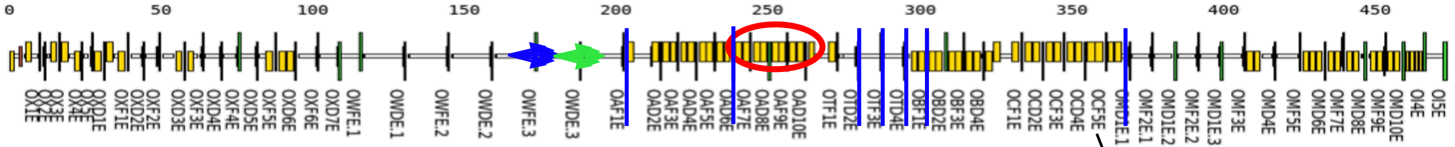
δ direction:



- For LER, horizontal emittance limits raw inj. efficiency.
- BxB FB significantly improves the injection.

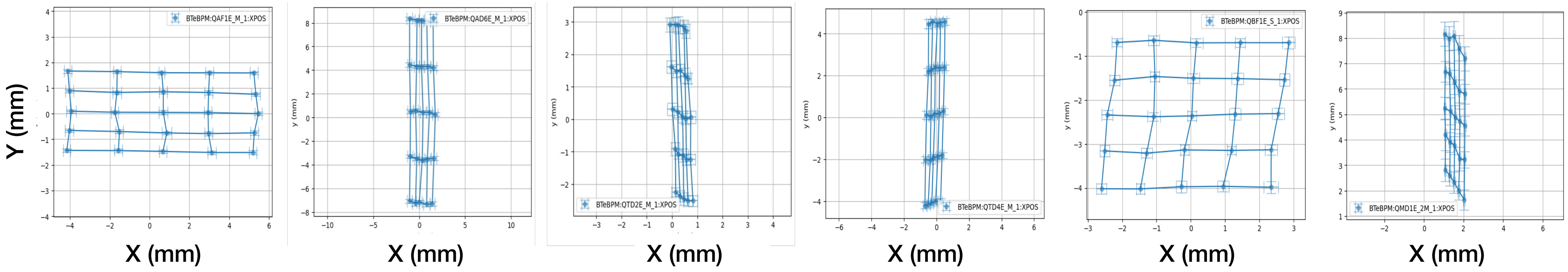
HER Injector Status

New Findings



1) X-Y couplings[1]

Strong X-Y (undesigned) magnetic couplings at BT-arcs1&3 were observed with raster scan[2].
The sources remains unaddressed. => It likely causes ver. emittance blowup between BT1 and BT2.



Emittance summary[3]

- For HER, vertical emittance limits raw inj. efficiency, since BxB FB (τ:~100 turns) does not improve injection efficiency.

	BT1 2 nC		BT2 2 nC	Injection (design) 4 nC
	Bunch 1	Bunch 2	Bunch 1	
$\gamma\varepsilon_x$ [μm]	52.35±8.26	74.48±11.58	153.42±2.38	<40
$\gamma\varepsilon_y$ [μm]	22.30±5.98	62.97±11.09	167.25±2.03	<20

[1] T. Yoshimoto, https://kds.kek.jp/event/52321/contributions/275231/attachments/184463/247799/2024-08-08_BAG_BTE_XY_coupling_summary_yoshimoto_ver2.pdf
[2] T. Yoshimoto, "Injection", SuperKEKB MAC2024 review, https://www-kekb.kek.jp/MAC/2024/
[3] LCG_Injection_KBP-2bunchOrbit_MatchingInjection_20241211_Iida.pdf

N. Iida

How to improve the raw injection efficiencies?

Revisiting Injection Efficiency Degradation

To get higher luminosity, we need to achieve:

A) higher current operation (**as much as possible**) > ~1.5 A
B) lower ver. beam emittance/size (**as small as possible**), design: < 10 pm
C) crab-waist* ~80%　　　*Its effect is weak for HER.
D) lower β^*_y (**as small as possible**) ~0.3 mm

Smaller dynamic apertures…
=> Shorter lifetimes…
=> Lower injection efficiencies

Nonlinear beam-beam effect [1]

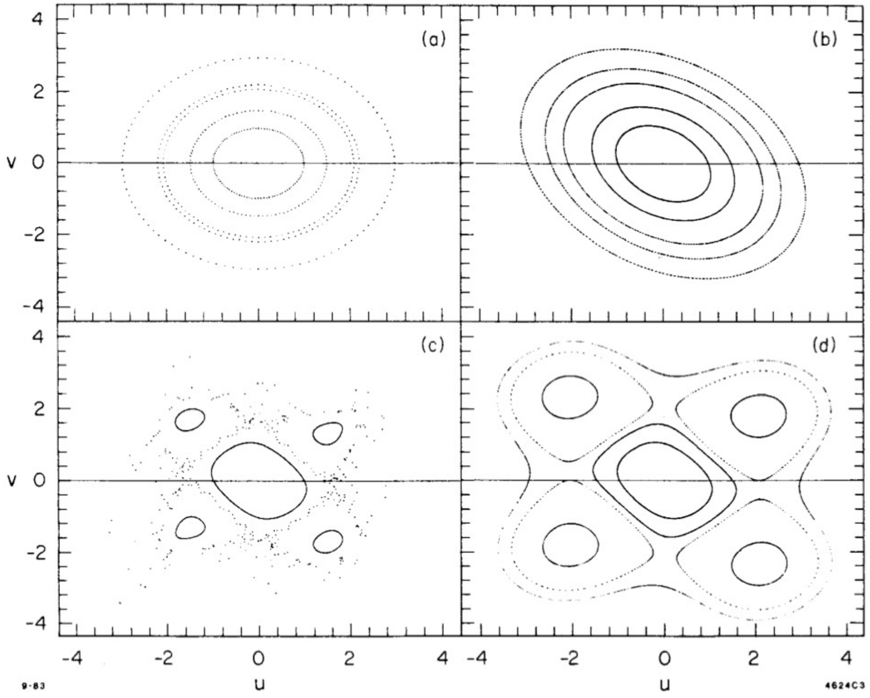
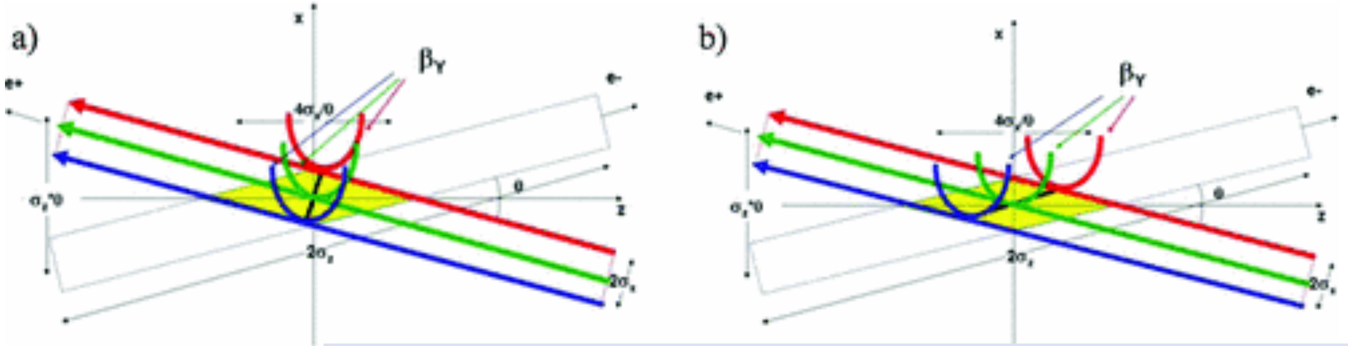


Fig. 3. Weak beam trajectories in the normalized phase space (u, v), where $u = y/\sigma$, $v = \beta_0^* y'/\sigma$. We assume $\mu/2\pi = 0.23$. (a) We ignore the beam-beam force. (b) We include only the linear term of the beam-beam force. (c) We include the linear and the octupole terms. (d) We take into account the complete beam-beam force. In each diagram, trajectories of the same five sets of initial conditions are followed. Note the qualitative difference between (c) and (d).

Crab-Waist[2]



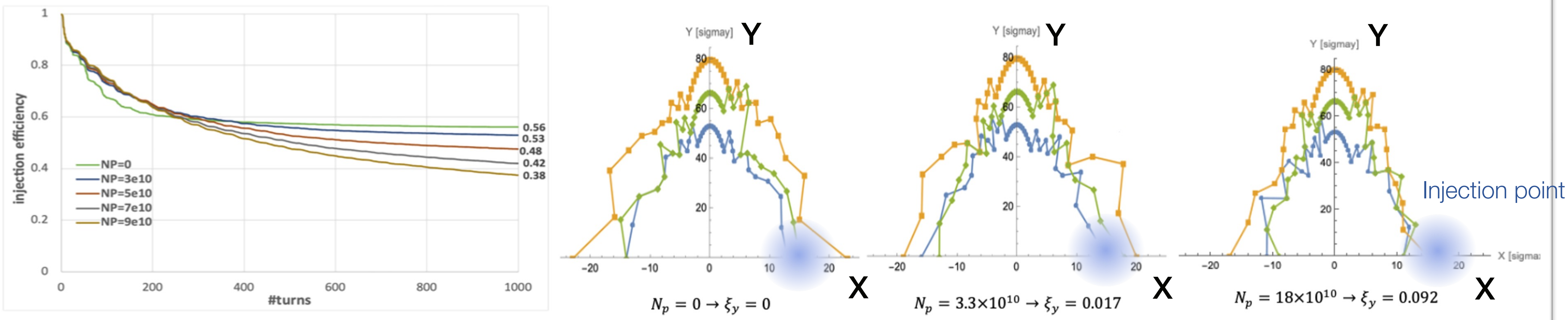
Pursuing higher luminosity inevitably causes smaller dynamic apertures and conflicts with injection efficiency improvement.

[1] A.W. Chao, Beam-beam instability, SLAC-PUB-3179 (1983).
[2] M. Zobov *et al.*, Test of "Crab-Waist" Collisions at the DAΦNE Φ Factory, Phys. Rev. Lett. 104, 174801 (2010).

Bunch Current Dependence of HER Dynamic Aperture

Meng Li

➢ **Beam-beam is important for both injection efficiency and the small beam losses of background duration**

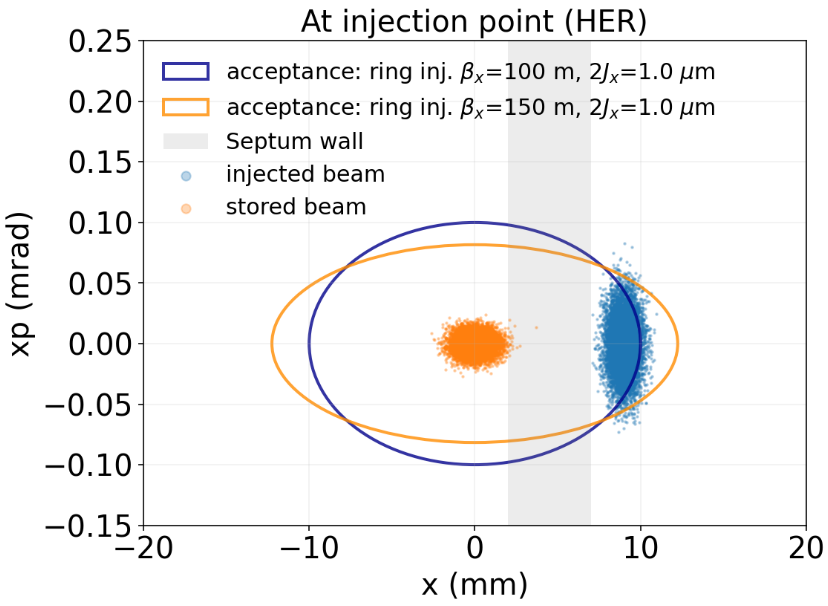


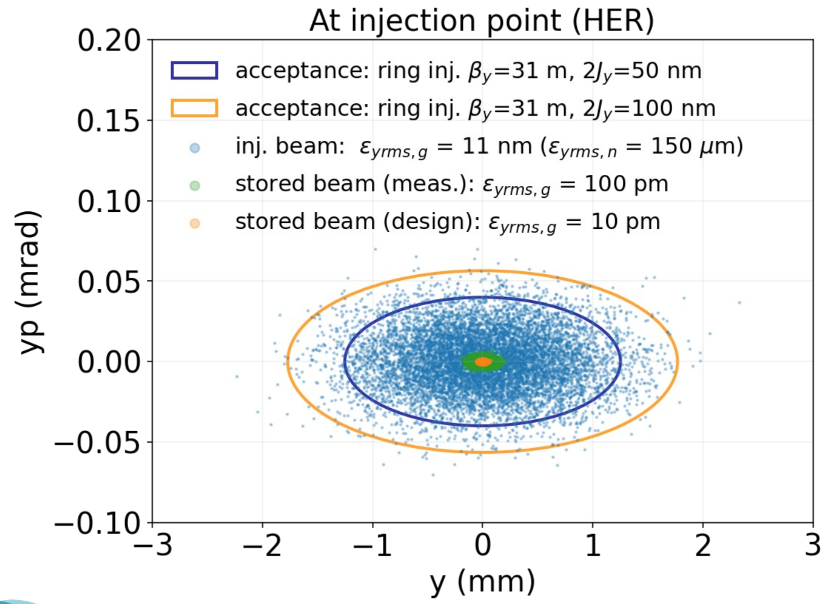
[1] Meng Li, Summary of SuperKEKB injection-related beam loss investigation, SuperKEKB commissioning meeting, Sep 27, 2024, https://kds.kek.jp/event/52406/contributions/275898/attachments/183389/245958/Meng_injection_commissin.pdf
[2] Meng Li, Summary of SuperKEKB injection-related beam loss investigation, https://kds.kek.jp/event/52865/contributions/281981/attachments/185900/250113/MengLI_injection_simulation.pdf
[3] Y. Ohnishi, https://kds.kek.jp/event/44562/contributions/227034/attachments/161845/208670/Lifetime_Summary.pdf
[4] A. Morita, Crab Waist Scheme for SuperKEKB, Beam Dynamics Newsletter No. 67, https://www-linac.kek.jp/mirror/icfa-bd/Newsletter67.pdf

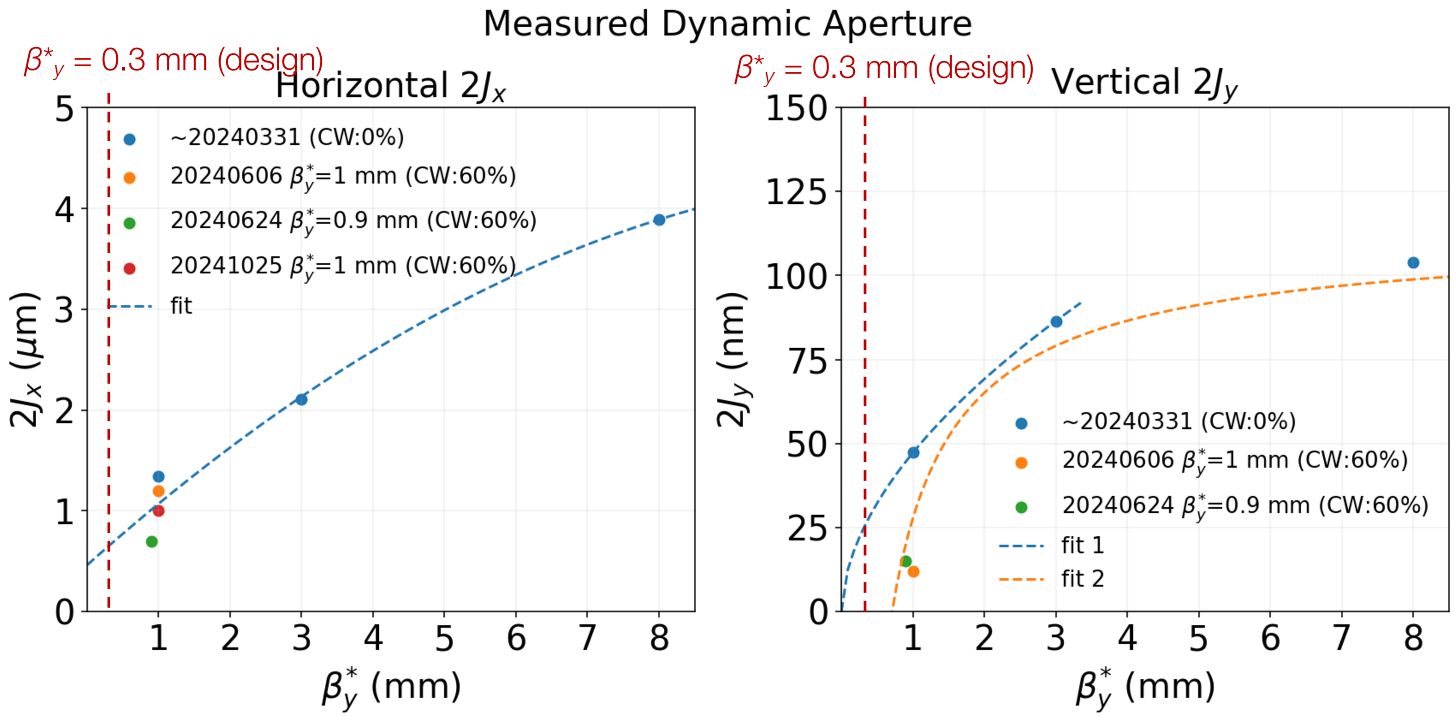
- Numerical simulations reveal that beam-beam force (∝ LER bunch current) shrinks horizontal dynamic aperture even at HER.

β^*_y Dependence of Dynamic Apertures (HER)

DA measurement: Y. Onishi, N. Iida

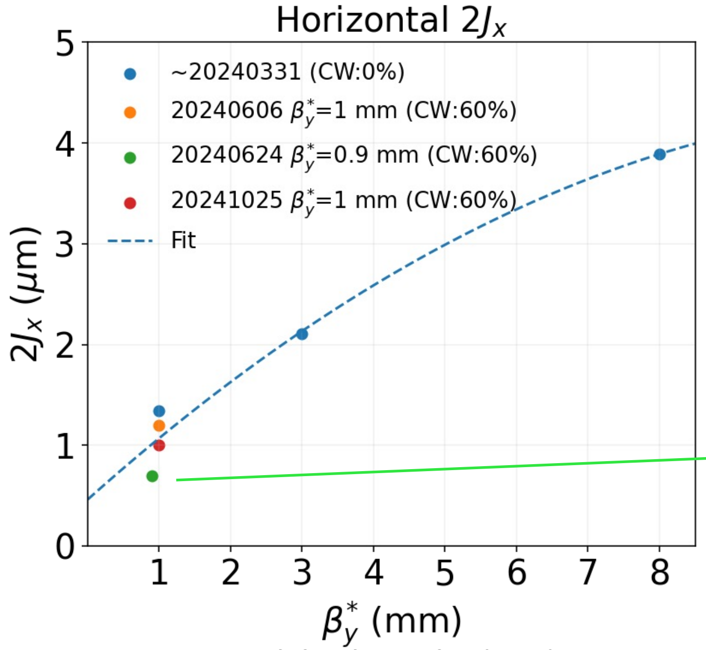


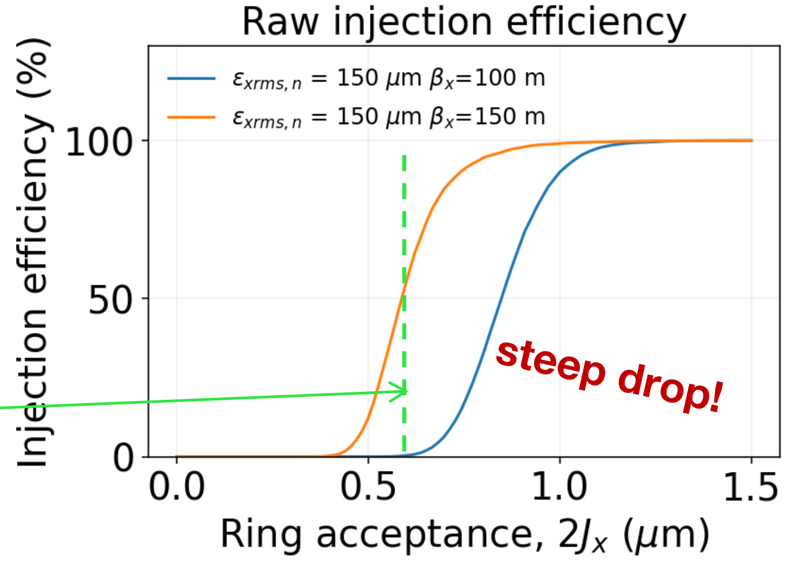


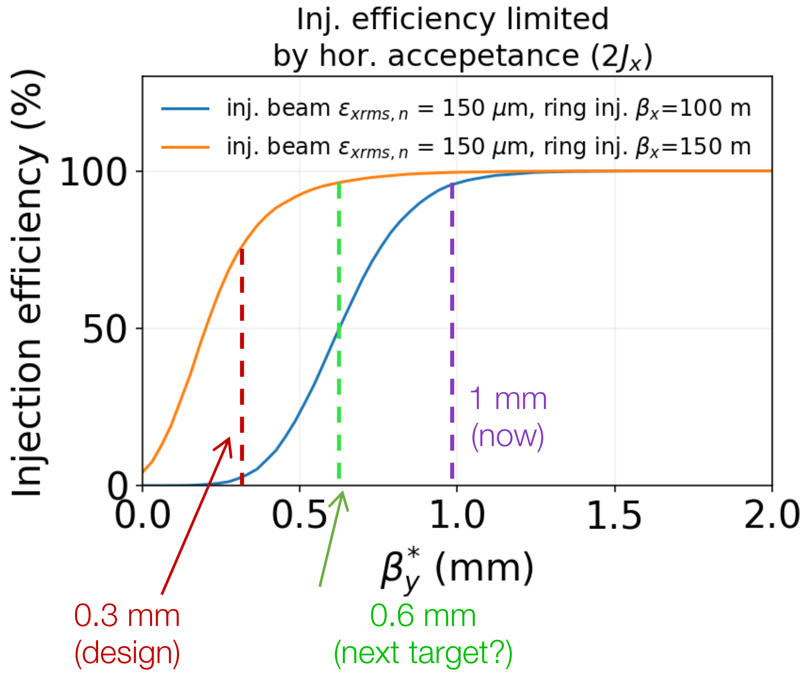


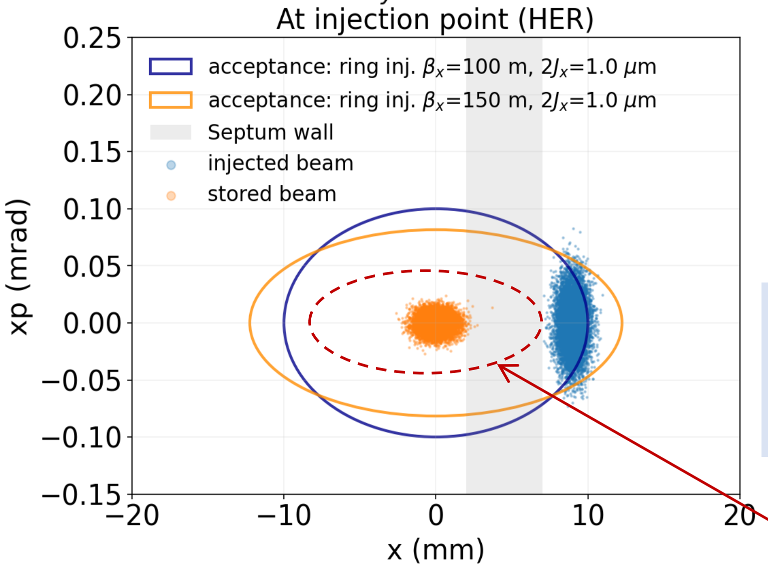
Note:
Dynamic apertures (DA) here were measured without beam-beam effect from e^+ beam. Hence, DAs at high current operation are much smaller than measured ones.

Horizontal Acceptance Dependence of Injection Efficiency (HER)







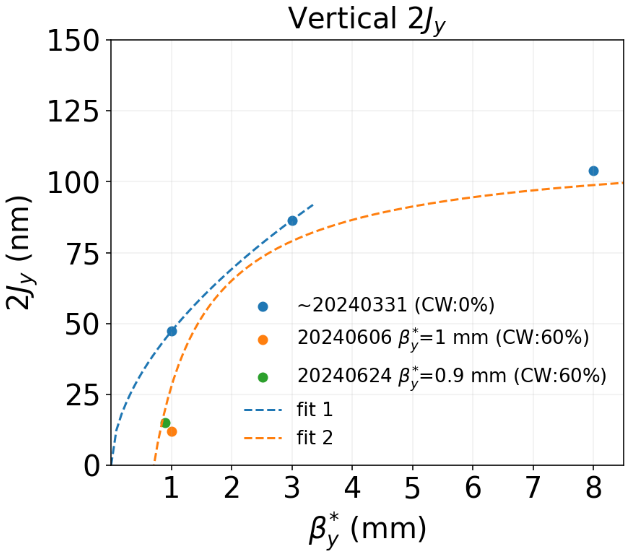


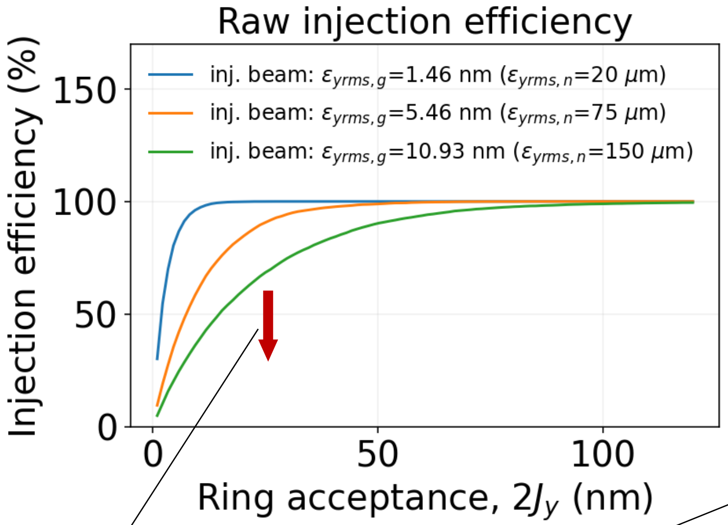
- There is a steep injection efficiency drop as we go to smaller β^*_y (or hor. dynamic aperture/acceptance $2J_x$), **regardless of horizontal emittance of an injected beam**.

Even if the emittance of the incident beam is improved,
it is becoming a dynamic aperture that cannot accommodate it.
=> A fundamental improvement on the ring side would likely offer a higher cost-effectiveness.

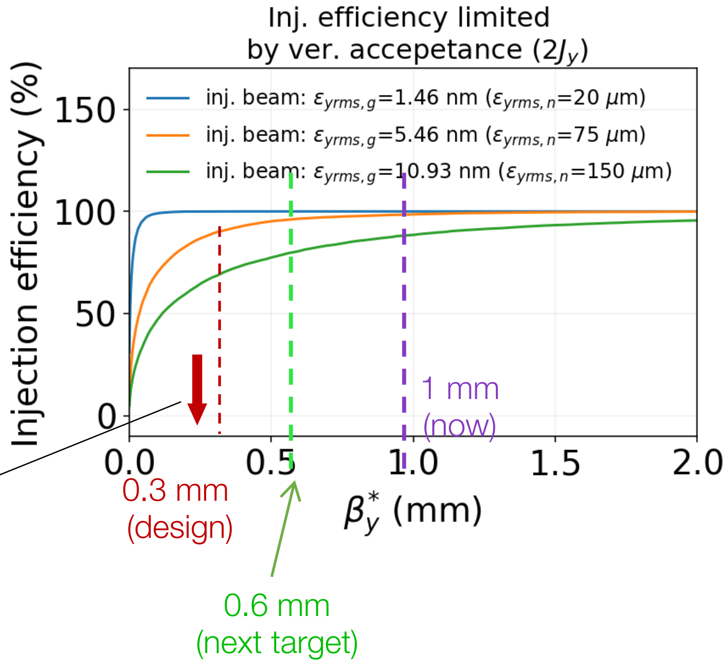
Physical limit (0.4): The narrow DA cannot accept any injected particle, regardless of horizontal emittance of an injected beam.

Vertical Acceptance Dependence of Injection Efficiency (HER)

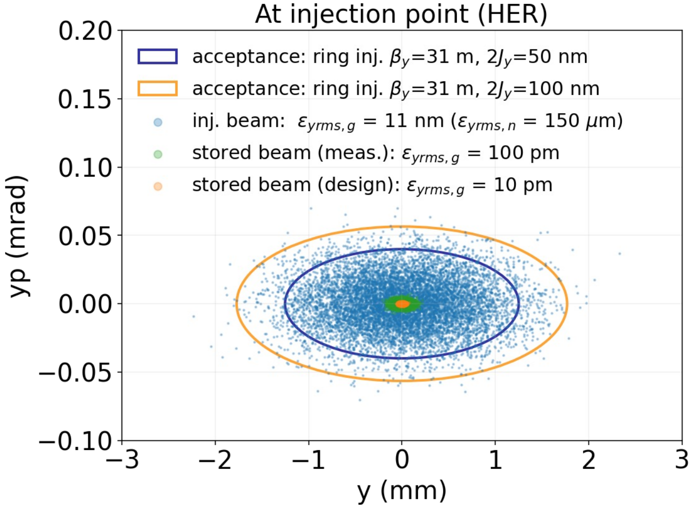




Fit 1 estimates:



Beam-beam effect further decreases inj. eff.



Note:
Dynamic apertures (DA) here were measured without beam-beam effect from e^+ beam.
Hence, DAs at high current operation are much smaller than measured ones.

What is a solution for higher-current operation and lower β^*_y optics

Higher luminosity (= higher-current operation, lower β^*_y) inevitably causes narrower dynamic aperture (DA) below the hor. DA limit.

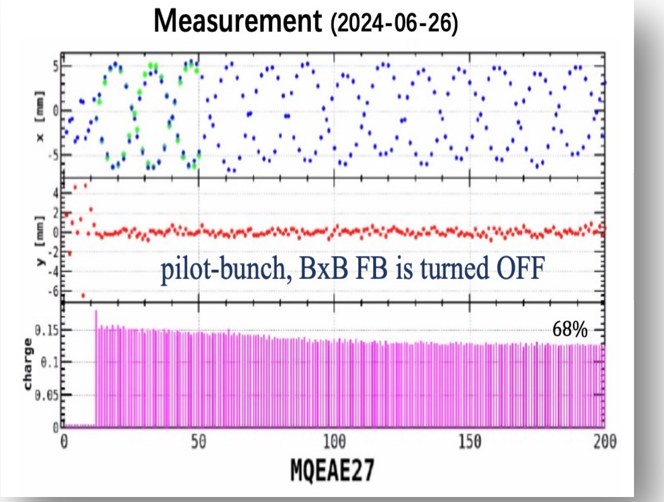
Question:

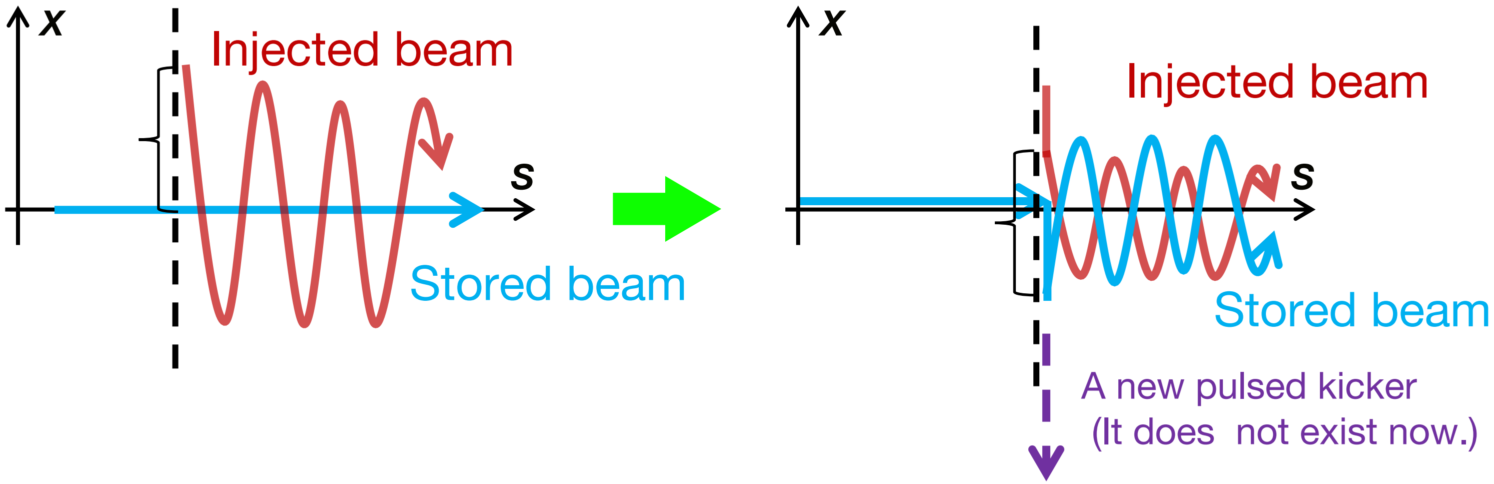
What is the potential solution?

Answer (?):

Minimize the horizontal envelope (action) of stored and injected beams at the 0th turn with a pulsed kicker, using a sophisticated B-by-B FB that turns off only for injected buckets and remains on for others.

Nominal beam oscillation:





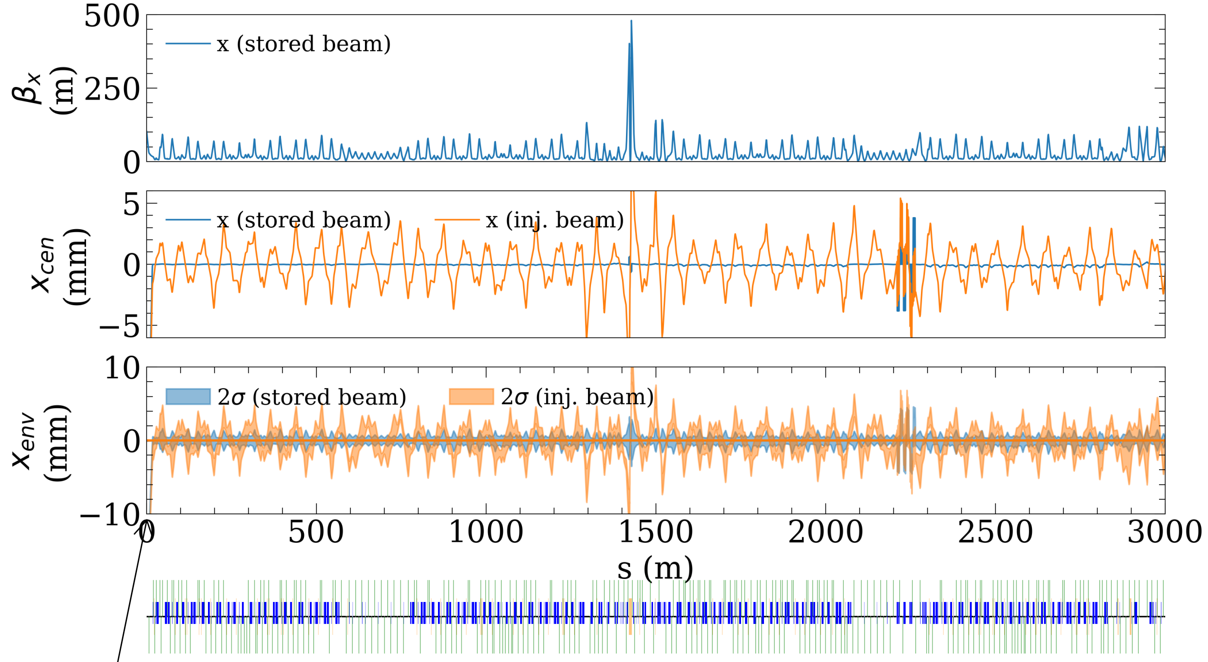
Then, we can further explore lower $\beta^*_y < 1$ mm and higher current operation > ~1.4 A (HER).

Minimum Envelope Injection With A Sophisticated Bunch-by-Bunch Feedback System (Proposal)

TbT FB: off for injected buckets

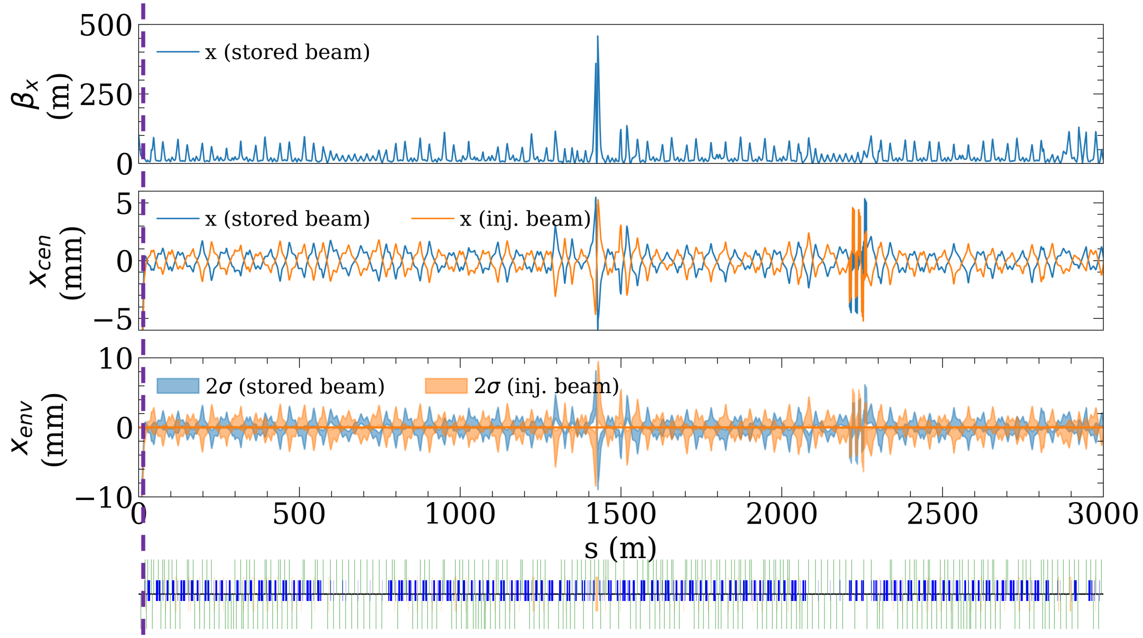
Very preliminary

Present Scheme: 0th turn



Injection point: 0 m

New Scheme: : 0th turn



A new pulsed kicker
(It does not exist now.)

Is it possible?

- Proposed scheme can reduce the total hor. envelop of inj. and stored beams significantly.
- 1) Single-bunch instabilities , 2) coupled-bunch instabilities, and 3) the technical feasibility of the new turn-by-turn (TbT) feedback (FB) system, should be examined in detail.

Summary

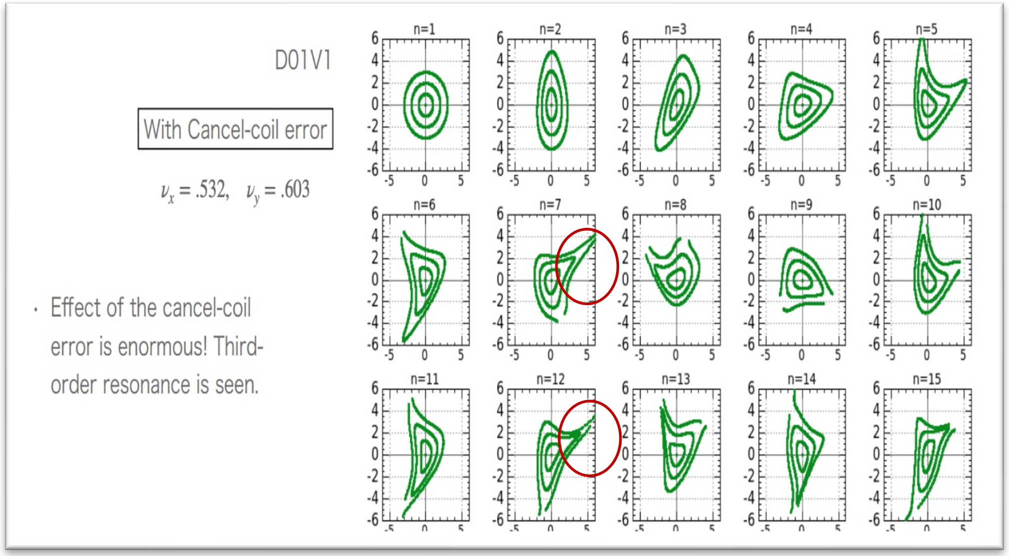
- In Run 2024c, the luminosity $\mathcal{L} = 5.1 \times 10^{34}$ cm^{-2}s^{-1} was achieved.
- Luminosity was partially limited by the injection powers, due to poor raw injection efficiencies (HER/LER).
- Strong x-y coupling was observed in BTe. => large ver. emittance of injected beam (e^-)
- β^*_y dependence of dynamic apertures was studied.
- Minimum envelope injection was proposed.

Thank you for your attention.

Possible Positive Side-Effects of Min. Envelope Injection (1)

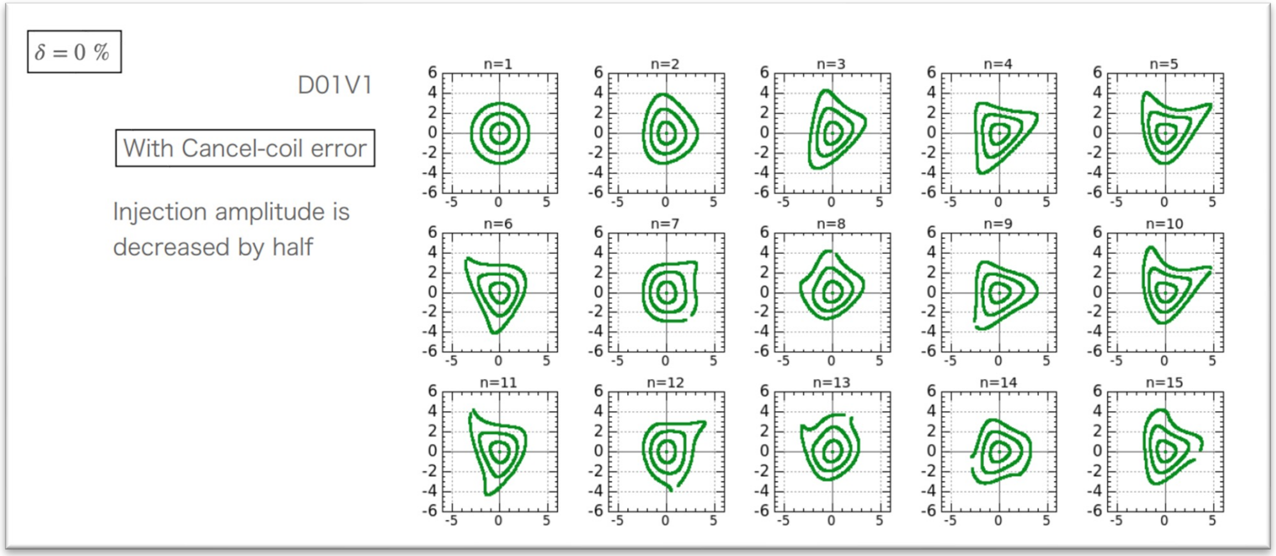
1. Lower injected beam oscillation ($2J_x$) gives large vertical acceptance ($2J_y$) due to less amplitude-dependent optics distortion.
=> further injection efficiency improvement
Reason: Currently QCS cancel-coil error causes enormous amplitude-dependent third-order resonance in vertical phase space

Present hor. inj. amplitude:



Half of present hor. inj. amplitude:

M. Kikuchi



*M. Kikuchi, "Simulation of the injected beam in HER (2)", SKB Commissioning meeting, Dec. 22, 2023, https://kds.kek.jp/event/49259/

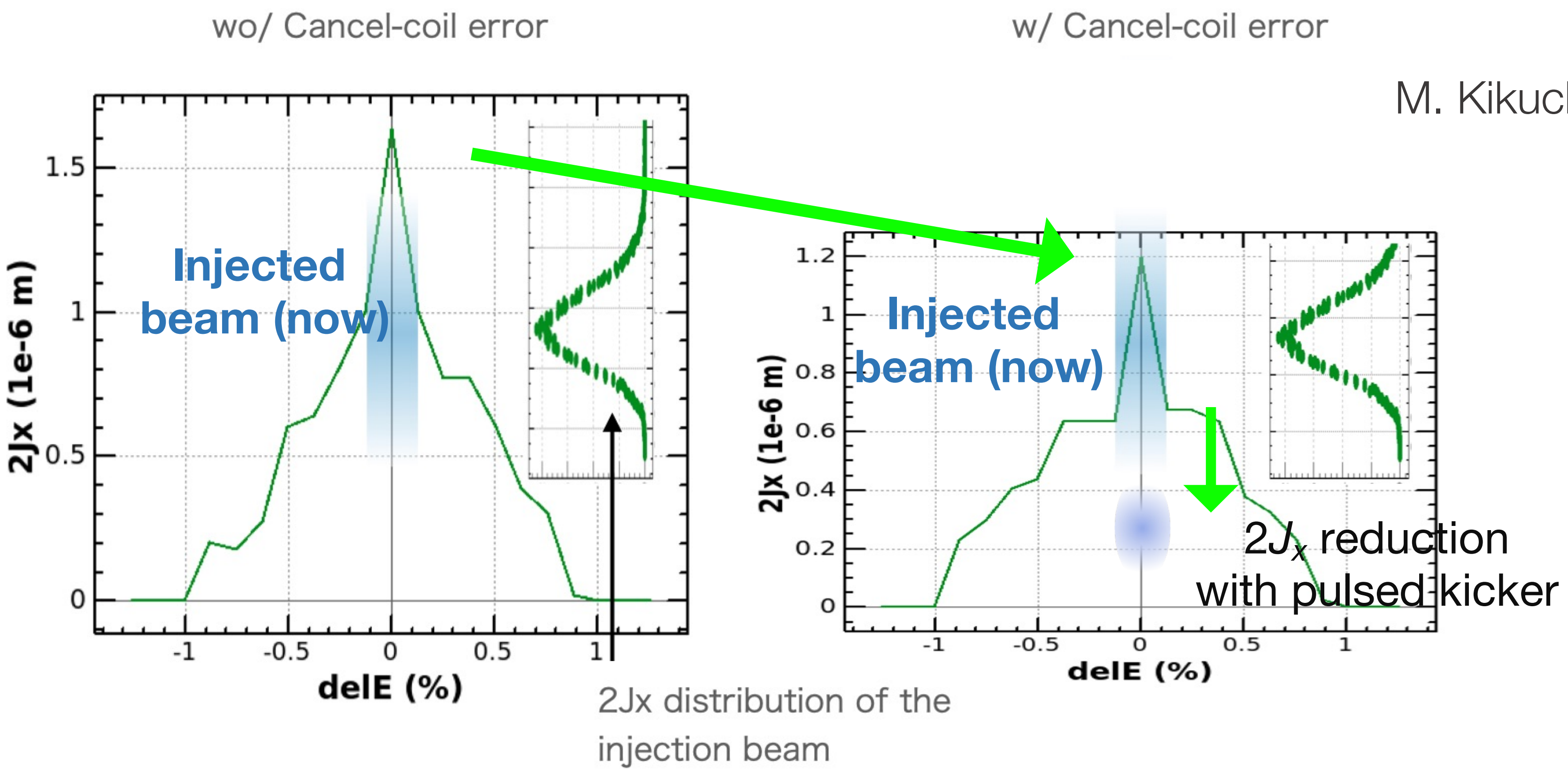
QCS background reduction gives:

2. Abort reduction triggered by HER-injected-beam-driven QCD diamond background spikes.
3. Wider HER collimator aperture (to reduce HER injection background) => longer HER beam lifetime
4. Shorter "veto" time => higher Belle2 data-taking efficiency.

It is essential to evaluate such items qualitatively.

Possible Positive Side-Effects of Min. Envelope Injection (2)

M. Kikuchi



- Lower horizontal oscillation of injected beam gives more relaxed constraint on dynamic aperture (DA).
- Further lower-beta high-current operation (that require smaller DA) can be explored.
- There is a BTe upgrade option; skew quads are placed at BTe2 for x-y emittance conversion to reduce ver. emittance for injection efficiency improvement.

[1] M. Kikuchi, "Simulation of the injected beam in HER (2)", SKB Commissioning meeting, Dec. 22, 2023, https://kds.kek.jp/event/49259/