SuperKEKB injection status and issues

2025.Oct.2
IJCLab
N. Iida (KEK)

I would like to thank A. F. Golf, P. Bambard, and S. Hashimoto for giving me the opportunity to present at IJCLab.
I would also like to thank Y. Arimoto, Y. Funakoshi, H. Kaji, T. Kamitani, M. Kikuchi, H. Koiso, M. Li,
Y. Ohnishi, N. Ohuchi, K. Oide, M. Satoh, M. Tawada, S. Terui Y. Seimiya, Y. Shimosaki, Y. Shoji,
T. Yoshimoto for providing the materials.

Injection limits luminosity

BEAM INJECTION ISSUES AT SuperKEKB

IPAC2023, N. Iida et. al., MOPL120

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 1×10^{35}/cm^{2}s;
* denotes the values at the interaction point.

Parameters	LER	HER	LER	HER
bunches/ring	2345+1		2345+1	
Luminosity [/cm^{2}s]	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]			2.6	0.69

←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.

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

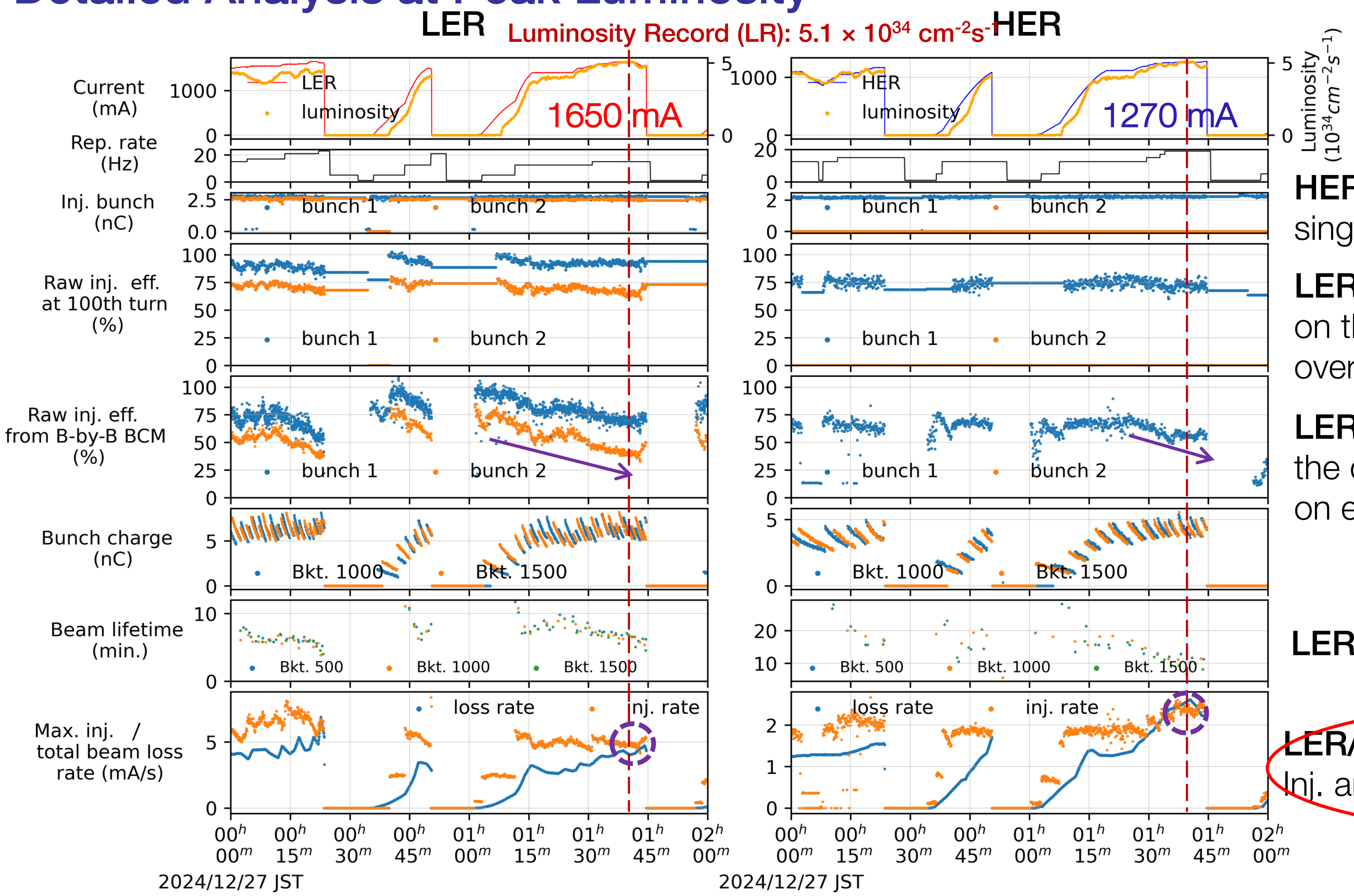
Two-bunch operation(two bunches in one linac pulse) has been done at LER in 2024 autumn run.

SuperKEKB injection

- Currently, the highest luminosity achieved by SuperKEKB is only 0.51×10^{34} [/cm^2/s], and the HV of Belle II is off.
- It will not be easy to achieve the design luminosity of 6.5×10^{35} [/cm^2/s], even the next milestone of 1×10^{35} [/cm^2/s].
- There are many reasons why luminosity may not be produced, but poor injection is one of the biggest factors that hinders luminosity growth.
- The causes of low injection efficiency are also varied:
  - The emittance growth of the injection beam (all for e-, e+, horizontal, vertical)
  - Lower injection efficiency at high bunch current
  - A narrower dynamic aperture of the ring than the design
  - Reduced dynamic aperture (especially for the injection beam) due to QCS cancel coil error

Detailed Analysis at Peak Luminosity

T. Yoshimoto



B-by-B BCM system: H. Kaji

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 a few seconds after injection) 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:

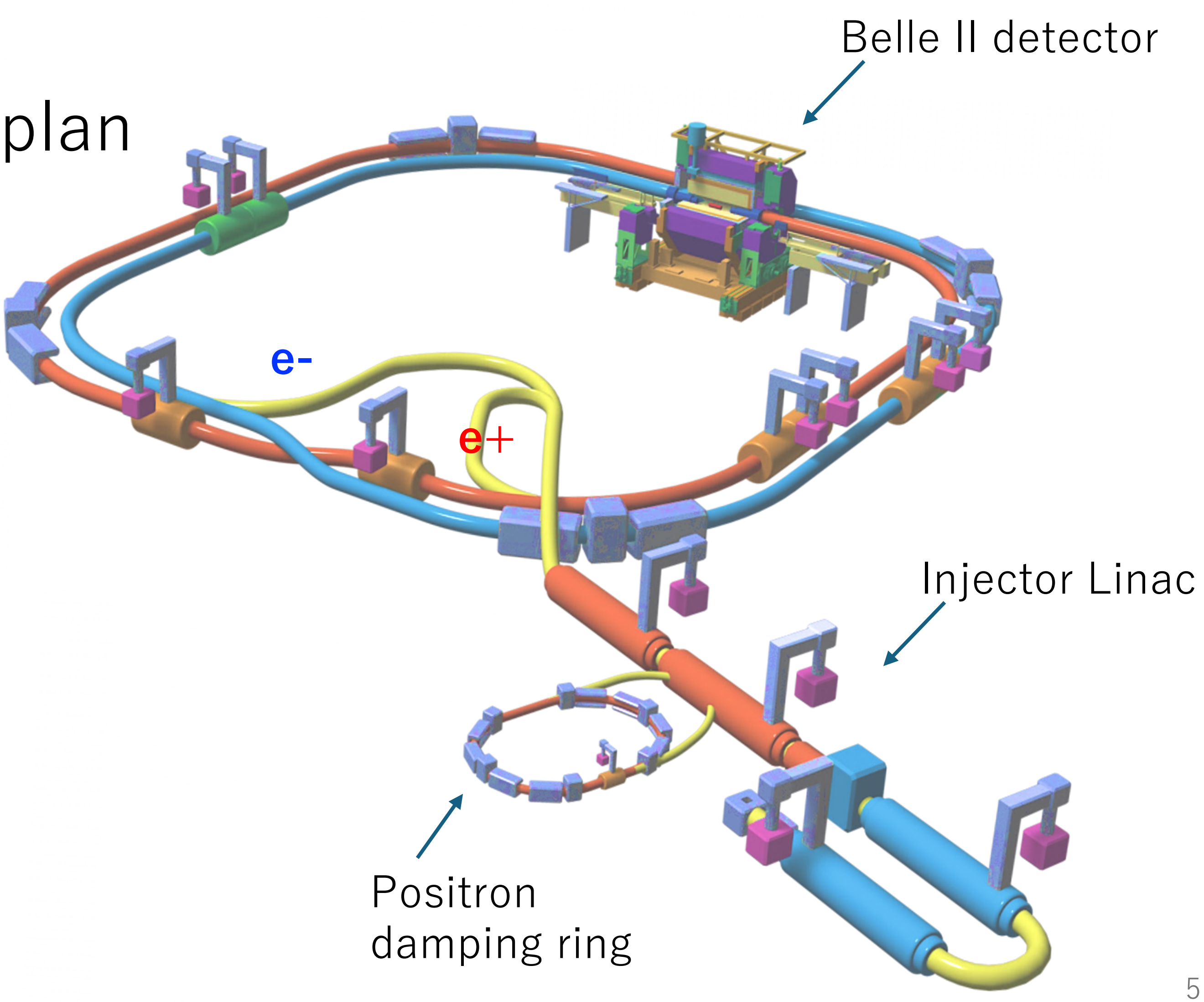
LER: 1) higher raw inj. efficiencies (**Max.: ~1.6x**), 2) higher bunch charge 3 nC -> 4 nC, 3) higher. rep. rate: 15 => 23Hz (**Max.: ~1.53x**)

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

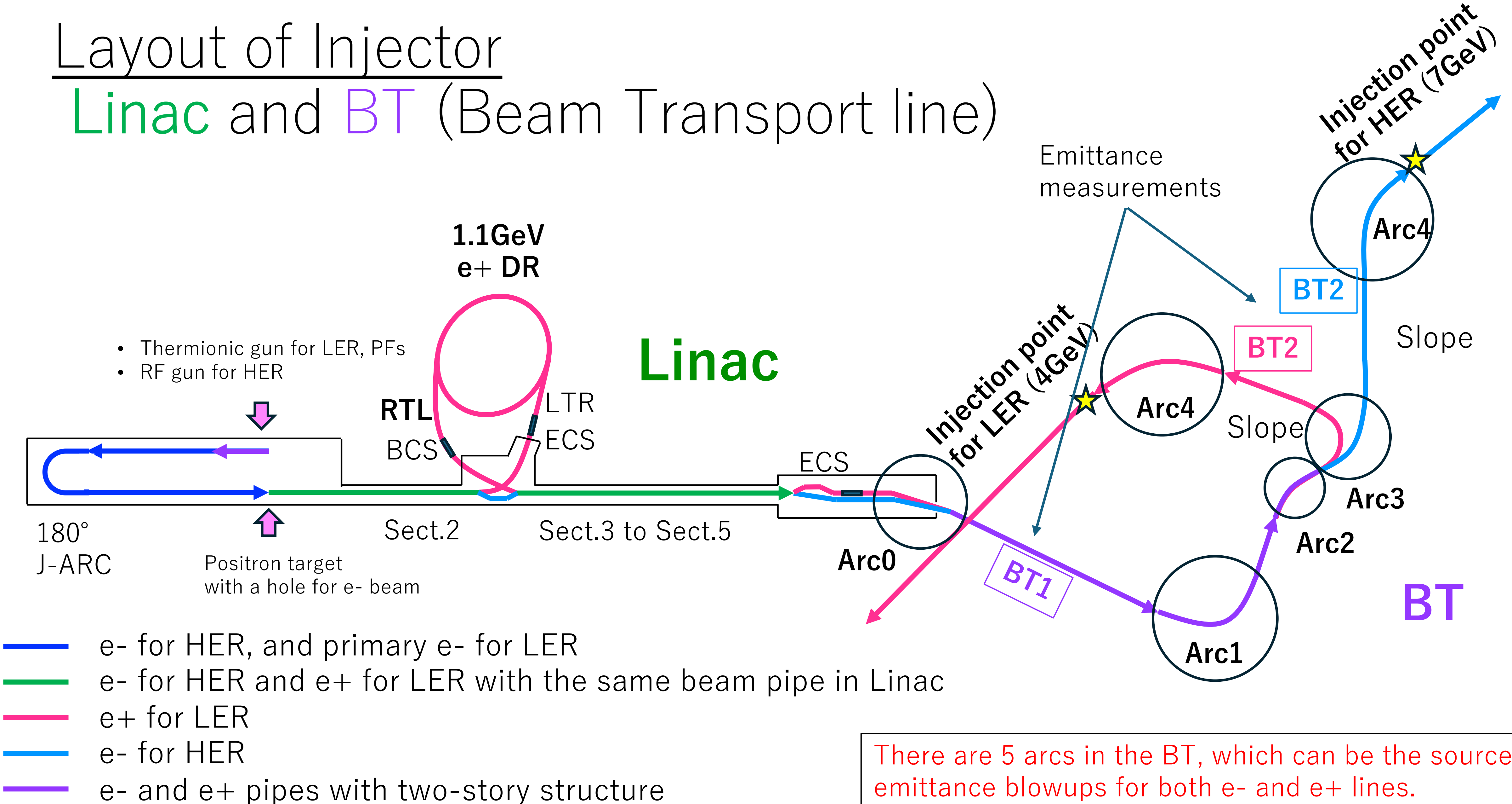
Contents

- e- injection issues and plan
- e+ injection
- collider rings

Schematic layout of SuperKEKB



Layout of Injector
Linac and BT (Beam Transport line)



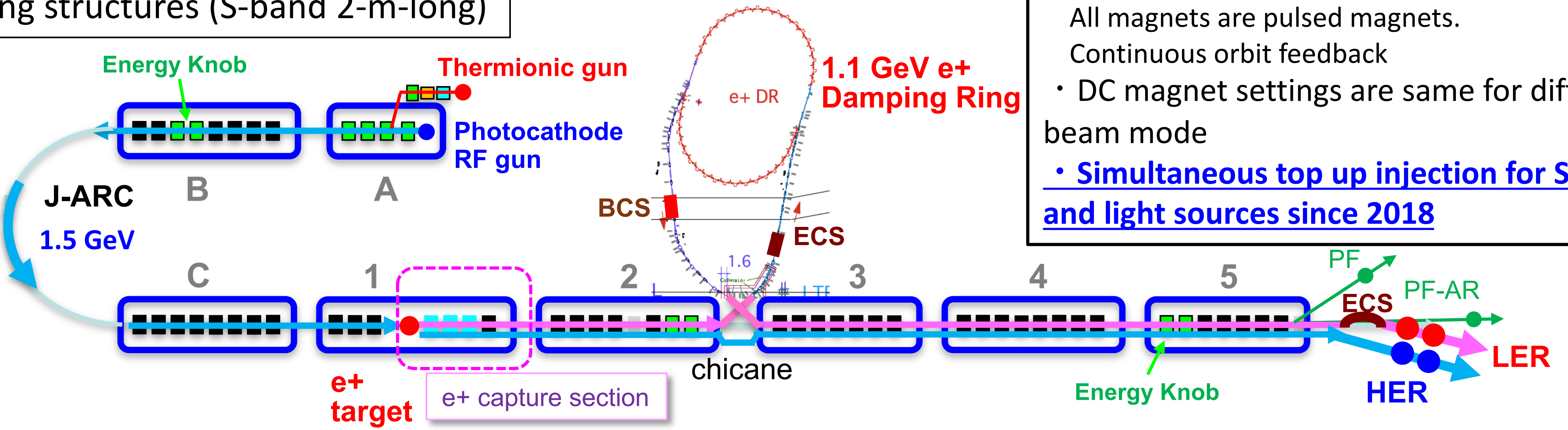
There are 5 arcs in the BT, which can be the source of emittance blowups for both e- and e+ lines.

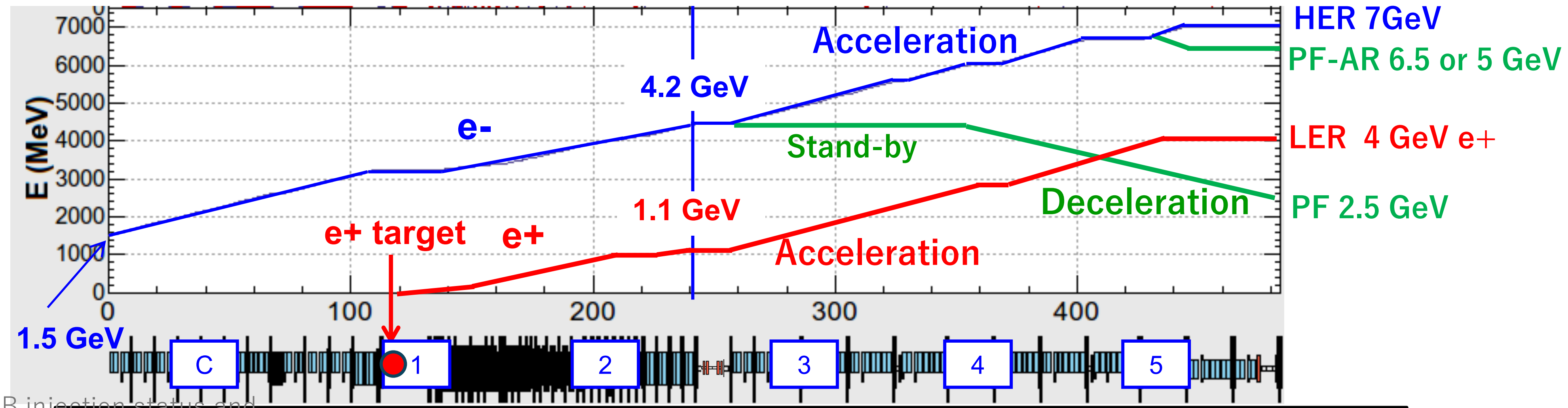
Linac Layout

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**





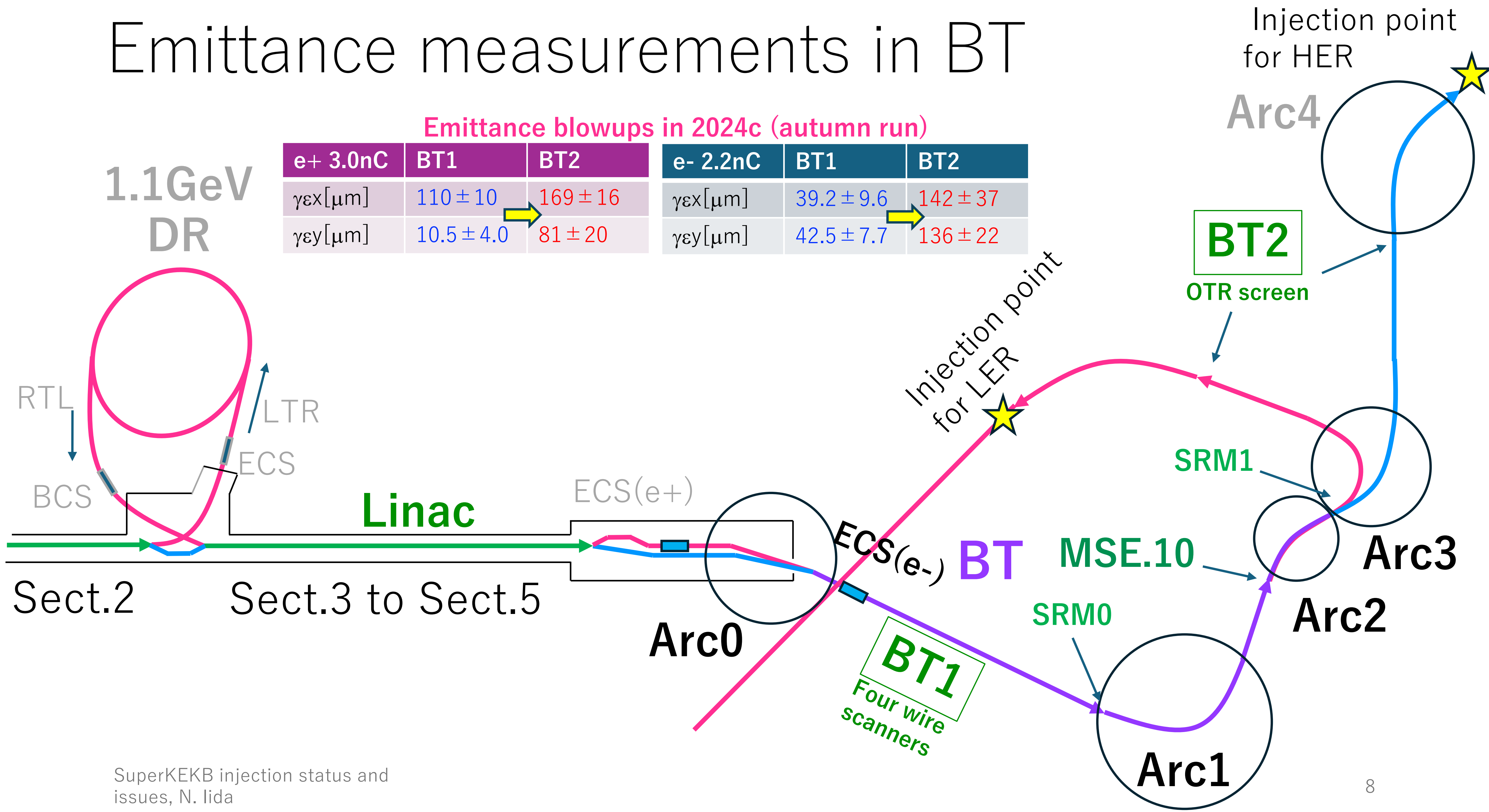
Beam energy variation for each beam mode along the beam line after J-ARC

Emittance measurements in BT

Emittance blowups in 2024c (autumn run)

e+ 3.0nC	BT1	BT2
γεx[μm]	110±10	169±16
γεy[μm]	10.5±4.0	81±20

e- 2.2nC	BT1	BT2
γεx[μm]	39.2±9.6	142±37
γεy[μm]	42.5±7.7	136±22

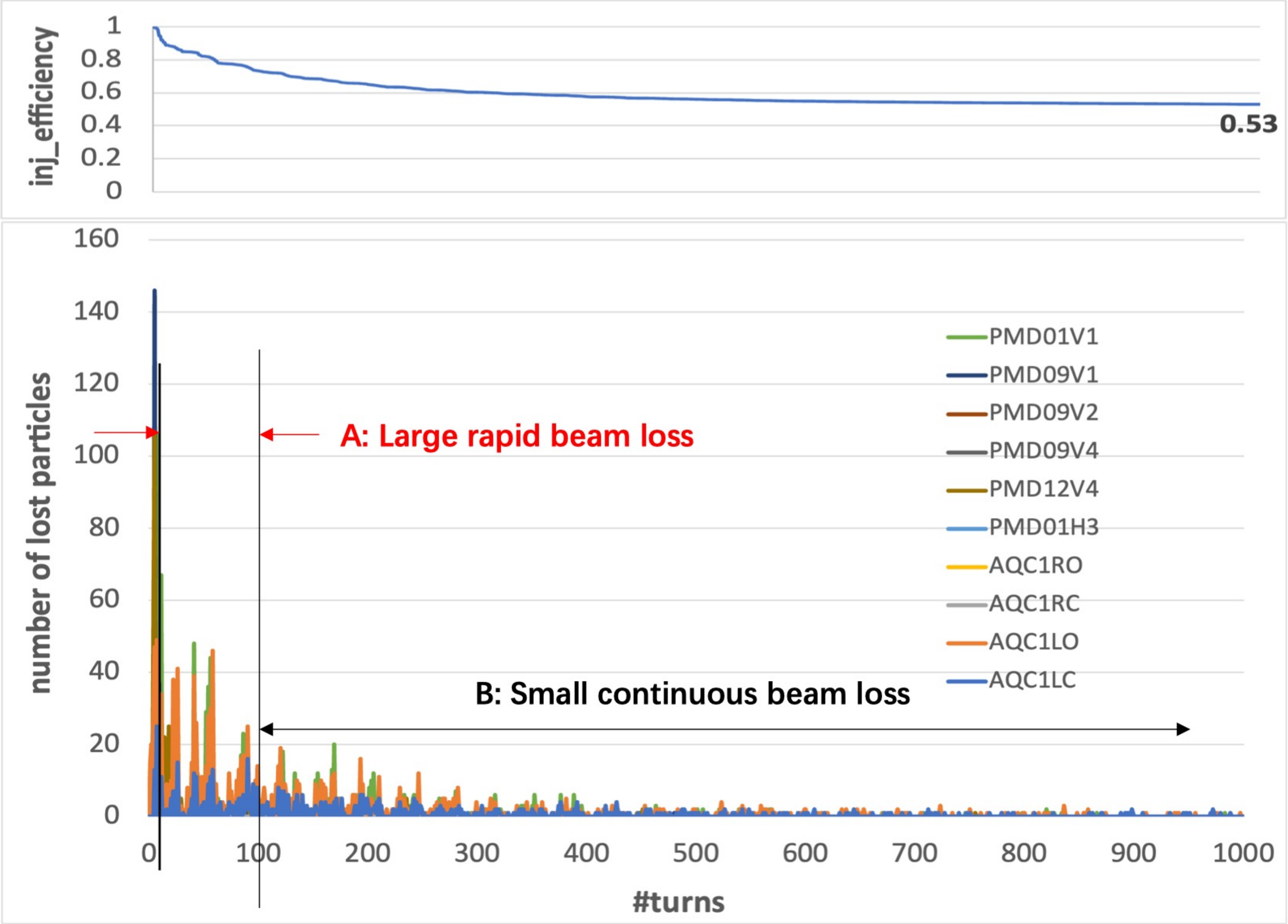


e- injection issues and plan

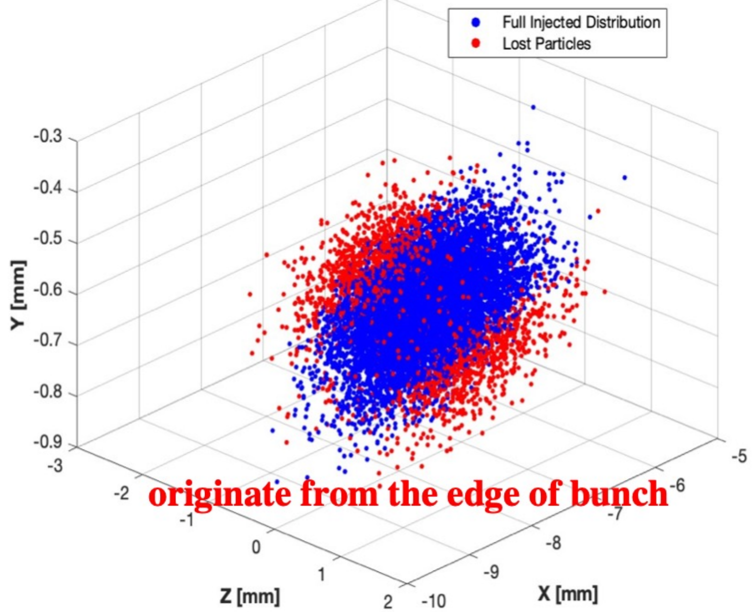
1. Emittance growth in the BT
2. Newly installed ECS in the BT
3. Synchrotron injection
4. Correction of QCS cancel coil error in the HER

HER Injection efficiency and beam loss

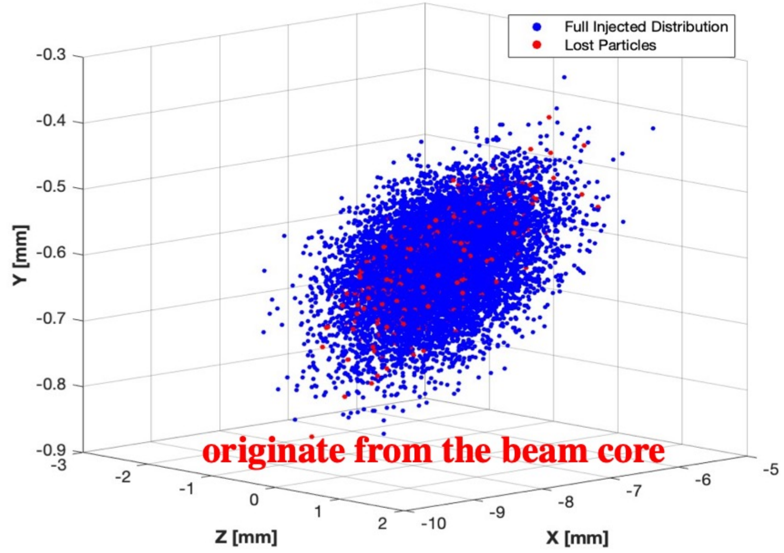
M. Li



A: Large rapid beam loss



B: Small continuous beam loss



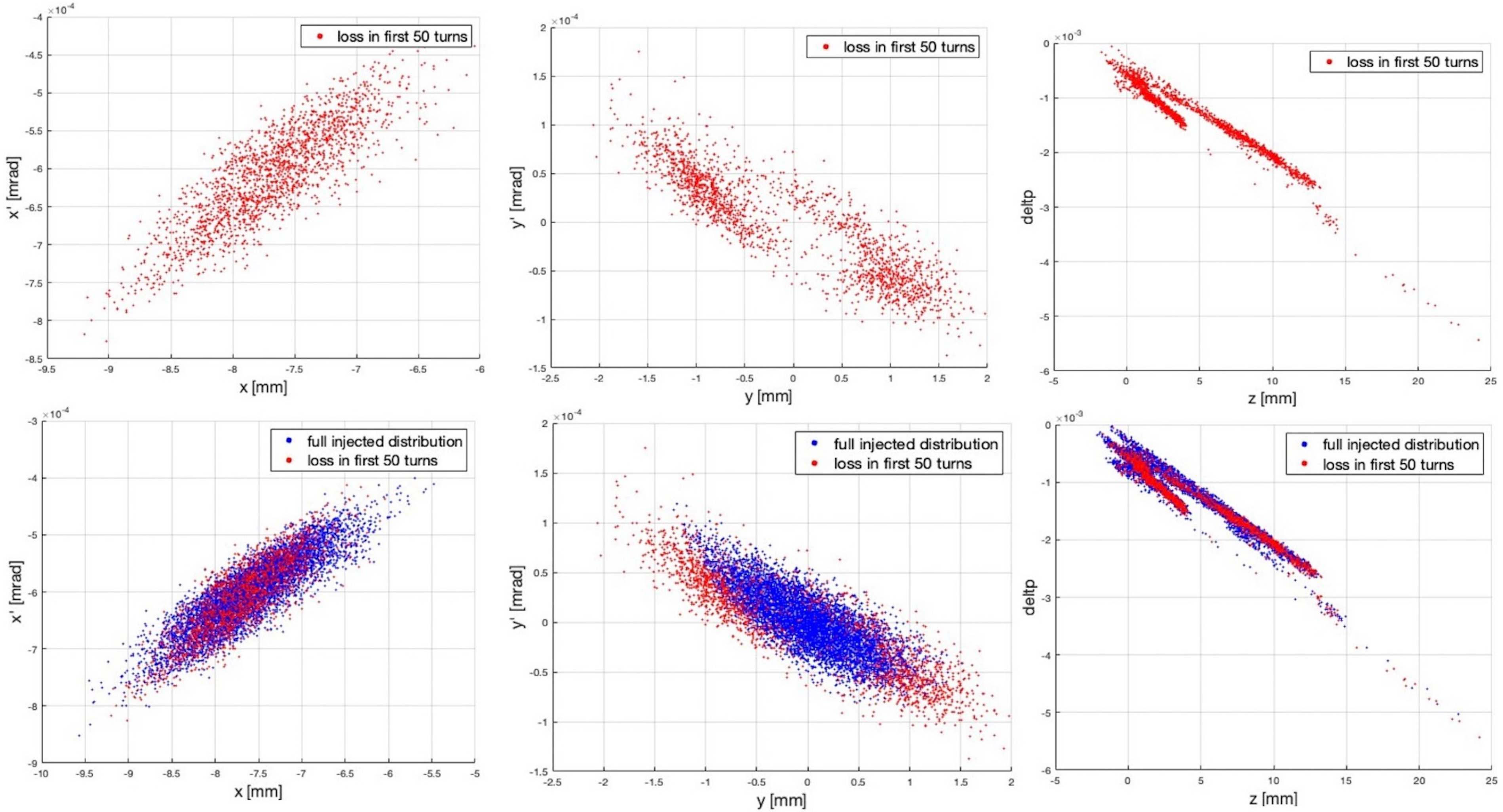
- There are 2 different types of beam loss:

1) large and fast beam loss in the first 100 turns(30%) →injection efficiency

2) small and continuous beam loss until 1000 turns(10%) →injection BG duration

M. Li

Initial coordinate of lost injection particles (lost in first 50 turns)

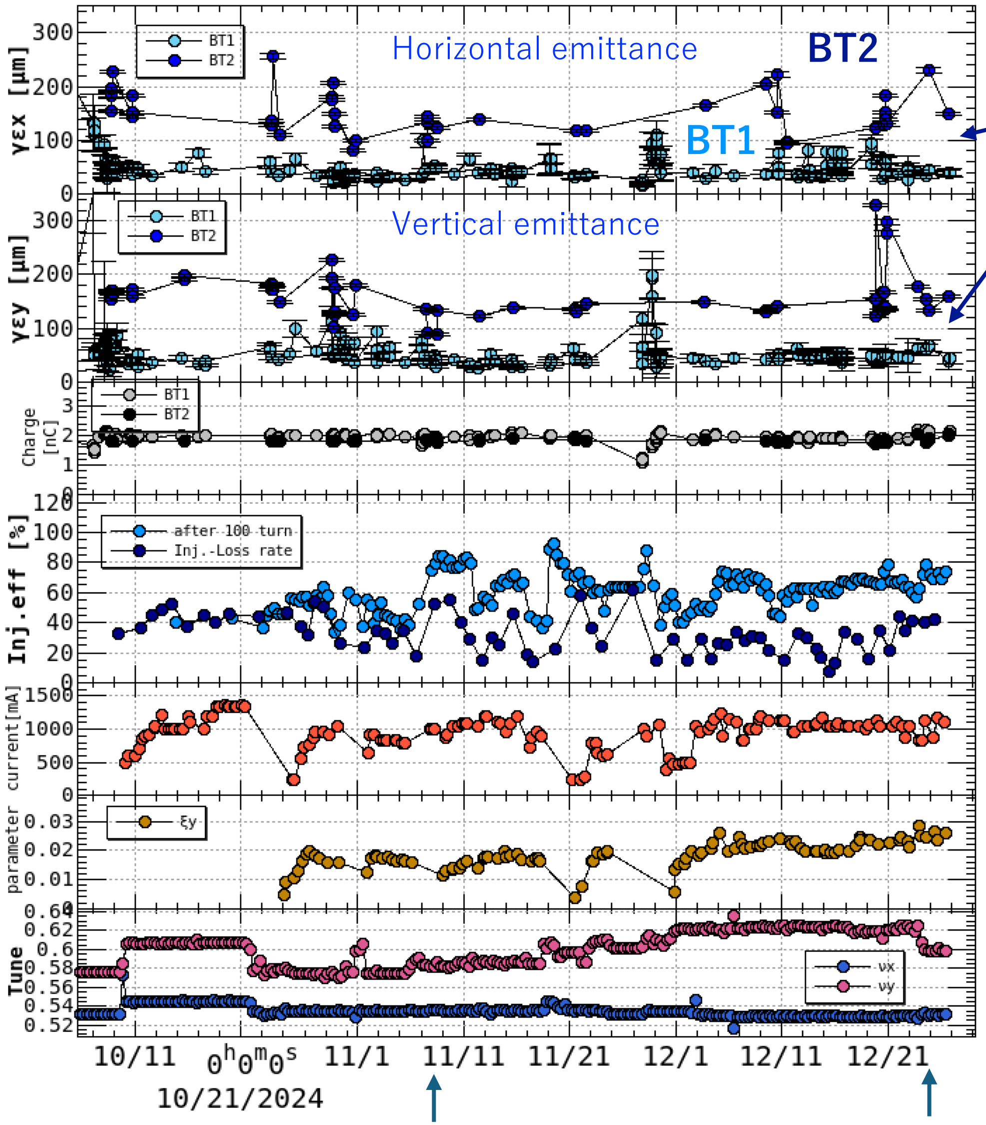


The injection particles lost in first 50 turns originate from the edges of the transverse bunch distributions → related to the injection efficiency

Mainly, the vertical edges of the injected positrons are lost.

HER

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



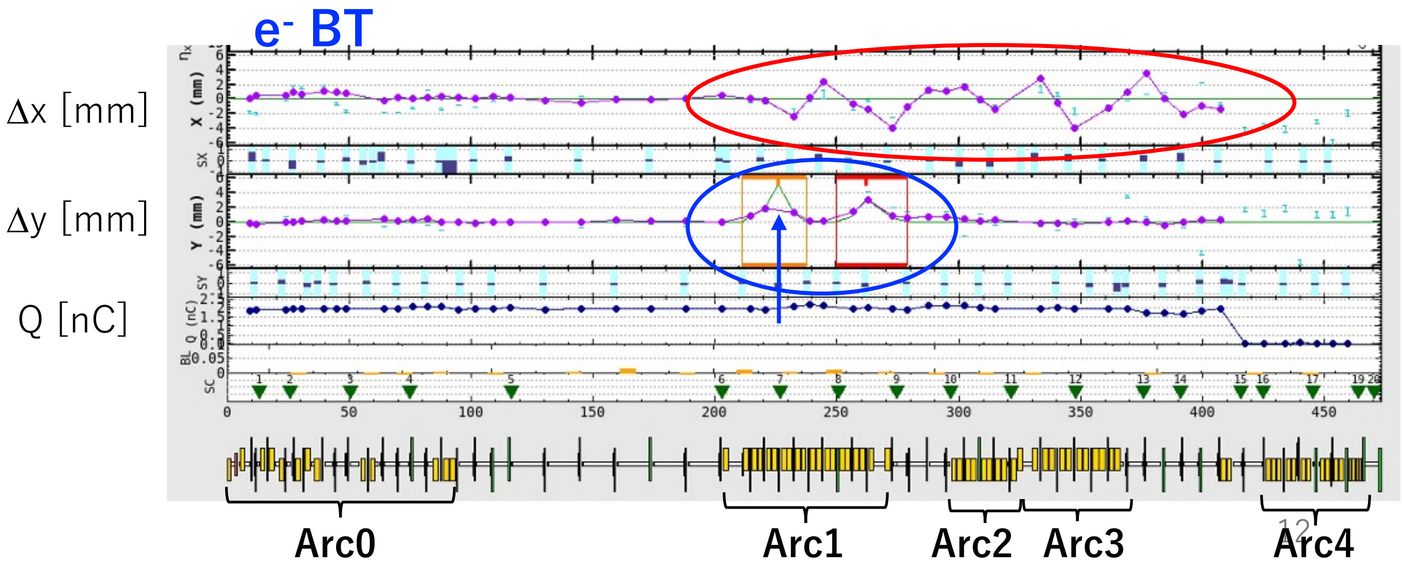
Inj. tuning w TbT BPM, and Collimator tuning

βx*=80mm to 60mm

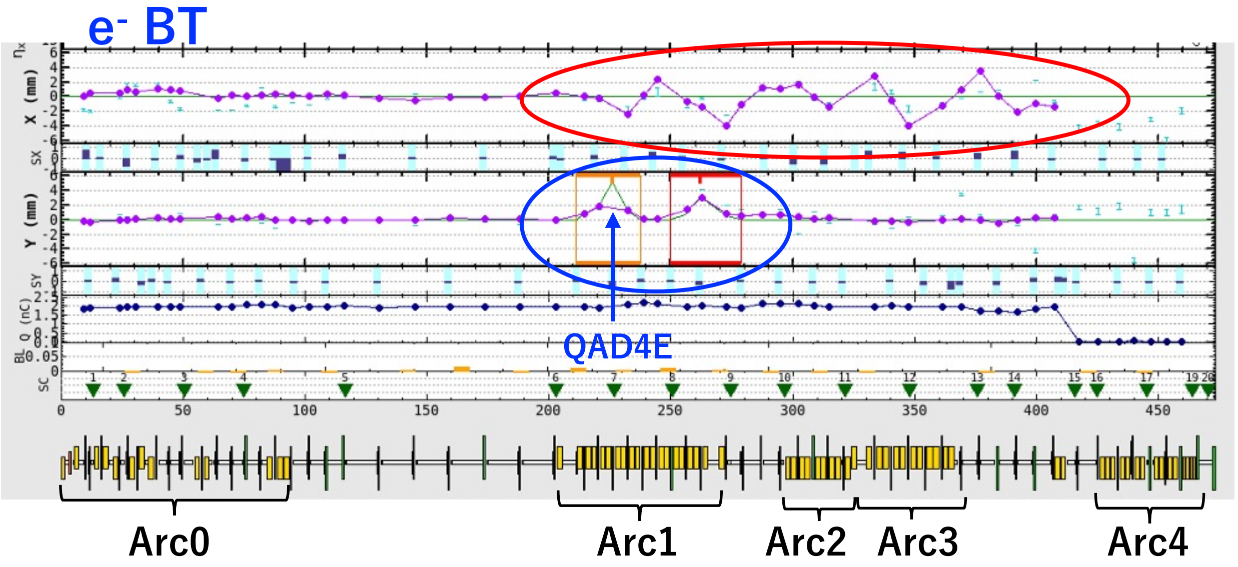
e- 2.2nC	BT1	BT2
$\gamma\varepsilon x$[μm]	39.2 ± 9.6	142 ± 37
$\gamma\varepsilon y$[μm]	42.5 ± 7.7	136 ± 22

- 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): ~50 μm
    2. CSR(Coherent Synchrotron Radiation): ~20 μm(2 nC)
  - $\gamma\varepsilon x$ = 40 μm(BT1) to 110 μm(BT2) has been understood.

- However, 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 Arc1 of e- BT.)



Measured unexpected X-Y couplings in BT Arcs

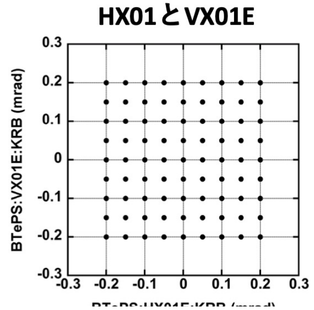


Raster scan

Y. Shimosaki

Example of the response

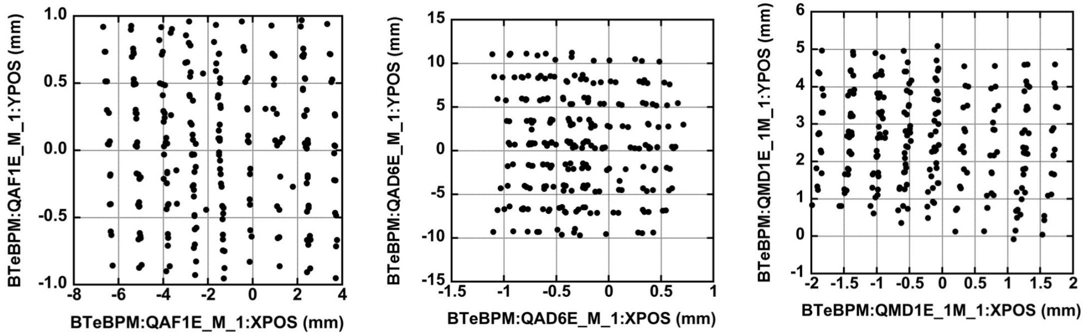
Beam response when kicked with horizontal and vertical steering at the top of the BT



X and Y positions at the top of Arc1

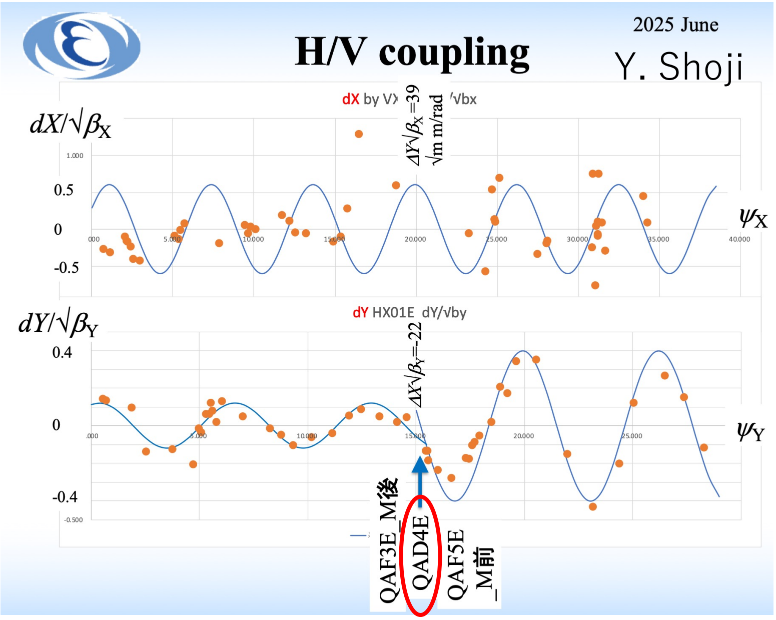
X and Y positions at the middle of Arc1

X and Y positions after Arc3

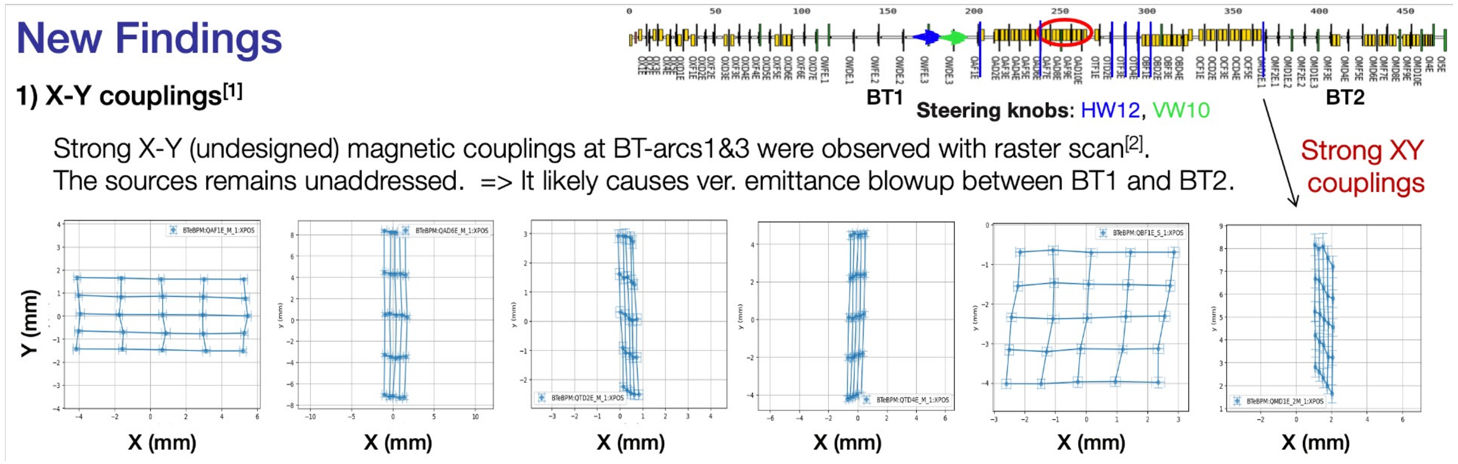


Horizontal beam position kicked by the vertical steering

Vertical beam position kicked by the horizontal steering



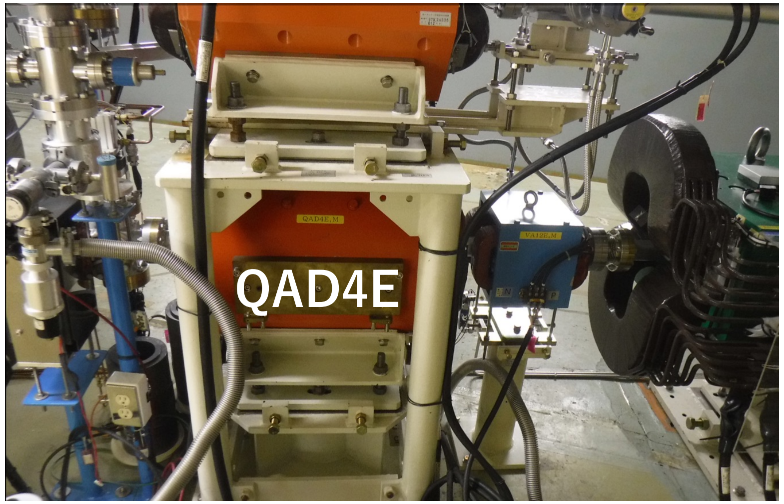
T. Yoshimoto

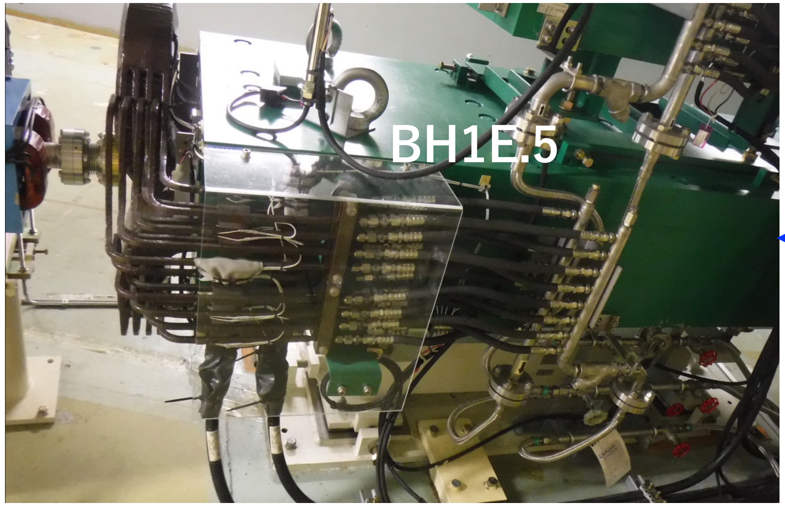


There might exist something wrong near QAD4E...

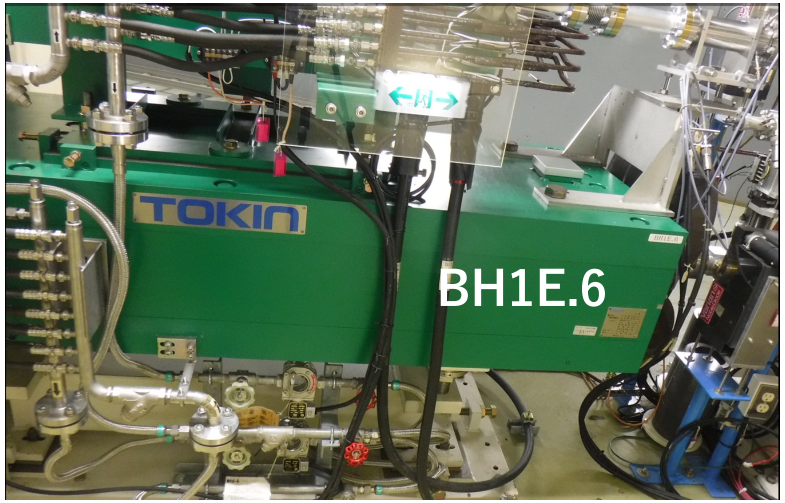
Arrangement around QAD4E

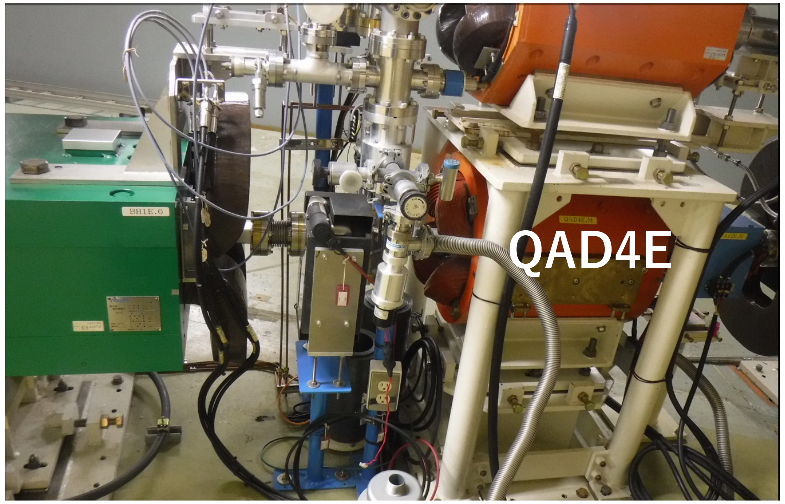
- But now QAD4E is OFF !!
- Who makes the X-Y coupling??





e-





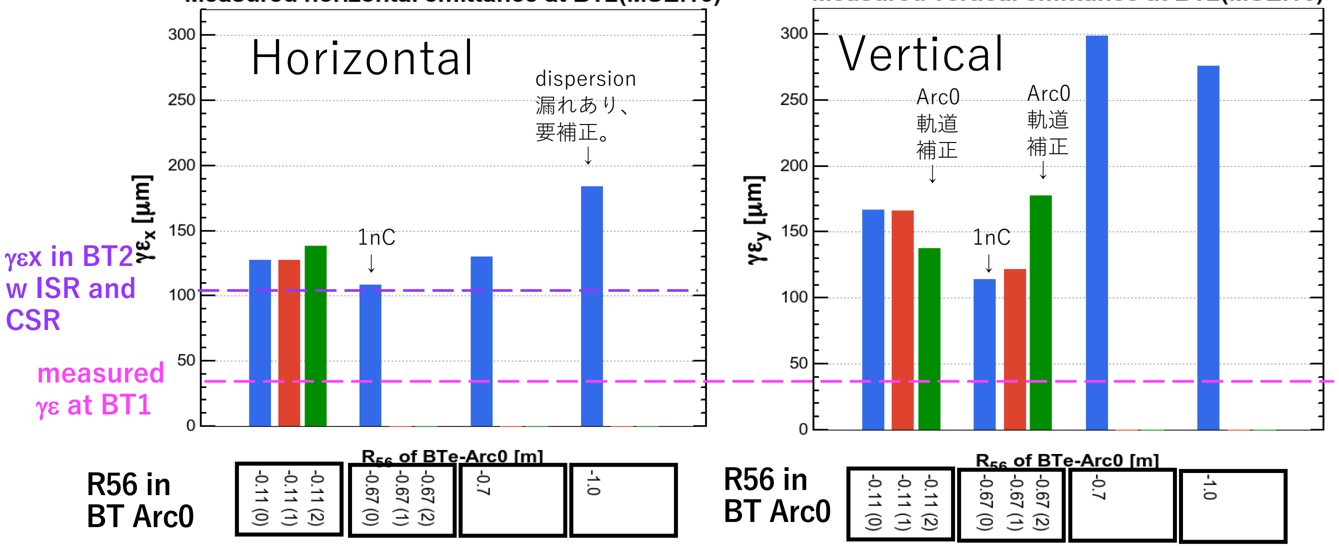
e-

We need to simulate about this.

More emittance blowup with ECS optics, or 3nC

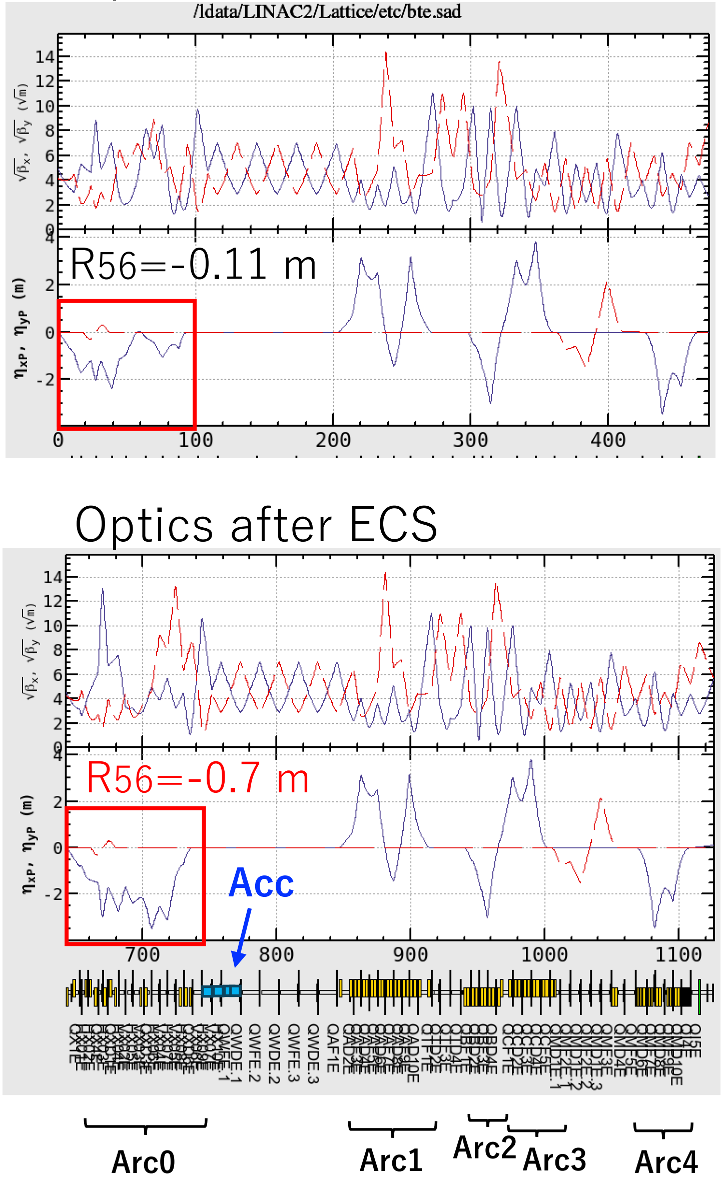
- Setting ECS optics (R56~-0.7m in BT Arc0) without RF often enlarges the horizontal and vertical emittances.
- Increasing e- charge from 2.2 nC to 3 nC also enlarges the emittances as well, probably due to transverse wake.
- However, the measured emittances in BT1 don't increase at all for the both cases, which is very mysterious.

2.2nC Measured emittances at BT2 in 2024c



Optics before ECS

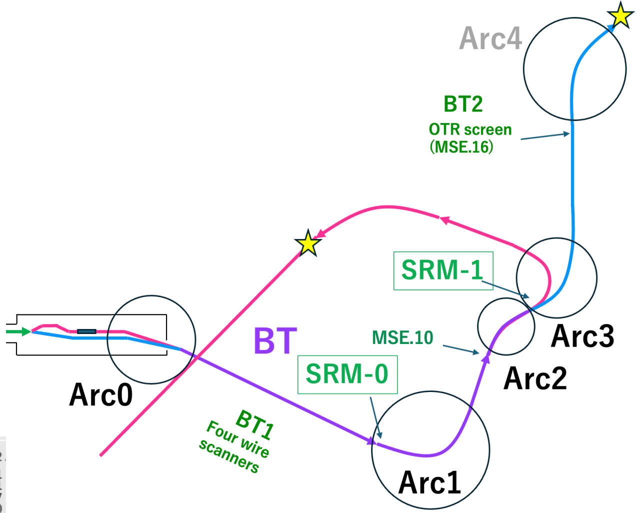
Optics after ECS



2.2nC

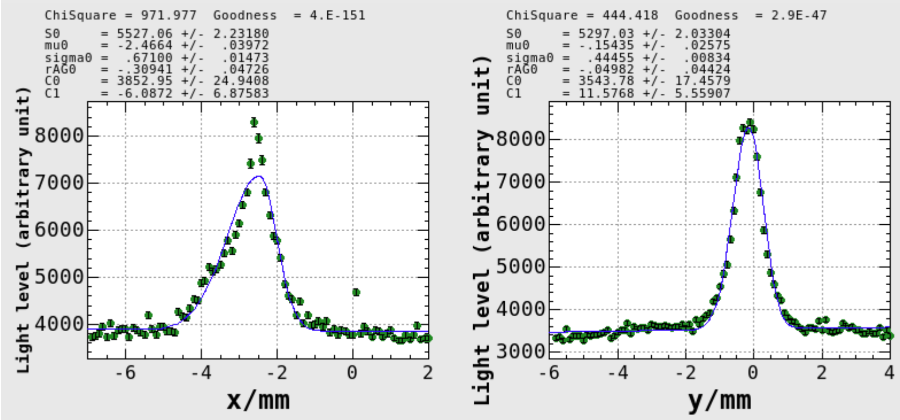
SRM profiles change

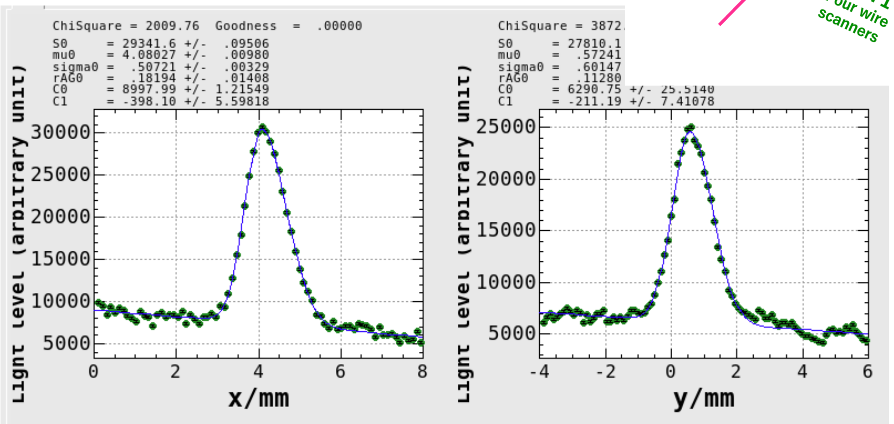
The vertical beam size blowup is also monitored at two SRMs in the BT.



SRM-0 (entr. Arc1) | SRM-1 (entr. Arc3)

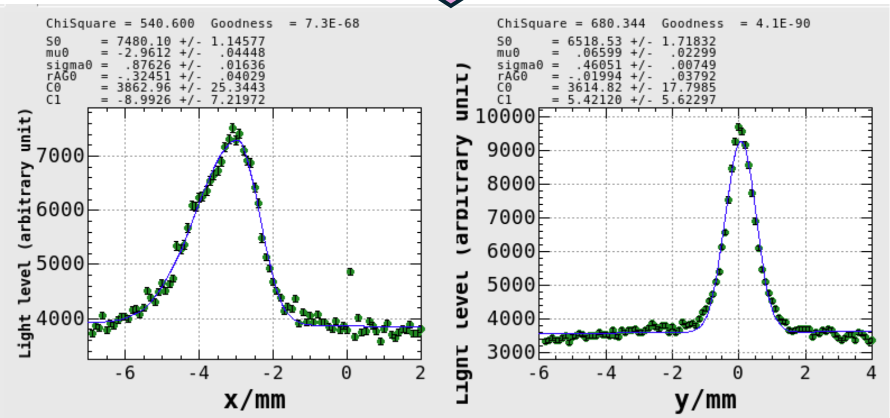
R_{56}=-0.11 m

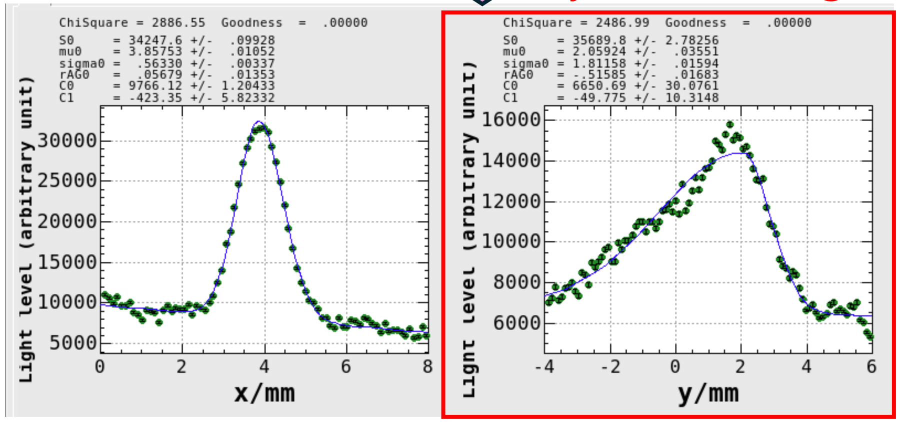




R_{56}=-0.67 m

σy became larger!!





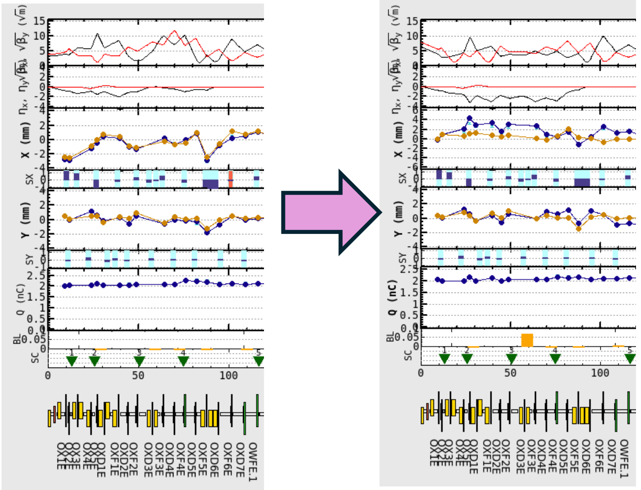
2.2nC

SRM profiles change by R_{56}

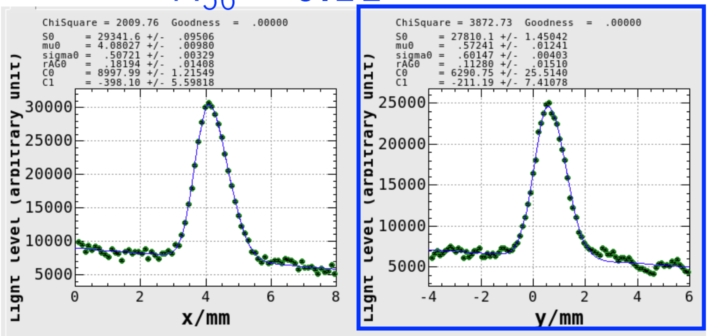
While observing **SRM-1**, the orbit and SB_35 were scanned.

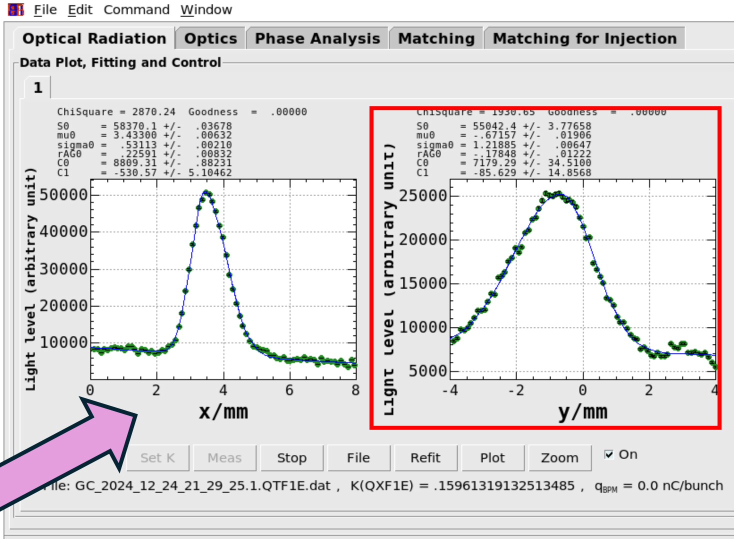
Although it became slightly smaller, didn't recover to the original size.

- Changed the orbit in Arc0

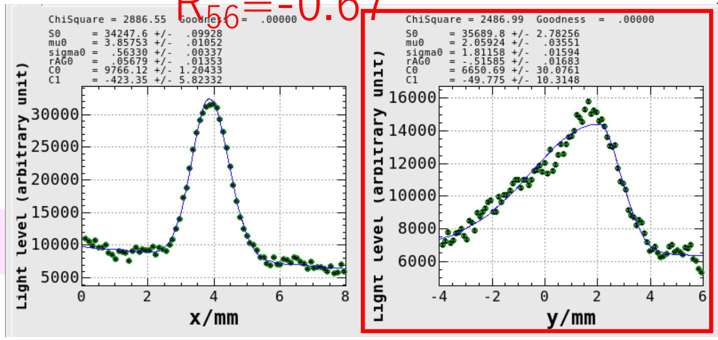


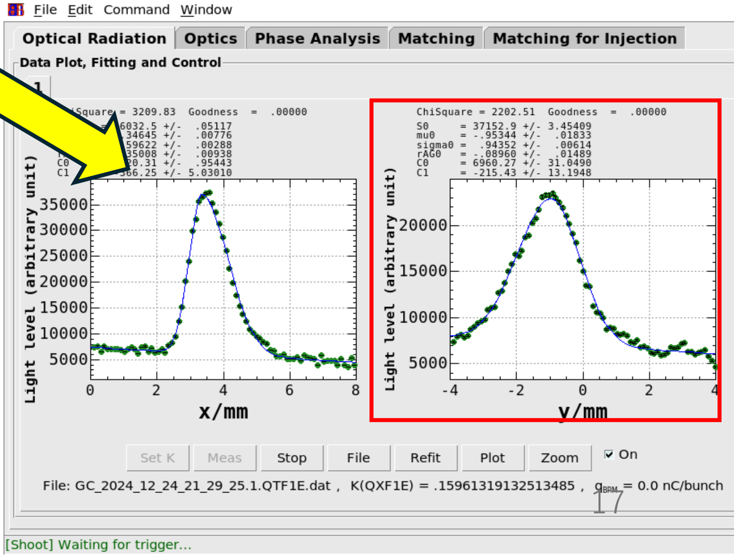
R_{56}=-0.11





R_{56}=-0.67

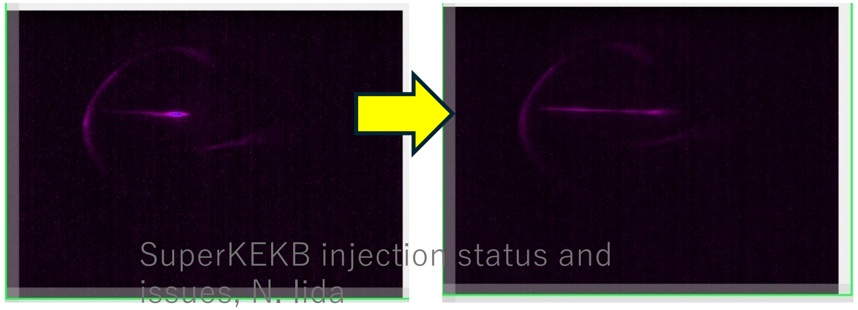




- Changed the RF phase of sector 3-5 in Linac

18:27:02

SB_3 (KBE) 92.0°、SB_4 (KBE) 93.1°、SB_5 (KBE) 95.1°
SB_3～5(KBE) 元値 → -1° → -2° → ±0° → +1° → +2° → +3° → +4° → +5°

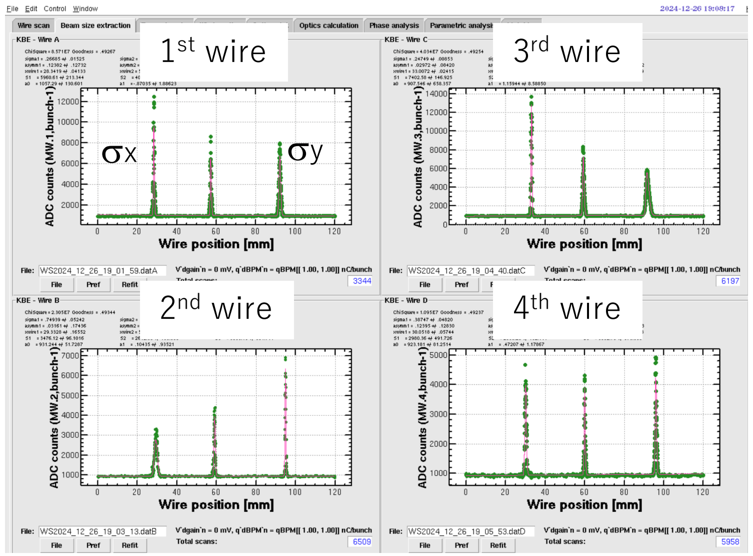


No emittance growth in BT1 WS measurements

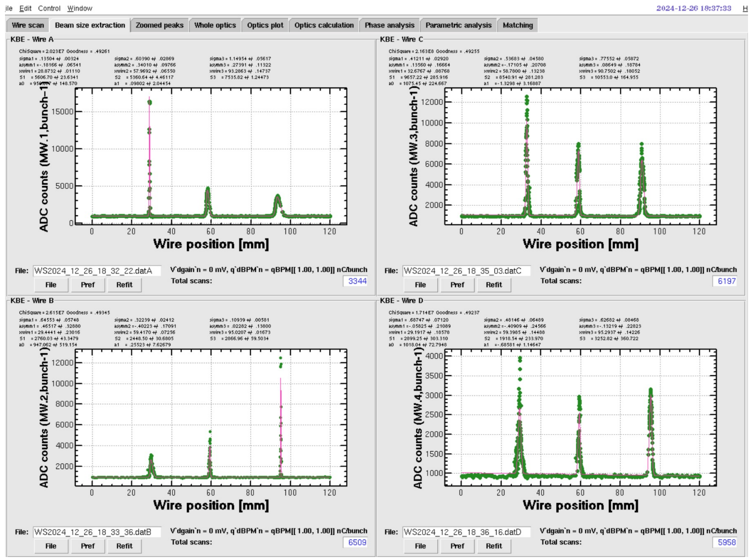
2.2nC

	R56=-0.11	R56=-0.67
γεx [μm]	40.17±8.17	39.22±5.40
BMAGx	1.22	1.73
γεy [μm]	43.02±10.71	39.78±16.88
BMAGy	1.50	3.71

R56=-0.11 m

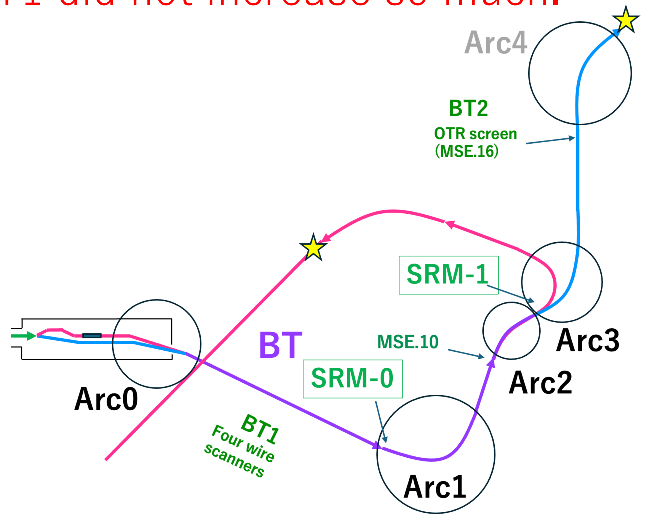


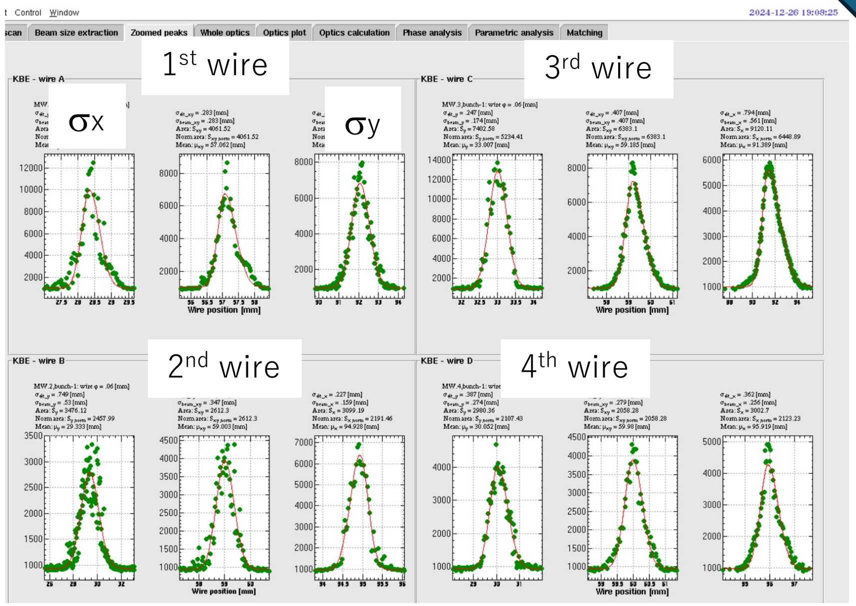
R56=-0.67 m

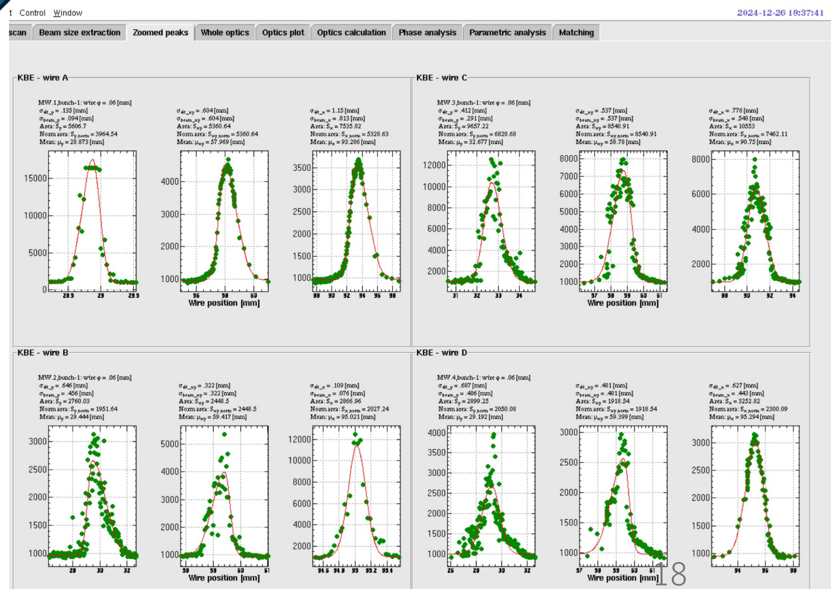


However, the measured emittances in BT1 did not increase so much.

Zoom up







SuperKEKB injection status and issues, N. Iida

BT Study – e^- Beam in May-June in 2025

Emittance Blowup Due to Large R56 Optics for ECS and 3 nC Beams

- 3 nC electron beams were successfully transported through the BT line with small emittance up to BT1. However, the emittance increased significantly after BT-Arc1 (OTR "MSE.10").

  - No data obtained at BT2, which is located after the BT beam dump, since the beam operation was in dump mode.

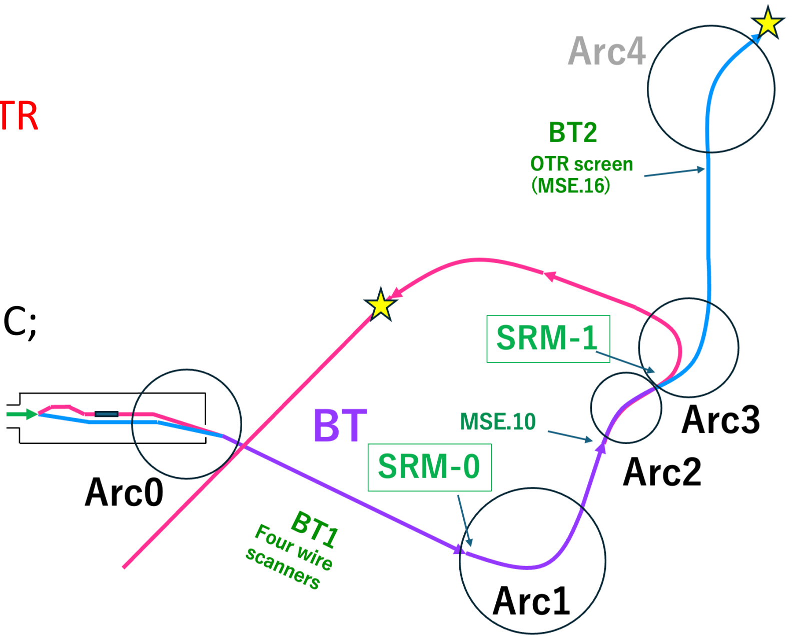
- A double-peak structure was observed at the OTR screen in the large R56 optics or 3 nC; attributed to wakefields and energy spread tuning.

  - The R56 in the Arc0 changed from -0.11 m to -0.7 m for ECS, with the RF turned off during this study.

  - The "double-peak" structure is a newly observed phenomenon in this study.

  - The presence of a double peak effectively results in emittance blowup.

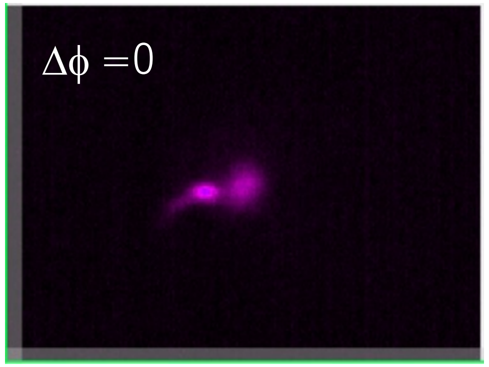
- Beam studies with the Linac-mode were done to find orbit settings that suppress this blowup[A2].
  [Y. Seimiya *et al.*]



Results	BT1 (2025b)	BT2 (2024c, Ref.)	MSE.10 (2025b)	MSE.10 (2025b)	MSE.10 (2025b)	MSE.10 (2025b)
	2, 3 nC	2 nC	2nC	3nC	3nC	3nC
R56 [m]	-0.11, -0.7	-0.11	-0.7	-0.11	-0.7 w bump	-0.7 w/o bump
$\gamma\varepsilon x$ [μm]	30-40	140	300	210-337	342	333
$\gamma\varepsilon y$ [μm]	30-40	140	107	90-106	158	170

2024c: Oct-Dec, 2024 **2025b:** May-June, 2025

MSE.10(η_x~0 m)

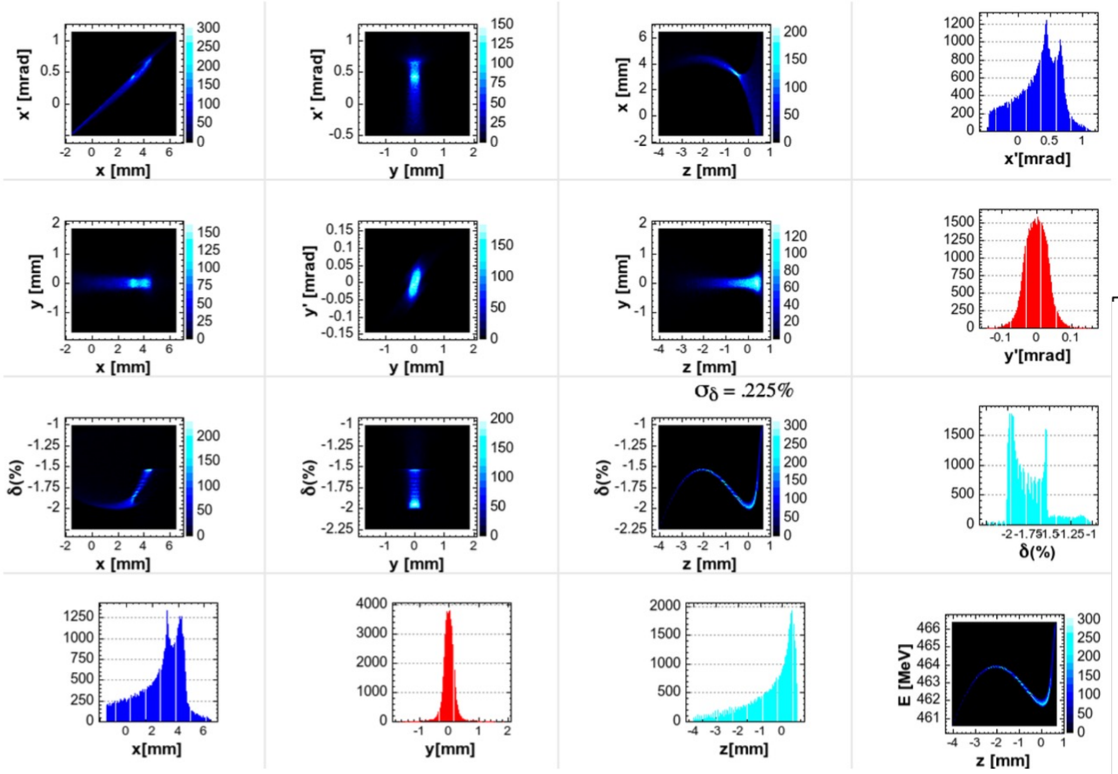


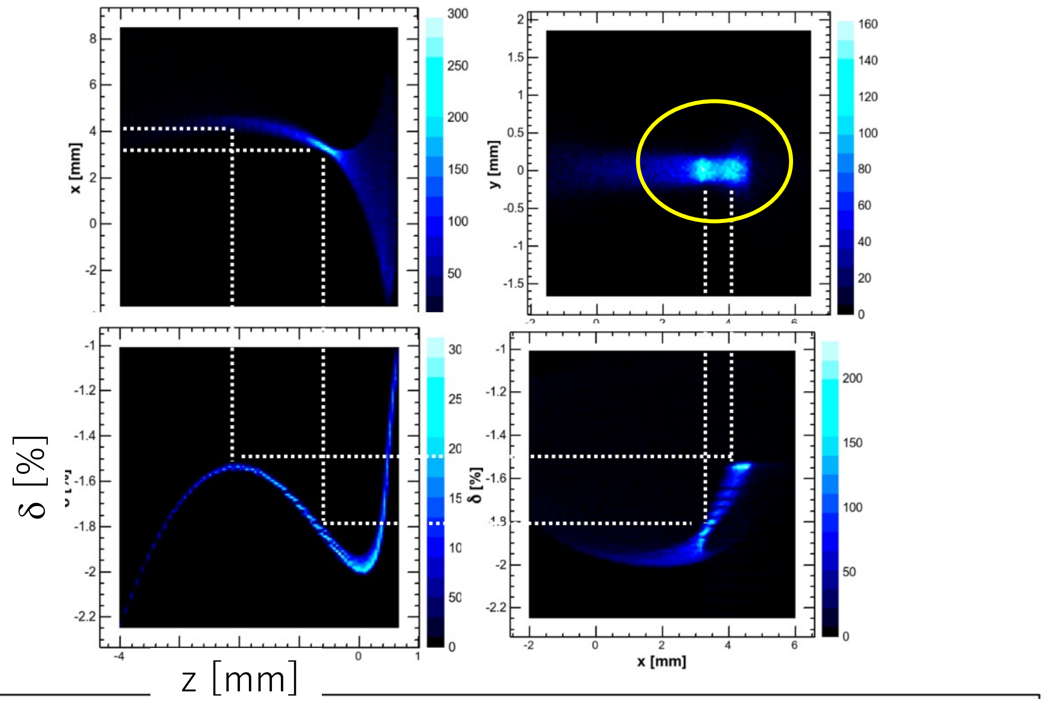
Y. Seimiya

The result of tracking simulation from RF-gun(Wake ON)

At the end of sector A
$\Delta\phi$(RF phase in sector A)=-3 deg

Two ball profile also appears in simulation.





- The size of core beam is smaller than the bunch length.
  →Depending on the position of the tail, it may look like two balls.
- When the x-z dependence due to wake is added to a beam with z-d correlation, x-d dependence automatically appears → dispersion (R16) occurs.
  - If there are two peaks in the energy, they will appear as two balls depending on the phase of the tail.
  - This does not contradict the fact that two balls can be corrected by adjusting the energy spread.

- Depending on the phase of the tail, there is a point where the orbit becomes constant, and that point becomes the second ball.

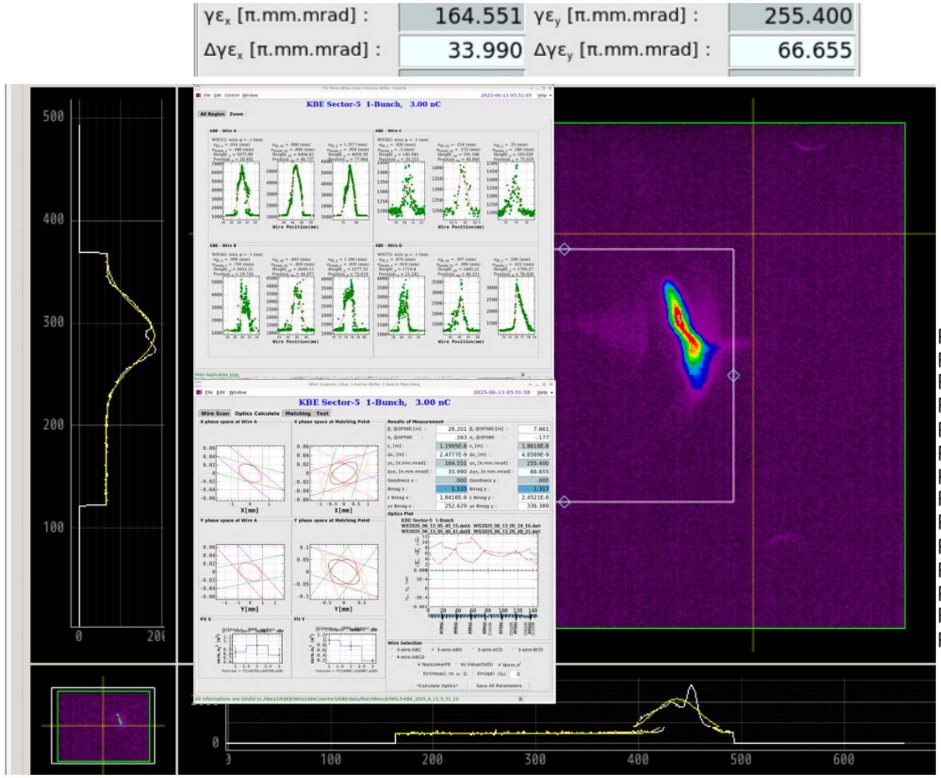
SuperKEKB injection status and issues, N. Iida

Emittance control by orbit tuning

Y. Seimiya

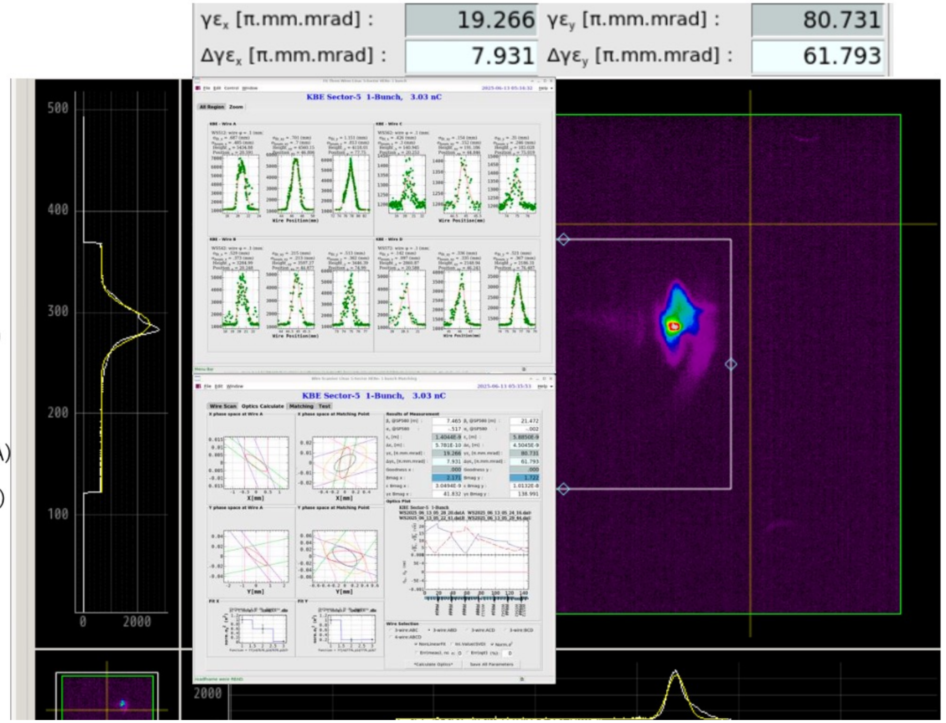
- Successfully combining two balls into one by simply tuning the orbit
- The emittances also improved.
- The source of beam profile jitter needs to be investigated.

- 調整時間はトータルで1日程度
- 運転員さんの運と実力によって大きく左右される
- プログラムでなんとかしたいところ



after tuning the orbit

PY_A1_M-KBE -2.120A → -2.140A (-0.020A)
PY_A2_2-KBE 0.410A → 0.360A (-0.050A)
PX_A4_4-KBE -0.450A → -0.430A (+0.020A)
PY_A4_4-KBE -0.350A → -0.340A (+0.010A)
PX_R0_01-KBE 3.250A → 3.550A (+0.300A)
PX_R0_61-KBE -2.660A → -2.560A (+0.100A)
PY_R0_61-KBE 4.070A → 3.670A (-0.400A)
PX_R0_63-KBE -2.599A → -2.699A (-0.100A)
PY_C7_4-KBE -0.400A → -0.500A (-0.100A)
PY_12_2-KBE 0.000A → 0.200A (+0.200A)
PX_13_5-KBE -1.920A → -1.820A (+0.100A)
PY_13_5-KBE -3.850A → -3.800A (+0.050A)
PX_21_4-KBE -1.000A → -1.200A (-0.200A)
PY_21_4-KBE -0.800A → -1.000A (-0.200A)



X has improved considerably (the tail swings left and right).
Y's tail doesn't swing up and down, so there seems to be room for improvement.

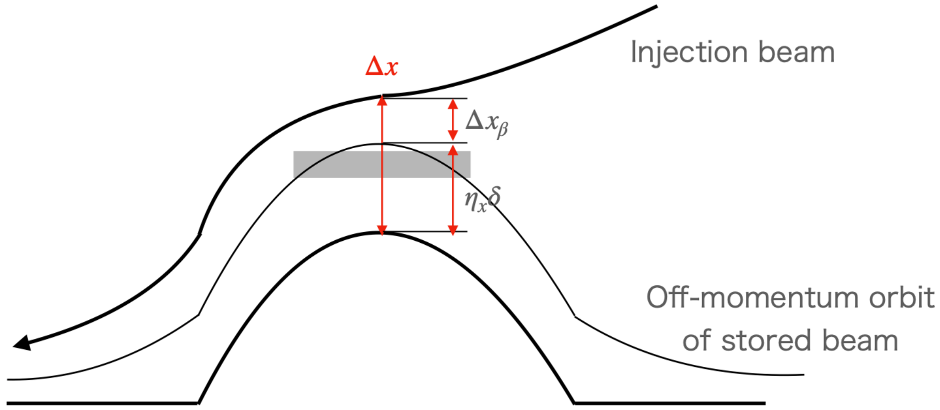
Next operation, an emittance feedback system will be implemented.

Synchrotron injection (SI)

- Convert the transverse displacement to the longitudinal by the dispersion at the injection point.
- Betatron oscillation of the injected beam produces Belle II background.
  - Synchrotron radiation of the injection beam hitting the detector beam pipe
- HER Dynamic Aperture (DA)
  - The DA seems to be narrower than the design value.
  - The center of injected beam comes right on the closed orbit by the SI.

Synchro-beta Injection

- Synchrotron injection was proposed to recover the aperture for the injected beam.
- But momentum aperture is not enough.
- Synchro-beta scheme may be a possible option.

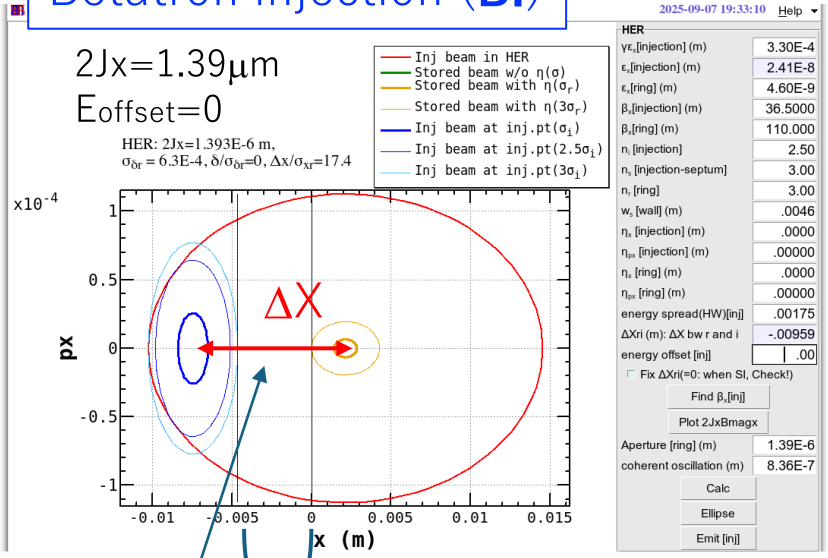


Injection oscillation

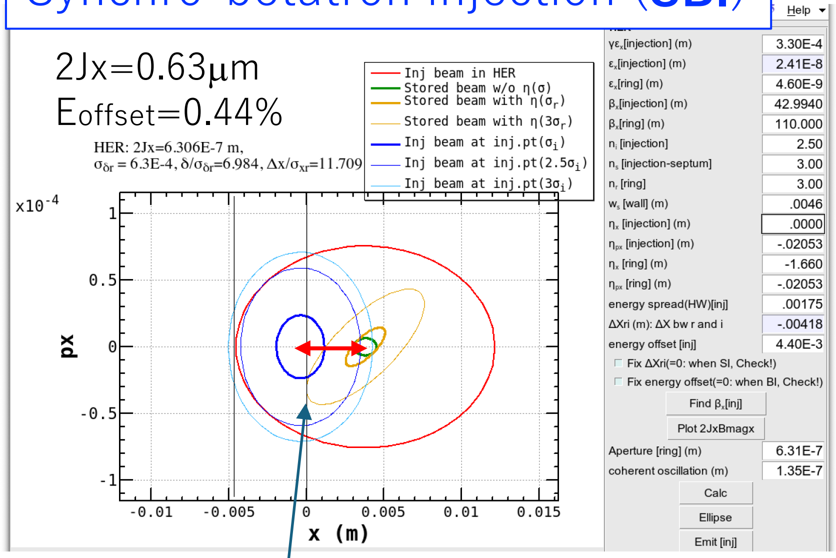
Synchrotron injection

- Introduced to **eliminate horizontal injection oscillation.**

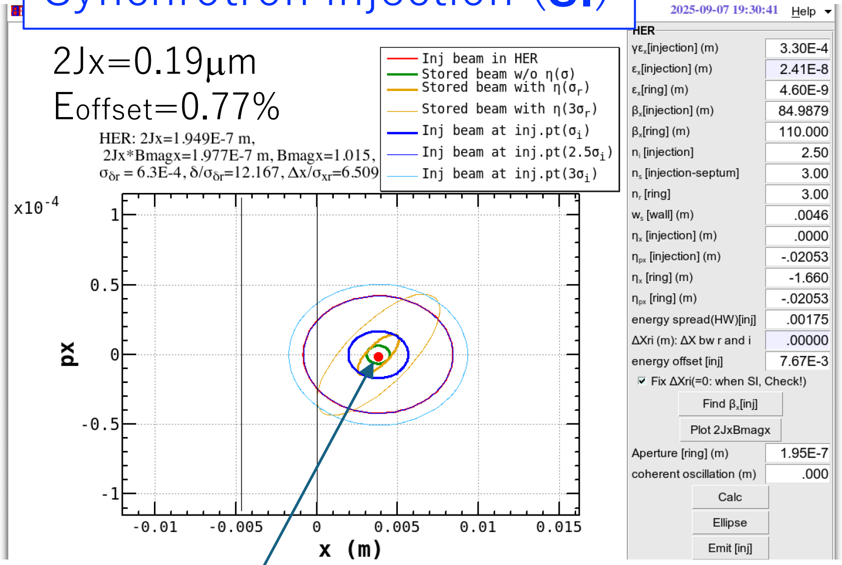
Betatron injection (**BI**)



Synchro-betatron injection (**SBI**)



Synchrotron injection (**SI**)



Septum wall

Since a part of the ΔX is converted into longitudinal oscillation, both horizontal and longitudinal oscillations can be made smaller.

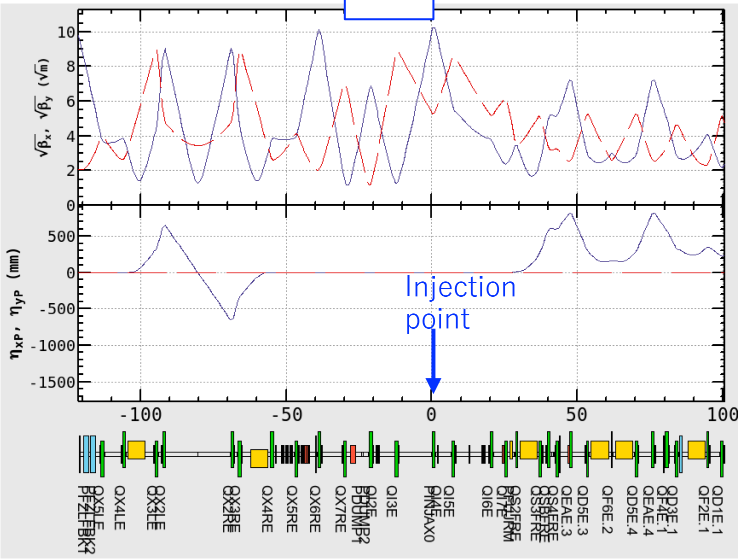
ΔX is completely converted into longitudinal oscillation, so no horizontal oscillation occurs.

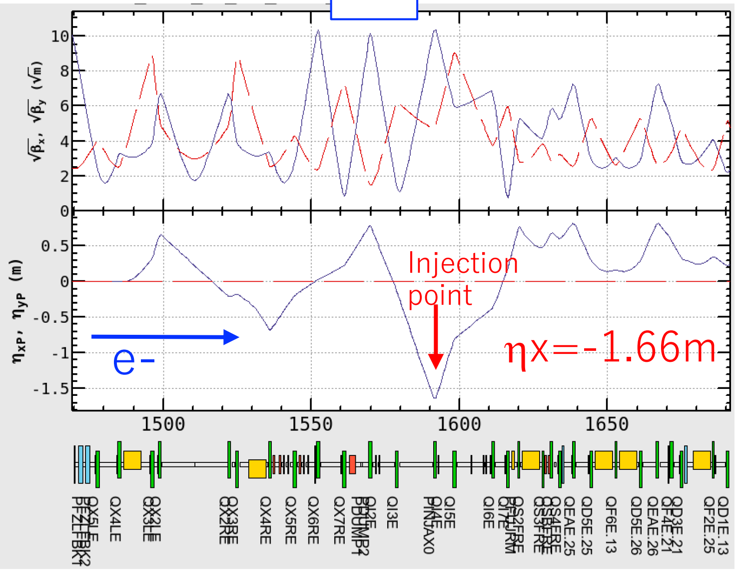
First of all, ΔX cannot be set to 0 due to the septum wall thickness.
Furthermore, if $\sigma x = \sqrt{(\varepsilon x\ \beta x)}$ is large, it will not be possible to approach the septum, and ΔX will become longer, increasing the injection oscillation.

Optics for BI and SI

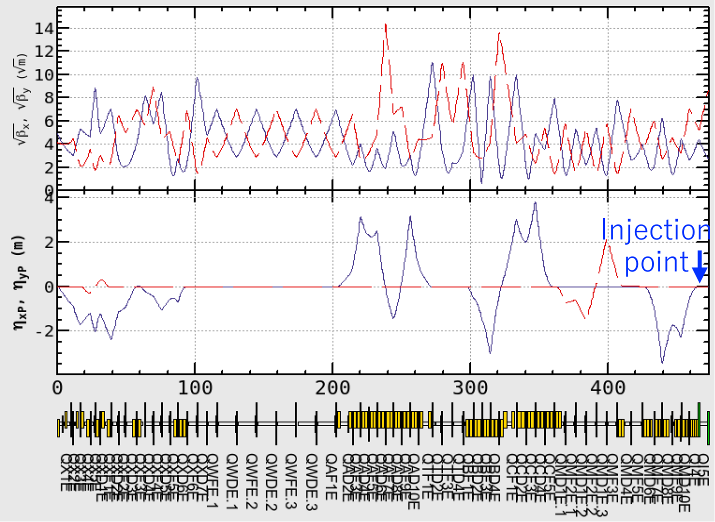
BI | **SI**

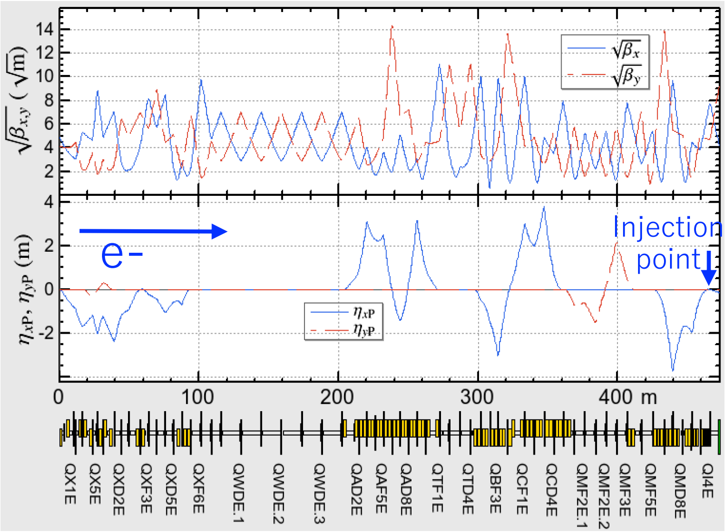
HER





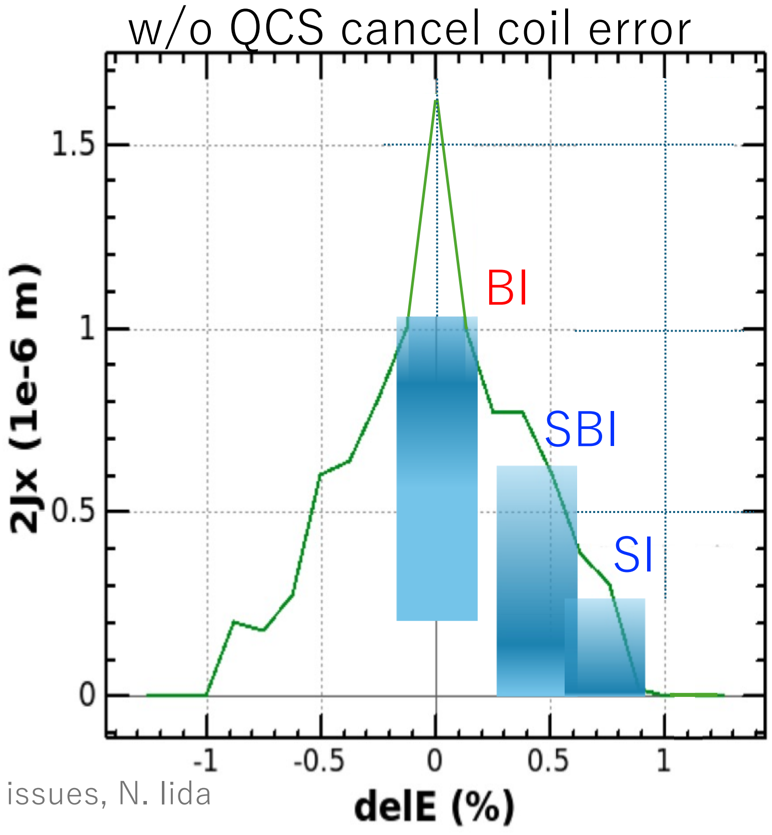
e- BT





- $\gamma\varepsilon_x$=330μm (ε_x=0.024μm)
- W_δ=±0.175%

	energy offset (Δδ) [%]	$2J_x$ (2.5σ) [x 10^{-7} m]	η_x [m]	η_{px} [m]	β_x [m]	comment
BI	0	10.4	0	0	36.5	**possible**, but large 2Jx
SBI	0.44	5.55	-1.66	-0.0205	53.5	difficult to make ηx at BT end
SBI	0.44	6.31	0	-0.0205	43.0	**possible**
SI	0.804	1.52	-1.66	-0.0205	110	difficult to make ηx and βx at BT end
SI	0.802	2.28	0	-0.0205	110	difficult to make and βx at BT end
SI	0.77	1.95	0	-0.0205	85.0	difficult to make and βx at BT end
SI	0.73	2.76	0	-0.0205	60.0	**possible**



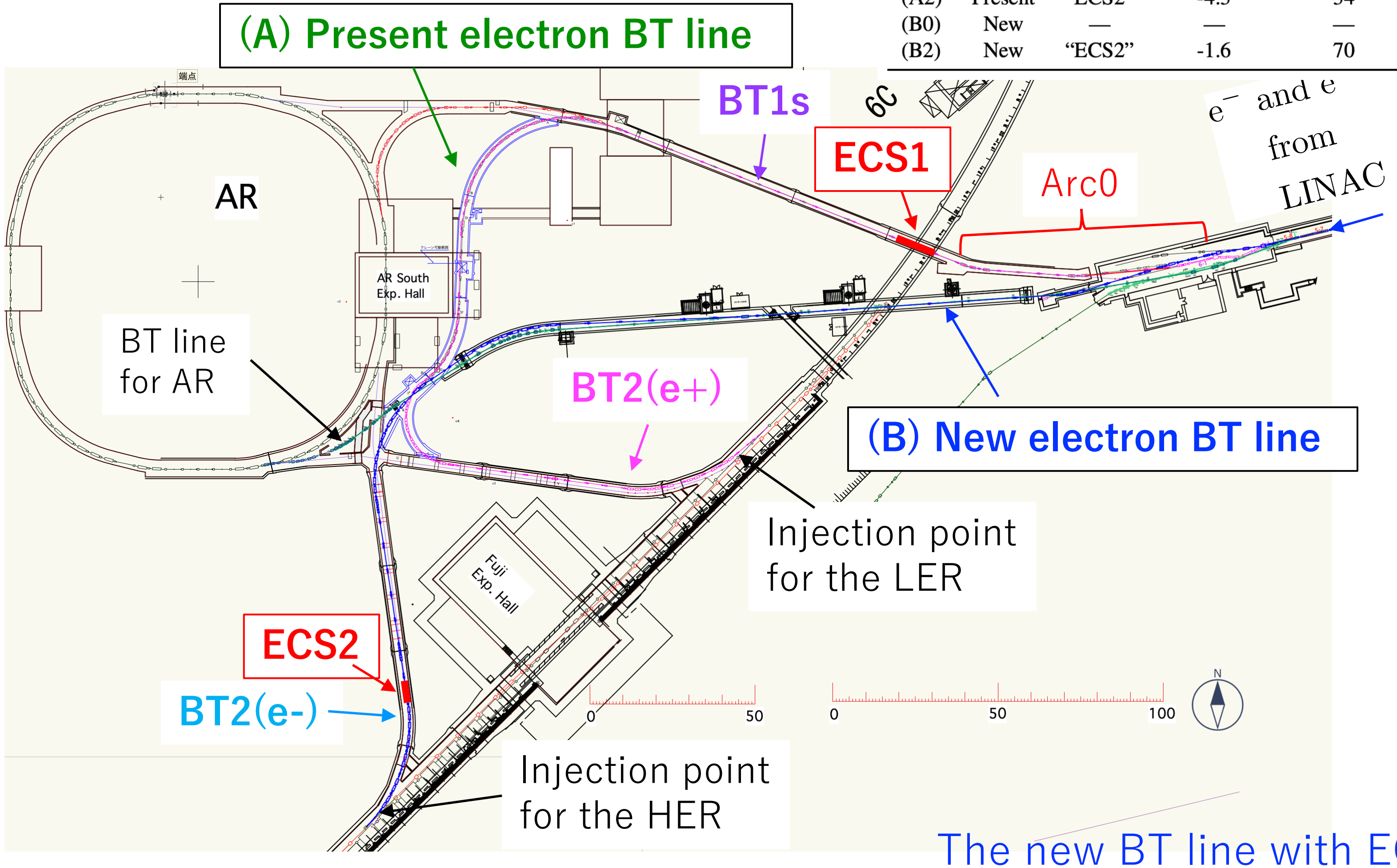
- Considering the **central value** of the distribution, **SI and BSI** are farther from the DA boundary than BI, so good injection can be expected.

Dynamic aperture is plotted by M. Kikuchi.

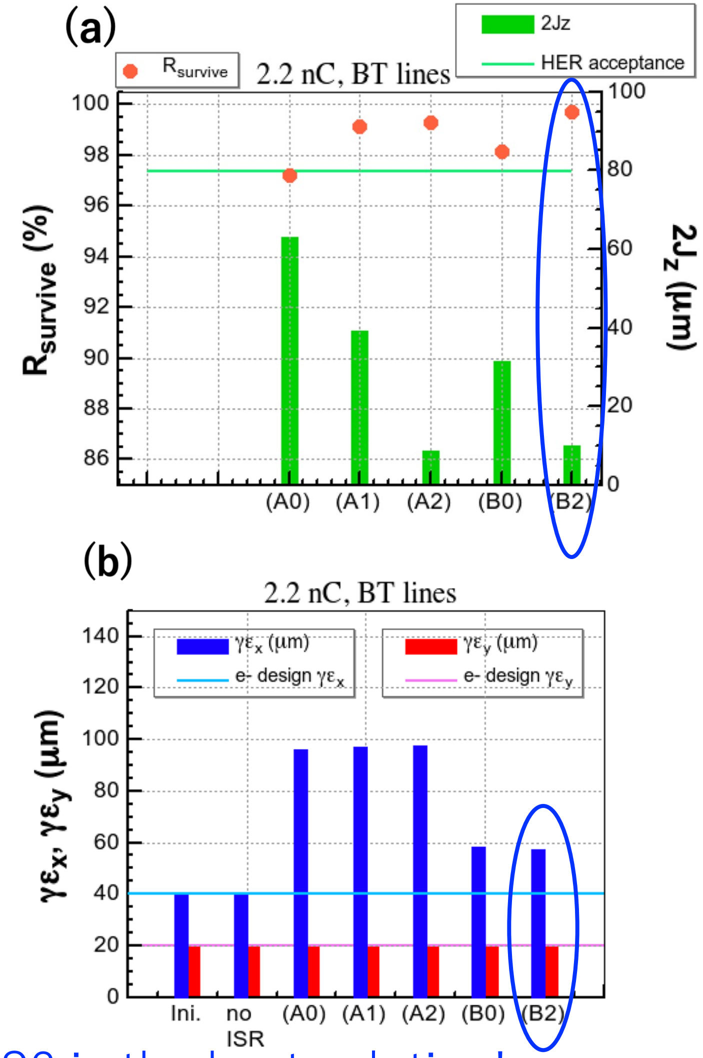
Proposal of the new straight e- BT line and The energy compression system (ECS) for e- beam

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!!

HER QCS cancel coil miswiring

Sextupole winding of the LER leak field cancel coil had installed with the opposite angle.

Manufacturing Failure of Cancel Coil in HER

N. Ohuchi, Y. Arimoto

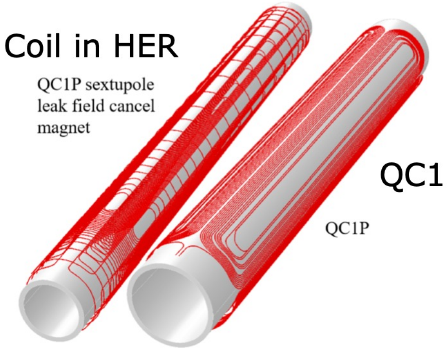
Skew sextupole and skew octupole increase (Not cancelled).

Table 24: Measured integral leak fields at R_{ref}=10 mm

Multipole coefficient	QCSL, Tm without cancelling	QCSL, Tm with cancelling	QCSR, Tm without cancelling	QCSR, Tm with cancelling
b_3	3.36×10^{-3}	2.32×10^{-5}	-3.53×10^{-3}	1.27×10^{-5}
b_4	-7.58×10^{-4}	-2.83×10^{-6}	8.02×10^{-4}	4.39×10^{-6}
b_5	1.57×10^{-4}	3.66×10^{-6}	-1.67×10^{-4}	-3.73×10^{-6}
b_6	-2.98×10^{-5}	7.8×10^{-7}	3.24×10^{-5}	2.35×10^{-6}
a_3	-2.42×10^{-4}	-3.88×10^{-4}	-2.52×10^{-4}	-4.93×10^{-4}
a_4	-5.88×10^{-5}	-1.16×10^{-4}	4.94×10^{-5}	1.71×10^{-4}
a_5	-1.48×10^{-5}	-1.48×10^{-5}	6.26×10^{-6}	-8.31×10^{-6}
a_6	1.88×10^{-5}	1.48×10^{-5}	-4.31×10^{-6}	-1.09×10^{-6}

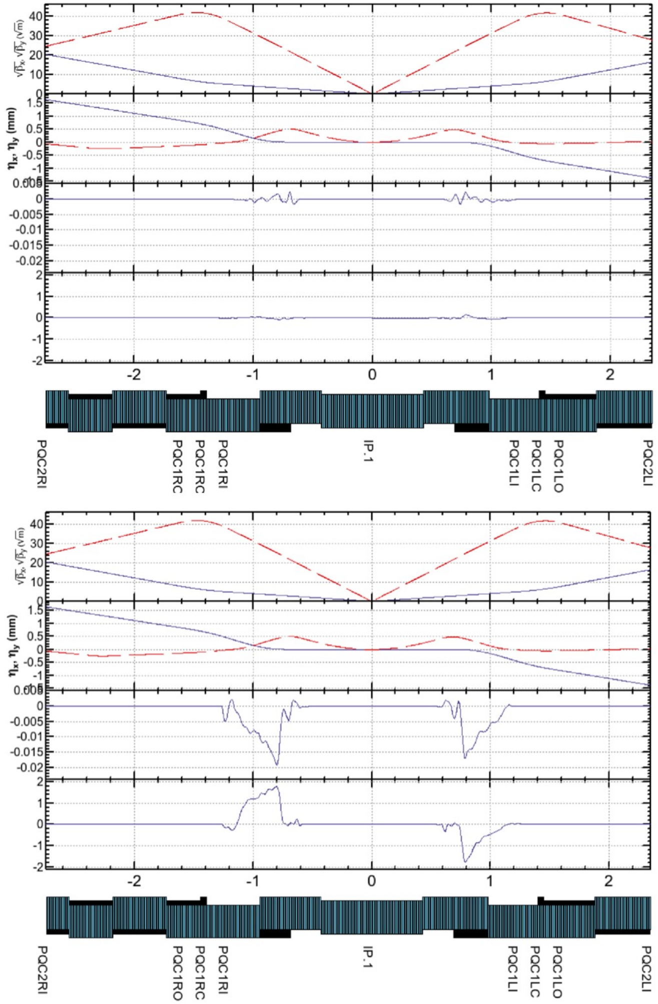
Definition of the coordinate system seems to be wrong.

Cancel Coil in HER



QC1 in LER

Y. Ohnishi

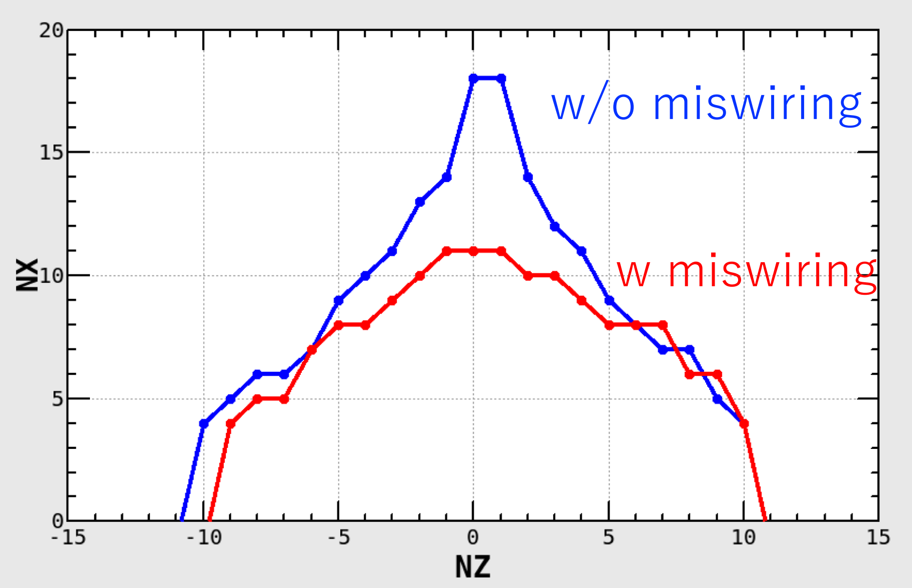


HER dynamic apertures

Miswiring: Sextupole winding of the LER leak field cancel coil had installed with the opposite angle.

H. Koiso

キャンセルコイルのエラー有無による力学口径の違い



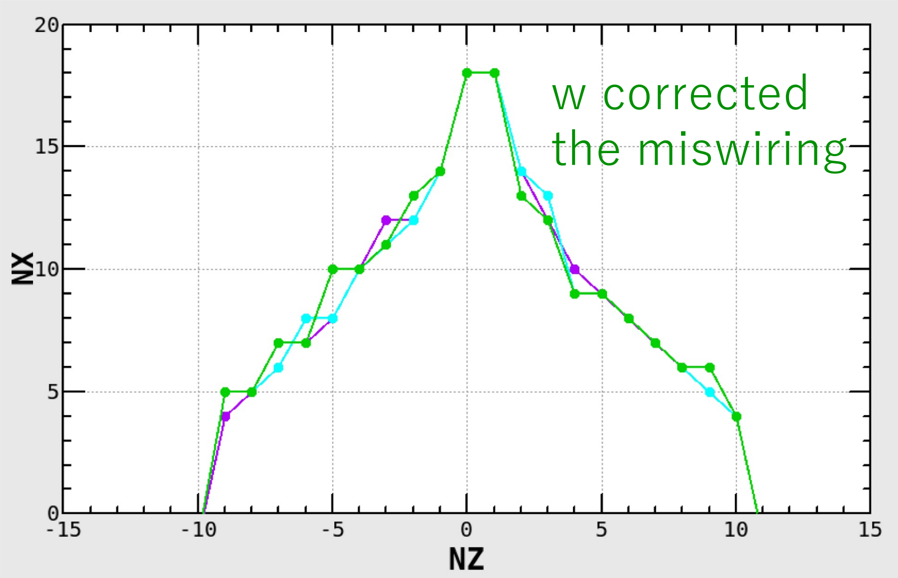
キャンセルコイルのエラー有無
による力学口径の違い

エラーなし
In[8]:= Plus@@LINE["SK2"]
Out[8]:= -.00906788959623384
sher_5781_60_1-YO20250213.sad

エラーあり
In[26]:= Plus@@LINE["SK2"]
Out[26]:= -.7442901095589288
sher_5781_60_1-can2-VSKQC1RE.sad
(VSKQC1RE SK2=0)

EMITY/EMITX
= 25 E-12 / 4.44 E-9
= 0.00563
2/27(木)杉本さんのスライドp.2
と同じ垂直エミッタンス

キャンセルコイルのエラー補正



キャンセルコイルのエラー補正

VKQC1REの直前に thin element
VSKQC1REを置きSK2を調整する。
sher_5781_60_1-can2-VSKQC1RE.sad

VSKQC1REは軌道上に配置する。
SK2を変えても線形オプティクス
は変化しない。

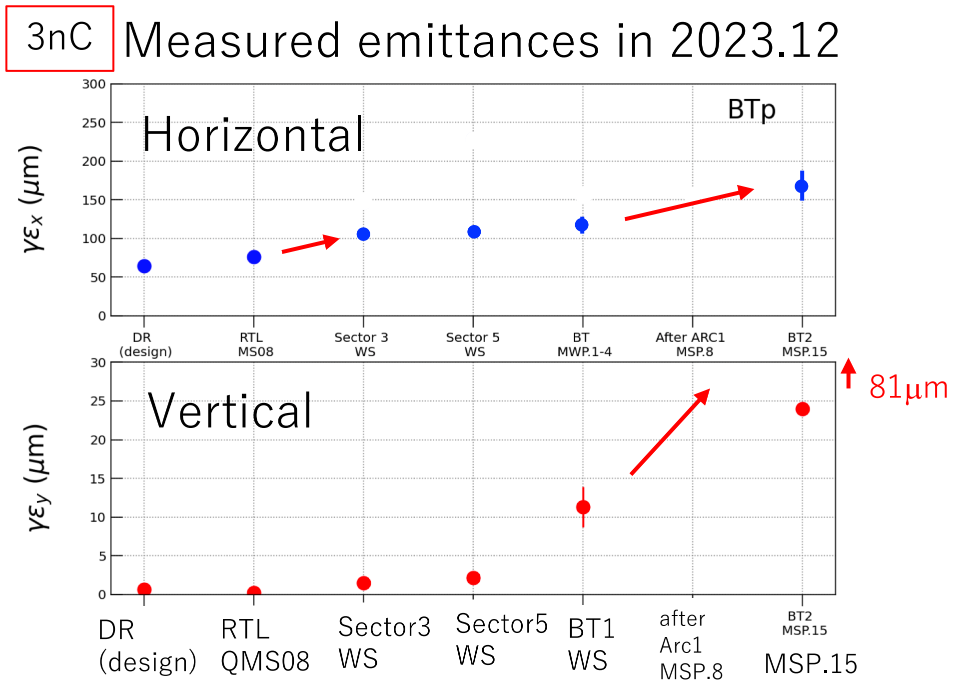
VSKQC1RE SK2 に
+0.03、+0.04、+0.05
を与えた場合、NZ = -5 ~ +5
あたりの力学口径はほぼ回復する。
これは予想通り IP左右のSK2の
アンバランスを補正する方向。

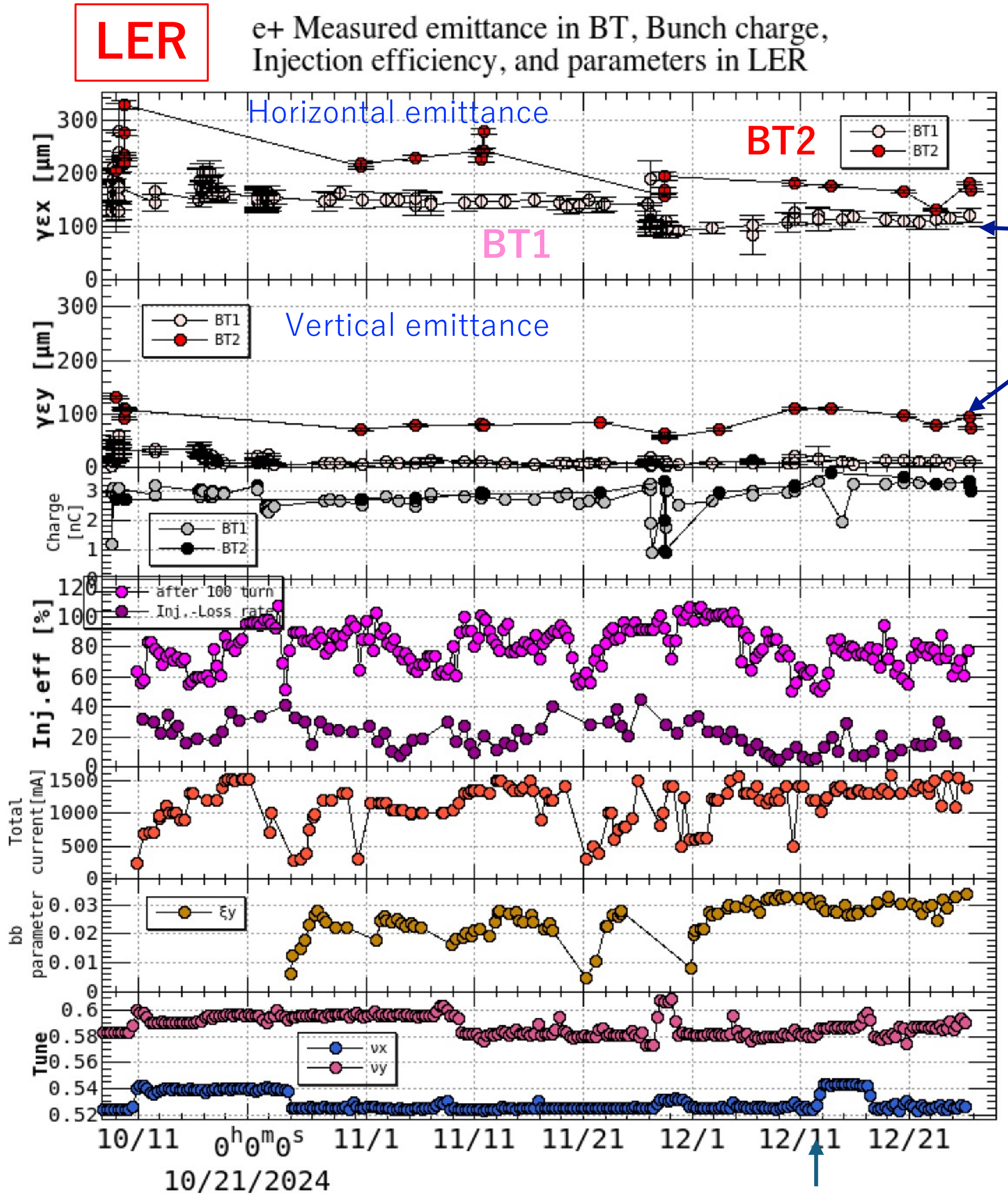
e+ beam issues

- Emittance growth in BT
- Abnormal horizontal orbit of 2nd bunch from e+ damping ring

Emittance growth of e+

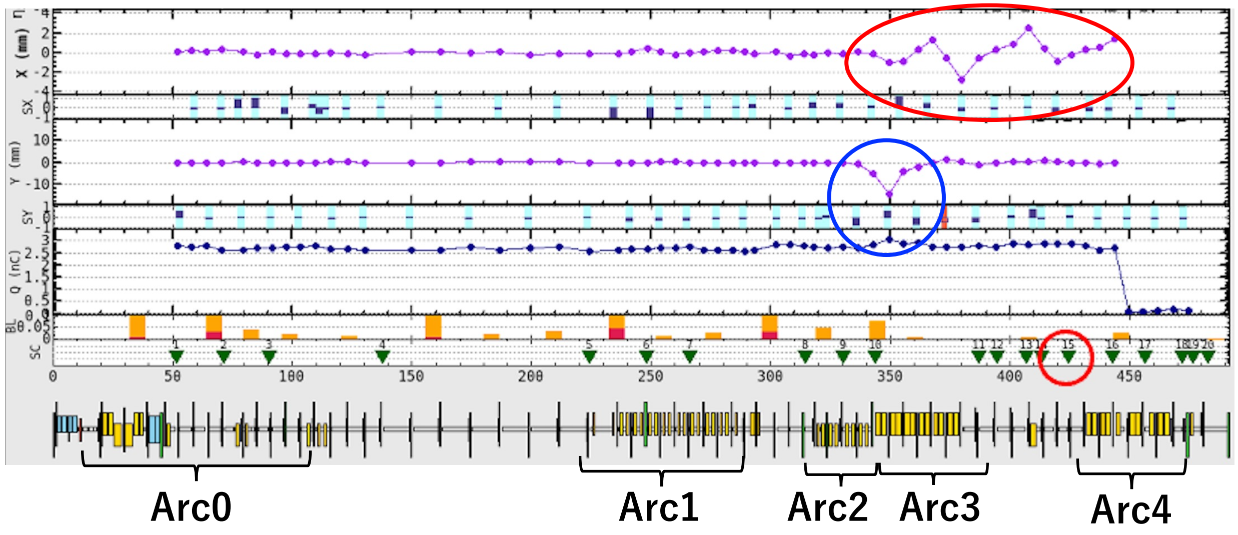
- Horizontal:
  - The effect of both ISR and CSR on the increase in emittance is negligible.
  - It increases in the latter half of RTL and within BT.
- Vertical:
  - The emittance has increased significantly at BT.
  - One of the reasons for this increase is the nonlinear magnetic field at the BT Arc2-3 bend.
    - The magnetic poles are replaced in the summer of 2025.
    - This will reduce the vertical emittance to about one-quarter of the current level.





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.

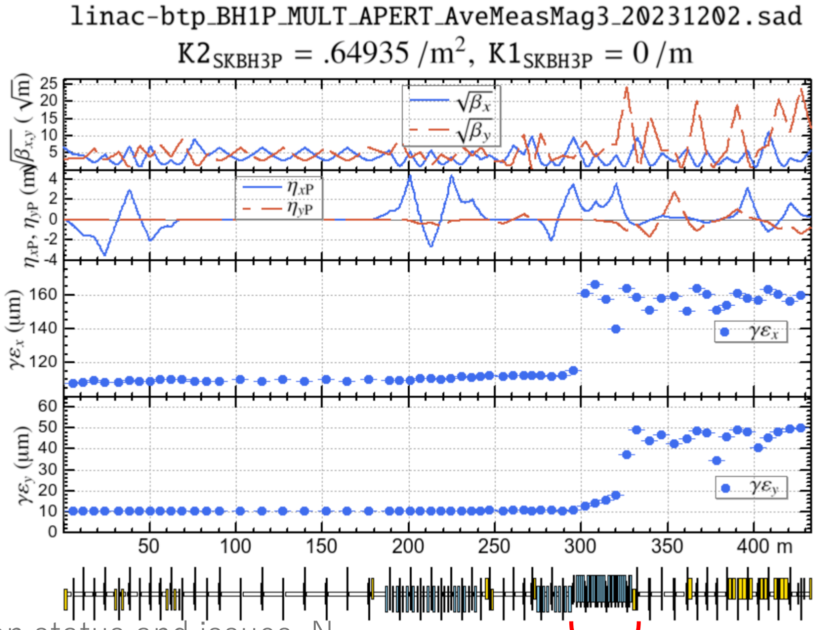
Reformed multipoles on BH3P (M. Tawada, M. Kikuchi)

Arc3

K. Oide, Feb. 25, 2025 updated 2025/4/3
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

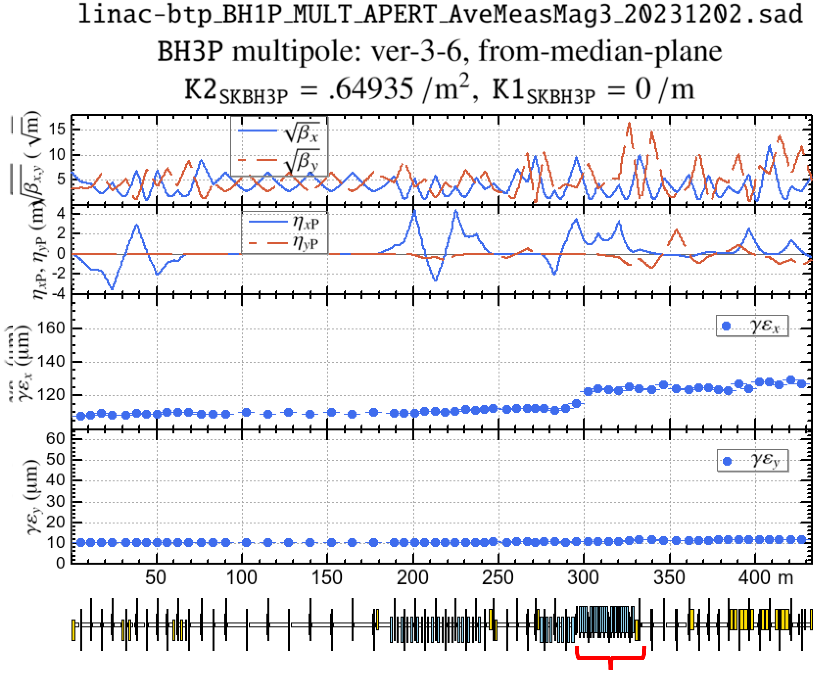
- **Tracking by SAD includes:**
  - **multipoles in BH1P/2P/3P, reform of BH3P (Tawada, Kikuchi, ver-3-6 from-median-plane)**
  - **vertical offset of BH1P (Iida)**
  - **measured rotation/pitch errors of quads in ARC3 (Tawada)**
  - **perm. skew quads for dispersion correction (Kikuchi)**
  - **measured 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**

	Meas.	Simulation	
BH2P/3P		present	reformed
K2, 1/m^2		0.65	
$\gamma\varepsilon x$@BT2 [μm]	169 ± 16	160	125
$\gamma\varepsilon y$@BT2 [μm]	81 ± 20	47	12



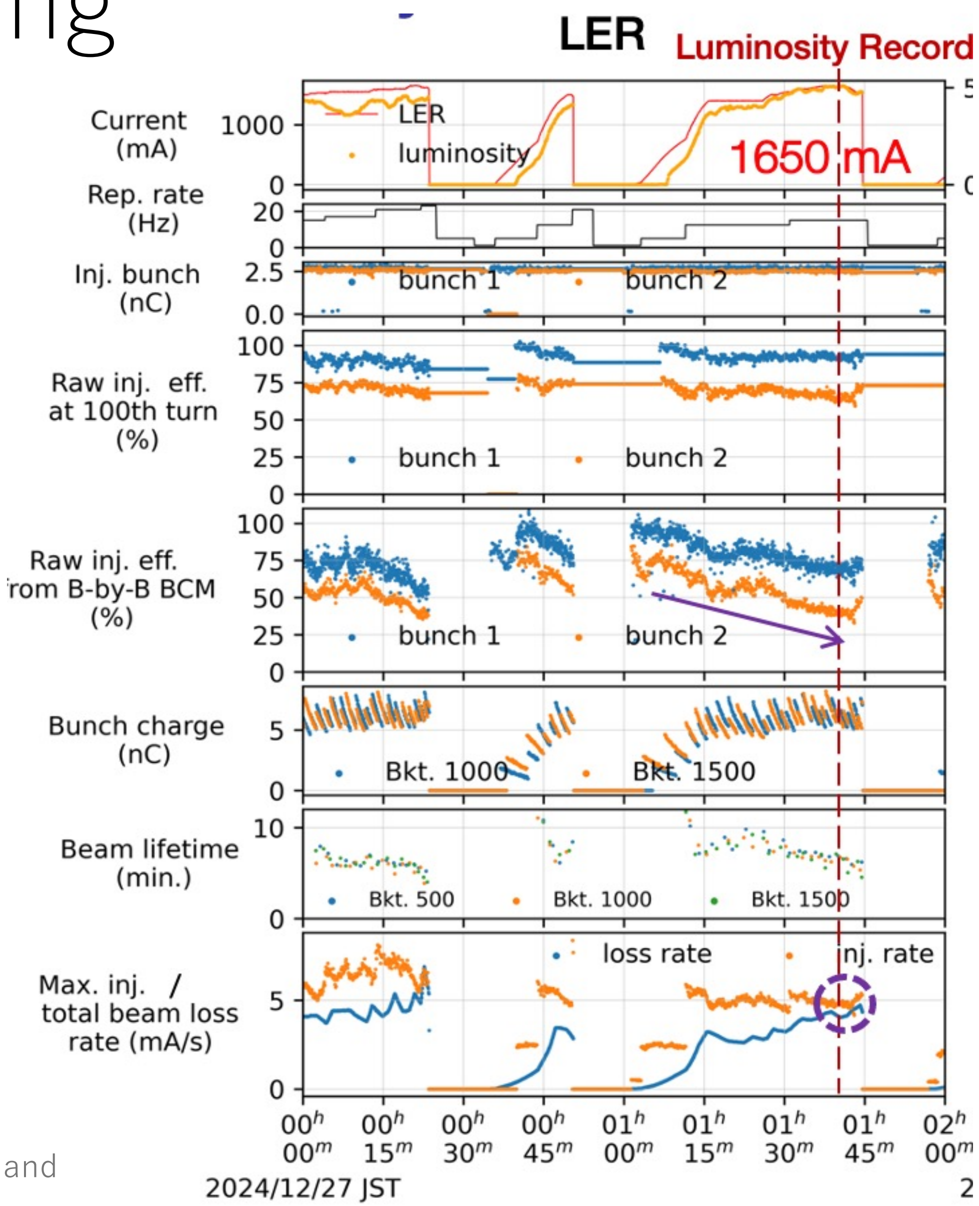
11xBH3P in Arc3

Reformed BH3P



11xBH3P in Arc3

Abnormal horizontal orbit of 2nd bunch from e+ damping ring



The injection efficiency of the 2nd bunch is lower than the 1st bunch's.

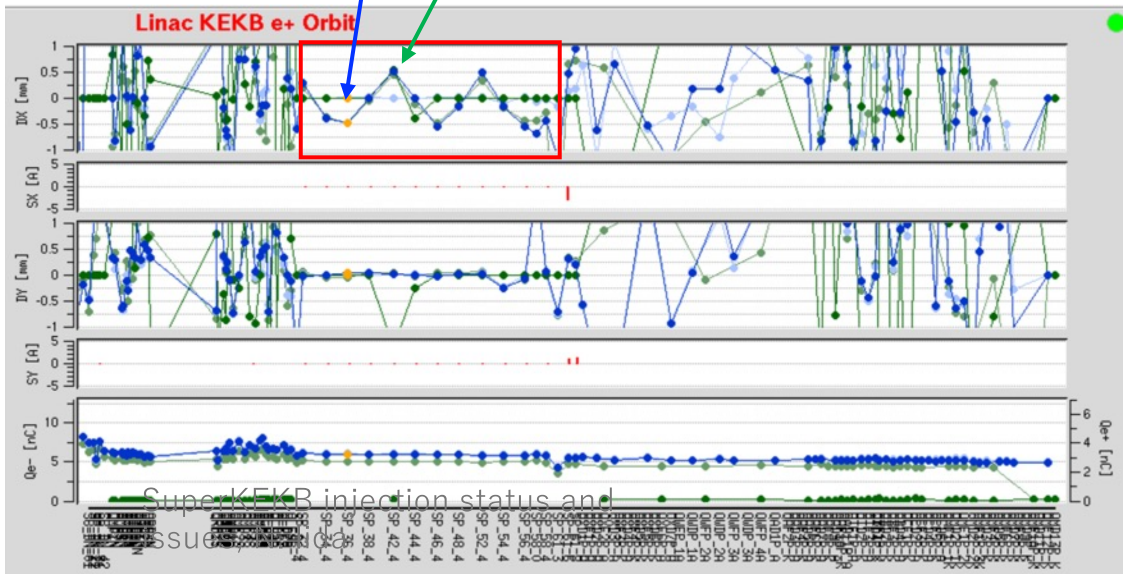
Orbit difference in two e+ bunches

- Horizontal orbit difference (~0.5 mm) is stably observed between the two bunches.
- This is considered to be caused by a pre-pulse of the DR extraction kicker, which gives different amount of kick to the two bunches one turn early before extraction.
- In the model, the resulting kick angle can explain the orbit shift in the Linac.
- While the orbit of the 1st bunch is maintained by the orbit feedback, the orbit deviation of the 2nd bunch is susceptible to the wake field in the accelerator structures, which generates the emittance growth.
- A countermeasure for the 2nd bunch is done in this summer.

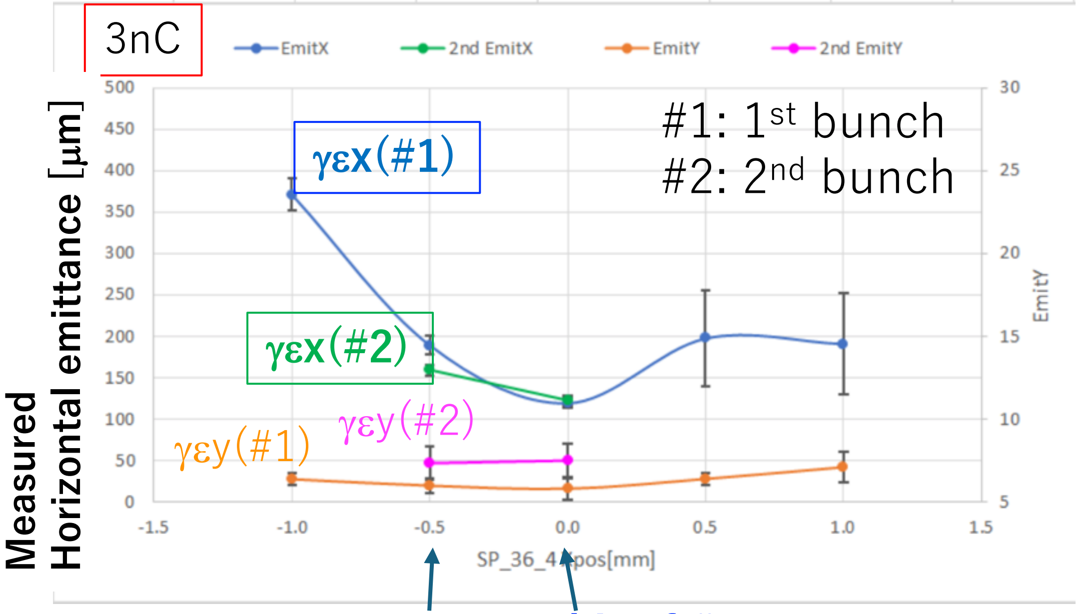
orbit of #1 (kept straight thanks to the orbit feedback)

orbit of #2

e^+ orbit



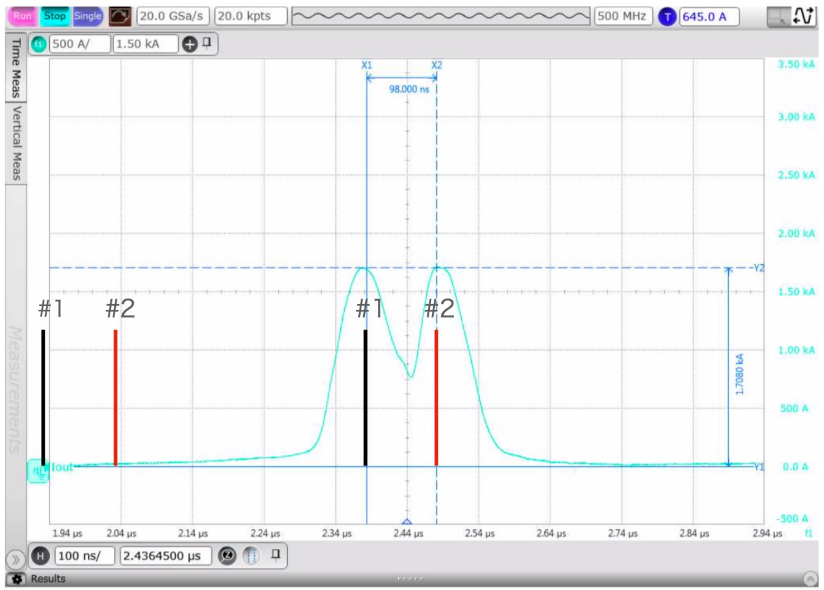
Horizontal orbit and emittance for each bunch



Pre-pulse of the extraction kicker

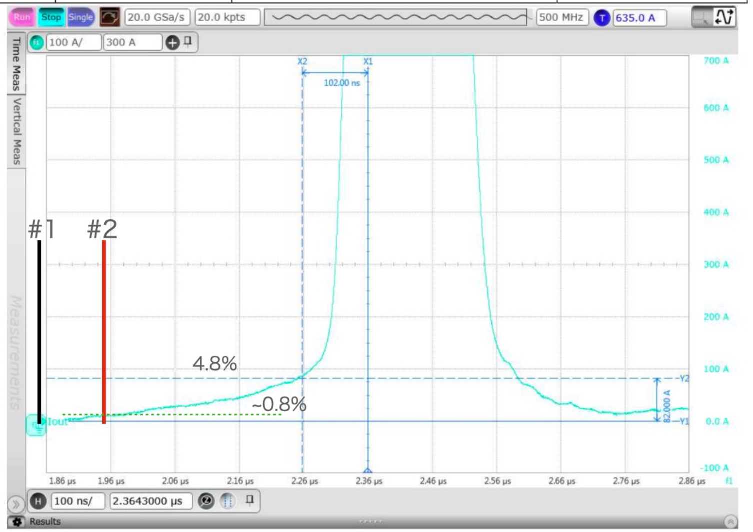
M. Kikuchi

- Pre-pulseの#2と#1の差は約0.8%と見積もられる.



(1)-4 プリパルス

N-pre	unDes / I-out =4.8%	X:100ns/div Y:300A/div	測定器：MSOS054A



- Kicker蹴り角を5 mradとすると，Pre-pulseによる バンチ#2 と バンチ#1の蹴り角の差$\Delta\theta$は，

  $\Delta\theta = 5\ \mathrm{mrad} \times .008 = 40\ \mu\mathrm{rad}$.

- 出射キッカーと出射セプタムとの位相差$\Delta\nu$は，$\Delta\nu =$ (Twiss[“nx”,$$$]-Twiss["nx","BKE*"]+Twiss["nx",PESPTU])/(2Pi) = {.2482,.2305}. （{ , }は2台のキッカーに対応する．）
- Pre-pulseによって蹴られてから1ターン後に取り出されるので，DRの水平チューン$\nu_x = 8.83$を足して，

  $\Delta\nu =$ {9.078, 9.061}

  故に，Pre-pulseによるkickは出射セプタムと同相である．

- 出射セプタムにおけるkickに換算すると，

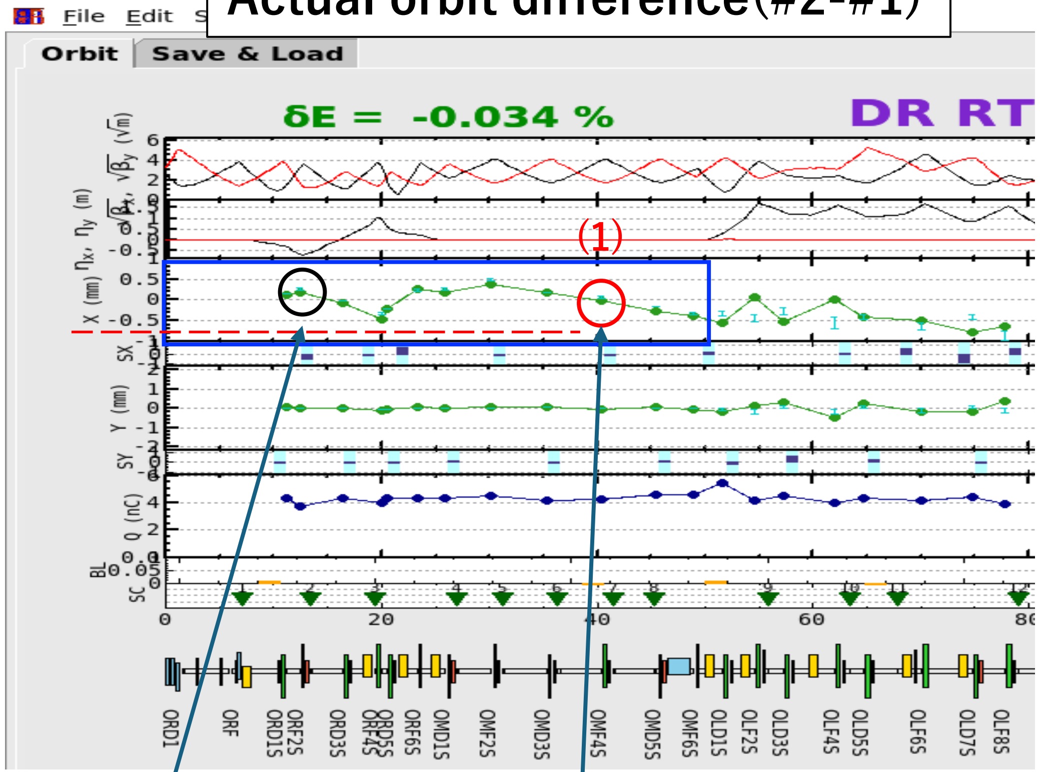
  $\sqrt{\beta_{\mathrm{kicker}}/\beta_{\mathrm{septum}}}\Delta\theta = 23\ \mu\mathrm{rad}$

  これは観測値～50μradと同程度といってよい．

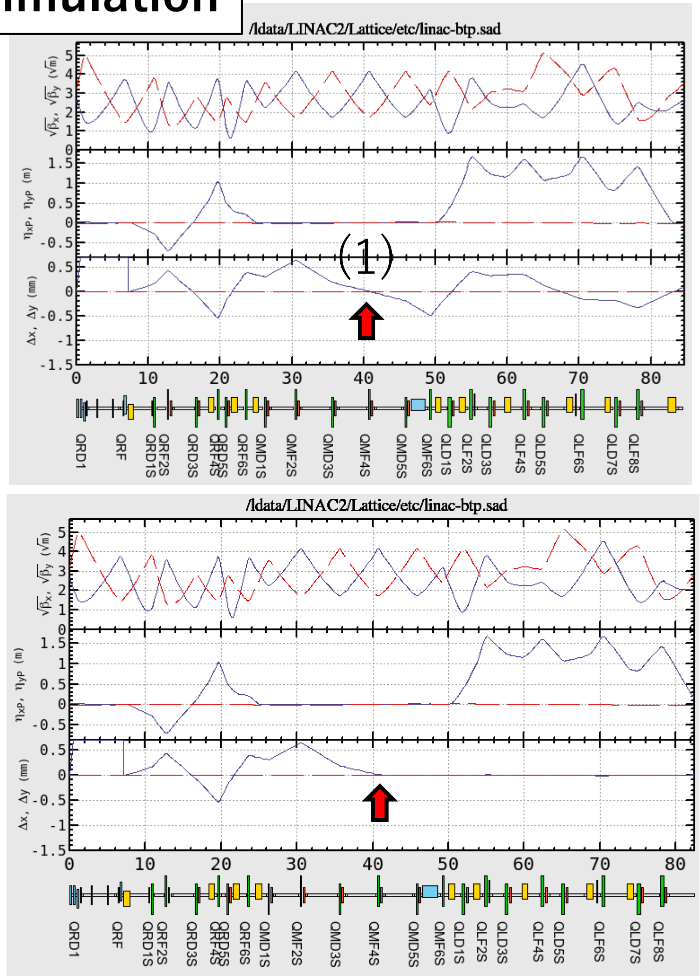
A strip line kicker installation

- The phase of the existing kicker is different, so this orbit cannot be corrected by this.
- The source is known to be the pre-pulse of the kicker.

Actual orbit difference(#2-#1)



Simulation



This cannot be corrected with existing strip line kickers.

(1)**K0**=-3.8933e-5 rad~**40μrad** of kick angle required.

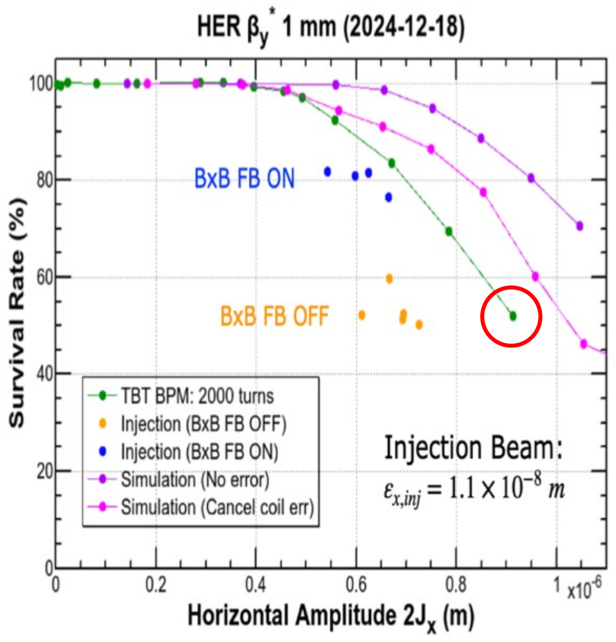
(1) can correct the orbit successfully

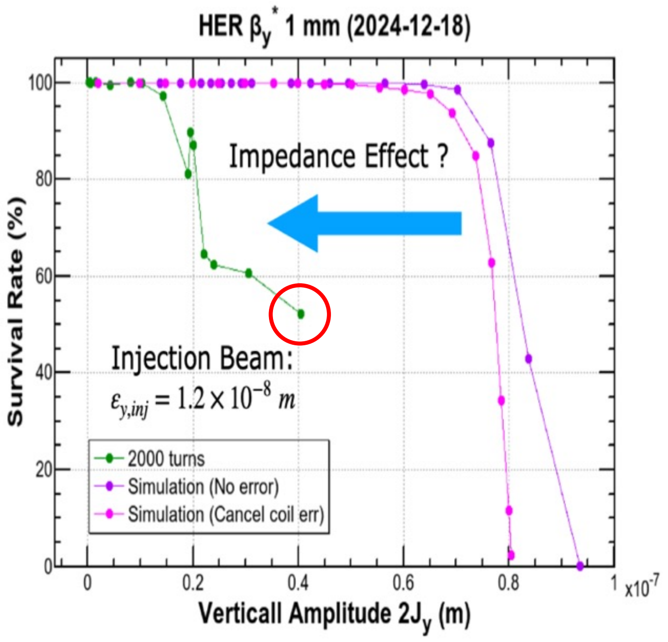
Issues in the main rings

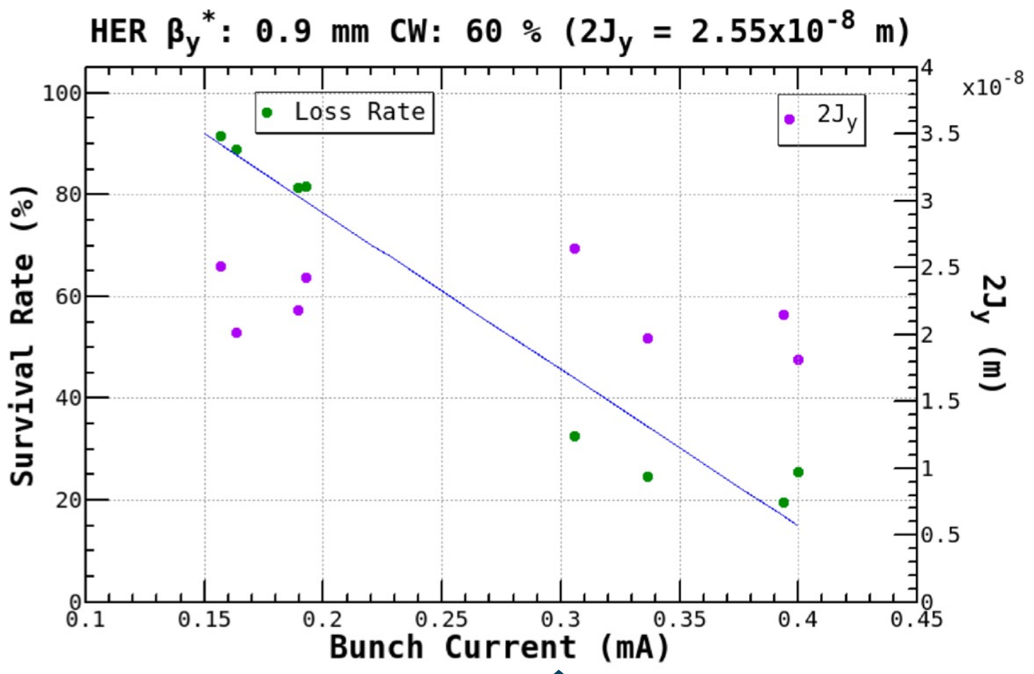
$\beta_x^* = 60\ mm\ /\ \beta_y^* = 1\ mm$

- Injection efficiency depends on the injected bunch charge.

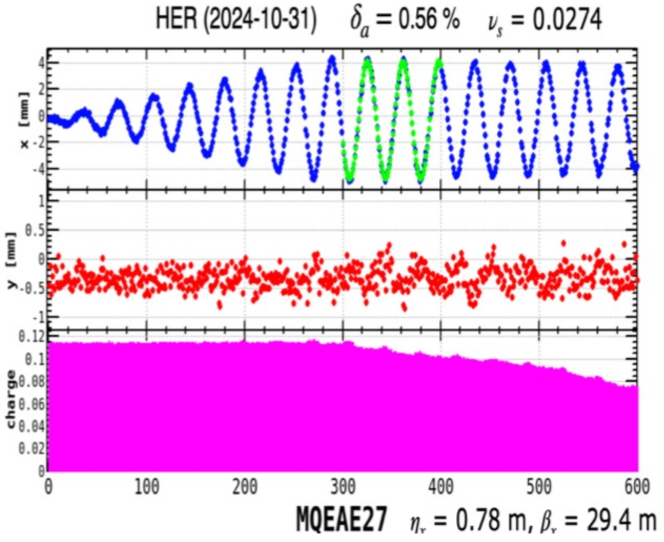
Y. Ohnishi







3 nC/bunch



2025b: 2025.May-June

- The injection efficiency ("survival ratio") clearly depends on the bunch current.
- On the other hand, it depends on the BxB FB on/off, which means there should be al least a beam oscillation at high bunch current.

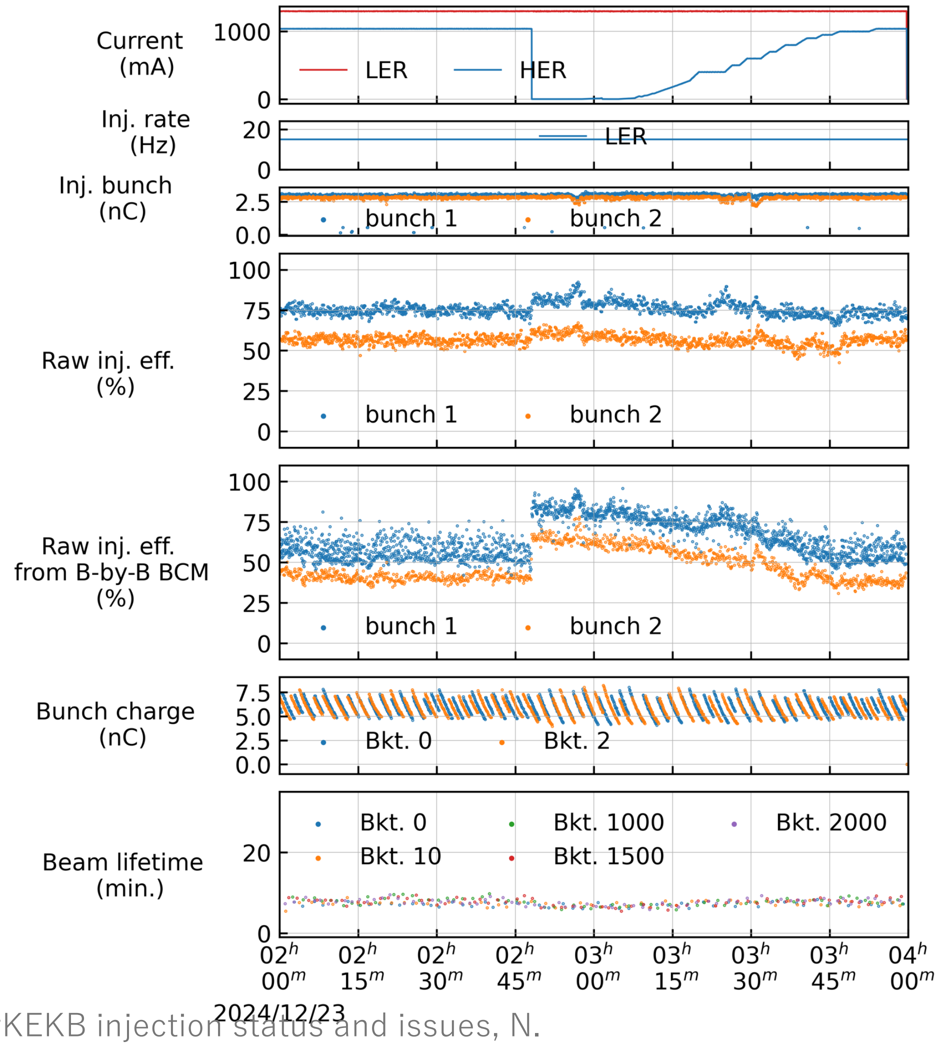
[1] Y. Ohnishi, https://kds.kek.jp/event/54174/attachments/187807/253831/SuperKEKB_eeFACT2025.pdf P.17, 19

Beam-Beam effects on Beam Injection Efficiencies

T. Yoshimoto, H. Kaji, S. Terui

- 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.

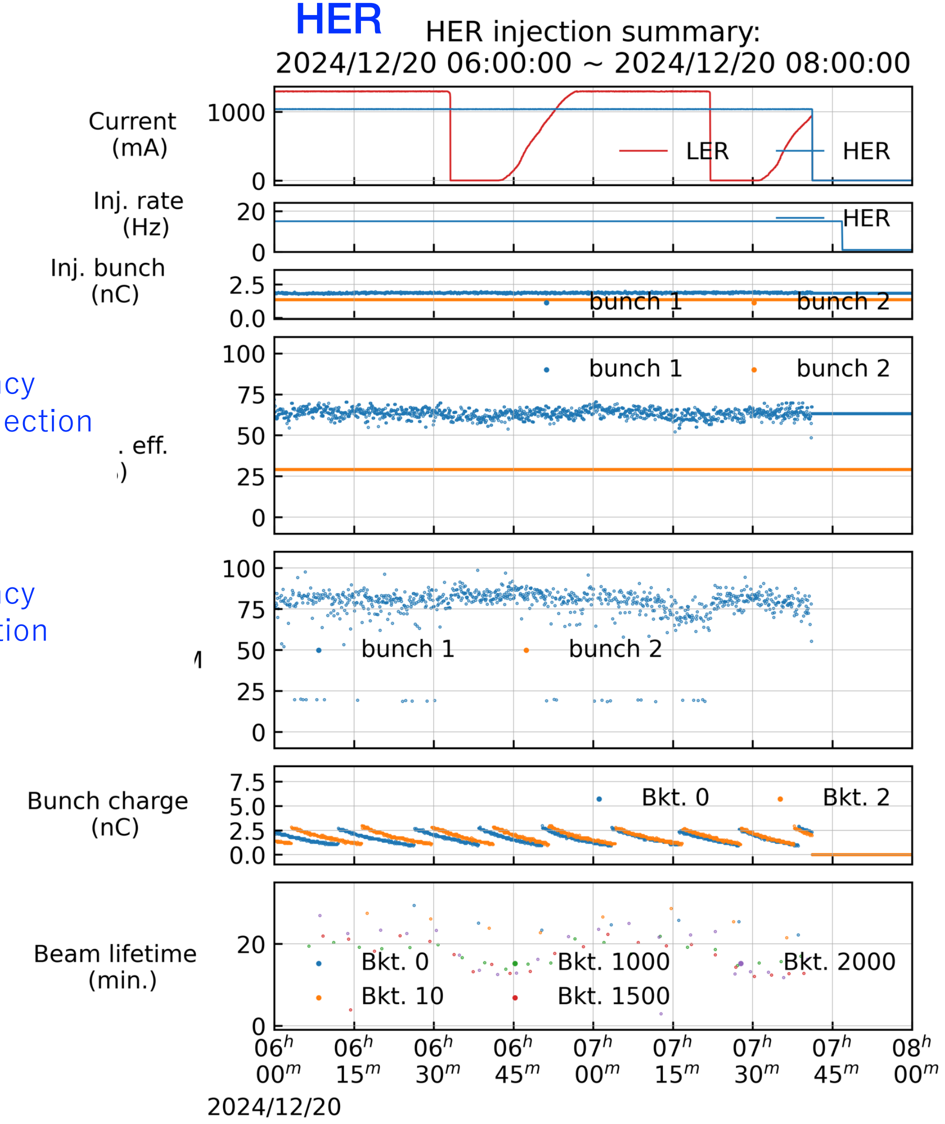
LER



Injection efficiency 100 turn after injection (%)

Injection efficiency 5 sec after injection (%)

HER

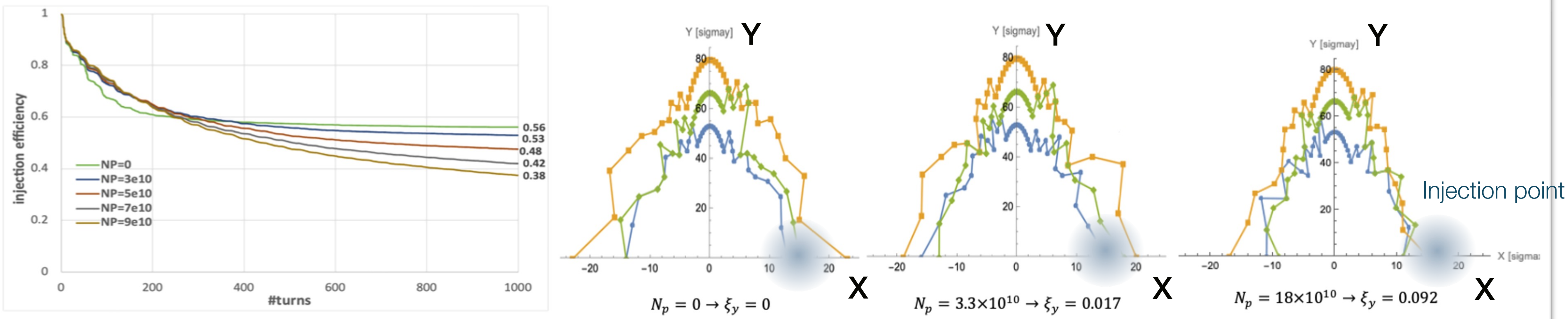


Bunch Current Dependence of HER Dynamic Aperture

T. Yoshimoto

Meng Li

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



$N_p = 0 \rightarrow \xi_y = 0$

$N_p = 3.3\times10^{10} \rightarrow \xi_y = 0.017$

$N_p = 18\times10^{10} \rightarrow \xi_y = 0.092$

[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.

40

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

T. Yoshimoto

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

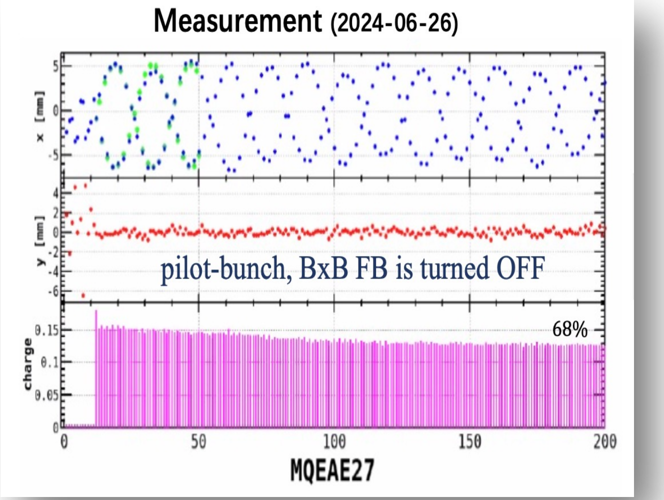
Question:

What is the potential solution?

Answer (?):

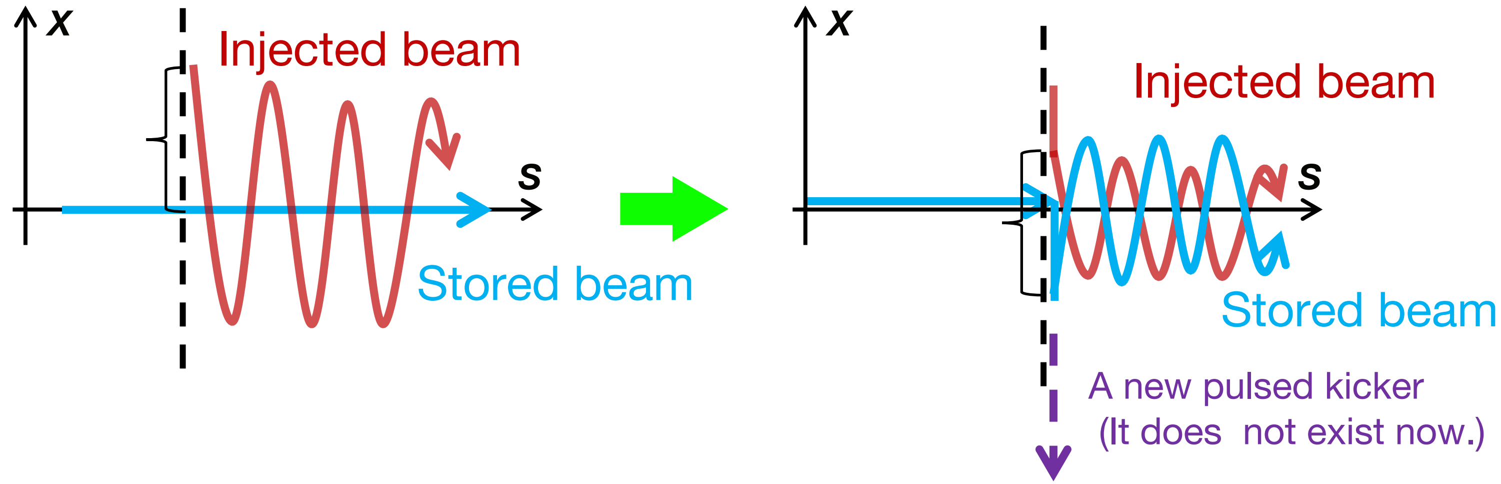
Minimize the horizontal envelope (action) of stored and injected beams at the 0th turn with a pulsed kicker, using a sophisticated B-by-B FB that turns off only for injected buckets and remains on for others.

Nominal beam oscillation:



- **Minimize the maximum betatron amplitude of injected and stored beams.**

Nominal injection (now) | **Minimum envelope injection**



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

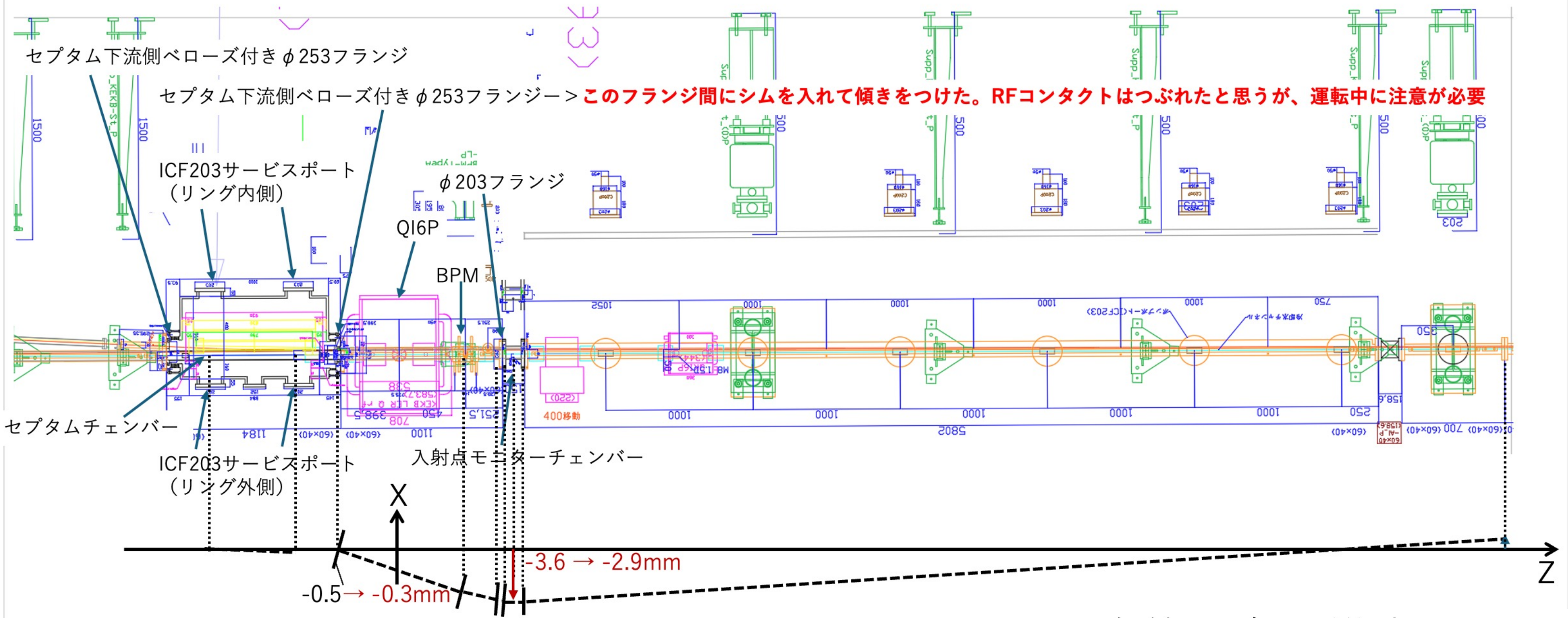
https://meow.elettra.eu/81/pdf/MOPM045.pdf

41

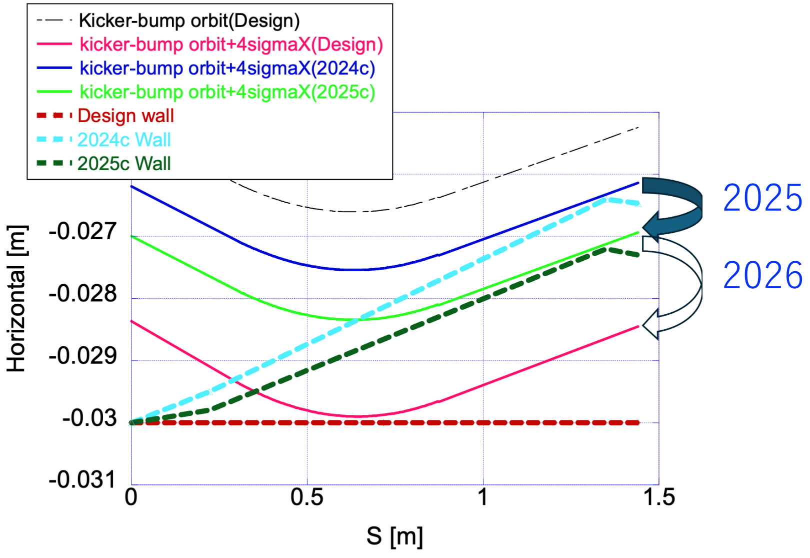
LER chamber alignment

S. Terui

入射点周辺レイアウト

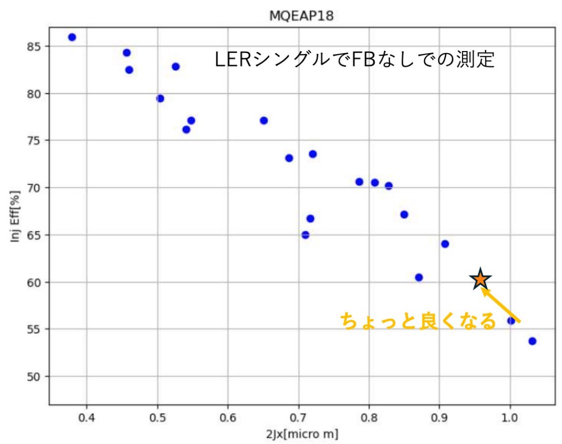


8月19日時点測定結果概略
※実測をもとに縮尺した図ではない



- The chamber aperture at the injection point had been narrowed.
- It will be gradually improved from this summer.

By*1mmでの２Jxの改善具合の推定



- ライフ４分、入射電荷 6 nC、入射レート 23 Hz、周長 3000m、入射効率 60% ->1.99A
- **LERシングル、By*1mm の条件で 2Aに到達可能！（かも？）**

Summary

- e- beam
  - The emittance blowups are observed in both of horizontally and vertically.
    - An unexpected X-Y coupling in BT Arc1 is generated.
  - The emittance blowups are enhanced by increasing bunch charge from 2.2 nC to 3 nC, or making R56 in BT Arc0 from -0.11 m to -0.7 m.
    - However, the emittances in BT1 are same value for both cases.
    - A new emittance feedback system will be operated in the next study.
  - QCS cancel coil error will be corrected by tuning the QCS auxiliary winding, which is effective to improve the injection efficiency.
- e+ beam
  - The dipole magnet with a high magnetic field installed on BT Arc3 was causing an emittance blowup.
    - Replacing the pole this summer in ongoing.
  - The DR extraction septum unexpectedly kicked the second bunch, causing the horizontal emittance of the second bunch to increase due to the Linac wake.
    - A fast kicker kicking only the second bunch is currently being installed.
  - The chamber re-alignment is expected to improve the injection efficiency by 10%.
- Collider rings
  - Measured dynamic aperture is smaller than designed.
  - Injection efficiency becomes lower at the higher bunch current.
  - Injection efficiency becomes lower at the collision.
  - Minimize the maximum betatron amplitude of injected and stored beams.

Thank you for your attention!!!

Backup

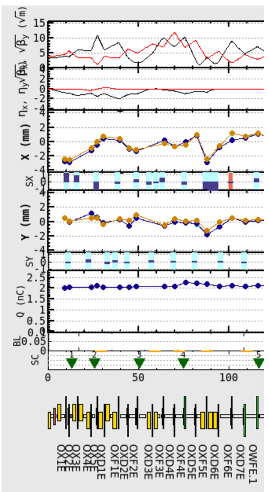
2.2nC

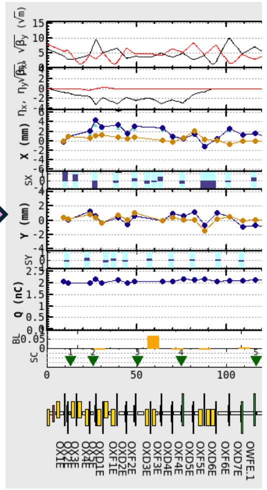
SRM profiles change by R_{56}

While observing **SRM-1**, the orbit and SB_35 were scanned.

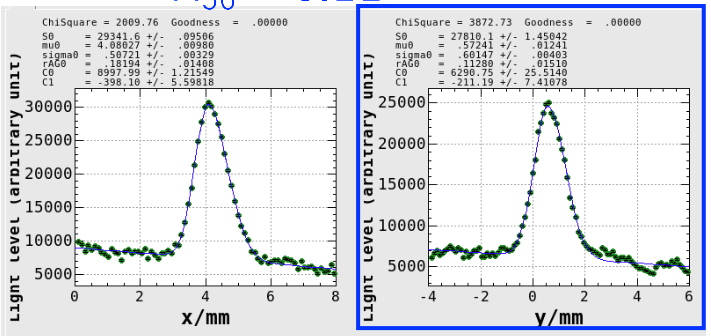
Although it became slightly smaller, didn't recover to the original size.

- Changed the orbit in Arc0

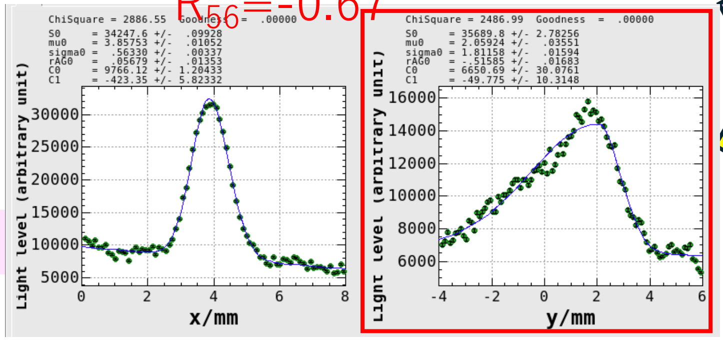


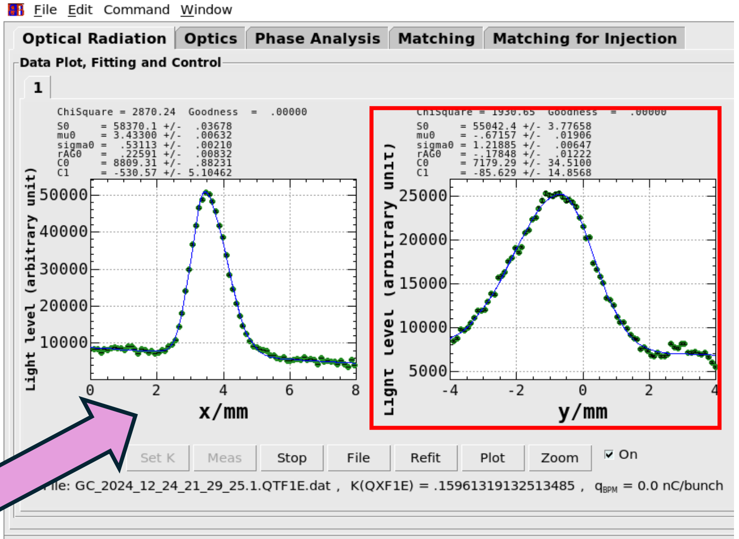


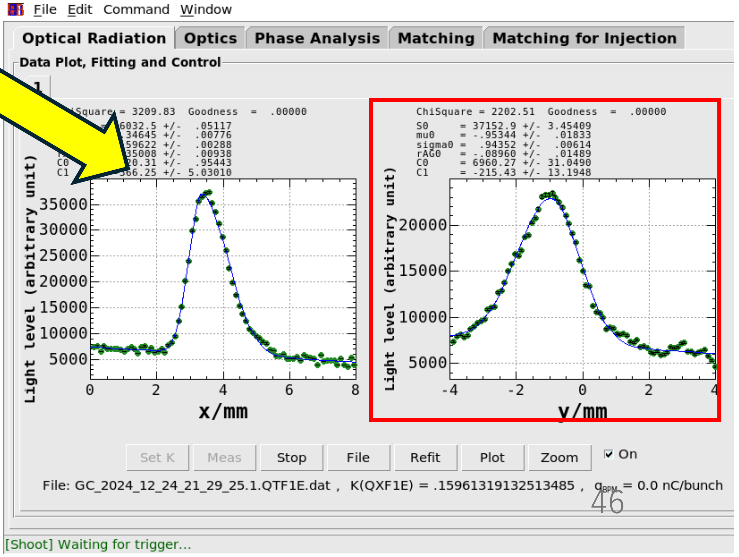
R_{56}=-0.11



R_{56}=-0.67





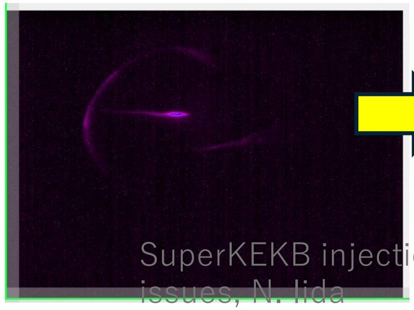


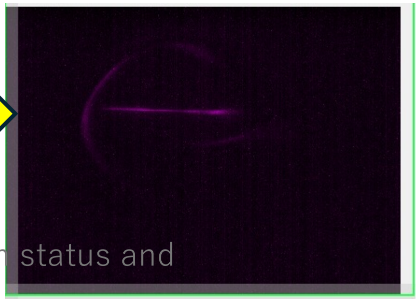
- Changed the RF phase of sector 3-5 in Linac

18:27:02

SB_3 (KBE) 92.0°、SB_4 (KBE) 93.1°、SB_5 (KBE) 95.1°

SB_3～5(KBE) 元値 → -1° → -2° → ±0° → +1° → +2° → +3° → +4° → +5°





June.2-5間のエミッタンス履歴

Date	Charge [nC]				γεx [μm]	Δγεx [μm]	BMAGx		γεy [μm]	Δγεy [μm]	BMAGy	R56-Arc0 [mm]	# of shot	
2025.6.2	2.845	2025-6-2-12-00-34	MSE.10	QTF1E	338.97	4.868	2.117					-0.11	50	before orbit correction
2025.6.2	2.792	2025-6-2-12-58-13	MSE.10	QTF1E	298.73	4.556	1.921					-0.11	50	after orbit correction
2025.6.2	2.511	2025-6-2-13-13-24	MSE.10					QTD2E	169.81	2.228	1.073	-0.11	50	after orbit correction, しかしSRM_BH3E_1, screen:-10になっている
2025.6.2	2.816	2025-6-2-14-12-54	MSE.10	QTF1E	237.443	3.559	1.759					-0.11	50	after -2mm H.orbit with BM_61_H1(161 → 169mA)
2025.6.2	2.493	2025-6-2-14-41-43	MSE.10					QTD2E	271.646	3.678	1.075	-0.11	50	after -2mm H.orbit with BM_61_H1(161 → 169mA)
2025.6.2	2.497	2025-6-2-15-21-3	MSE.10					QTD2E	265.633	3.689	1.083	-0.11	50	after -2mm H.orbit with BM_61_H1(161 → 169mA)
2025.6.2	2.497	2025-6-2-15-57-35	MSE.10					QTD2E	240.908	3.214	1.081	-0.11	50	reset 0mm H.orbit with BM_61_H1(169 → 161mA)
2025.6.2	2.497	2025-6-2-16-20-24	MSE.10	QTF1E	264.794	3.848	1.78					-0.11	50	reset 0mm H.orbit with BM_61_H1(169 → 161mA) Reference orbit
2025.6.2	2.815	2025-6-2-18-46-11	MSE.10					QTD2E	106.432	1.436	1.01	-0.11	50	SRM1を見てsigma_yが小さくなるようにPY_A1_M等で調整
2025.6.2	2.769	2025-6-2-20-4-19	MSE.10	QTF1E	320.51	4.67	1.407					-0.11	50	ECSに山脈H.bump-6mmを立てる
2025.6.2	2.776	2025-6-2-20-21-58	MSE.10	QTF1E	337.373	5.188	2.036					-0.11	50	Reference orbit
2025.6.2	2.766	2025-6-2-20-48-29	MSE.10					QTD2E	106.137	1.448	1.041	-0.11	50	Reference orbit
2025.6.2	2.776	2025-6-2-22-46-17	MSE.10	QTF1E	421.353	5.635	1.863					-0.67	50	R56=-0.67m
2025.6.2	2.835	2025-6-2-22-54-39	MSE.10					QTD2E	170.693	2.229	1.167	-0.67	50	R56=-0.67m←あきらめる
2025.6.3	1.287	2025-6-3-11-41-48	MSE.10	QTF1E	127.341	2.664	1.308					-0.11	50	R56=-0.11m, 1nC
2025.6.3	0.923	2025-6-3-12-1-30	MSE.10					QTD2E	99.768	2.298	1.411	-0.11	50	R56=-0.11m, 1nC
2025.6.3	0.912	2025-6-3-19-58-47	MSE.10	QTF1E	173.337	3.629	1.512					-0.7	50	R56=-0.7m, Optics matching BT1, 1nC
2025.6.3	0.911	2025-6-3-20-17-10	MSE.10					QTD2E	99.921	2.222	1.353	-0.7	50	R56=-0.7m, Optics matching BT1, 1nC
2025.6.3	0.912	2025-6-3-20-33-40	MSE.10	QTF1E	167.07	3.746	1.462					-0.7	50	R56=-0.7m, Dispersion corr., 1nC
2025.6.3	0.918	2025-6-3-20-49-27	MSE.10					QTD2E	97.395	2.177	1.388	-0.7	50	R56=-0.7m, Dispersion corr., 1nC
2025.6.3	2.845	2025-6-3-23-2-0	MSE.10	QTF1E	599.799	8.006	1.331					-0.7	50	R56=-0.7m, 3nC
2025.6.3	2.871	2025-6-3-23-14-19	MSE.10					QTD2E	138.861	1.885	1.255	-0.7	50	R56=-0.7m, 3nC
2025.6.4	2.872	2025-6-4-20-13-7	MSE.10	QTF1E	342.785	5.023	1.954					-0.7	50	R56=-0.7m, 3nC, 山脈Bump H: -6mm, V; +6mm
2025.6.4	2.89	2025-6-4-20-29-37	MSE.10					QTD2E	157.697	2.131	1.127	-0.7	50	R56=-0.7m, 3nC, 山脈Bump H: -6mm, V; +6mm
2025.6.4	2.911	2025-6-4-23-38-20	MSE.10	QTF1E	333.392	4.778	1.88					-0.7	50	R56=-0.7m, 3nC, 山脈Bump 0mm
2025.6.4	2.863	2025-6-4-23-53-18	MSE.10					QTD2E	170.107	2.315	1.025	-0.7	50	R56=-0.7m, 3nC, 山脈Bump 0mm
2025.6.5	1.887	2025-6-5-1-51-09	MSE.10					QTD2E	107.14	1.852	1.074	-0.7	50	R56=-0.7m, 2nC
2025.6.5	1.869	2025-6-5-2-2-59	MSE.10	QTF1E	299.838	5.154	1.896					-0.7	50	R56=-0.7m, 2nC

BT先頭(QX1E)でDX=-2mm
よくないので０mmに戻す

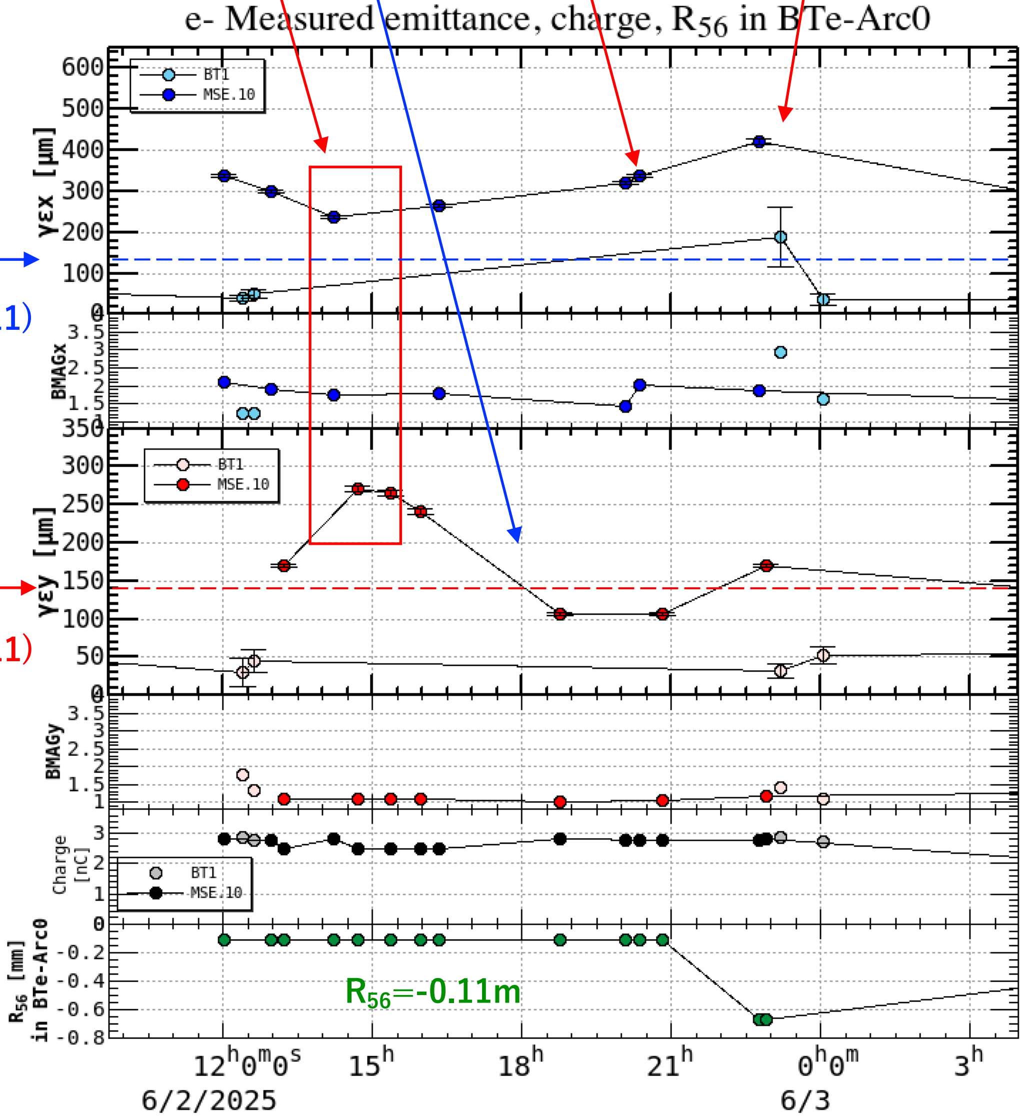
SRM1を見てσyが小さくなる
ようにA1からの軌道を調整

ECS cavityに山脈Bumpを立
てたが、効果なく元に戻す

R56=-0.67mにSet
BT1でMatching断念

BT2
2024c
(R56=-0.11)
2nC

BT2
2024c
(R56=-0.11)
2nC



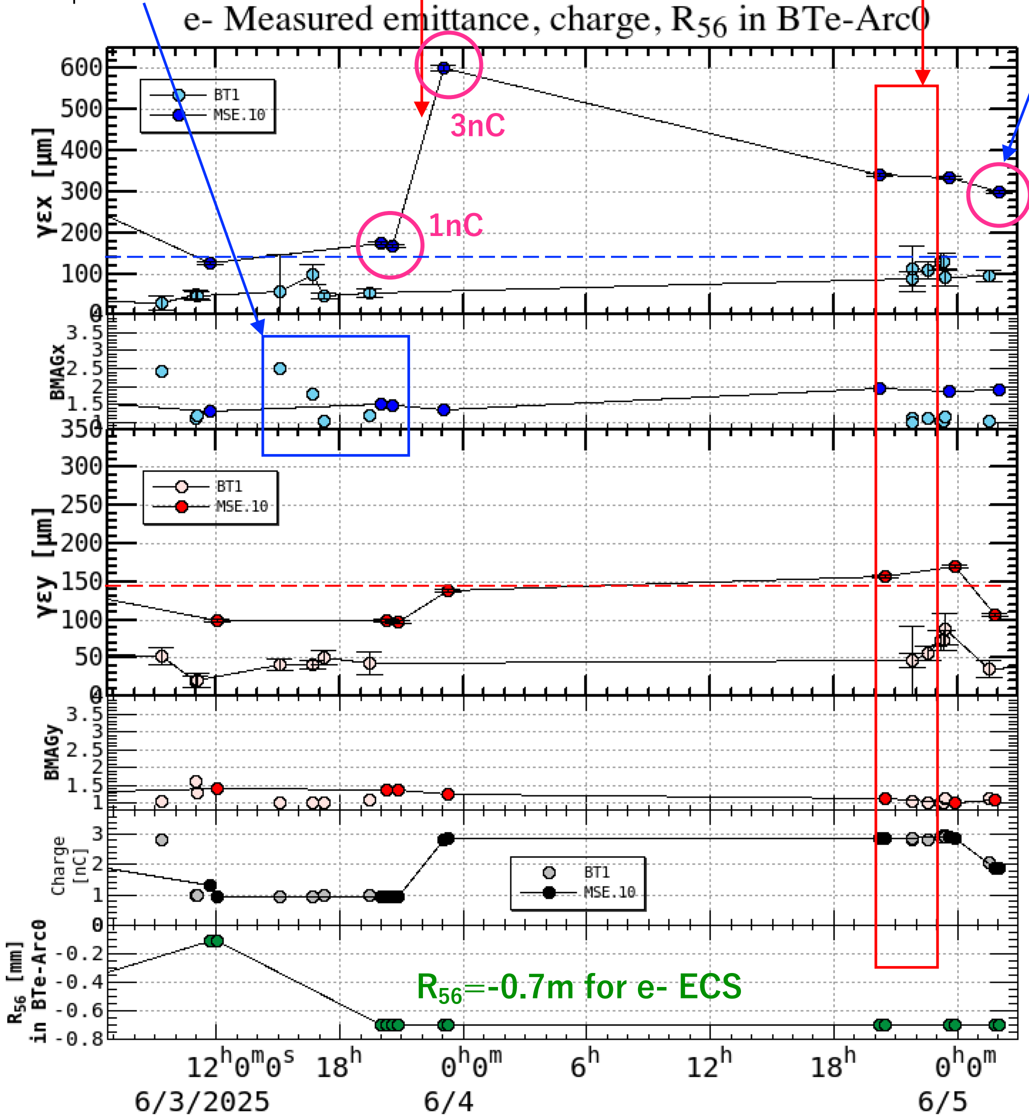
次頁に拡大図

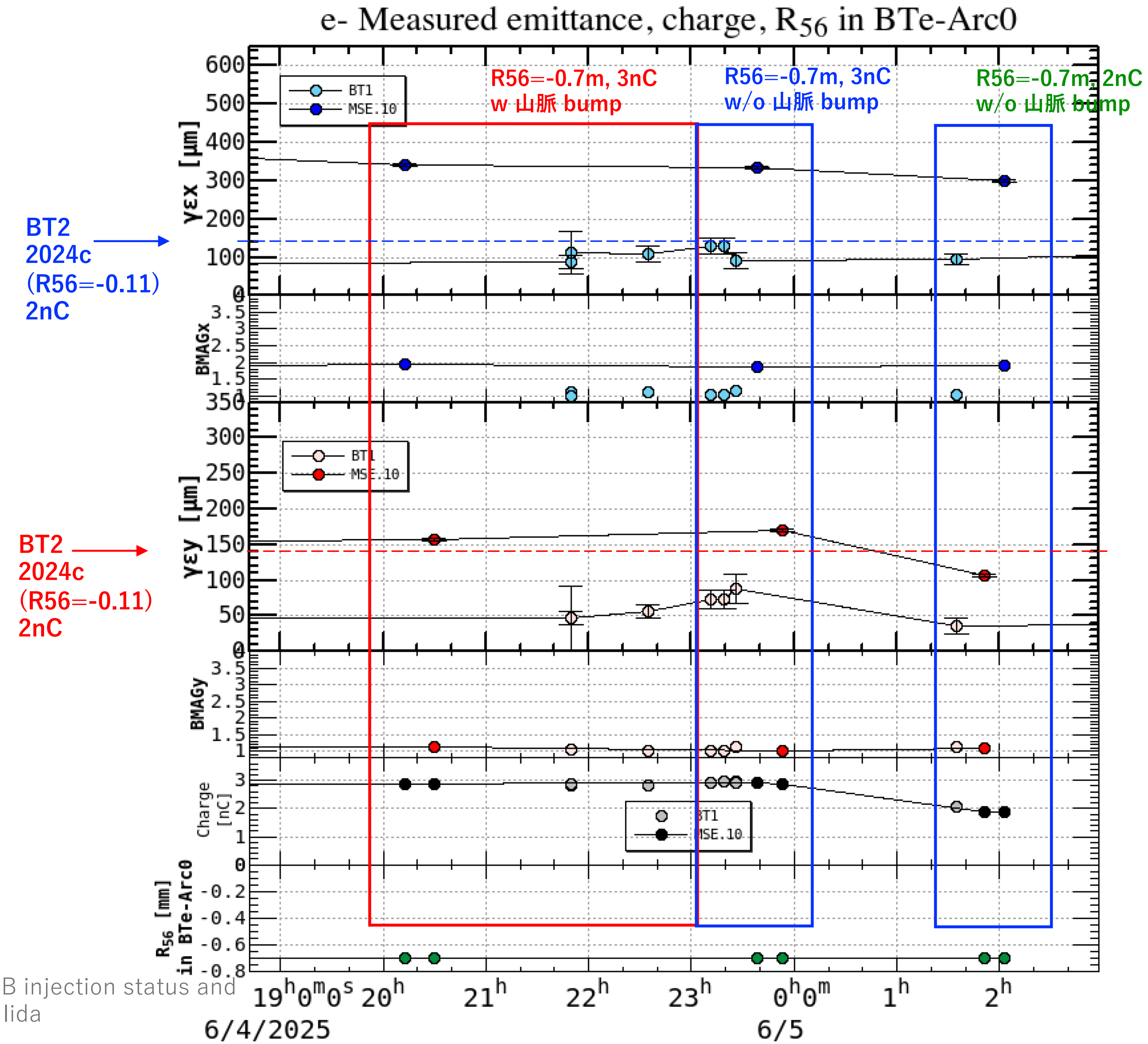
R56=-0.7m, 1nC、BT1
でmatching、
Dispersion correction

R56=-0.7m, 3nC

R56=-0.7m, 3nC
w 山脈 bump

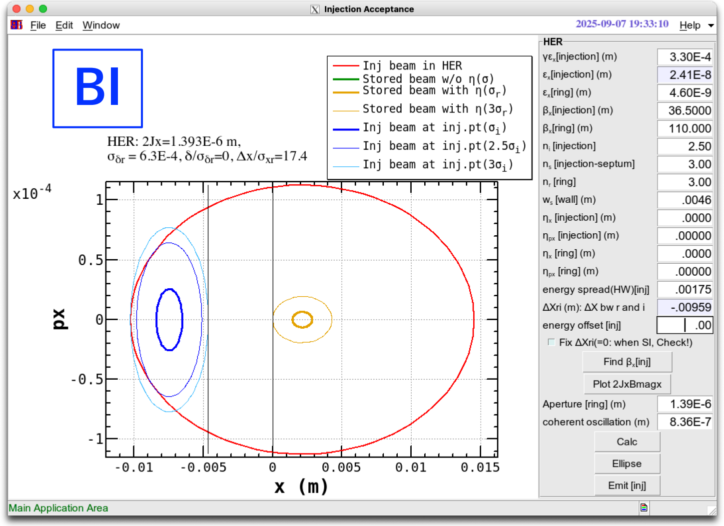
R56=-0.7m, 2nC
w/o 山脈 bump




e- Measured emittance, charge, R_{56} in BTe-Arc0
R56=-0.7m, 3nC
w 山脈 bump
R56=-0.7m, 3nC
w/o 山脈 bump
R56=-0.7m, 2nC
w/o 山脈 bump
BT2
2024c
(R56=-0.11)
2nC
BT2
2024c
(R56=-0.11)
2nC
BT1
MSE.10
γεx [μm]
BMAGx
γεy [μm]
BMAGy
Charge [nC]
R_{56} [mm] in BTe-Arc0
19h0m0s 20h 21h 22h 23h 0h0m 1h 2h
6/4/2025
6/5

$\gamma\varepsilon x$=330μm, εx=24.1nm

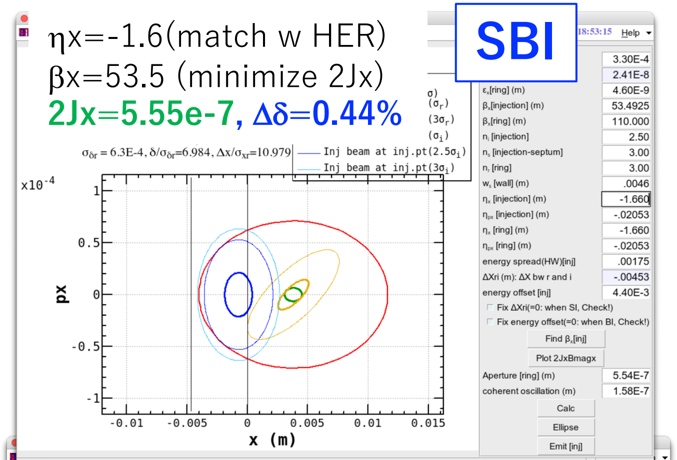
BI



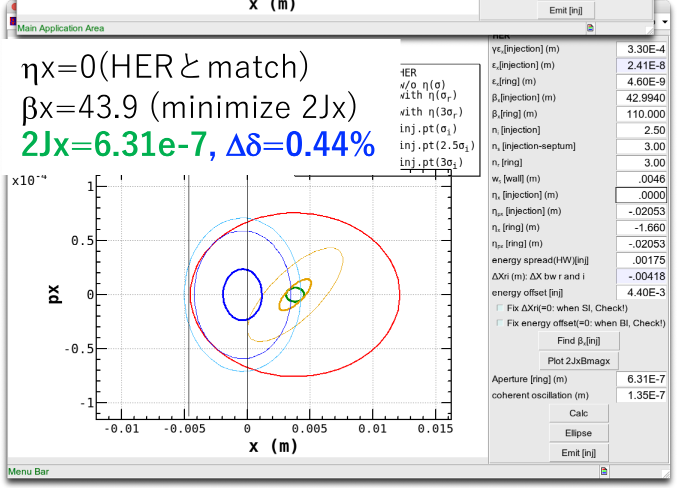
ηx=0(match w HER)
βx=36.5 (minimize 2Jx)
2Jx=10.4e-7, Δδ=0%

- It was investigated whether optics matching was actually possible on SI.
- It's difficult to make ηx=1.66m at the BT end.
- In the case of matching only with ηpx, βx is best at 85m(difficult to match), but even 60m is within the acceptable range.
- Furthermore, if hx=1.6m in Septum, and there is energy jitter, the DX will become even larger.

SBI

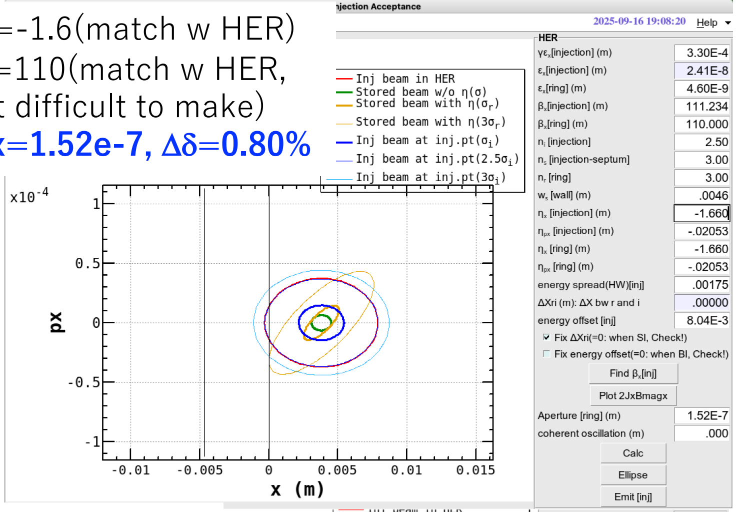


ηx=-1.6(match w HER)
βx=53.5 (minimize 2Jx)
2Jx=5.55e-7, Δδ=0.44%

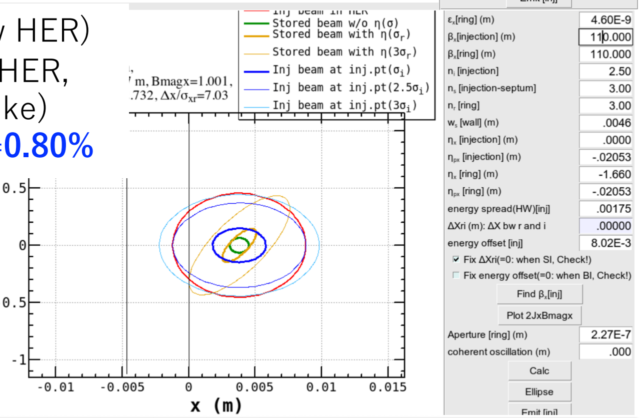


ηx=0(HERとmatch)
βx=43.9 (minimize 2Jx)
2Jx=6.31e-7, Δδ=0.44%

SI

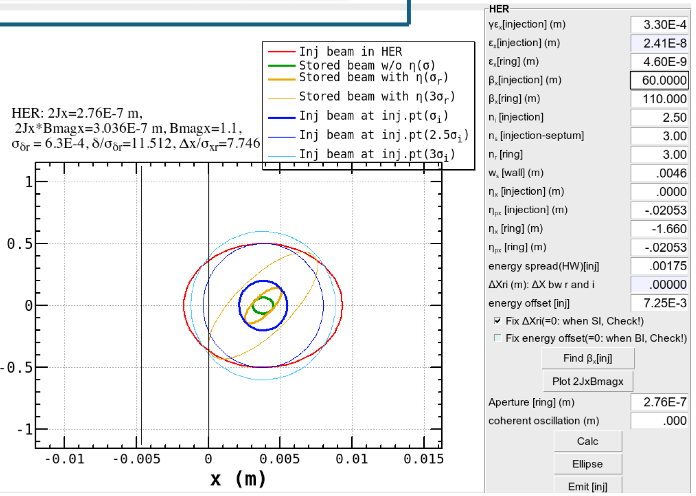


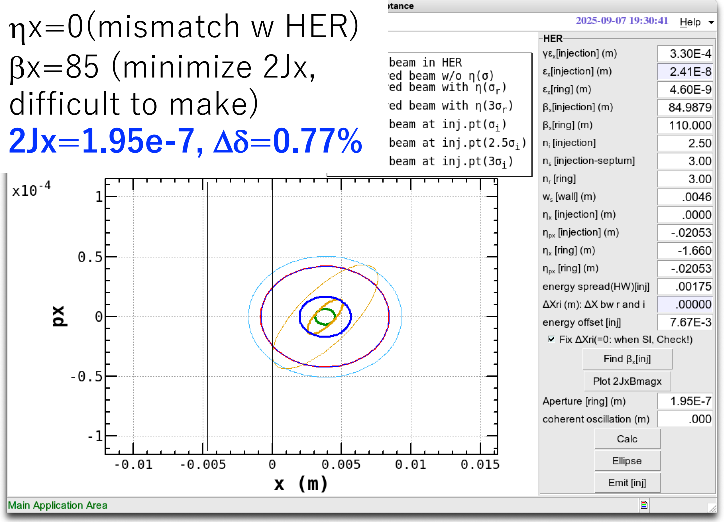
ηx=-1.6(match w HER)
βx=110(match w HER, but difficult to make)
2Jx=1.52e-7, Δδ=0.80%



ηx=0(mismatch w HER)
βx=110(match w HER, but difficult to make)
2Jx=2.28e-7, Δδ=0.80%

ηx=0(mismatch w HER)
βx=60(minimize 2Jx)
2Jx=2.76e-7, Δδ=0.73%
↑
twice of the perfect matching





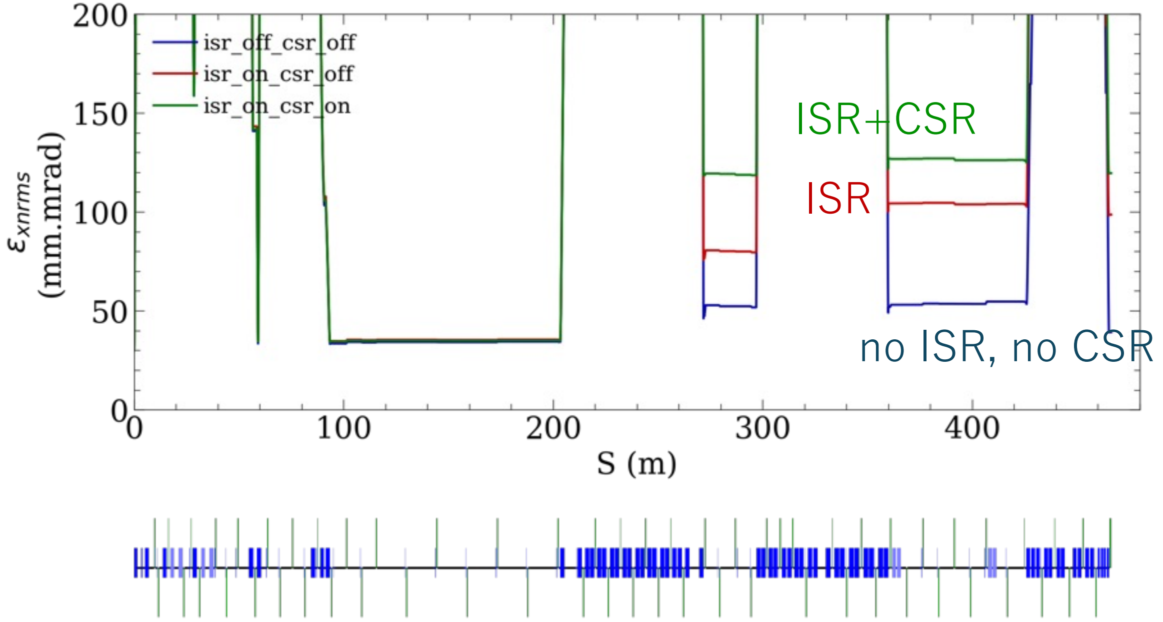
ηx=0(mismatch w HER)
βx=85 (minimize 2Jx, difficult to make)
2Jx=1.95e-7, Δδ=0.77%

Present and straight BT line

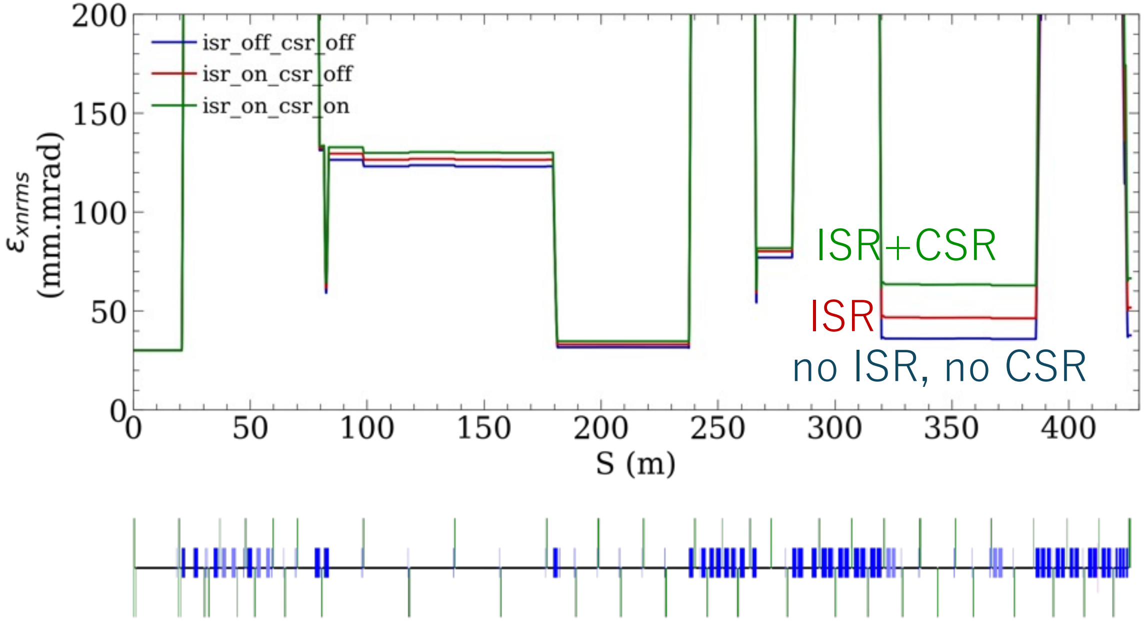
- x/y nemit: 30 um.rad
- Bunch charge: 2.2 nC

T. Yoshimoto

Current beam transport

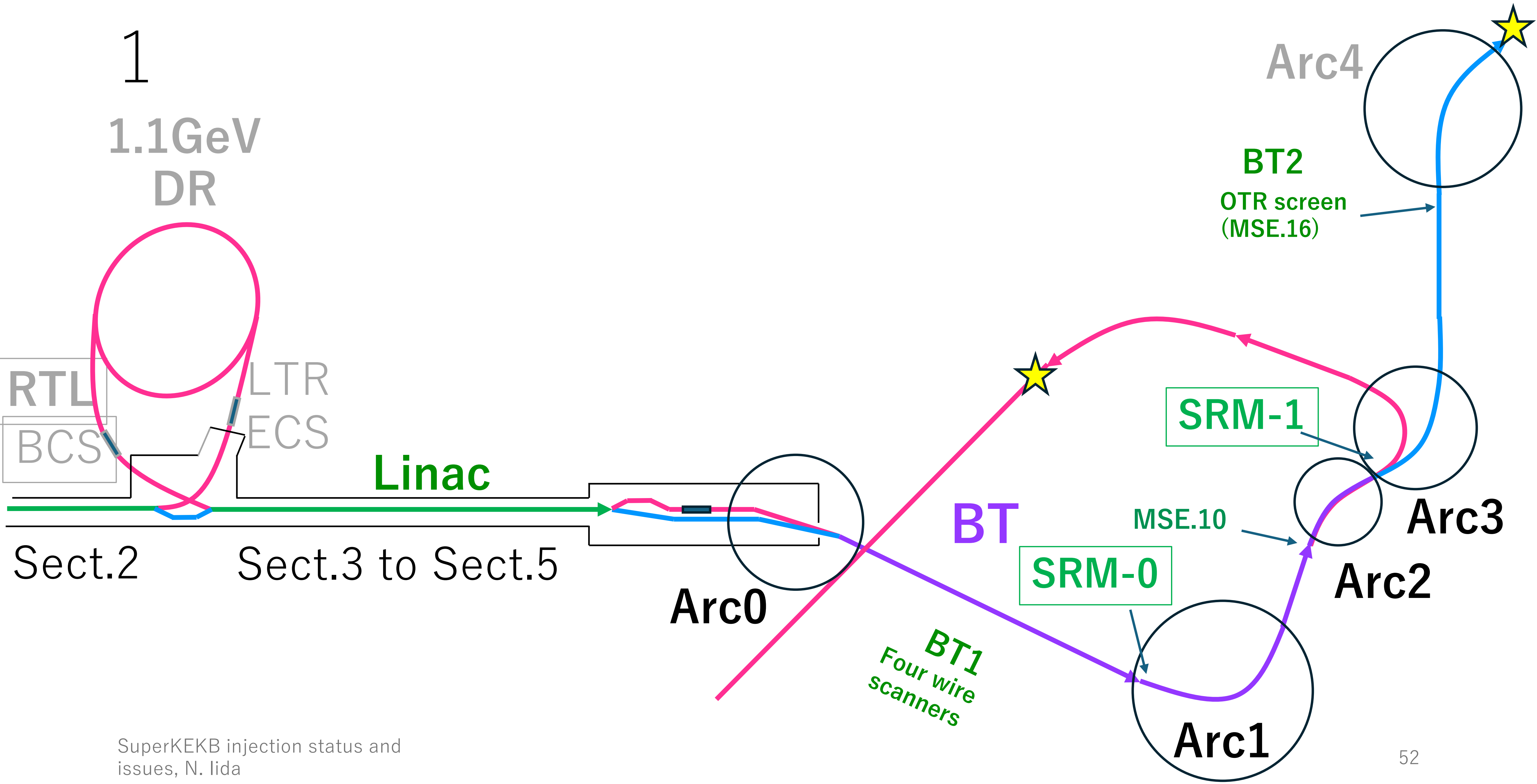


straight beam transport (design)



- 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		$\gamma\varepsilon x$ [μm] at the end of BT	
ISR	CSR	present BT	new BT
Off	Off	53	36
On	Off	104	46
On	On	126	63

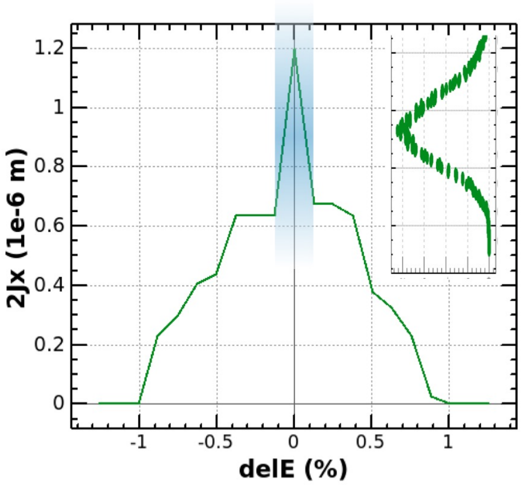


1
1.1GeV
DR
RTL
BCS
LTR
ECS
Linac
Sect.2
Sect.3 to Sect.5
Arc0
BT
BT1
Four wire
scanners
SRM-0
MSE.10
SRM-1
Arc1
Arc2
Arc3
Arc4
BT2
OTR screen
(MSE.16)

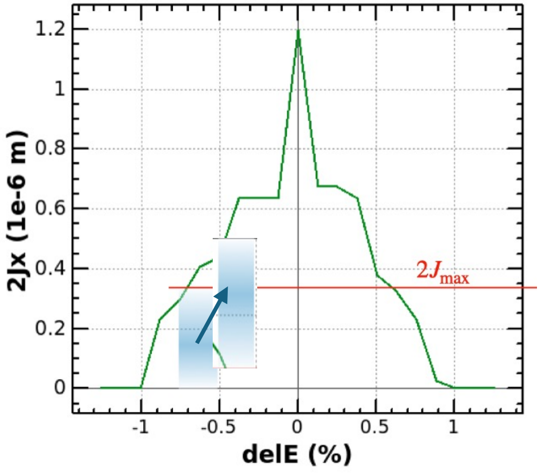
Injection schemes

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

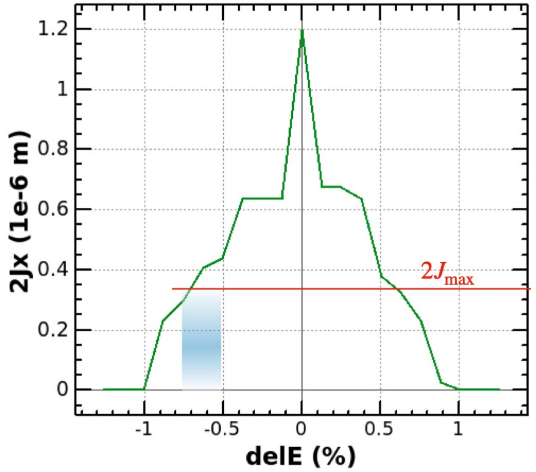
(BI)
betatron injection



(SBI)
Synchro-beta injection

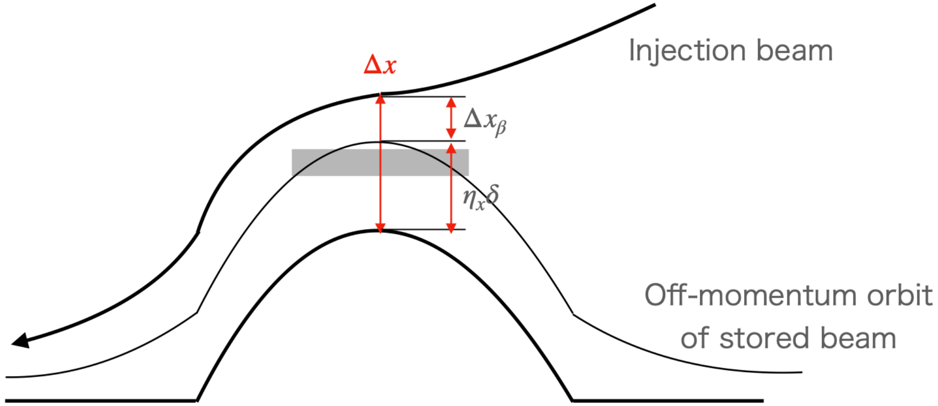


(SI)
Synchrotron injection w cancel-coil error



Synchro-beta Injection

- Synchrotron injection was proposed to recover the aperture for the injected beam.
- But momentum aperture is not enough.
- Synchro-beta scheme may be a possible option.

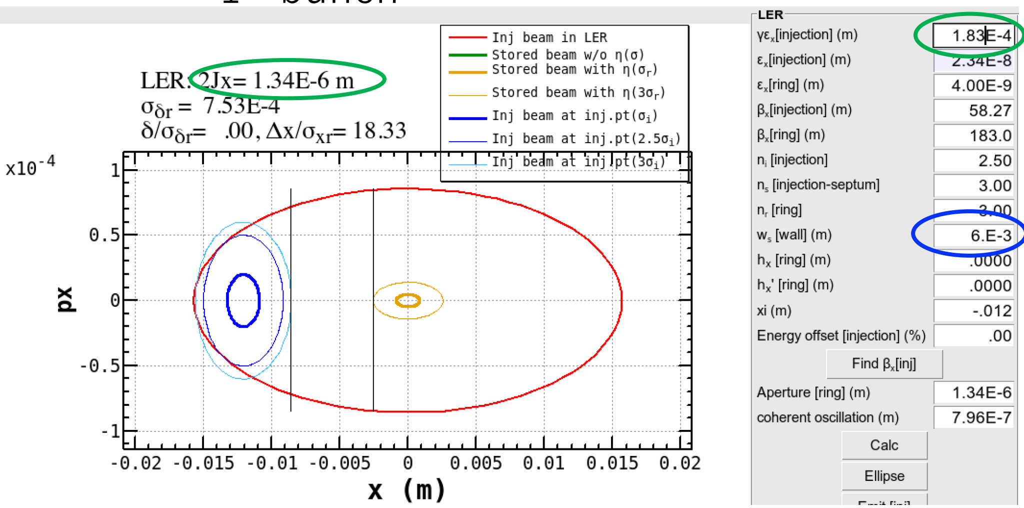


Plotted by M. Kikuchi

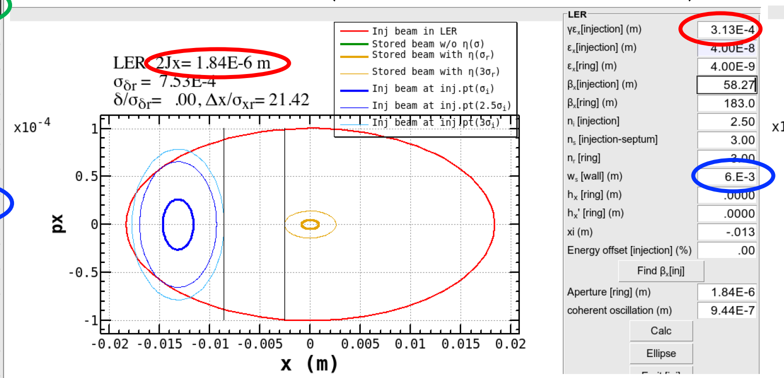
SKBコミッショニング・ミーティング(36), M. Kikuchi, https://kds.kek.jp/event/49259/contributions/256267/attachments/174527/230659/Injection%20Simulation%20(2).pdf

2Jx of injected beam in LER and Ring acceptance

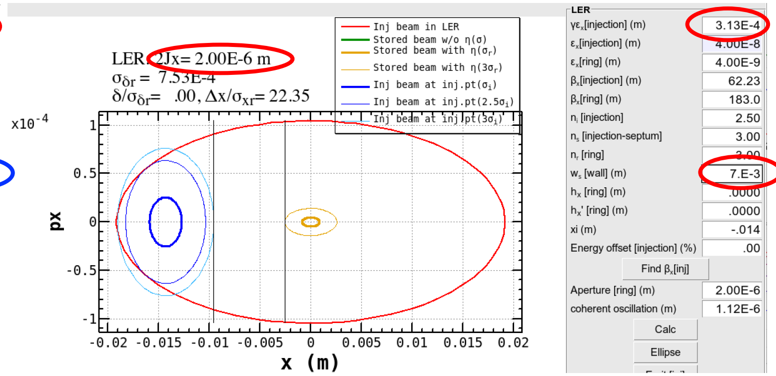
1st bunch



2nd bunch (increased emittance)



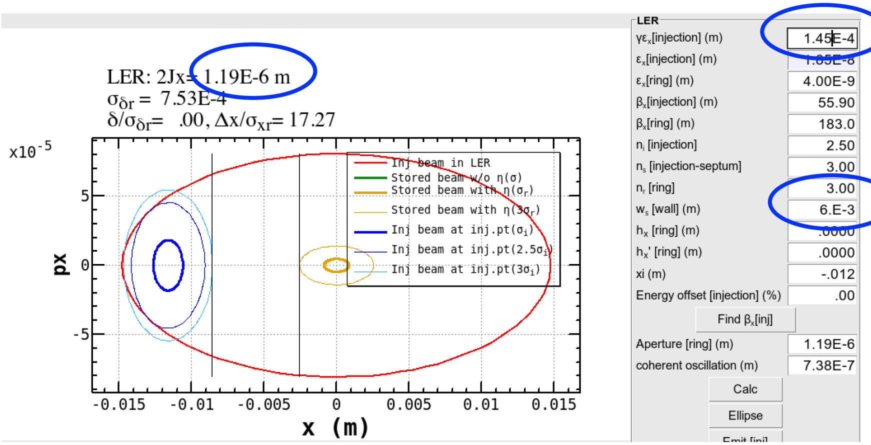
2nd bunch (increased emittance + orbit(Max: 1mm))



Measurement results in May 2025

e+ 3nC	BT1 1st	BT1 2nd	BT2 1st	BT2 2nd like orbit
γεx[μm]	136.3	173.4	183.7	**312.7**
γεy[μm]	5.4	5.6	64.3	(57.6)

LER	γεx[μm]	Injection beam	Ring(meas.)[1]
2Jx [μm] 1st bunch	**183**	**1.34 <~**	1.4
2Jx [μm] 2nd bunch	**312.7**	**1.84 >**	1.4
2Jx [μm] 2nd w ΔX1mm	**312.7+ΔX**	**2.00 (max.) >**	1.4
2Jx [μm] *	145	**1.19 <**	1.4
2Jy [μm]		0.049 (6εy)	>0.03
δ_{max} [%]		±0.32(99% Incl.)	±1.03



- The 1st bunch is just inside the aperture of the ring.
- **The 2nd bunch is outside, which clearly reduces the injection efficiency.**
- **After replacement of BH3P and installation of the strip line kicker, both bunches can be safely injected in LER acceptance.**
- **The fast kicker for 2nd bunch is going to be installed in this summer(d).**

* The poles of BH3P are replaced (See next page).