Beam Transport

Accelerator Review Committee, March 25–27 2024, KEK

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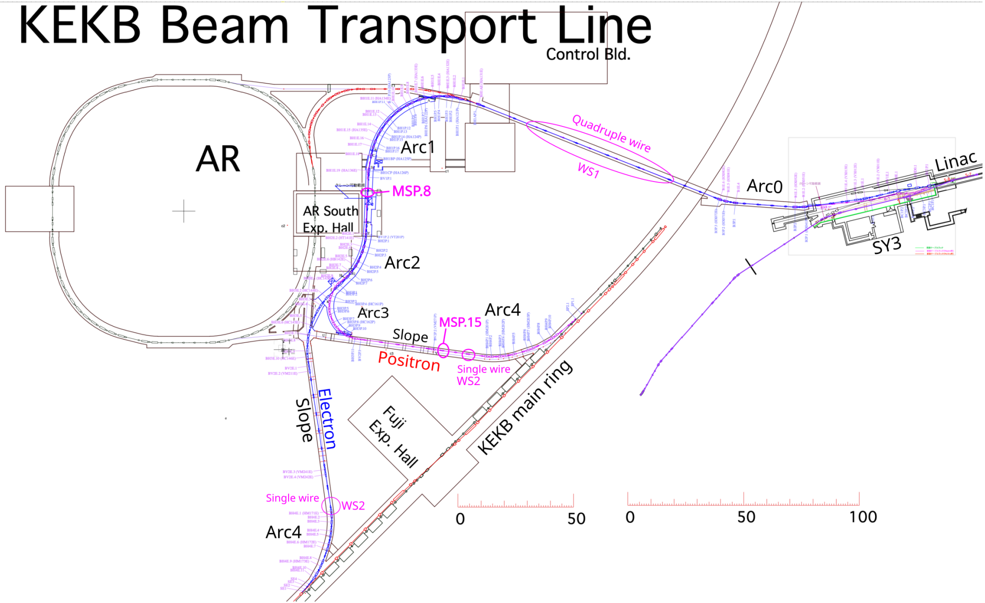
SuperKEKB/BT group

Mar. 26, 2024

Table of contents

KEKB Beam Transport Line



Beam transport issues and countermeasures

- Issue-1: injection efficiency improvement
- Issue-2: emittance growth suppression
- Issue-3: countermeasure for self-firing of injection kickers
- Issue-4: Machine stabilization

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  - adoption of Libera system for BPM readout
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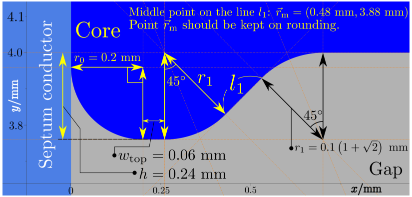
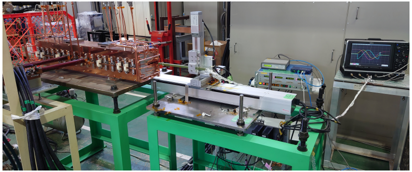
The hardware work will be mainly presented in this talk.

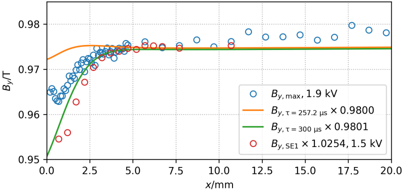
Table of contents

HER injection septum SE1 upgrade

- According to the study on septum width, drive pulse period and leakage field[1], new SE1 design was decided.
- As the result, the field uniformity is improved about 54%,
  - which is not consistent with the simulation result,
  - some unknown factors which should be investigated.
- Injection capable region seems to have expanded, tracking simulation will be done to estimate the border position quantitatively.
- Q-chamber next to SE1 is also improved, margin for injection bump is also increased by 0.8 mm.
- it is worth to try to find more tuning space.
- MR collimator settings are also very important for injection efficiencies.

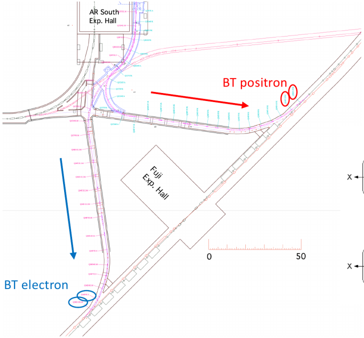


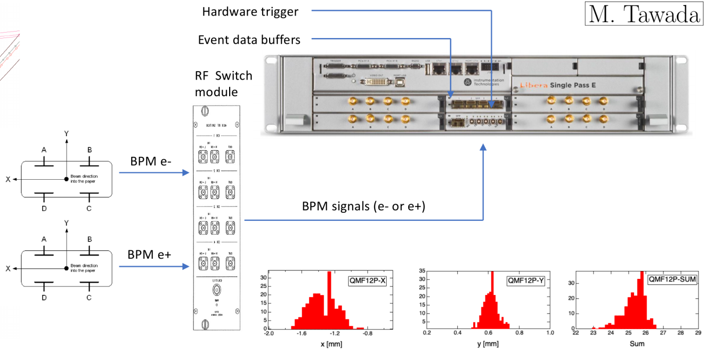




R&D of Libera-SPE BPM system for BT end

M. Tawada

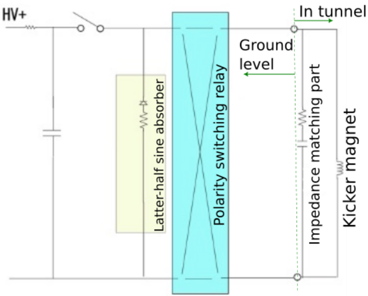


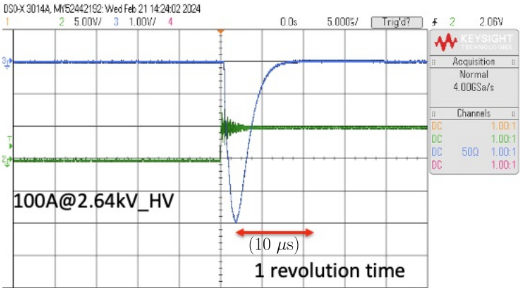


- I-tech Libera-SPE is under the test for BT end BPMs, which have one-to-one channel connections to Libera-SPE.
- Libera-SPE has 4 BPM modules, each one reads 2 independent BPMs ($e^{\pm}$) by using RF switch module.
- Successive trains of 2 bunches separated 96 ns are measurable individually.
- Signal nonlinearities are corrected using a 7th order polynomial fit.
- SPE parameters (e.g. offset, attenuation, trigger offset, etc) and marking the BPM data are controlled via event data buffers.
- Each shot is uniquely numbered by extended ShotID, which is 32-bit long.

Vertical kicker

T. Naito



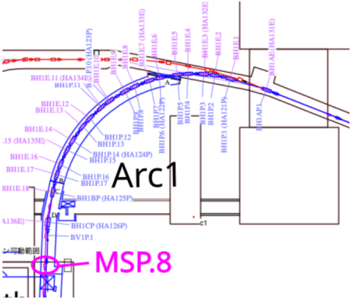


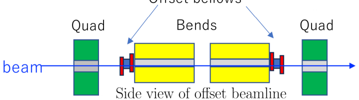
- Single kick, 1 Hz, ~ 70 μrad (~ 150 A_{peak}),
- semiconductor switch,
- pulse tail 0.5% @ 50 μrad kick angle,
- polarization inversion available without kick angle variation,
- installed in Fuji-straight of HER, in production for LER.

Table of contents

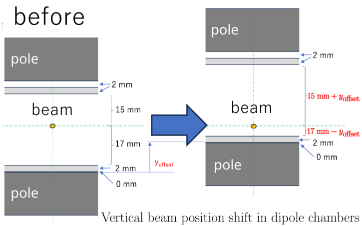
BT(e^+) vertical offset

of vacuum chamber reduces emittance growth in BT(e^+) if the source is also CSR effect as BT(e^-) [2].



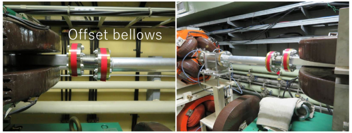


Side view of offset beamline



Vertical beam position shift in dipole chambers

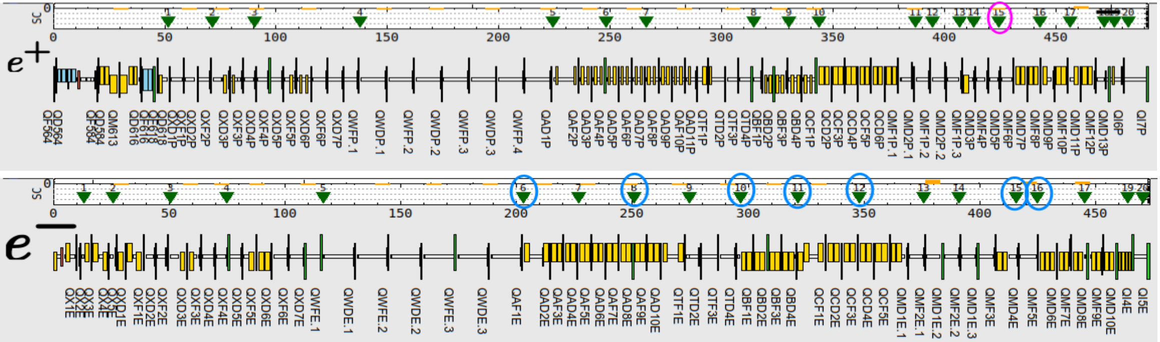
K. Shibata



- We offset the chambers and dipoles in Arc1 where the most suspicious region for the emittance growth,
- horizontal emittance can be measured at OTR monitor MSP.8,
- number of offset dipoles: 17.

Installation of OTR monitors

For emittance measurement, the OTR monitor was adopted to be installed, since it could be achieved by the screen monitor upgrade. OTR monitors indicated with circles surrounding numbers and triangles.



Before LS1

Installation of OTR monitors

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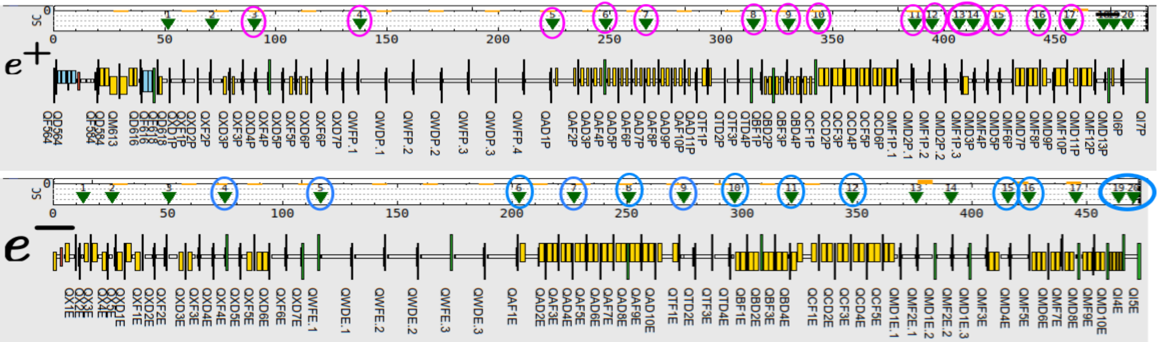
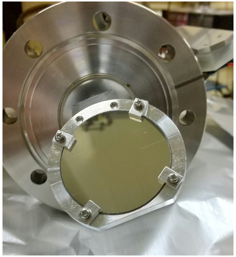


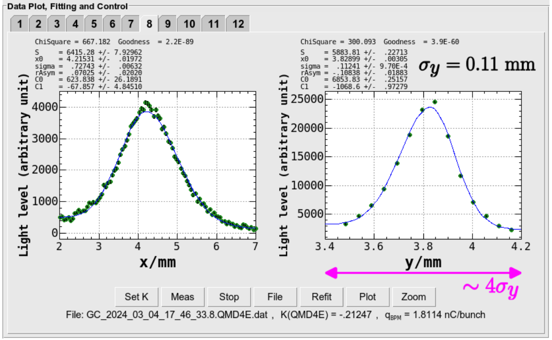
After LS1

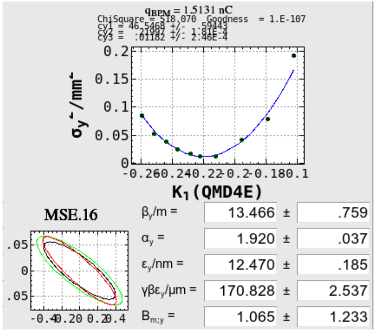
Installation of OTR monitors

Schedule was very tight, thanks to the help of N. Taniguchi and Y. Nakazawa from Belle II group, installation was completed just on time. I appreciate their hard and thoughtful works very much!



40 nm Al coated 0.5 mm silicon plate with some scratch lines for calibration.

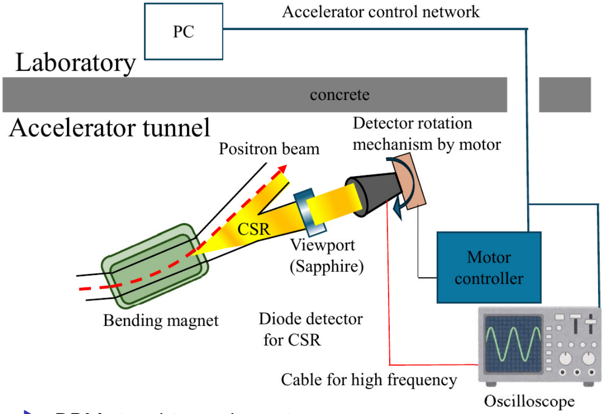


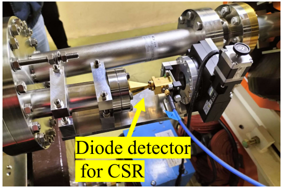


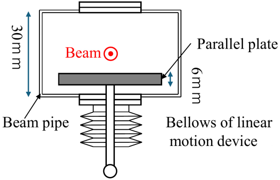
- Emittance measurement is available in many (dispersion free) location in BT.
- Typical resolution: $\Delta x \simeq \Delta y \sim 60\ \mu\mathrm{m}$
  - beam size comparable to resolution $\Rightarrow$ upgrades may be necessary for OTR readout.

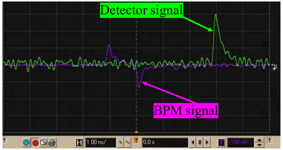
CSR direct measurement in Arc 1

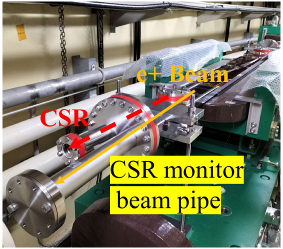
S. Terui et al.

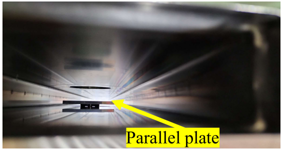








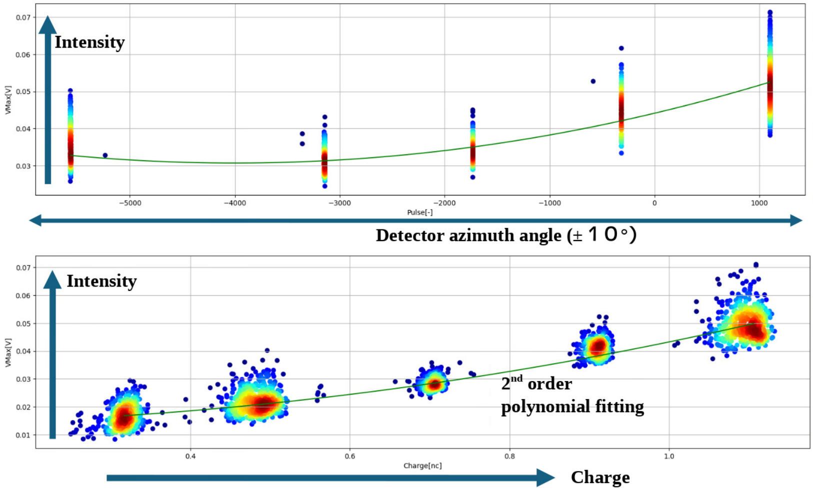




- BPM signal is used as trigger,
- detector (with rectangular cross section horn) azimuth angle variable for polarization measurement (only $\pm 10^\circ$ at this time).

CSR direct measurement in Arc 1: results

S. Terui et al.



- Charge squared dependency was seen,
- Issues:
  - 180° rotatable system for clear CSR polarization measurement,
  - CSR suppression effect of vertical offset of the parallel plate,
  - detector saturation occurs for higher bunch charge

Table of contents

Injection kicker status overview

K. Kodama, T. Mimashi

LER Injection bump leakage

- due to differences of sizes & Ti-coat thicknesses of ceramic ducts was reported in previous ARC,
- K1 ceramic duct will be replaced with K2 type duct (in production now) in summer shutdown 2024.

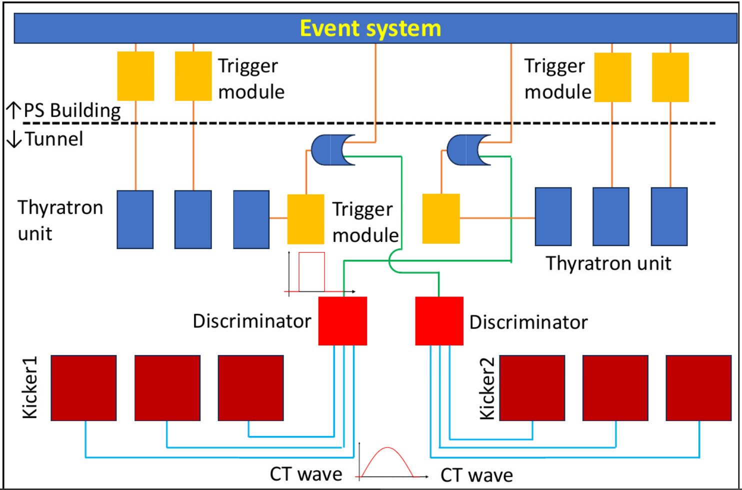
Accidental spontaneous firing (LER)

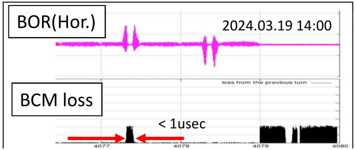
- denoted by ASFs, occurred 10 times in this run 2024a,
- K1-unmonitored $\times 2$, K1-2 $\times 1$, K1-3 $\times 7$ (K1-3 thyratron replaced on Mar. 19, the removed thyratron successively caused ASFs during the bench test $\Longrightarrow$ thyratron failure.)
- Short term countermeasure ideas:
  - changing trigger system for CX1174 from single to double,
  - replacing thyratron with CX1826A (HER type, no ASF in HER),
  - immediate triggering the rest of paired kicker on ASF detection. $\longleftarrow$ New!
- Long term countermeasure ideas:
  - two kickers driven by one thyratron $\rightarrow$ in search of optics solution,
  - changing pulsed power source from thyratrons to semiconductor switch,
  - one kicker driven by two thyratrons with a half output currents.

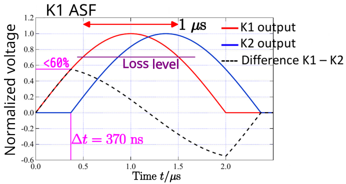
Immediate triggering the rest of paired kicker on ASF detection

K. Kodama, T. Mimashi

- From BOR or BCM data, the bunches with ASF oscillation amplitude less than 70% of maximum survive.







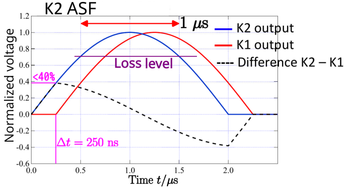
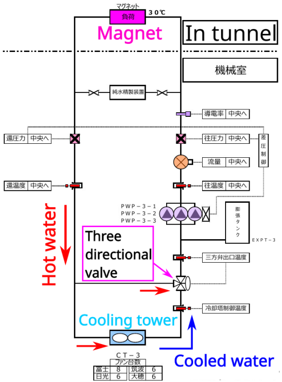


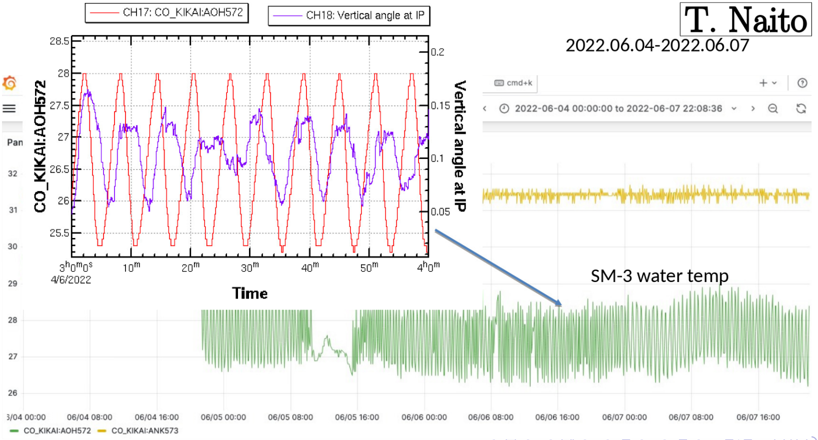
Table of contents

Temperature stability improvements of facility cooling water

In previous ARC, DR cooling water improvement was reported. The improvement was continued for BT and MR.



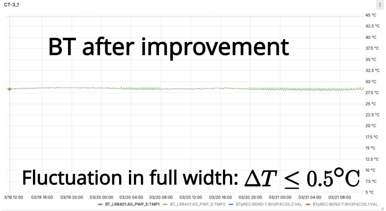
Correlation between the MR facility cooling water temp and vertical angle at IP was observed.

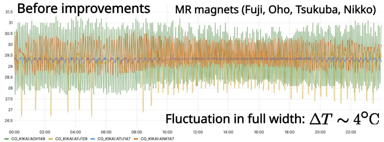


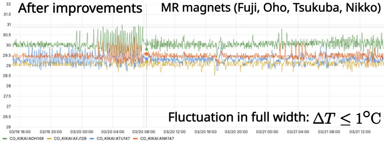
Temperature stability improvements of facility cooling water

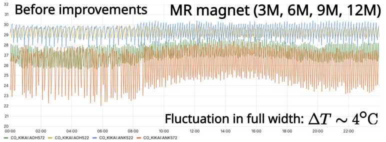
T. Naito

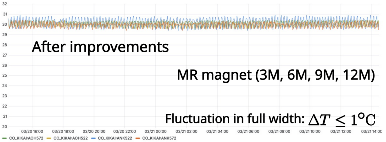
The optimization of the temperature control parameters for the cooling towers and the PID control of the three-directional valve was carried out.







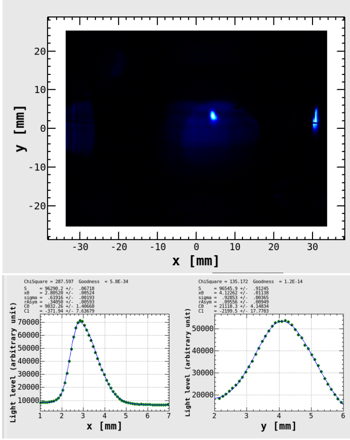




MR cooling system consists of Fuji, Oho, Tsukuba, Nikko, 8 cooling towers along the tunnel: 3M, 6M, 9M, 12M.

BT-SRM

- BT-SRM@BH3E.1 (the first dipole in Arc 3) is operated as beam size monitor,
- used for Linac tuning, wakefield minimization.
  - It is useful to detect the condition drifted, since beam size can be measured without any device inserted in beam line.
- Typical beam size: $\sigma_x \approx 0.6\ \mathrm{mm}, \sigma_y \approx 0.9\ \mathrm{mm}$ in 2022,
- it seems larger and unstable in this run.
- BT-SRM@BH1AE (the first dipole in Arc 1) was fabricated, installation has been postponed.



Summary and future prospect

- Issue-1: injection efficiency improvement
  - More tuning space may be found with better HER septum (SE1) calibration,
  - MR collimator adjustments are also very important.
- Issue-2: emittance growth suppression
  - The cause of emittance growth in BT(e^+) was not CSR effect and seemed to be the higher order field.
  - Core replacement of top/bottom asymmetric poles with symmetric ones will mitigate the problem.
  - As for e^-, the following items may be effective:
    - thin chamber installation,
    - lattice modification for smaller dispersion (c.f. new beamline using PF-AR direct injection tunnel).
- Issue-3: countermeasure for ASF of injection kickers
  - direct triggering the rest of paired kicker for compensation:
    new countermeasure has been proposed.
- Issue-4: Machine stabilization
  - temperature stability improvements of facility cooling water: it is very stable now.
  - For e^- beam, orbital and energy spread jitters, vertical emittance are larger than the previous run.

Thank you for your attention.

Appendix

Effect of injection beam quality to luminosity

K. Oide

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

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

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

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

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

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

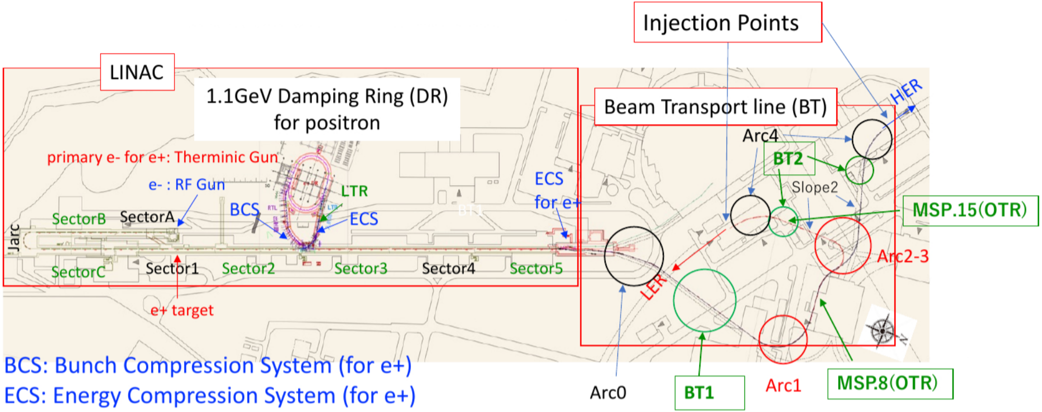
$$N_\pm = N_\pm(0)e^{-\frac{t}{\tau_\pm}}$$

$$\frac{\mathrm{d}(eN_\pm N_\mathrm{b} f_0)}{\mathrm{d}t} = I_{\pm\mathrm{inj}}\varepsilon_\pm$$

The quality of injection beam is vitally important for SuperKEKB.

Layout from origin to MR

- e+ beam is injected into the LER via DR:
  The injection BG is not almost affected by the beam condition at upstream of the DR.
- e- beam directly injects into HER:
  The injeciton BG is directly affected by the condition of RF-gun, LINAC, and BT.



BCS: Bunch Compression System (for e+)
ECS: Energy Compression System (for e+)
BT1 and BT2: Wire scanners(WSs), MSP.8, 15:OTR measure beam emittances.

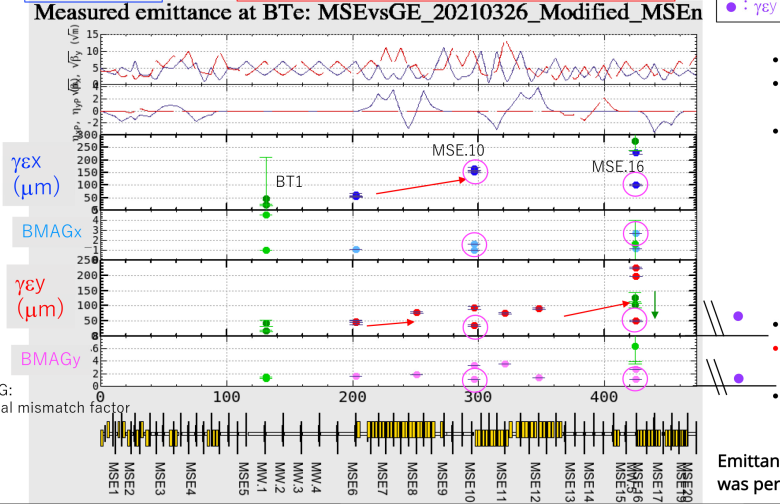
Summary of the previous measurements of emittance and β-mismatch(BMAG) in e- BT

N. Iida

1.0~1.1nC

The measurements should be checked !

- ● : γε with WS
- ● : γεx measured with OTR
- ● : γεy measured with OTR
- ● : γεy with SRM+gated camera



BMAG:
Optical mismatch factor

- ◯ are measured in 2021.Mar.26.
- The others are measured in 2020.Dec.22.
- There are still uncertainties in absolute values because an error of the quadrupole strength used in the Q-scan turned out to give a sizable effect to the measured values in the study. We plan to precisely measure the quadrupole errors using the beam.
- Anyway, it is considered that;
- The horizontal emittance growth occurs in the Arc1.
- The vertical emittance growth occurs in the Arc1 and Slope2.

Emittance measurement with vertical bump orbit was performed using MSE.10.

Current status

Parameters	LER	HER	LER	HER
N_b/(bunches/ring)	2345+1		2345+1	
Luminosity $\mathcal{L}/\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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
$Q_e^{inj} \times n_b$ [a] /nC	3×2	2×2	3×2	2×2
q_{pulse} [a] /(nC/pulse)	4.1	0.68	4.0	0.64 ← Requirement
q_{pulse} [b] /(nC/pulse)			2.3	0.34-0.65 ← Achievement

[a] Requirement for injection for 25 Hz, $q_{pulse} \equiv \epsilon_{inj} Q_e^{inj} n_b$.
[b] Parameters when maximum luminosity was achieved in 2022.

- Especially $4\ \mathrm{GeV}\ e^+$ ring (LER) performance should be doubled.
- As for $7\ \mathrm{GeV}\ e^-$ ring (HER) performance, the requirement is satisfied only on the best condition.

From the publication in IPAC'23 proceedings [3].

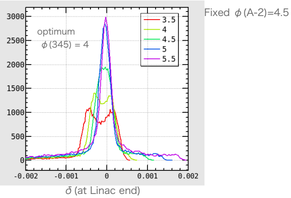
Quest for source of emittance growth

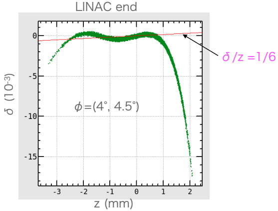
M. Kikuchi

We have investigated for years about emittance growth issue, some sources concerning the issue have been found, but they all have not played the main role. Found sources of emittance growth so far:

- transverse wake field by accelerating tubes,
- higher order dispersion in BT,
- radiation excitation in BT,
- leakage of dispersion to straight section,
- jitter emittance,
- interaction of energy jitter with leakage dispersion,
- dispersion leakage to ECS accelerating tubes.

Recently we examine a effect of coherent synchrotron radiation (CSR) generated by micro-bunch to the emittance.





Electron beam

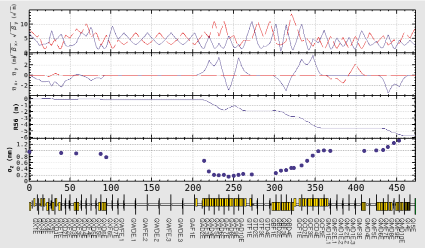
Microbunching

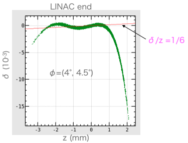
M. Kikuchi

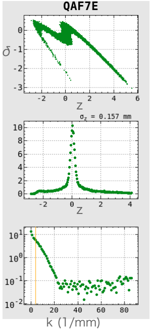
Longitudinal simulation

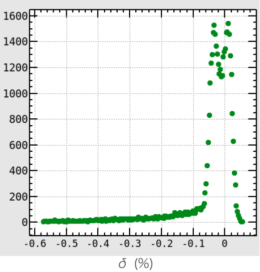
- Bunch is compressed in the ARC-1, ARC-2, (and ARC-3)

ϕ=(4, 4.5)









Positive correlation in (z, δ) space, $R_{56} < 0$, then BT-line $\Rightarrow$ bunch compressor.

- Partial cancelation of longitudinal wake with RF curvature makes local z-δ correlation, thus inducing possible micro-bunch in the subsequent BT line.
- Condition of compression:

$$R_{56}\left(\frac{\partial\delta}{\partial z}\right) = -1 \qquad (\#)$$

Since the R_{56} component varies in wide range from 0 to -6 m the correlation $\left(\frac{\partial\delta}{\partial z}\right)$ satisfies the condition (#) elsewhere in the BT line, if it is greater than 1/6.

- Bunch length shrinks to 0.16 mm. CSR effect may be concerns for emittance blowup.

$$k_{th} = \sqrt{\frac{2\rho}{3}\left(\frac{\pi}{h}\right)^3} = 3.69\times10^3\ \mathrm{m}^{-1}$$

$$\sigma_{z,th} = 0.27\mathrm{mm}$$

Emittance measurement with vertical bump orbit

- One of the most important issues for BT-line is to suppress the emittance growth,
- currently CSR is the most suspicious as the cause.
- The CSR shielding effect of vertical beam offset from median plane of beam chamber pointed out qualitatively by Takeshi Nakamura,
  - resulting in the suppression of the emittance growth,
- the measurement performed with electron beam, the suppression of emittance growth actually observed.
- It was important to understand the shielding effect in theory, we derived the scaling factor by reformulation of preceding research [4].
  - Essential points of the derivation will be explained in this report.

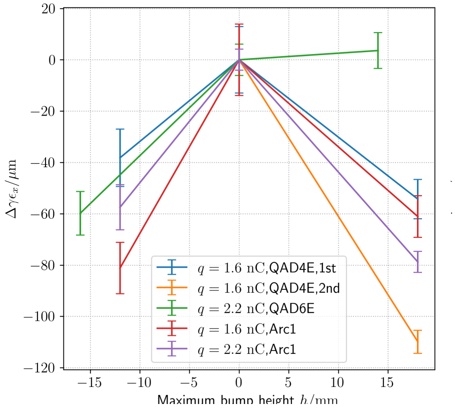
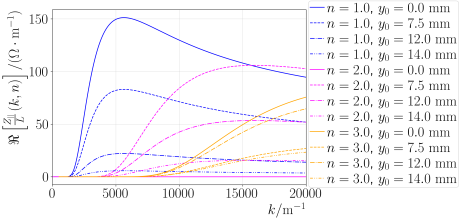
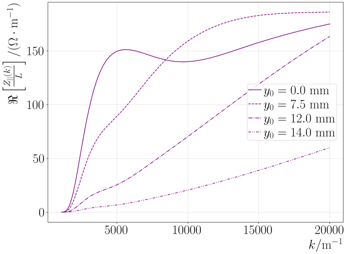


Figure: The result of experiments.

CSR scaling factor

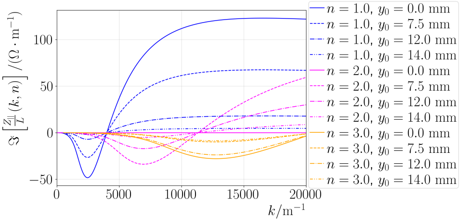




$$\Lambda_n = \sin^2\left[\frac{n\pi}{2b}(b + y_0)\right], \quad (1)$$

where the symbols denote items as follows:

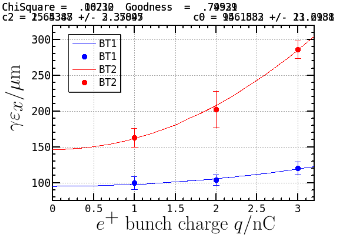
- n: mode number,
- b: inner height of chamber cross section,
- y_0: vertical offset of beam from the median plane of chamber.



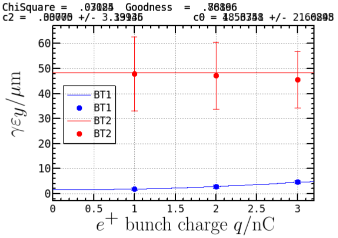
n-even modes are induced largely for the small offsets. $b = 16$ mm.

The suppression of emittance growth with vertical offset has been explained theoretically, cf. [2].

Emittance growth in BT(e^+)

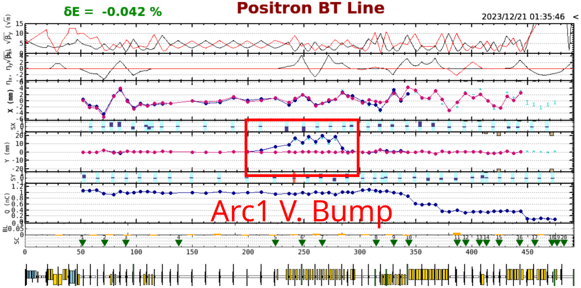


CSR charge dependency: $\gamma\varepsilon(q) = C_0 + C_2 q^2$



- The charge quantity dependence of normalized horizontal emittance were seen in the previous measurement.
- Thus we suspected CSR as the source of emittance growth.
- Eventually we decided to offset the vacuum chambers vertically to investigate whether the CSR suppression effect also exists in e^+ beam or not.
- As for the emittance measurement, we modified the screen monitors from the fluorescence to optical transition radiation (OTR) measuring type. (14 screens for BT(e^+).)

Vertical bump height dependency of emittance (e^+) in Arc1

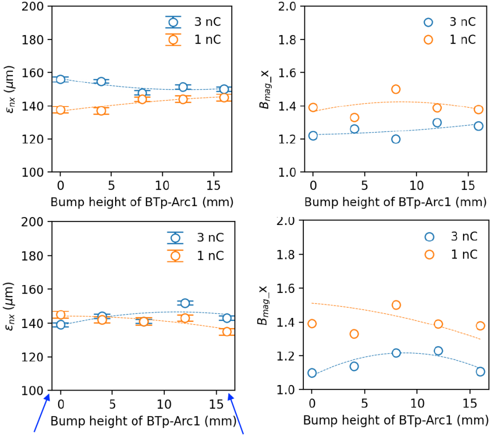


T. Yoshimoto

ECS-Es (kV)	Normalized hor. emittance	Mismatch factor: B_{mag}

35

37.5



Bottom of the inner wall

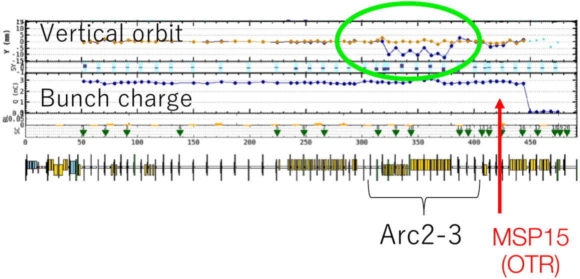
Center of the chamber

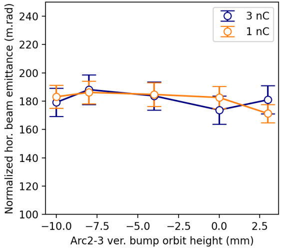
Measurement: 20231223

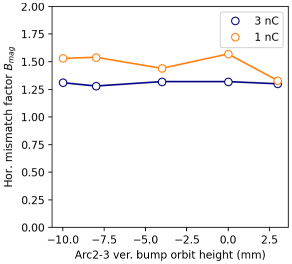
- Bump height $h = 0$ means no-bump,
- no strong bump height dependency, nor clear charge dependency of horizontal emittance was observed,

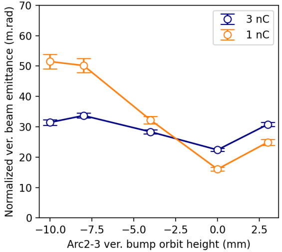
$\Longrightarrow$ No any significant wakes including CSR.

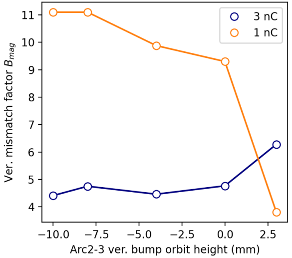
Vertical bump height dependency of emittance (e^+) in Arc2,3











- No bump height dependency was observed

$\Longrightarrow$ No any wake field effects including CSR.

  - We obtained consistent result in simulation study.

- As for vertical plane, bump height dependency has been observed, now we are investigating the cause of it.

Table of contents

DC magnets for BT

T. Ueda

Numbers of BT magnets

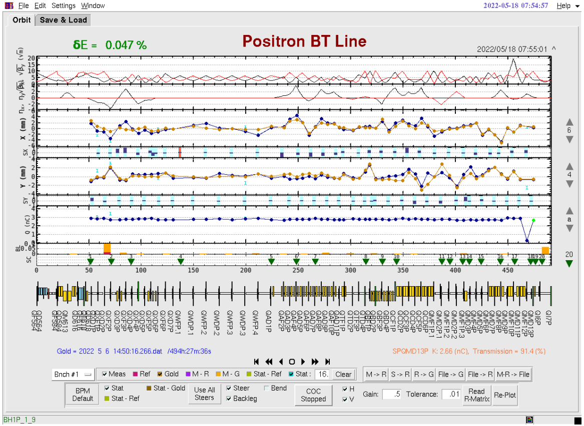
Line	Bend	Quad	V steering	H steering	Total
Electron	59	51	26	17	153
Positron	58	61	31	19	169

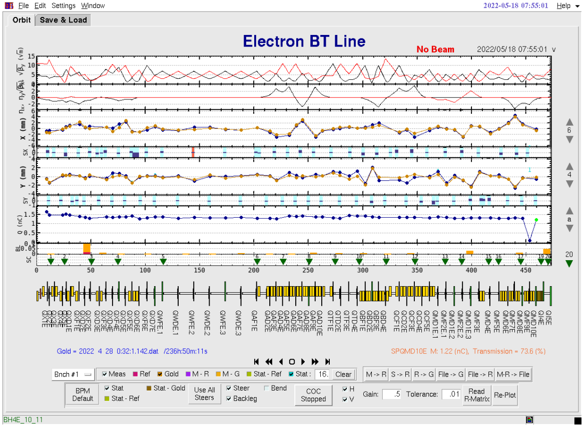
Bending magnets of BT Electron Line

Location	Number	Length [mm]	Turns/pole	Iset [A]
SY3	5	2000	130	141.8
ARC0	5	2000	130	140.8
ARC1	20	2000	112	156.6
ARC2	9	2000	112	14.7.7
ARC3	10	2200	112	150.6
Slope	4	1800	104	154.0
ARC4	11	1780	84	147.0

Bending magnets of BT Positron Line

Location	Number	Length [mm]	Turns/pole	Iset [A]
SY3	1	1500	112	162.5
ARC0	5	1000	112	200.6
ARC1	20	1000	112	182.2
V line	2	1000	96	140.8
ARC2	7	1200	112	164.3
ARC3	11	2000	112	175.9
Slope	2	1800	112	213.3
ARC4	10	1780	84	114.5


Orbit
Save & Load
δE = 0.047 %
Positron BT Line
2022/05/18 07:55:01
Gold = 2022 5 6 14:50:16.266.dat /494h:27m:36s
SPQMD13P K: 2.66 (nC), Transmission = 91.4 (%)
BH1P_1_9

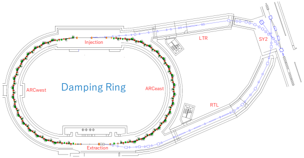

Orbit
Save & Load
Electron BT Line
No Beam
2022/05/18 07:55:01
Gold = 2022 4 28 0:32:1.142.dat /236h:50m:11s
SPQMD10E M: 1.22 (nC), Transmission = 73.6 (%)
BH4E_10_11

DC magnets for DR/LTR/RTL

DR Magnets

Line	Bend	Quad	Sx	V steering	H steering	Total
Ring	78	84	74	4	2	242
LTR/RTL	17	42	2	22	13	169

T. Ueda

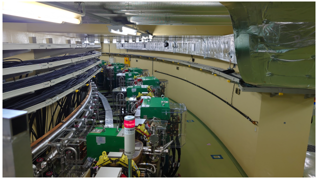


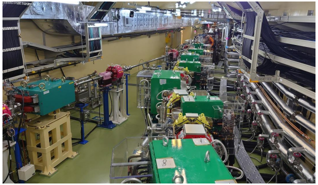
Bend magnets of DR

Type	Number	Length [mm]	Turns/pole	Iset [A]
B1	32	690	16	802.0
B2	38	230	16	747.7
B3	4	334	16	668.7
B4	4	420	16	666.9

Bend magnets of LTR/RTL

Location	Number	Length [mm]	Turns/pole	Iset [A]
LTR	2	650	60	419.1
RTL	6	650	28	435.7
SY2	9	1000	54	369.2



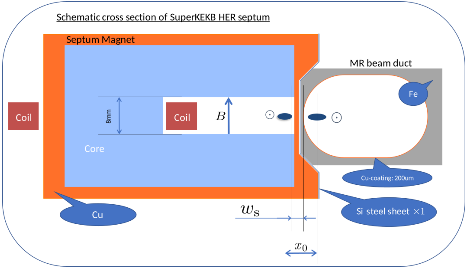


B2: "Reverse bend"s which make radiation damping time shorter with weak bending field ($B < 1.5[\mathrm{T}]$).

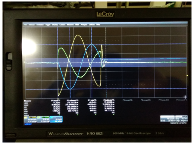
Pulsed magnets

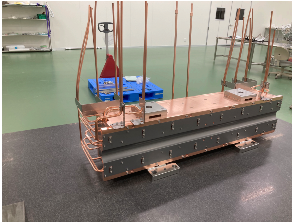
Line	Magnet	Length [m]	Number
Electron	Injection septum	1.0	4
	Injection kicker	0.225	3+3
Positron	Injection septum	0.79	2
	Injection kicker	0.225	3+3
DR	Injection septum	0.8	1
	Injection kicker	0.8	1
	Extraction septum	0.24	1
	Extraction kicker	0.24	1

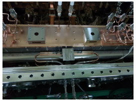
MR injection septa



Parameters	LER		HER	Unit
Core type	0.35mm Si-steel lamination			
Core gap		8.00		mm
Weight		∼ 260		kg
Field		∼ 1		T
Angle	∼ 50		∼ 37.5	mrad
Max peak current		10		kA
Max voltage		2		kV
Pulse shape		300 us full sine		







MR Injection Kicker

Parameters

T. Mimashi, et al, p2441, Proceedings of EPAC (2000)

Table 1: Parameters of the kicker magnet

Number of kicker magnets	6
Ferrite core length (mm)	225
Ferrite core gap (mm)	90
length of ceramic	420
Ti coating thickness (μm)	6 (Design)
Peak magnetic field (Gauss)	500
Peak current (A)	2000
Peak voltage (kV)	35
Time jitter (nsec)	2-3
Repetition rate (Hz)	50
Rise time (μsec)	1
Fall time (μsec)	1
Current shape	Half sine
Peak current stability (%)	< 0.1

LER1 : 3台, LER2 : 3台
HER3 : 3台, HER4 : 3台

運転時
LER1 : ≒ 16 kV, LER2 : ≒ 12 kV
HER3 : ≒ 15 kV, HER4 : ≒ 20 kV

ハード

MRトンネルに沿ってKicker1(LER) -> Kicker2(LER) -> Kicker3(HER) -> Kicker4(HER)

Optics

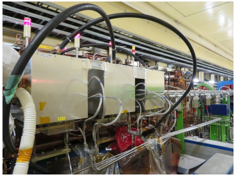
入射ビームを先に蹴る方をK1, 周回ビームを先に蹴る方をK2と定義.

LER Kicker：K1(LER Kicker1), K2(LER Kicker2)

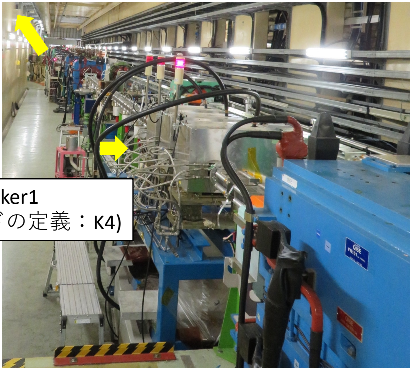
HER Kicker：K1(HER Kicker4), K2(HER Kicker3).

HER Kicker

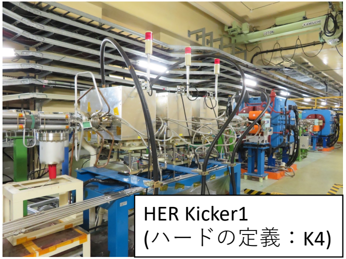
HER Kicker2
(ハードの定義：K3)



BT Line(e-)

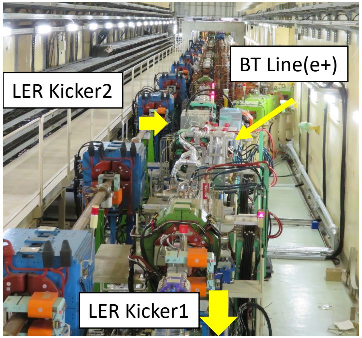


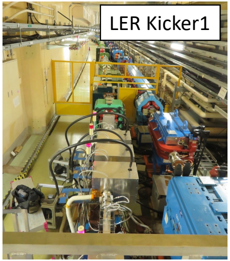
HER Kicker1
(ハードの定義：K4)

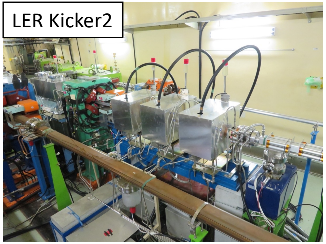


HER Kicker1
(ハードの定義：K4)

LER Kicker







MR Abort Kicker

Purpose

Chapter 14 Safety System, SuperKEKB Design Report

1. To transport the extracted beam to the beam dump safely.
2. Energy density dissipated at the Ti window is less than its allowable maximum value.
3. To minimize the abrupt change in beam loading, the beam abort gap that is an empty bucket space reserved for the rise time of the abort kicker magnet, must be less than 200 nsec. -> For the stable operation of RF cavities.

HER Abort Orbit	LER Abort Orbit

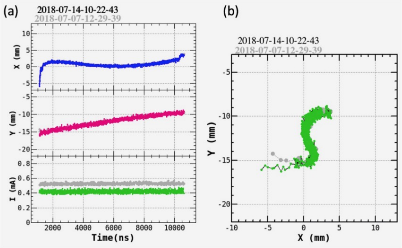
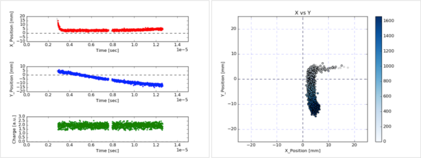


Figure 14.21: (a) The horizontal axis shows the time from the abort trigger. The vertical axes show the horizontal/vertical bunch position, and the bunch current. (b) Two-dimensional position plots are shown. The origin is the center of the BPM chamber. The gray points show the reference plots aborted manually.



Magnet Parameters

Table 14.5: Parameters of kicker and pulsed quadrupole magnets

	HER-H	HER-V	LER-H	LER-V	LER-Quad
B *or* B'	23(mT)	87(mT)	25(mT)	75(mT)	1.4(T/m)
BL *or* B'L	63(mTm)	30(mTm)	18(mTm)	26	0.96(T)
No. of Turns (coil)	1	3	1	3	1
Core Length (mm)	350 x 8	350	350 x 2	350	350 x2
Gap (mm)	70	90	70	90	70 (Bore radius)
No. of coils	4	1	1	1	2

Overview of HER Abort system

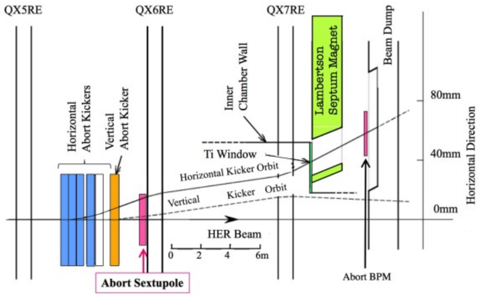
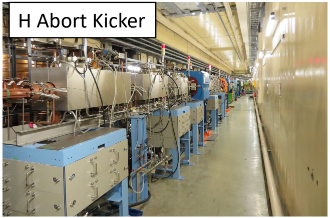
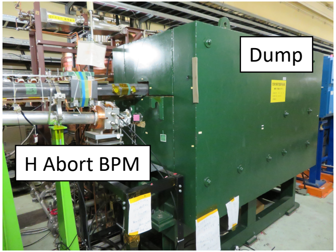


Figure 14.10: The schematic layout of the HER abort system. The horizontal axis shows the position along the electron beam. The transverse orbits at abort system region are shown. The stored beam passes the center of the abort sextupole. On the other hand, the aborted beam passes off-center of the sextupole magnet.





Overview of LER Abort system

Chapter 14 Safety System, SuperKEKB Design Report

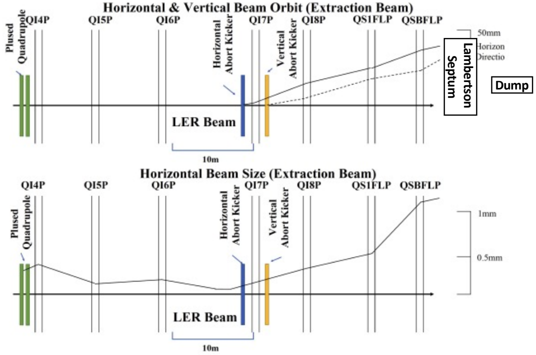
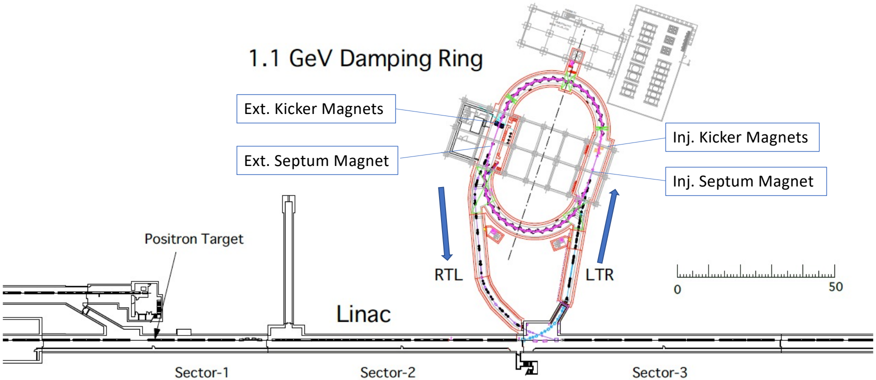


Figure 14.14: Configuration of the LER abort system.. The horizontal axis is the distance along the positron beam. The transverse orbits at abort region are shown.

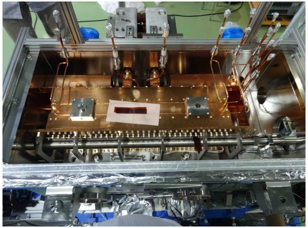
Damping Ring (Inj. & Ext. pulse magnets)



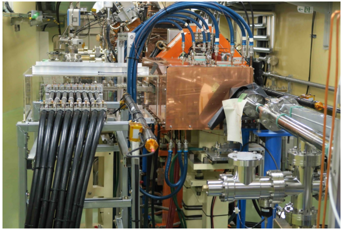
Design Parameters for DR septum magnets

	Inj.	Ext.
Deflection angle (mrad)	79.2	104
No. of magnets	1	1
Peak magnetic field (T)	0.4	0.477
Septum thickness (mm)	4	10.5
Core length (m)	0.8	0.8
Magnet field aperture (mm)	74(W)x24(H)	100(W)x30(H)
Max. peak current (A)	8000	12500
Pulse width (us)	234 (fill-sine wave)	216 (full-sine wave)
Repetition (Hz)	50	50
	In-vacuum	Out vacuum

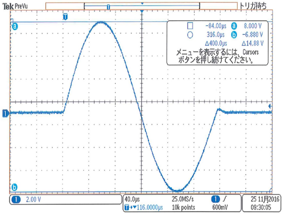
DR septum magnets



Inj. septum magnet



Ext. septum magnet



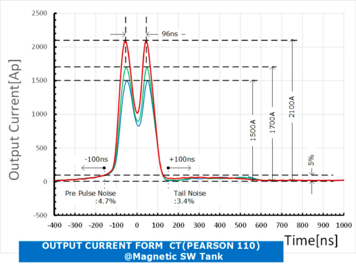
Output current of ext. septum

Design Parameters for DR kicker magnets

	Inj.	Ext.
Deflection angle (mrad)	5.2	4.7
No. of magnets	2	2
Peak field (T)	0.04	0.036
Magnet core length (m)	0.24	0.24
Magnet inductance (uH)	0.8	0.8
Peak current (A)	1708	1546
Pulse width (ns)	300 (half-sine wave)	300 (half-sine wave)
Rise time & Fall time (ns)	<100	<100
Timing jitter (ns)	<1.4	<1.4
Frequency repetition	50	50

DR kicker magnets

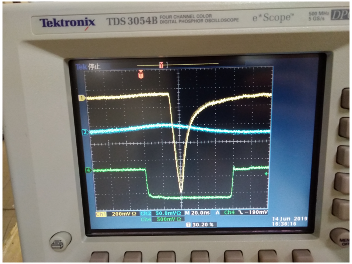
DR inj. kickers



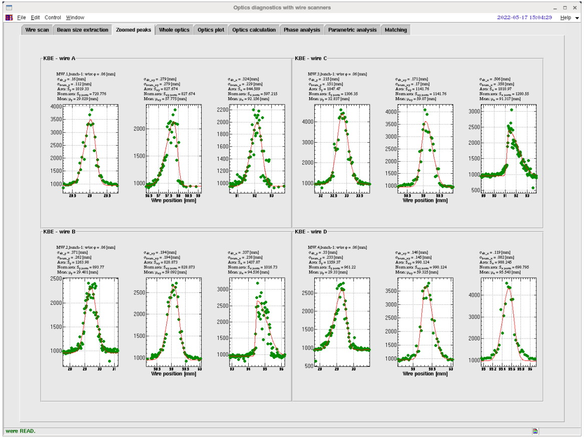
Beam instrumentations

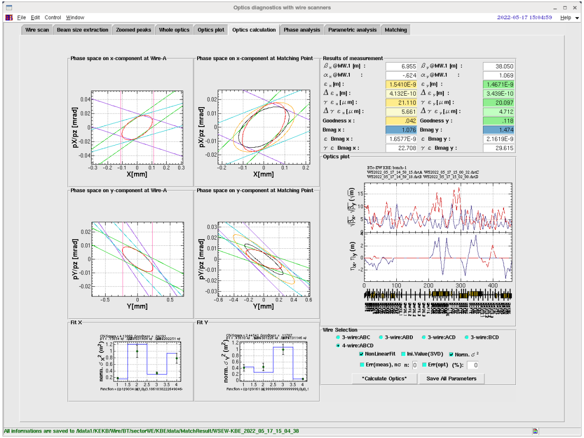
- Beam position monitors (BPM)
- Screen monitors
- Wire scanners
  Measuring emittance
- Beam collimators
  Setting transverse/energy acceptance cutoff
- Beam shutters

Wire scanners

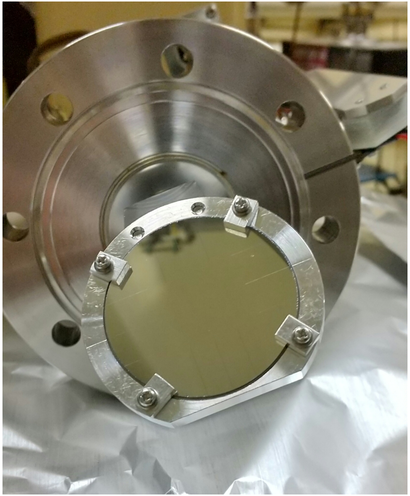


Wire scanners

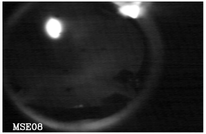


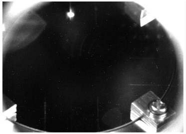


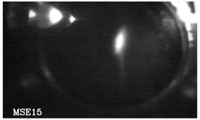
OTR screen monitor

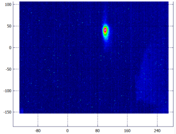


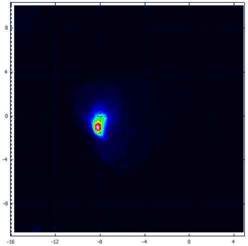
OTR screen monitor



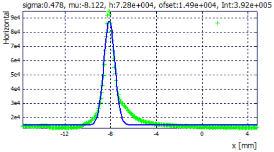


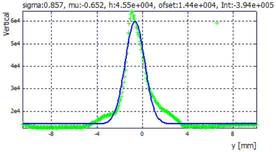






MSE.10





13

DC magnets for DR/LTR/RTL

DR

No.	magnet type	Bore or Gap [mm]	length [mm]	weight [kg]	used
1	B1	46	690	1850	32
2	B2	46	230	750	38
3	B3	46	334	1000	4
4	B4	46	420	1200	4
5	QM(F)	46	200	210	37
6	QM(D)	46	200	210	37
7	QRF	110	369	1000	3
8	QRD	60	287	400	7
9	SX	70	75	135	75
10	STV_C	60	100	56	3
11	STH_H	120	100	82	1
12	STH_H1	60	100	101	1
13	STH_H2	124	100	110	1

LTR/RTL

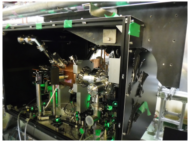
14	BC1E	50	1000	4240	2
15	BC2E	25	1220	2800	2
16	BLN	50	650	1410	5
17	BRN	50	500	620	1
18	BS	28	750	820	8
19	QLN1	98	400	1061	3
20	QLN2	98	400	1061	5
21	QLS	64	350	765	7
22	QMN	48	250	700	12
23	QMS	30	200	300	13
24	QRN	39	340	140	2
25	SFS	84	100	180	2
26	StH56	100	150	75	2
27	StHerH	80	283	-	12
28	StHerV	80	283	-	14
29	StV128	180	150	120	5
30	StV56	100	150	75	2

B2: “Reverse bend”s which make radiation damping time shorter with weak bending field.

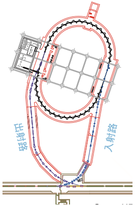
Coil parameters of DR magnets

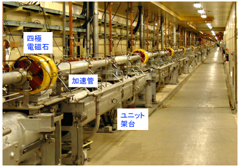
No	magnet type	main coil					Correction coil				
		peak voltage [V]	peak current [A]	Number of turns per coil [T]	Nominal Ampere Turns per coil [A T]	Number of coils per magnet	peak voltage [V]	peak current [A]	Number of turns per coil [T]	Nominal Ampere Turns per coil[A T]	Number of coils per magnet
1	B1	15.5	900	16	14400	2	4.6	7.7	39	300	2
2	B2	9.4	880	16	14080	2	2.6	7.7	39	300	2
3	B3	9.7	800	16	12800	2	3.2	7.7	39	300	2
4	B4	10.9	800	16	12800	2	3.4	7.7	39	300	2
5	QM(F)	5.2	330	16	5280	4	0.6	5.0	10	50	4
6	QM(D)	3.8	247.5	16	3960	4	0.6	5.0	10	50	4
7	QRF	11.3	500	25	12500	4	1.2	10.0	12	120	4
8	QRD	4.9	300	16	4800	4	0.7	10.0	10	100	4
9	SX	5.0	150	20	3000	6	2.5	10.0	50	500	6
10	STV_C	0.8	10	52	520	2	-	-	-	-	-
11	STH_H	2.2	10	86	860	2	-	-	-	-	-
12	STH_H1	1.6	10	52	520	2	-	-	-	-	-
13	STH_H2	3.4	10	137	1370	2	-	-	-	-	-
14	BC1E	23.0	498	54	26892	2	1.8	10.0	30	300	2
15	BC2E	25.3	450	80	36000	2	11.0	5.0	144	720	2
16	BLN	19.6	468	60	28080	2	2.4	10.0	30	300	2
17	BRN	10.2	468	44	20592	2	2.0	10.0	30	300	2
18	BS	7.8	468	28	13104	2	2.6	10.0	30	300	2
19	QLN1	-	80	110	8800	4	-	-	-	-	-
20	QLN2	-	80	110	8800	4	-	-	-	-	-
21	QLS	8.0	40	80	3200	4	-	-	-	-	-
22	QMN	8.0	37	110	4070	4	-	-	-	-	-
23	QMS	4.0	21	80	1680	4	-	-	-	-	-
24	QRN	4.4	25	70	1750	4	-	-	-	-	-
25	SFS	3.0	10	50	500	6	-	-	-	-	-
26	StH56	4.0	5	110	550	2	-	-	-	-	-
27	StHerH	25.0	5	648	3240	2	-	-	-	-	-
28	StHerV	25.0	5	648	3240	2	-	-	-	-	-
29	StV128	12.0	5	250	1250	2	-	-	-	-	-
30	StV56	4.0	5	110	550	2	-	-	-	-	-

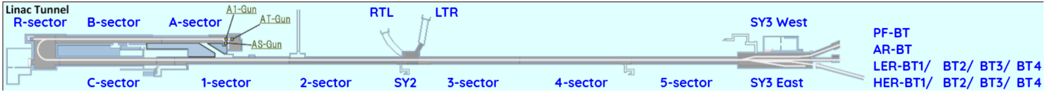
Linac introduction

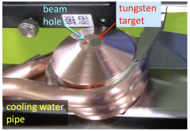


A1-gun



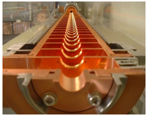




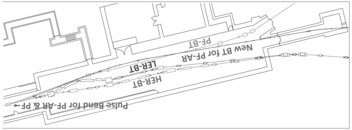


Sector 1-5
Tungsten: $r = 2$ [mm],
hole: $r = 1$ [mm].

- f = 2856 MHz, λ = 105 mm
- 2π/3-mode (cell length 35mm)
- 54 cells + in/output-coupler
- structure length ∼ 2 m
- typical iris diameter ∼ 20 mm
- field strength ∼ 21 MV/m@34 MW

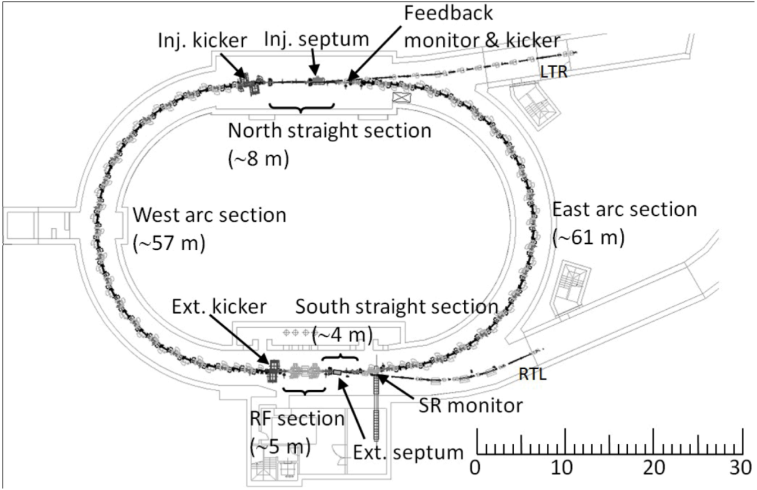


T. Kamitani



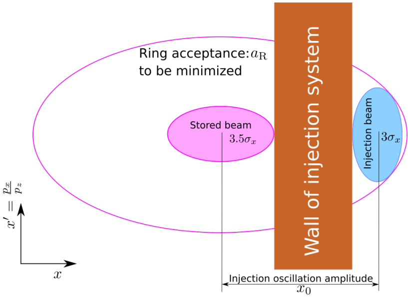
Beam	Positron	Electron	
Beam energy	4.0	7.007	GeV
Normalized emittance $\gamma\varepsilon_{x/y}$	100/15	40/20	μm
Energy spread	0.16	0.07	%
Bunch charge	4	4	nC
No. of bunches/pulse	2	2	
Repetition rate	50		Hz

DR



Energy	1.1		GeV
No. of bunch trains	2		
No. of bunches / train	2		
Circumference	135.49829		m
Max. stored current	70.8		mA
Energy loss / turn	0.091		MV
Hor. damping time	10.87		ms
Inj.-beam emittance	1400		nm
Emittance (h/v)	42.6 / 2.13		nm
Energy spread	5.5×10^{-4}		
Coupling	5		%
Extracted emittance (h/v)	43.5 / 3.15		nm
Cavity voltage	0.5	1.4	MV
Bucket height	0.8	1.5	%
Synchrotron tune	0.0153	0.0261	
Bunch-length	11.18	6.56	mm
Phase advance/cell (h/v)	64.39 / 64.64		deg
Momentum compaction	0.0143		
Bend-angle ratio	0.35		
No. of normal-cells	40		
RF frequency	509		MHz
Chamber diameter (h/v)	34 / 24		mm

Injection parameters



- Baseline injection scheme: betatron injection
- Injection oscillation amplitude: x_0

- Elliptic equation: $\frac{x^2}{a_i\beta_i} + \frac{x'^2}{a_i\gamma_i} = 1 \Rightarrow$ Area: $S_i = \pi\sqrt{\beta_i\gamma_i}a_i = \pi a_i$
  where $\beta_i\gamma_i - \alpha_i^2 \equiv 1$ with assumption: $\alpha_i \equiv 0 \quad (i = \mathrm{R}, \mathrm{I})$
  Storage beam: $\frac{x^2}{\beta_{\mathrm{R}}} + \frac{x'^2}{\gamma_{\mathrm{R}}} = a_{\mathrm{R}}$
  Injection beam: $\frac{(x-x_0)^2}{\beta_{\mathrm{I}}} + \frac{x'^2}{\gamma_{\mathrm{I}}} = a_{\mathrm{I}}$
- Injection parameters are optimum at a_{R} minimum
- Minimum a_{R} is derived when injection aperture is inscribed in the edge of a_{R}
- Solution:

$$a_{\mathrm{R}} = \frac{x_0^2\beta_{\mathrm{R}}}{\beta_{\mathrm{R}}^2 - \beta_{\mathrm{I}}^2} + \frac{\beta_{\mathrm{R}}}{\beta_{\mathrm{I}}}a_{\mathrm{I}} \tag{2}$$

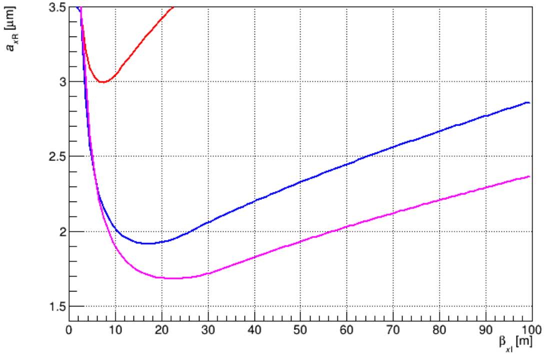
$$x_0 = 3.5\sigma_{x\mathrm{R}} + w_{\mathrm{s}} + 3.0\sigma_{x\mathrm{I}} + \mathrm{d}x_{\mathrm{bump}}{}^{\star 1} + \mathrm{d}x_{\mathrm{slope}}{}^{\star 2} \tag{3}$$

$$\begin{pmatrix}\Delta x \\ \Delta x'\end{pmatrix} = \begin{pmatrix}1 & 0 \\ -\frac{\alpha_{\mathrm{R}}}{\beta_{\mathrm{R}}} & 1\end{pmatrix}\begin{pmatrix}x_0 \\ 0\end{pmatrix} \tag{4}$$

$^{\star 1}$Kicker jitter.
$^{\star 2}$Including increase of x from injection point to top of bump in QI4E or QI6P.

Acceptance

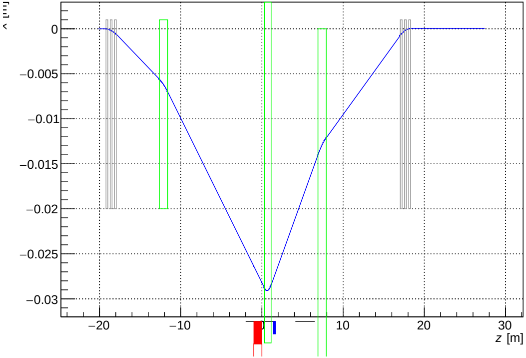
HER injection acceptance with $w_\mathrm{s} = 6.0$ [mm]



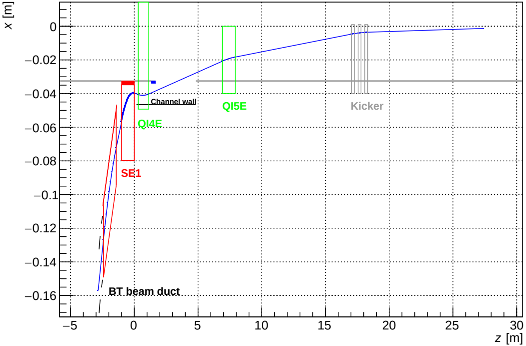
Input parameter	Value
$\varepsilon_{x\mathrm{R}}$ [nm]	4.6
$\varepsilon_{x\mathrm{I}}$ [nm]	7.3
n_R	3.5
n_I	3.0
w_s [mm]	6.0
$\beta_{x\mathrm{R}}$ [m]	40,80,100

$$\beta_{x\mathrm{I}} = 22.4 \ [\mathrm{m}]$$
$$n_\mathrm{R}\sigma_{x\mathrm{R}} = 2.374 \ [\mathrm{mm}]$$
$$n_\mathrm{I}\sigma_{x\mathrm{I}} = 1.213 \ [\mathrm{mm}]$$
$$\Delta x = 11.49 \ [\mathrm{mm}]$$
$$\Delta x' = 0.911 \ [\mathrm{mrad}]$$
$$x_\mathrm{R}^\mathrm{inj} \leq 28.2 \ [\mathrm{mm}]$$

Injection orbit for HER storage/injection beam



Kickers, Quadrupole magnets, Septa



Effective width	$w_s = 6.0$
Distance to SE1 plate [mm]	4.80
Distance to injection BPM [mm]	4.59
Local maximum in QI4E [mm]	41.04
Injection position x [mm]	39.69
Injection angle θ [mrad]	2.737

Bump height : $x_R^{inj} = 28.20$ [mm]

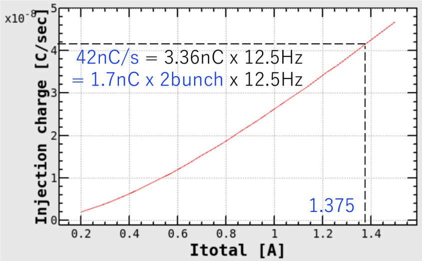
Maximum height : $x_R = 29.08$ [mm]

Tilt at inj. point : $\theta_R^{inj} = 1.827$ [mrad]

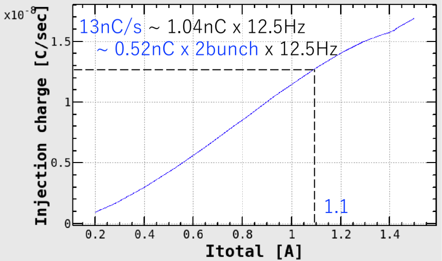
Allowed beam currents with current injection status in 2022b

Updated Apr. 20, Y. Funakoshi, N. Iida

LER Assumed ε_{inj}=60%



HER Assumed ε_{inj}=56%



Ishibashi-san's plan

Plan A

day	wk	num_bunch	I+ [mA]	I- [mA]
2022/6/30	木	1957	1375	1100

Plan B

day	wk	num_bunch	I+ [mA]	I- [mA]
2022/6/30	木	1761	1250	1000

It is assumed that the beam lifetimes are inversely proportional to the bunch currents.
Plan A will be able to realized, if current injections can be kept.

What is injection?

Injection succeeds if the injection beam is put in the dynamic aperture of the ring.

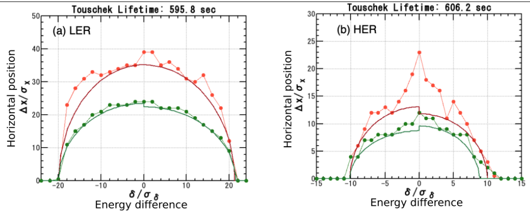


Figure 4.12: Dynamic aperture. (a) LER, (b) HER. Touschek lifetime is estimated by the dynamic aperture. Red line indicates $(\psi_{x0}, \psi_{y0}) = (0, 0)$ for the initial phase and green line indicates that the initial phase is $(\psi_{x0}, \psi_{y0}) = (\pi/2, \pi/2)$.

What is injection?

Injection succeeds if the injection beam is put in the dynamic aperture of the ring

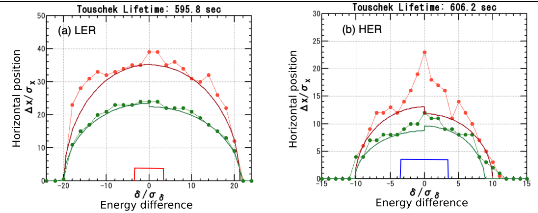


Figure 4.12: Dynamic aperture. (a) LER, (b) HER. Touschek lifetime is estimated by the dynamic aperture. Red line indicates $(\psi_{x0}, \psi_{y0}) = (0, 0)$ for the initial phase and green line indicates that the initial phase is $(\psi_{x0}, \psi_{y0}) = (\pi/2, \pi/2)$.

without any bad effects on stored beam.
"Injection system" aims at the optimum point of phase space in the dynamic aperture.

What is injection?

Injection succeeds if the injection beam is put in the dynamic aperture of the ring

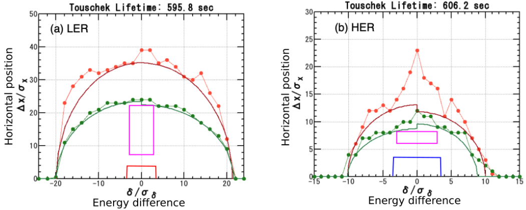


Figure 4.12: Dynamic aperture. (a) LER, (b) HER. Touschek lifetime is estimated by the dynamic aperture. Red line indicates $(\psi_{x0}, \psi_{y0}) = (0, 0)$ for the initial phase and green line indicates that the initial phase is $(\psi_{x0}, \psi_{y0}) = (\pi/2, \pi/2)$.

without any bad effects on stored beam.
"Injection system" aims at the optimum point of phase space in the dynamic aperture.
Betatron injection uses betatron phase space.

What is injection?

Injection succeeds if the injection beam is put in the dynamic aperture of the ring

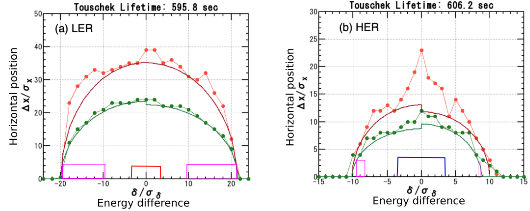


Figure 4.12: Dynamic aperture. (a) LER, (b) HER. Touschek lifetime is estimated by the dynamic aperture. Red line indicates $(\psi_{x0}, \psi_{y0}) = (0, 0)$ for the initial phase and green line indicates that the initial phase is $(\psi_{x0}, \psi_{y0}) = (\pi/2, \pi/2)$.

without any bad effects on stored beam.

"Injection system" aims at the optimum point of phase space in the dynamic aperture.

Synchrotron injection uses synchrotron phase space.

Modification of vacuum chambers on injection system

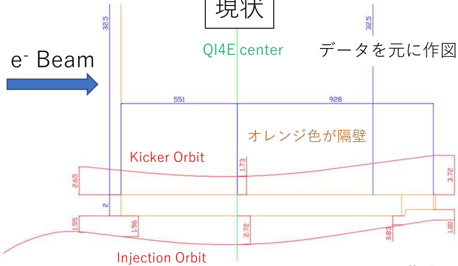
Y. Suetsugu

縦方向に50倍しています。

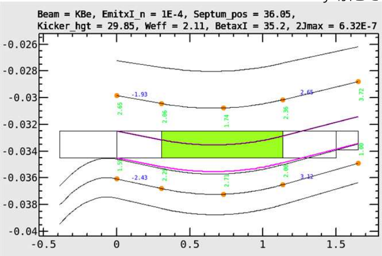
現状

データを元に作図

e⁻ Beam

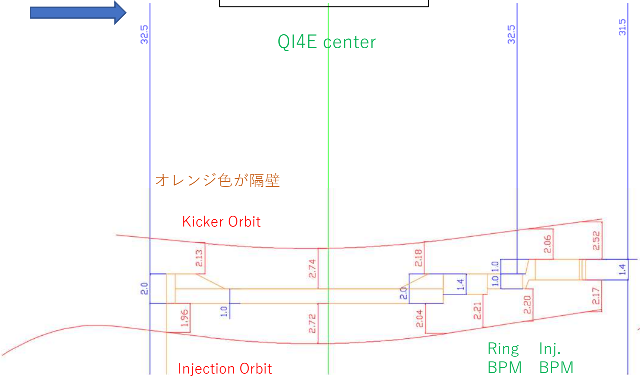


By菊池さん



変更案(改)
Pump ポート無し

e⁻ Beam

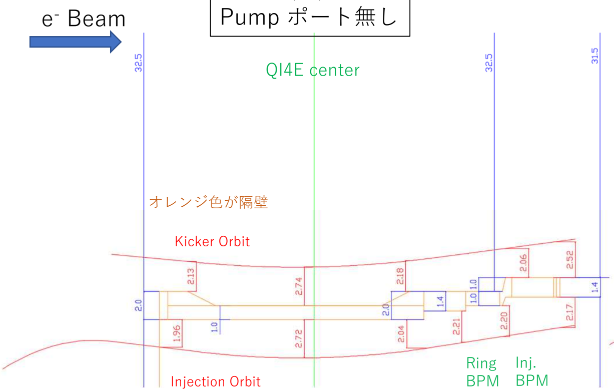


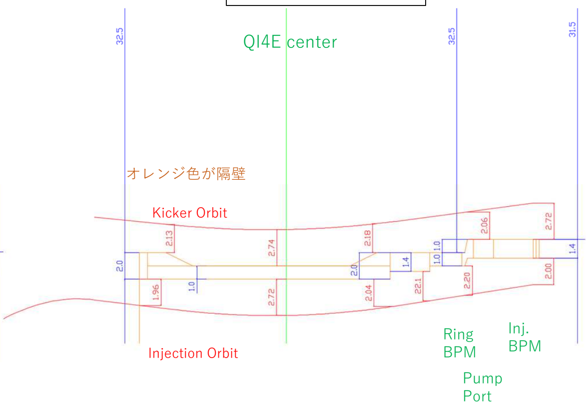
Modification of vacuum chambers on injection system

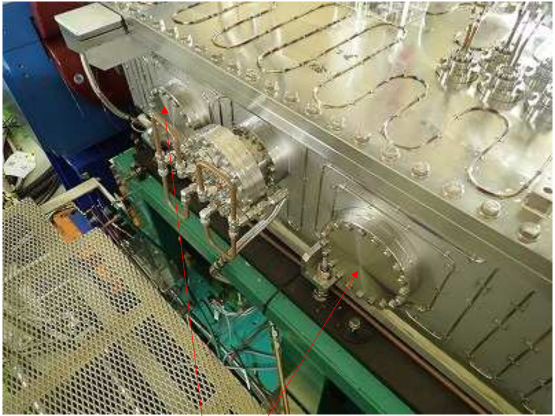
HER入射部変更案-3

2022/4/14 末次

縦方向に50倍しています。







イオンポンプとか取り付けられないか？

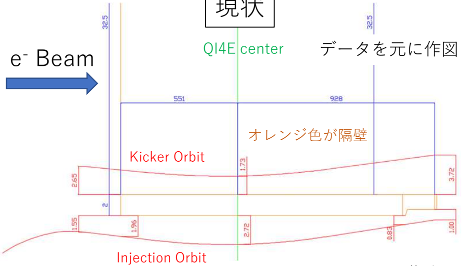
Back up

HER入射部変更案-2

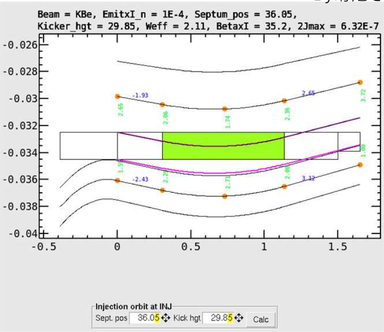
2022/4/11 末次

縦方向に50倍しています。

現状

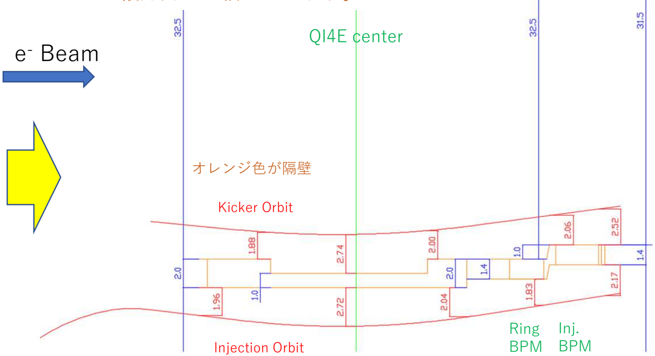


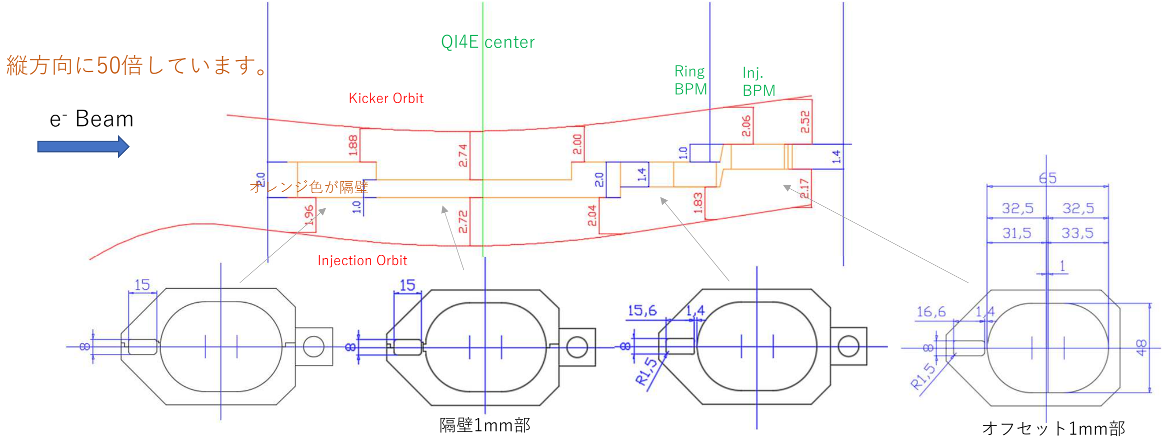
By菊池さん



縦方向に50倍しています。

変更案

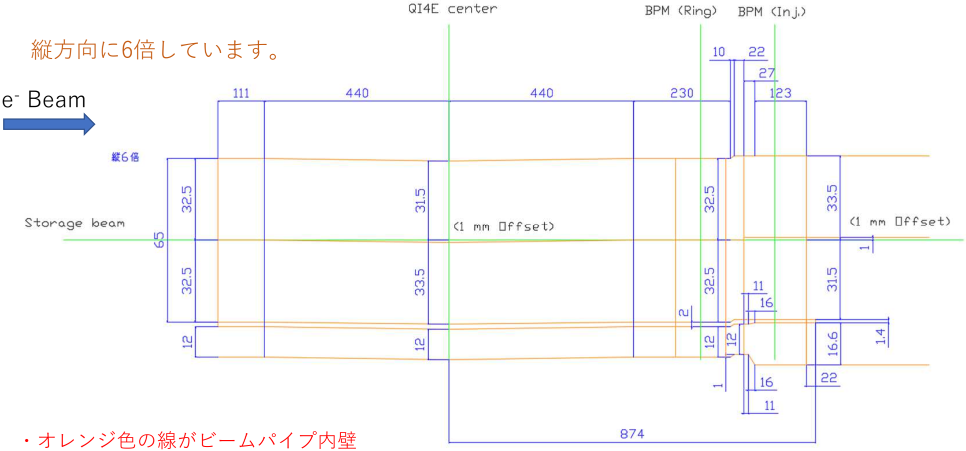




- オレンジ色の線がビームパイプ内壁
- 製作はQI4Eチェンバー、Inj. BPMチェンバー、および単管(L76)。下流の長いチェンバーは再利用。
- 入射ビームチャンネルの断面形状はLERに倣う。
- ポンプポートなし
- QI4Eセンターで部分で隔壁1mm(高さ4mm)。チェンバーは半割で製作する。
- Ring BPM中心はstorage beam
- Inj. BPMチェンバーはリング外側に1mmオフセット。チェンバーは半割で製作する。
- Inj. BPMチェンバーのビーム方向位置は、元位置より76mmQI4E側に移動。

HER入射部変更案-1

2022/4/6 末次

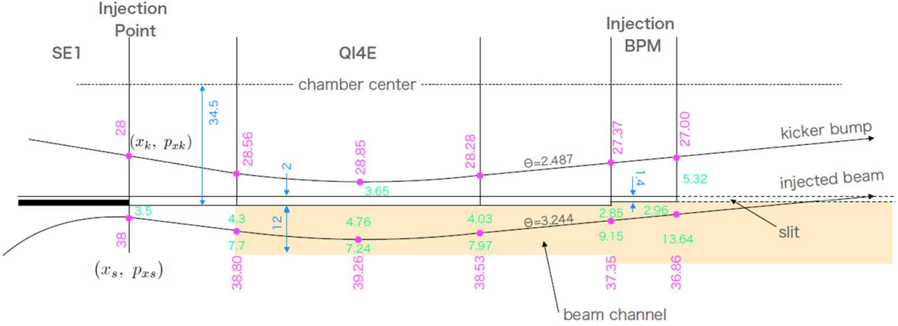


- オレンジ色の線がビームパイプ内壁
- 製作はQI4Eチェンバーおよび単管(L76)のみ。Inj. BPMチェンバー、下流の長いチェンバーは再利用。
- 入射ビームチャンネルの断面形状(上下方向も)は変えない。
- ポンプポートなし
- QI4Eセンターでリング内側に1mmオフセット。チェンバーは半割で製作する。
- Ring BPM中心はstorage beam
- Inj. BPMチェンバーはリング外側に1mmオフセット(2mmでも可)。チェンバーは半割で製作する。
- Inj. BPMチェンバーのビーム方向位置は、元位置より76mmQI4E側に移動。

HER

Injection orbit of the electron beam (unit in mm and mrad)

2022/2/4 菊池



Kicker height and septum position

$$(x_k, p_{xk}) = (28, -1.814)$$
$$(x_s, p_{xs}) = (38, -2.607)$$

$$\sigma_{xR} = 0.7$$
$$\sigma_{xI} = 0.48$$
$$(\varepsilon_{xI} = 100\ \mu\text{m}, \quad \beta_{xI} = 32\ \text{m})$$

xx.xx Orbit from the camber center
yy.yy Camber dimensions
zz.zz Orbit clearance from chamber wall

References I

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[3] N. Iida et al. "Beam injection issues at SuperKEKB". In: *Proc. IPAC'23* (Venezia). IPAC'23 - 14th International Particle Accelerator Conference 14. JACoW Publishing, Geneva, Switzerland, May 2023, pp. 814–817. ISBN: 978-3-95450-231-8. DOI: doi:10.18429/jacow-ipac2023-mopl120. URL: https://www.ipac23.org/preproc/pdf/MOPL120.pdf (cit. on p. 34).

[4] G. Stupakov and I. Kotelnikov. "Calculation of coherent synchrotron radiation impedance using the mode expansion method". In: *Phys. Rev. STAB* 12.104401 (2009). URL: https://doi.org/10.1103/PhysRevSTAB.12.104401 (cit. on p. 37).

[5] "SuperKEKB Design Report". In: (). URL: https://www-linac.kek.jp/linac-com/report/skb-tdr/ (cit. on p. 68).