Injector Linac

Kazuro Furukawa

for Injector Linac Groups

Many slides from M. Satoh and N. Iida

<http://www-linac.kek.jp/linac/>
< kazuro.furukawa @ kek.jp >

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Overview

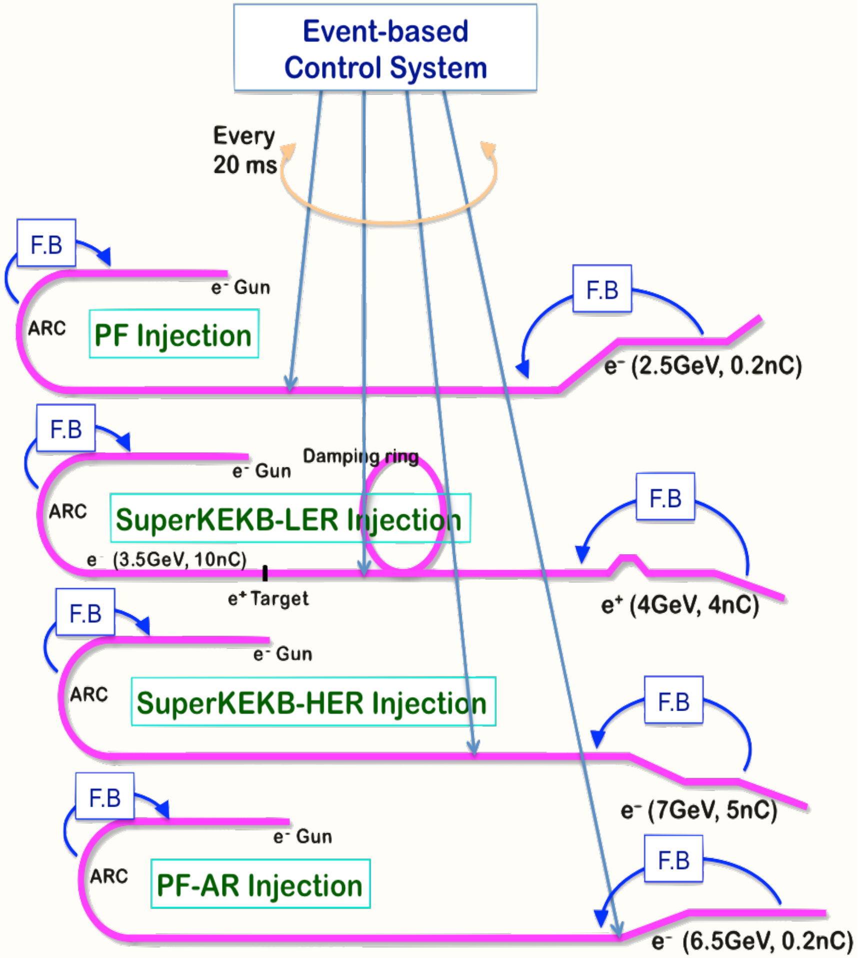
Fire Recovery

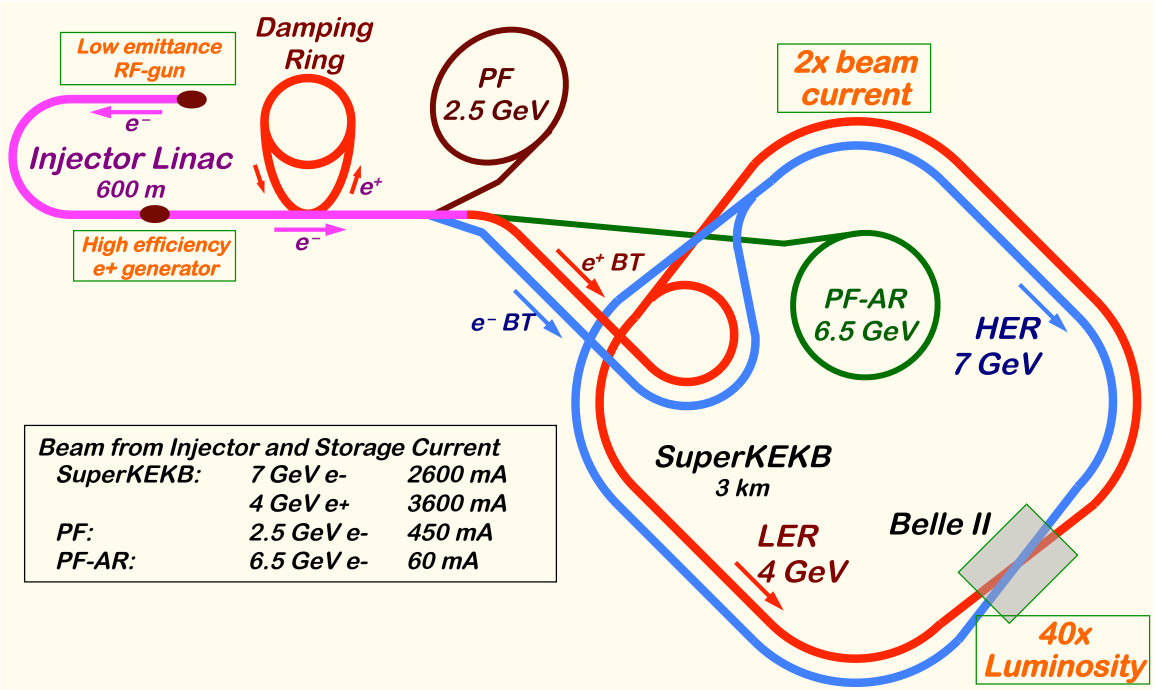
- Fire at acc. structure assembly room on Apr.3
  - Southern part of the injector was much damaged as well as the assembly room
- Interim injector recovery by Apr.26
- Full injector recovery during summer shutdown
- The assembly room cleaned up
  - Restoration in April
  - S-band structure tests and RF conditioning soon

Scaffold to clean up walls and ceiling at acc. structure assembly room

Mission of Electron/positron Injector in SuperKEKB

- **Low emittance & low energy spread injection beams with 4 times higher beam current**
  - New high-current photo-cathode RF gun
  - New positron capture section
  - Positron damping ring injection/extraction
  - Optimized beam optics and correction
  - Precise beam orbit control with long-baseline alignment
  - Simultaneous top-up injection to DR/HER/LER/PF/PFAR
- **Balanced injection for the both photon science and elementary particle physics experiments**





Beam from Injector and Storage Current

SuperKEKB:	7 GeV e-	2600 mA
	4 GeV e+	3600 mA
PF:	2.5 GeV e-	450 mA
PF-AR:	6.5 GeV e-	60 mA

The single injector would behave as multiple injectors to multiple storage rings by the concept of virtual accelerator

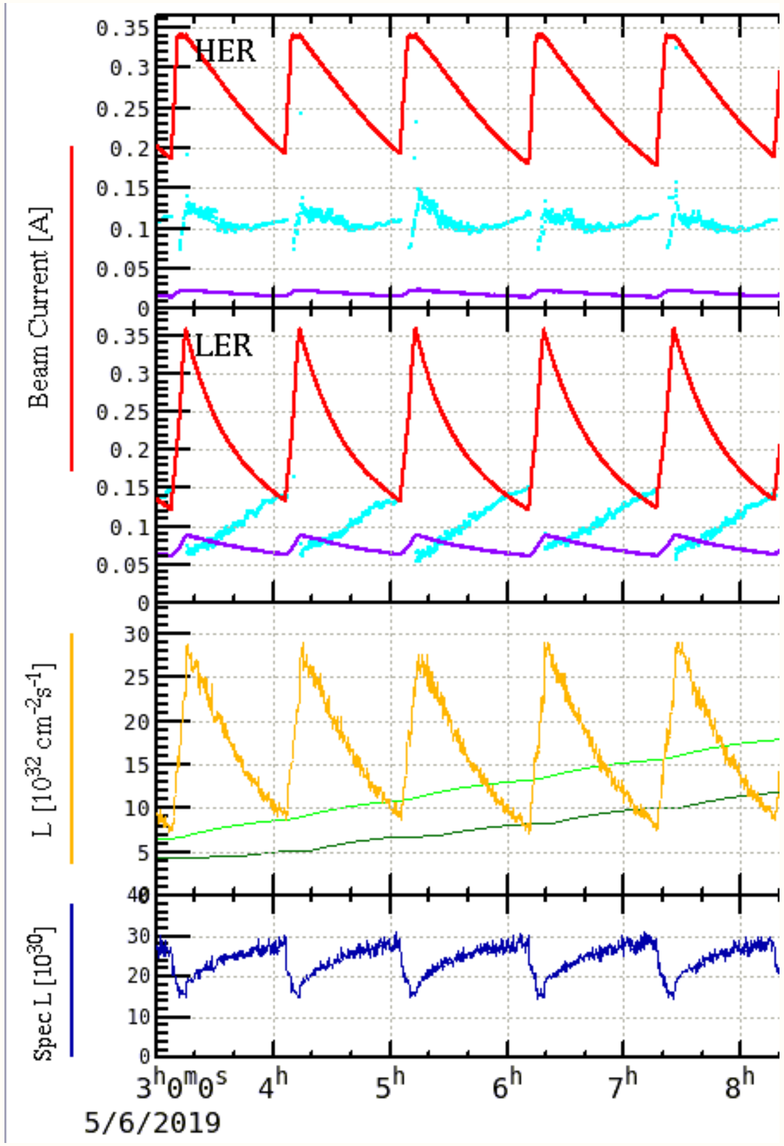
Linac Beam Parameters at KEKB/SuperKEKB

Stage	KEKB (final)		Phase-I		Phase-II		Phase-III (interim)		Phase-III (final)	
Beam	e+	e–	e+	e–	e+	e–	e+	e–	e+	e–
Energy	3.5 GeV	8.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV	4.0 GeV	7.0 GeV
Stored current	1.6 A	1.1 A	1.0 A	1.0 A	–	–	1.8 A	1.3 A	3.6 A	2.6 A
Life time (min.)	150	200	100	100	–	–	–	–	6	6
Bunch charge (nC)	primary e- 10 → 1	1	primary e- 8 → 0.4	1	0.5	1	2	2	primary e- 10 → 4	4
Norm. Emittance (γβε) (mrad)	1400	310	1000	130	200/40 (Hor./Ver.)	150	150/30 (Hor./Ver.)	100/40 (Hor./Ver.)	100/15 (Hor./Ver.)	40/20 (Hor./Ver.)
Energy spread	0.13%	0.13%	0.50%	0.50%	0.16%	0.10%	0.16%	0.10%	0.16%	0.07%
Bunch / Pulse	2	2	2	2	2	2	2	2	2	2
Repetition rate	50 Hz		25 Hz		25 Hz		50 Hz		50 Hz	
Simultaneous top-up injection (PPM)	3 rings (LER, HER, PF)		No top-up		Partially		4+1 rings (LER, HER, DR, PF, PF-AR)		4+1 rings (LER, HER, DR, PF, PF-AR)	

◆ **Limited improvements for operational electricity budget**

Simultaneous Top-up Injections

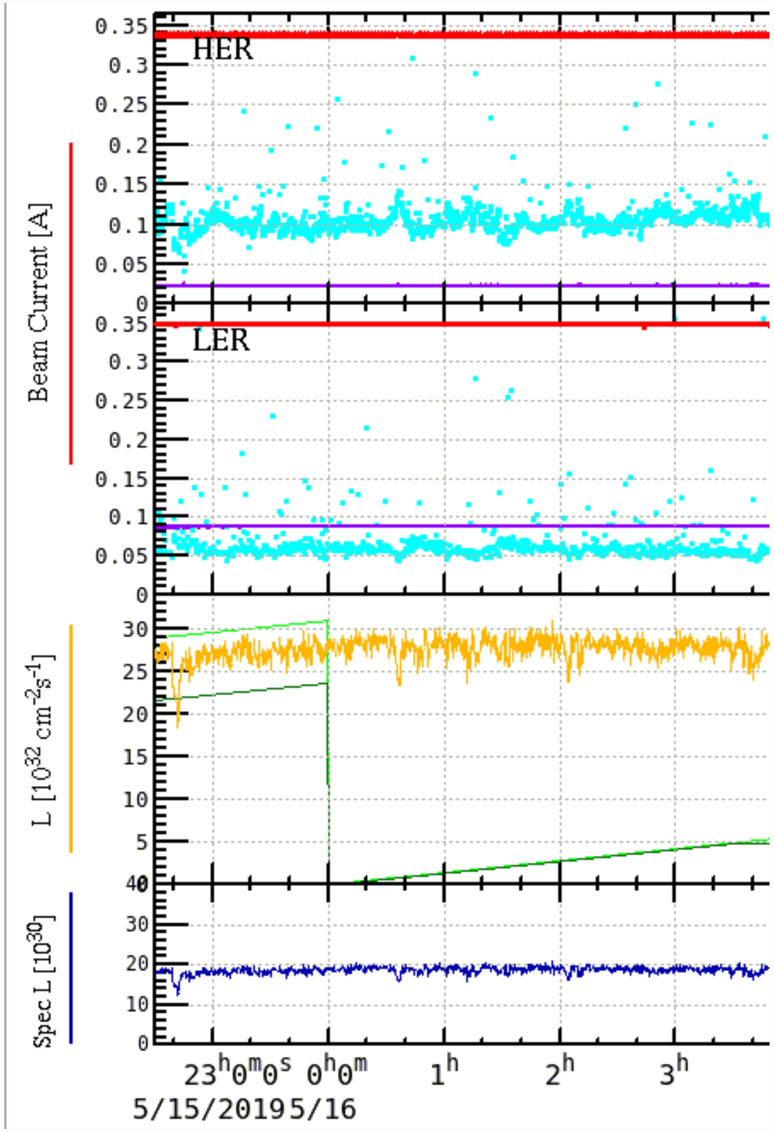
◆SuperKEKB integrated luminosity improvement



17.5 /pb in 5.15 hr
(5 fills)
on May.6

41.6 /pb in 5.15 hr
(top-up)
on May.16

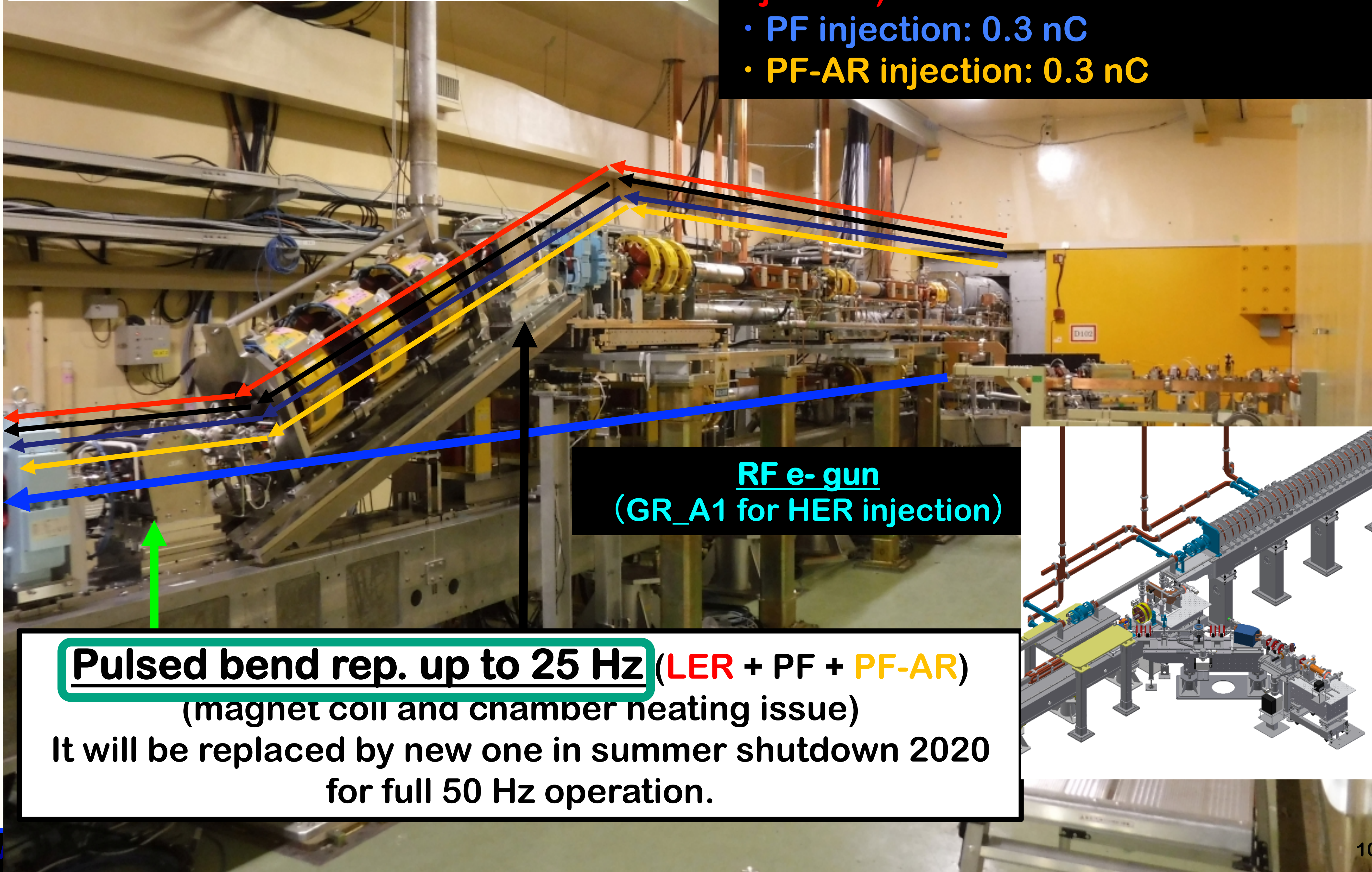
237% improvement



Beam Sources

Pulse to pulse switching: rf e- gun/thermionic e- gun

Thermionic DC e- gun (GU_AT)
w/ 2 subharmonic bunchers and 2 bunchers
・e+ production e-: 10 nC (for LER injection)
・PF injection: 0.3 nC
・PF-AR injection: 0.3 nC



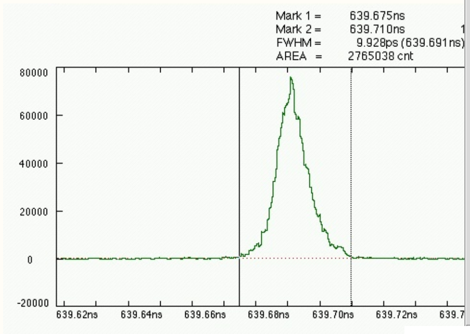
RF e- gun
(GR_A1 for HER injection)

Pulsed bend rep. up to 25 Hz (LER + PF + PF-AR)
(magnet coil and chamber heating issue)
It will be replaced by new one in summer shutdown 2020 for full 50 Hz operation.

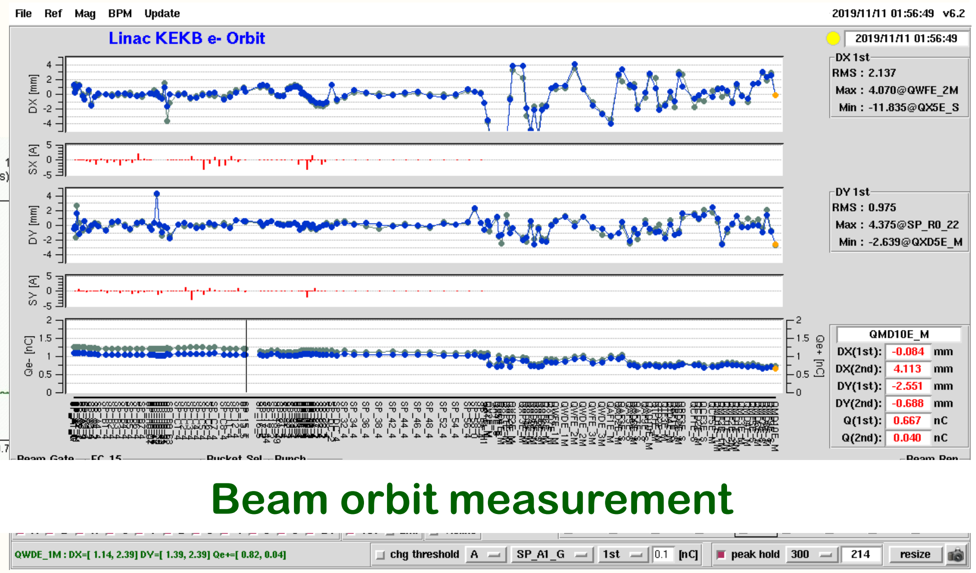
Development of Photo-cathode RF Gun

M.Yoshida et al.

- Successfully deployed for injection into SuperKEKB HER
- Employs Yb-doped-fiber and Nd/Yb:YAG laser, IrCe cathode, QTWSC or cut disk cavities
- Stability improving
- Beam instrumentation improvements and comparison with simulation codes

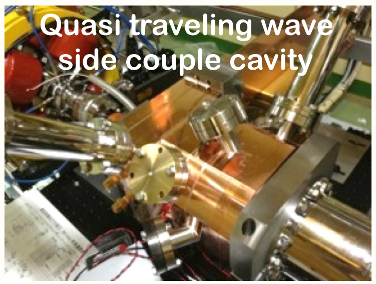


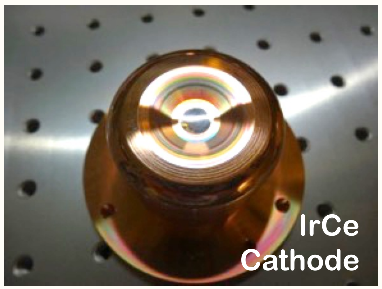
Bunch length

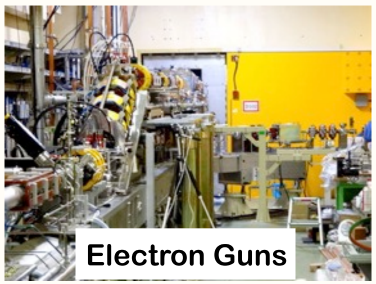


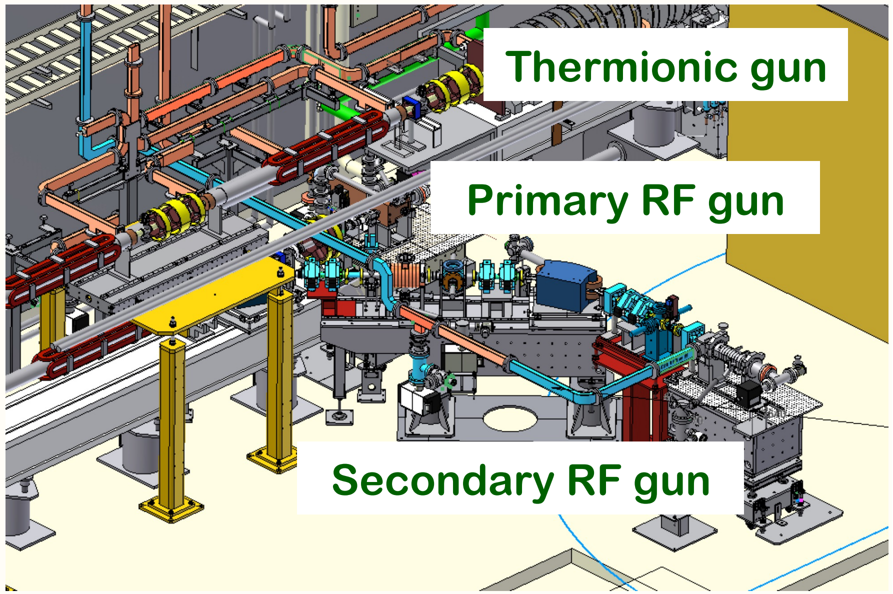
Beam orbit measurement

- Secondary RF gun was constructed as a backup (under tuning)
- Incorporate suggestions by review committee for availability





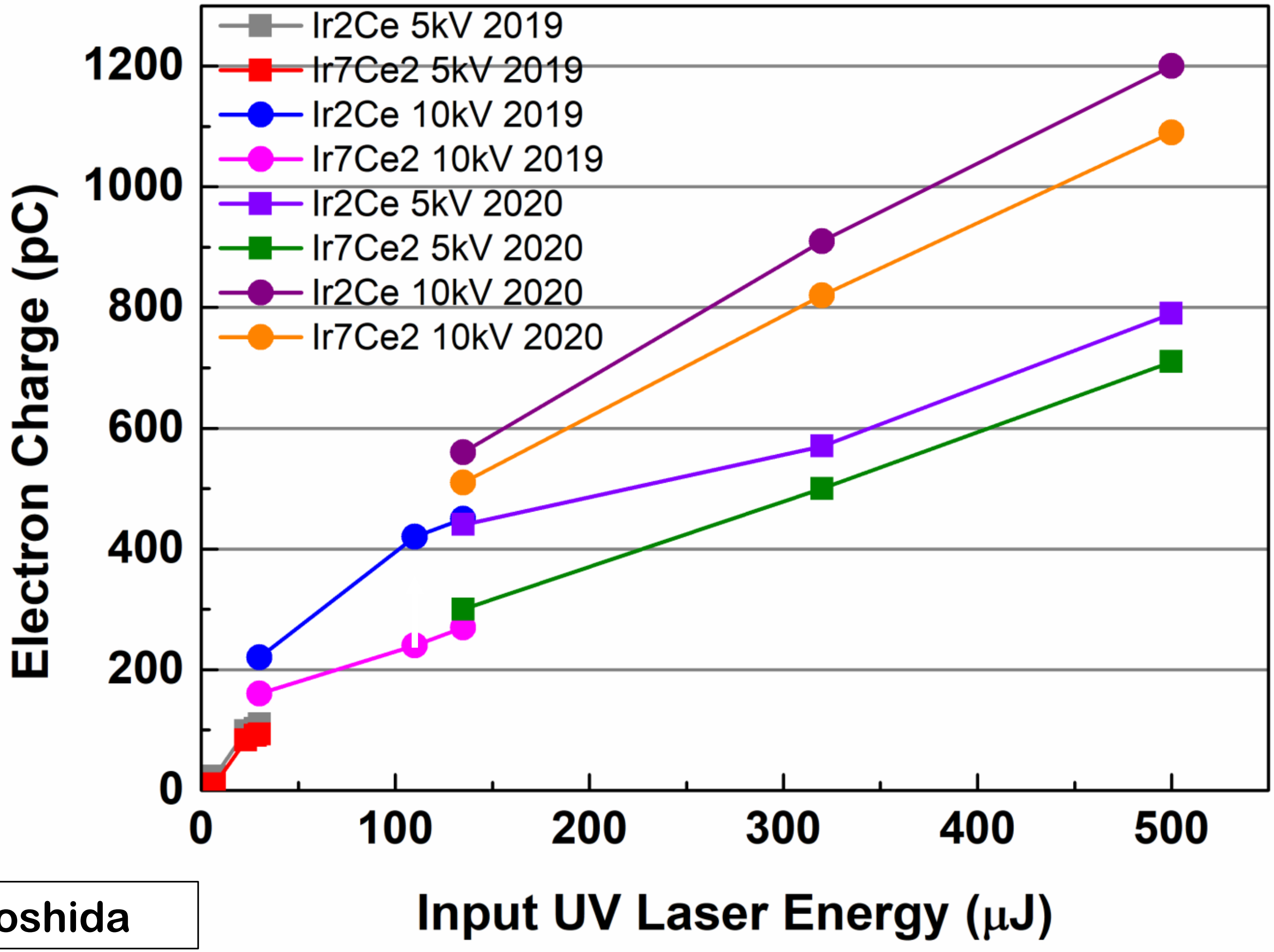




HER injection beam (RF e- gun) status

- HER injection has been done with only RF gun since the beginning of Phase III (Mar. 11th, 2019)
- Laser system has no significant fault
- In summer shutdown 2019, photocathode (Ir_7Ce_2) was replaced by new one (Ir_2Ce) aiming at better quantum efficiency (Qe)
  - Discharge, frequent VSWR, gradual decrease of bunch charge
- In this winter shutdown,
  - After applying heat and laser cleaning of cathode, bunch charge was not stable.
  - Finally, photocathode was replaced by previous one (Ir_7Ce_2) toward next run. Now, under rf conditioning.

Qe of photocathode (Ir_7Ce_2, Ir_2Ce)

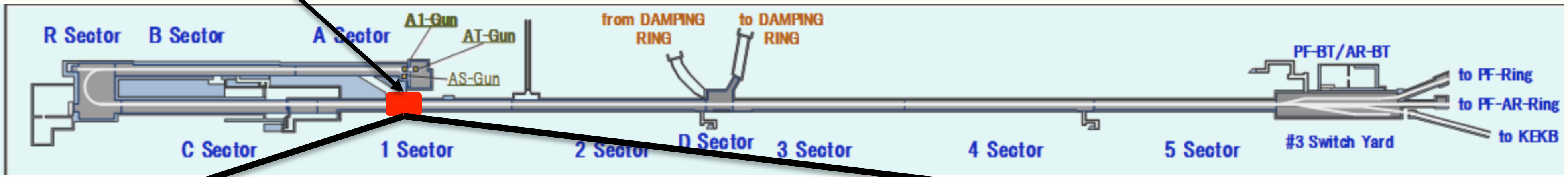


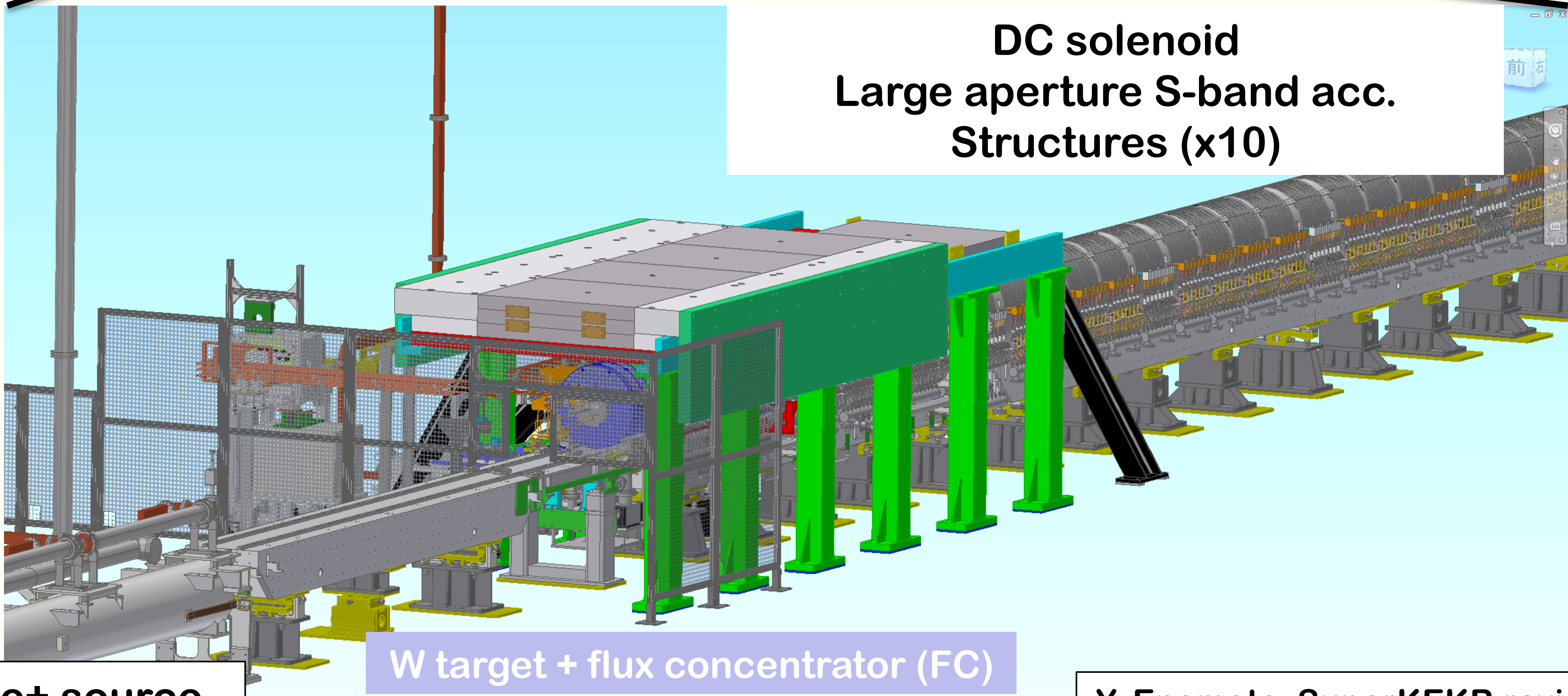
M. Yoshida

e- source

e+ source setup 1

Positron target and capture section

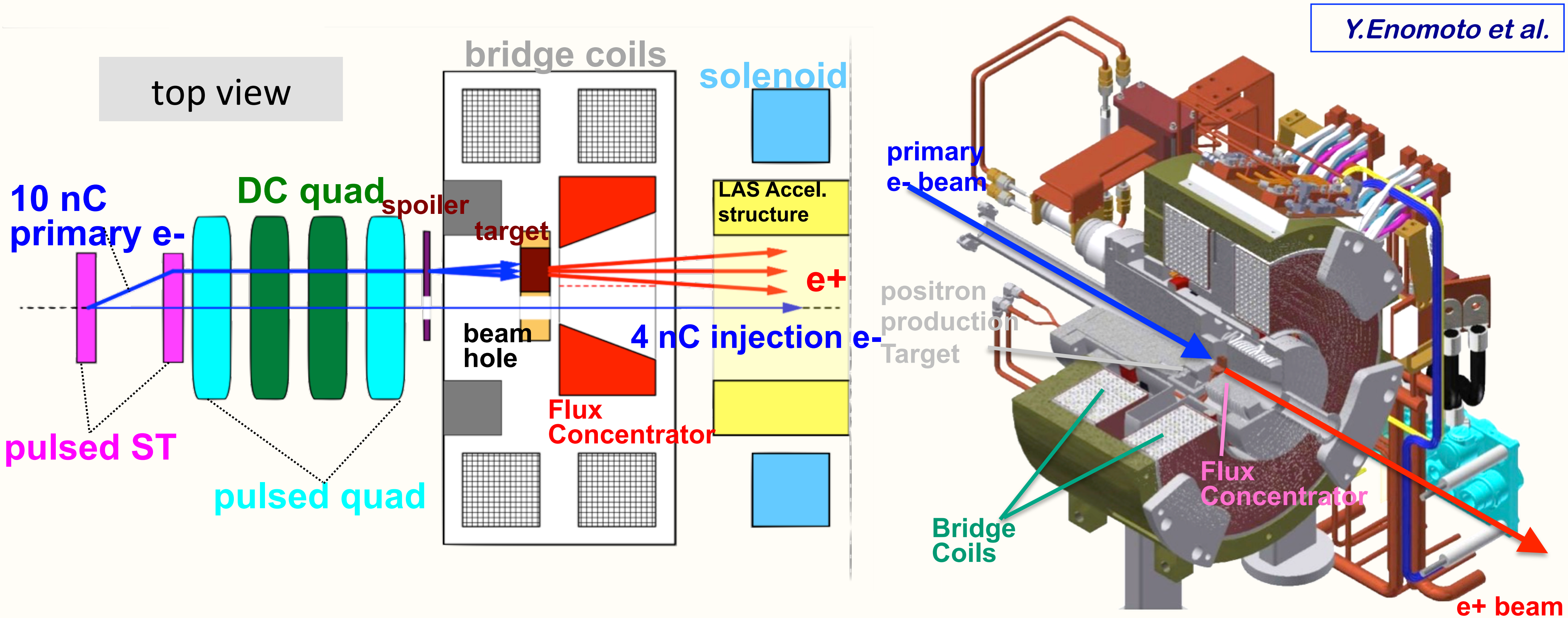




e+ source

Y. Enomoto, SuperKEKB review, 2019

Positron generation for SuperKEKB



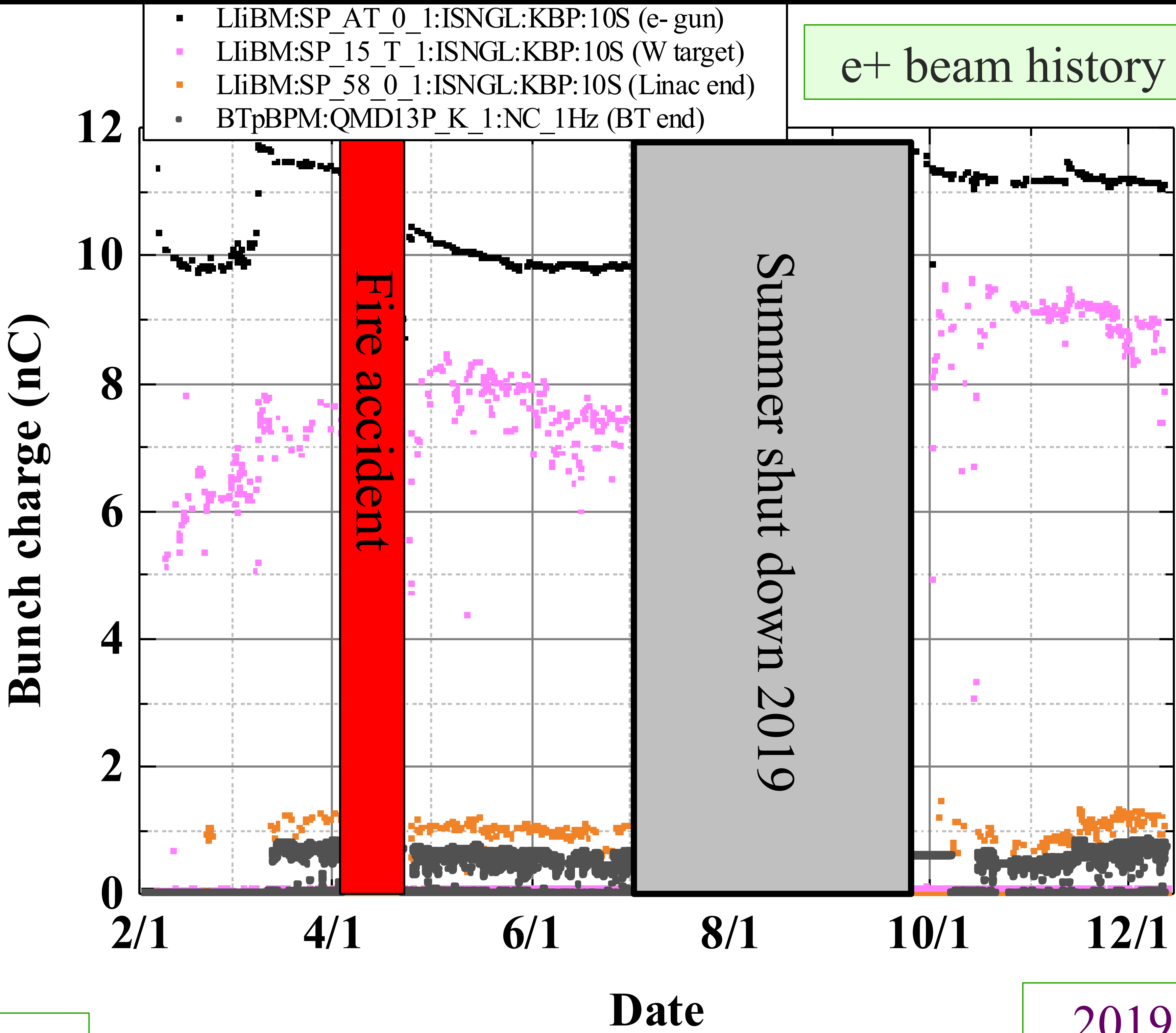
New positron capture section after target with
Flux concentrator (FC) and large-aperture S-band structure (LAS)

Satellite bunch (beam loss) elimination with velocity bunching

Pinhole (2mm) for passing low-emittance electrons beside target (3.5mm)

Matching the beam optics for the damping ring injection

e+ beam history in 2019



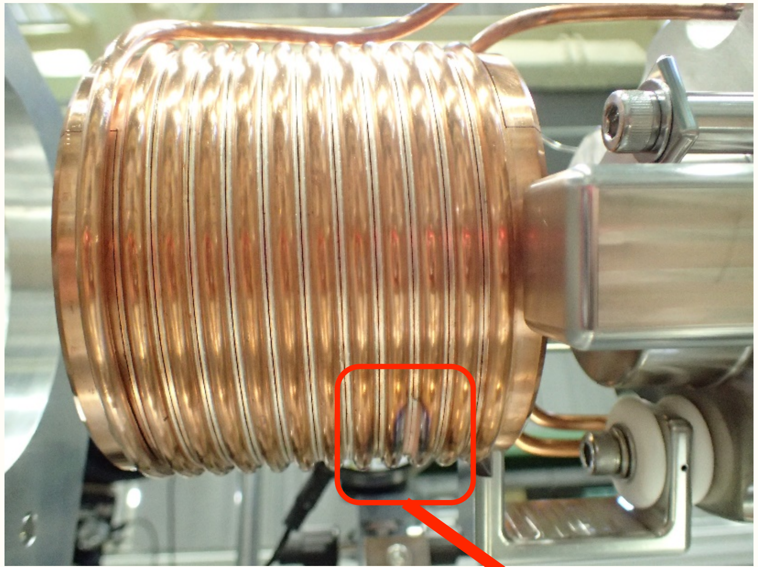
Primary e- beam

e+ beam

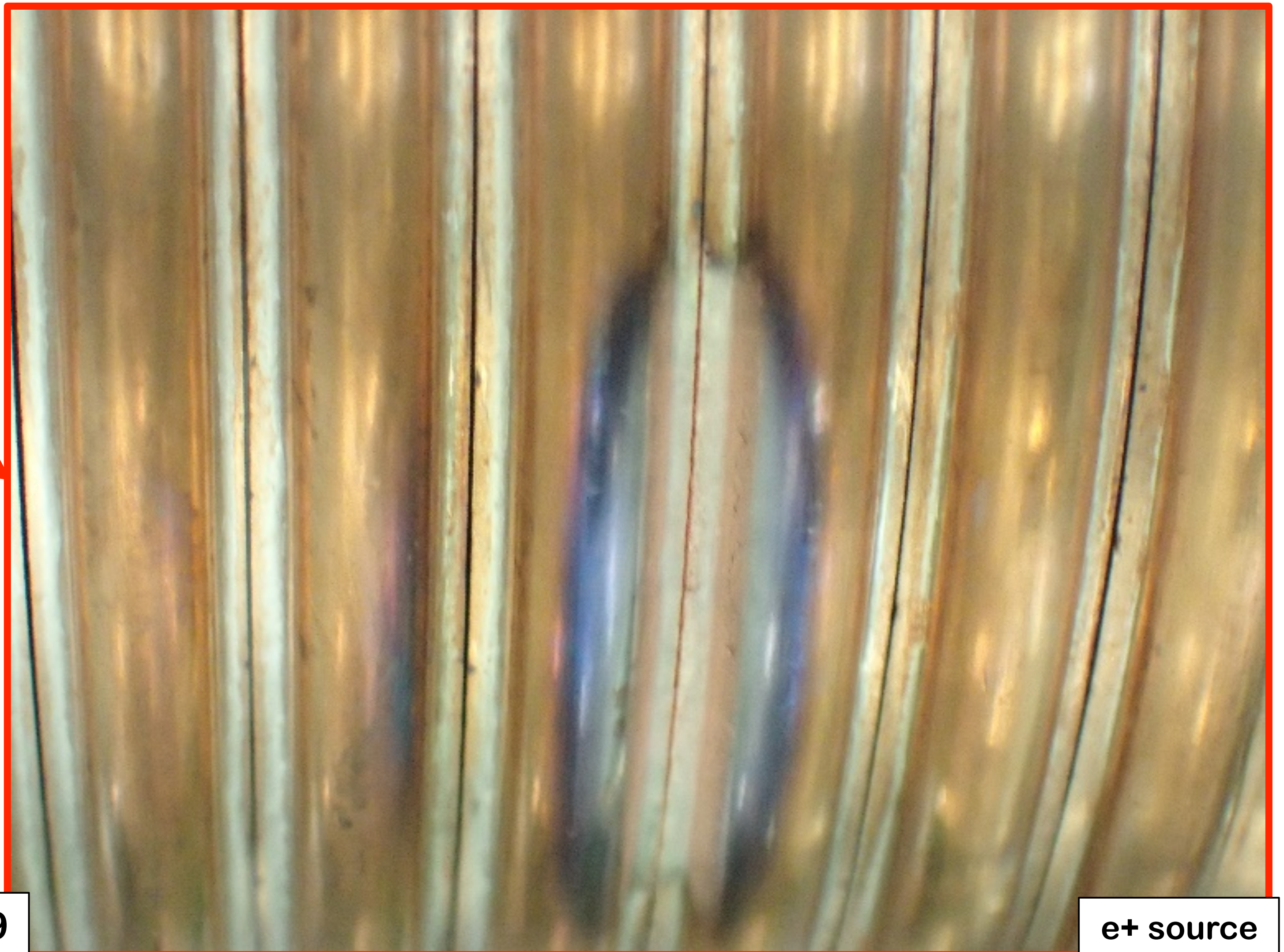
e+ source

2019

After large discharge...



After large discharge



Slit gap got narrow. Not possible to apply high voltage unless the gap will be expanded.

Y. Enomoto, SuperKEKB review, 2019

e+ source

LER injection beam status

- **Bunch charge**
  - Stable and enough bunch charge in this stage
  - Primary e-: 11 nC (from gun), 9 nC (on W target), e+ : 1.2 nC (linac end), 0.8 nC (BT)
- **Flux concentrator (FC)**
  - Previous FC was damaged by large discharge during PhaseII. It was removed in Sept. 2018.
  - Current FC was installed in Jan. 2019.
  - 2 ～ 3 kA operation current (design 12 kA) for stable operation. no significant fault.

> Requirements for material of the FC head are
> - Good brazing characteristic
> - High yield strength even after brazing
> - High electric and thermal conductivity

  - New FC made of Cu-alloy (NC50: Cu-Si-Ni) has been tested w/o fault (～ 12 kA).
  - New FC will be installed in summer shutdown of 2020 for aiming at design operation current.

e+ source

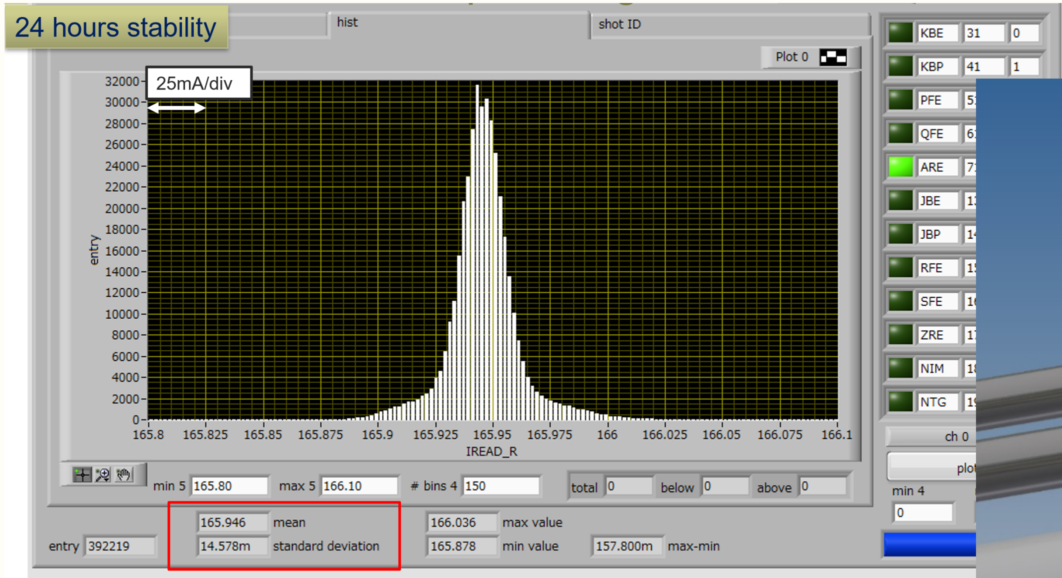
Accelerator Components

Accelerator Structure

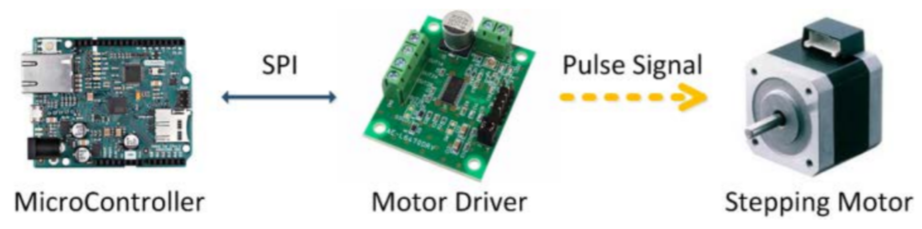
- Approx. 230 accelerator structures employed
- Many aged (40 years-old) structures are degraded
  - Risk of 7 GeV / 4 GeV acceleration for Y(4S)
  - Cannot reach Y(6S)
- As a 4-5 year plan, structures are being fabricated since the last year
- First tests will be performed at the assembly room
- Possibly, a couple of structures would be installed during summer

Pulsed magnet system

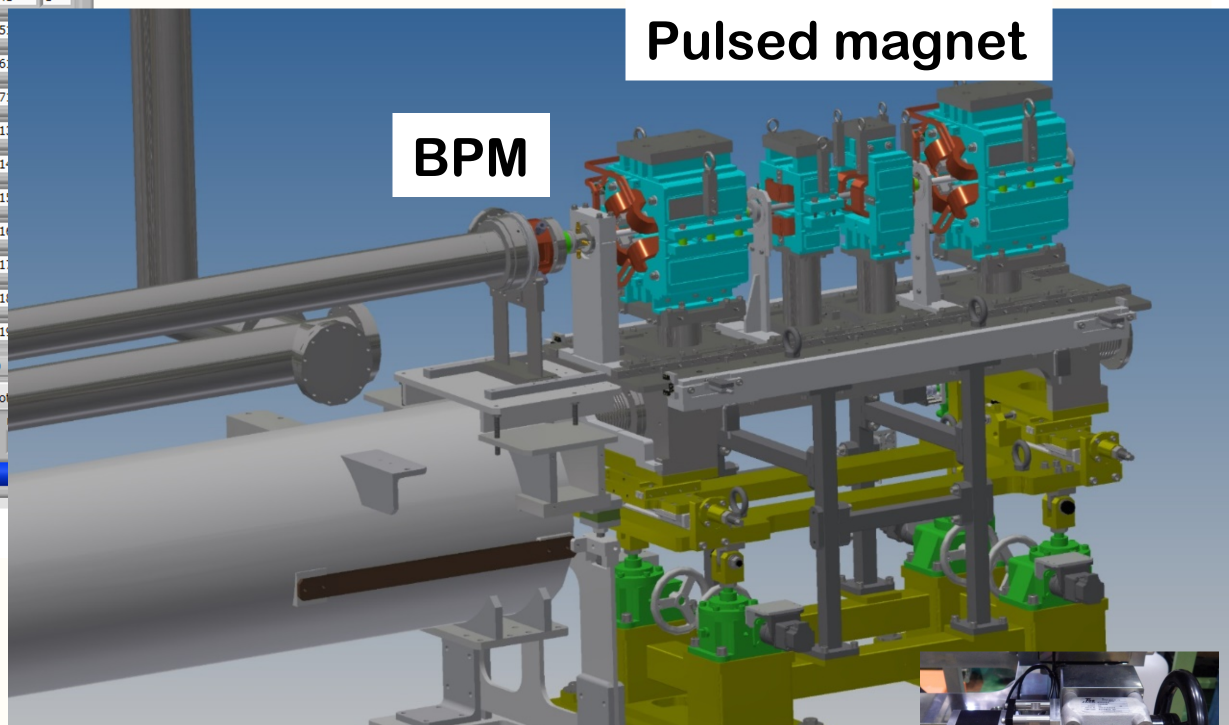
- Pulsed quads (x 28) (w/ ceramic duct) and steering (x 36) were installed at Sector3 to Sector5 in 2017 (on movable girder).
- Pulsed bend, additional quad and steering were installed in 2018 summer and winter shutdown.
- PXIe based control system (Windows 8.1, LabVIEW, EPICS) have worked fine w/o any serious trouble.
- Power supply stability: 0.01% (24 hours)

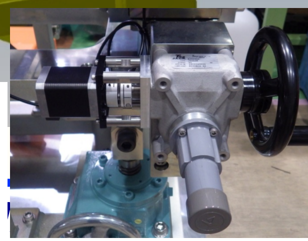


0.014578 / 165.946 = 0.01 % (requirement 0.1 % @ 330 A)



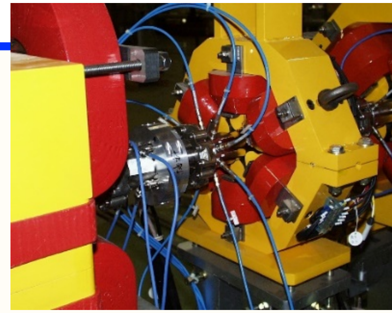
Subsystems



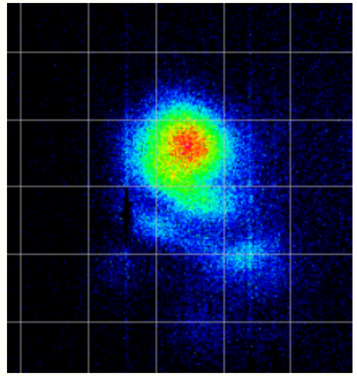


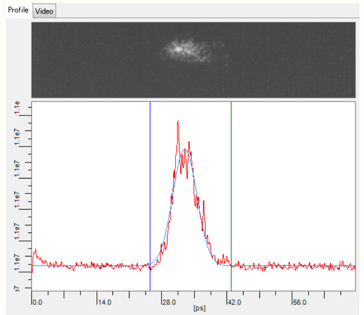
Movable girder for pulsed magnet (remote controllable, 10 μm step)

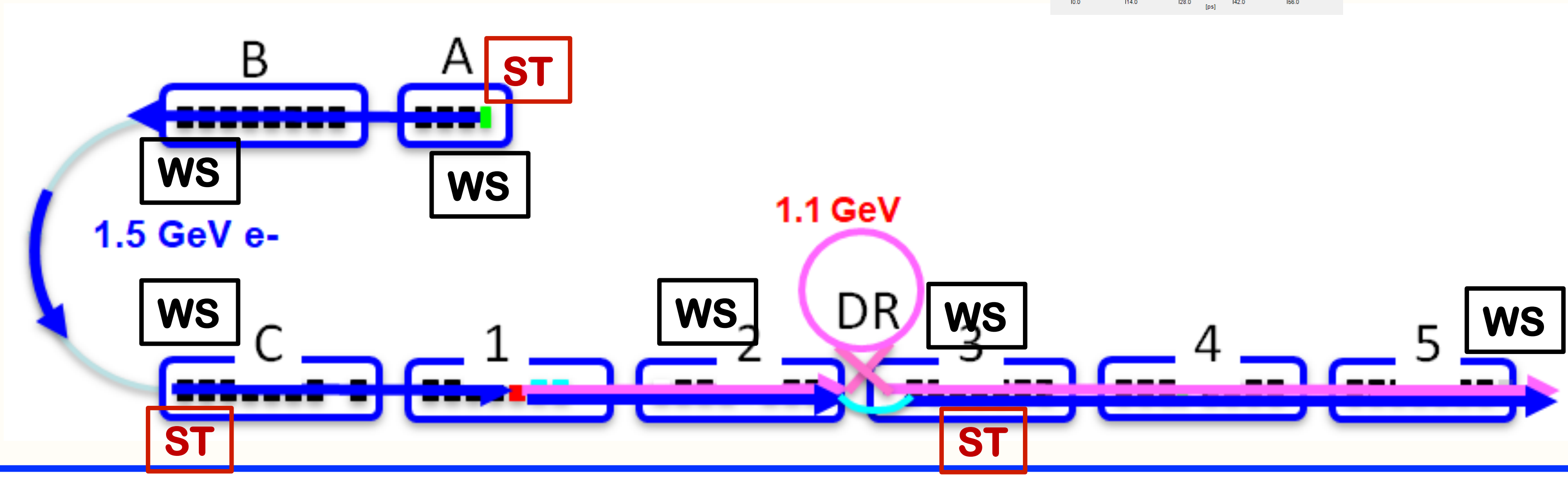
Monitors (1)



- **Beam position monitor (x 103)**
  - **Four strip line electrodes (x 97)**
    - **Measurement precision ~ 10 μm**
  - **Eight strip line electrodes (x 6) (J-ARC, LTR x2, PF BT, HER BT, LER BT)**
- **Profile monitor (x 104)**
  - **Al_2O_3/CrO_3 (AF995R, Demarquest Co.). (t: 1 mm, 0.1 mm), YAG:Ce (t: 0.1 mm)**
- **Wire scanner (WS) (x 6)**
  - **SectorA, B, C, 2, 3, 5**
- **Streak camera (ST) (x 2)**
  - **SectorA, ~~C~~, 3**
- **RF monitors for klystron, SLED, acc. structure**

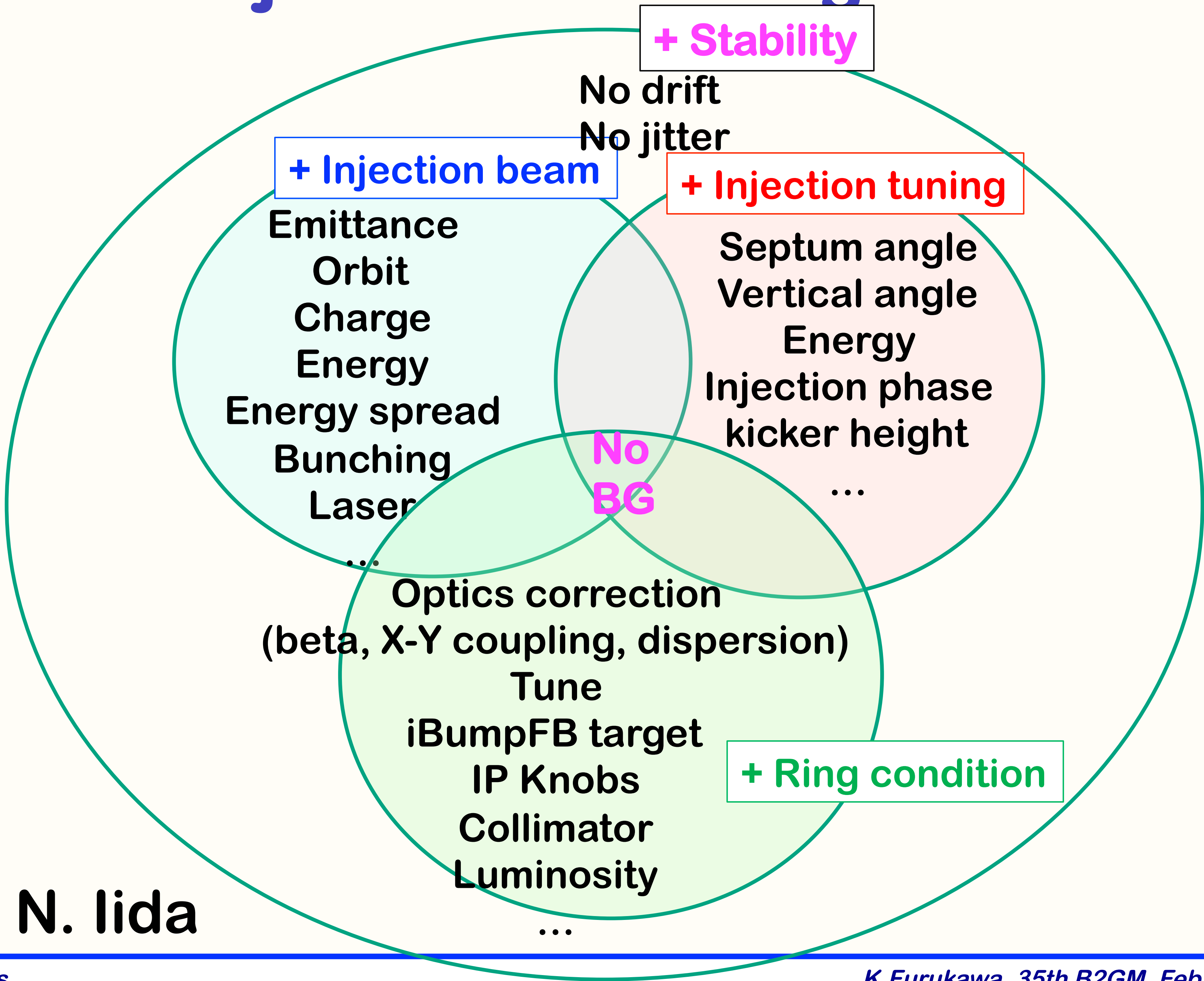






Injection Management

Injection BG tuning

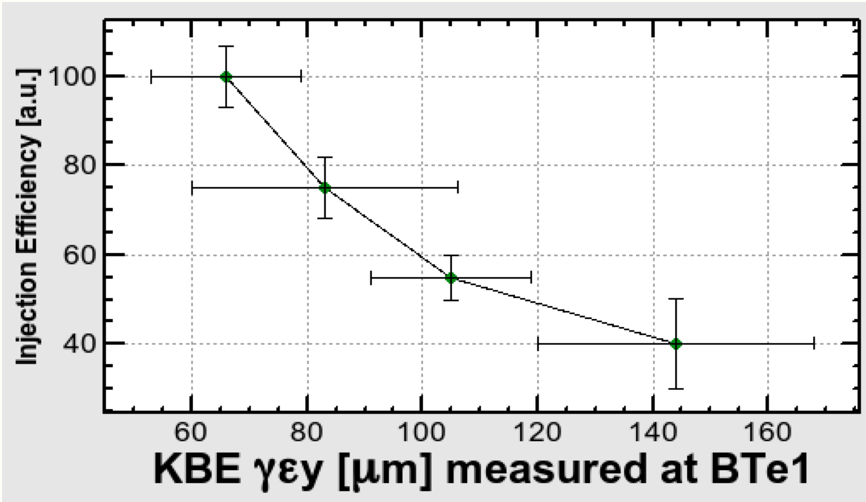


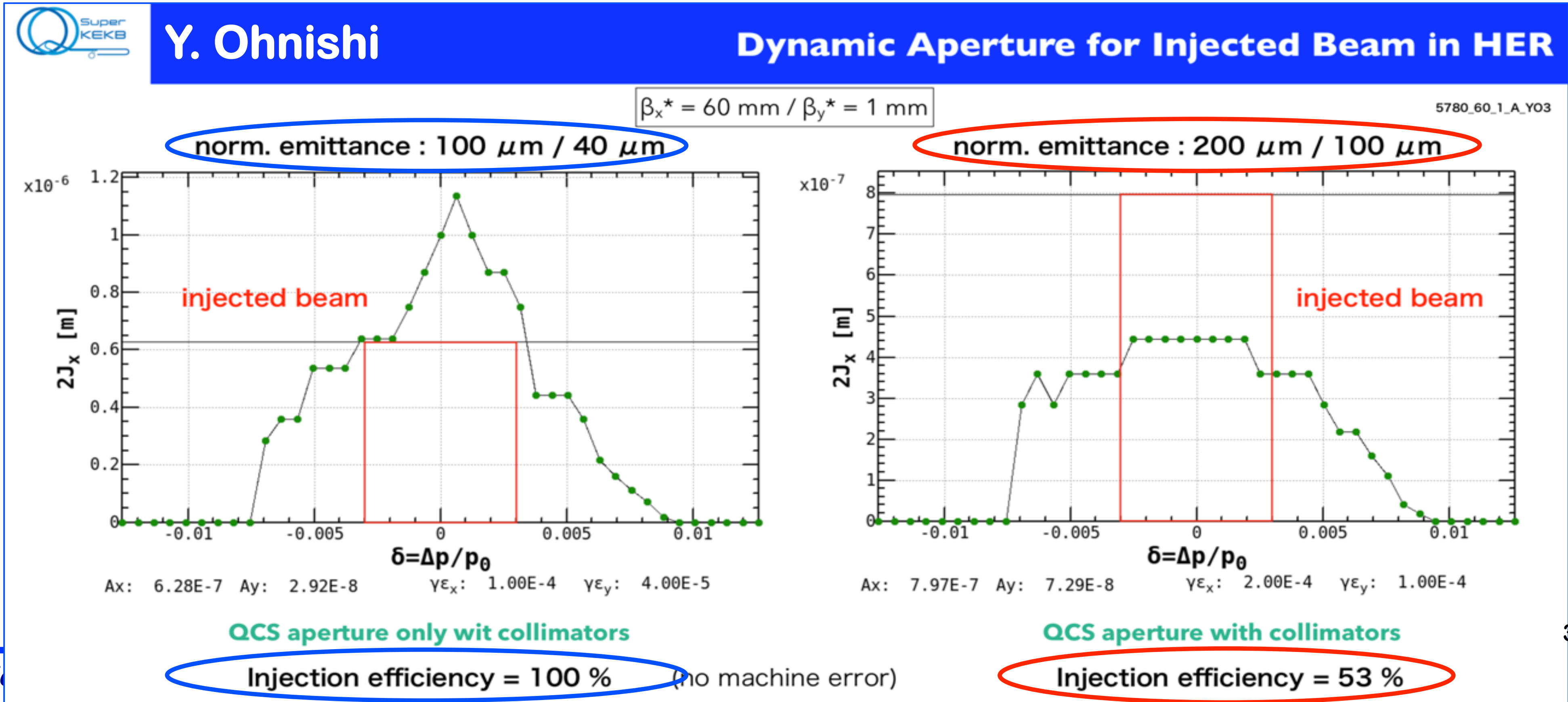
Injection efficiency and background

- **Injection tuning for squeezing βy***
  1. Open collimators in the MR
  2. Squeeze βy* -> Optics correction
  3. Injection tuning using Turn-by-turn BPMs
  4. Close collimators in the MR

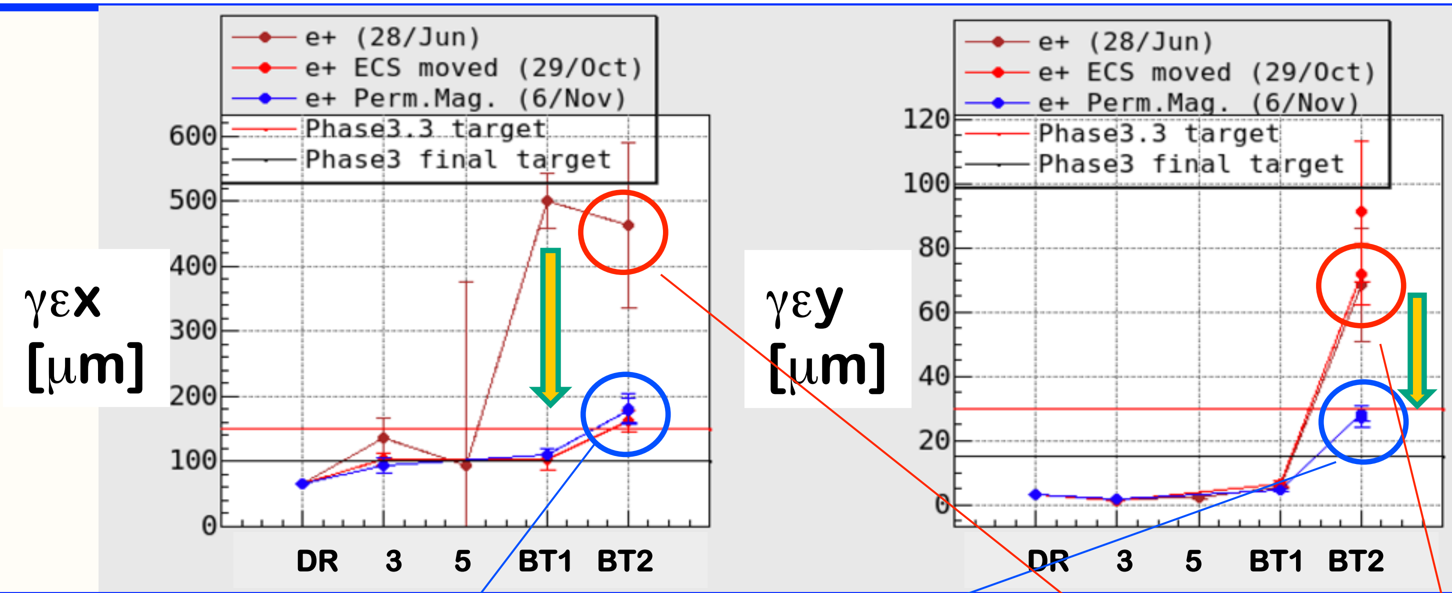
	LER	HER
Injection efficiency	・The emittance and energy spread of the injection beam are now good enough for βy*=1.0mm.	Depends on the vertical emittance and the energy spread of the injection beam
Background	・Mainly comes from stored beam caused by vacuum condition. ・Low enough from injection usually. ・"Spike" and "Duration of injection BG" are most serious problems.	Mainly comes during Injection. Stability of e- beam should be resolved.

Vertical emittance vs. HER Injection efficiency





• LER

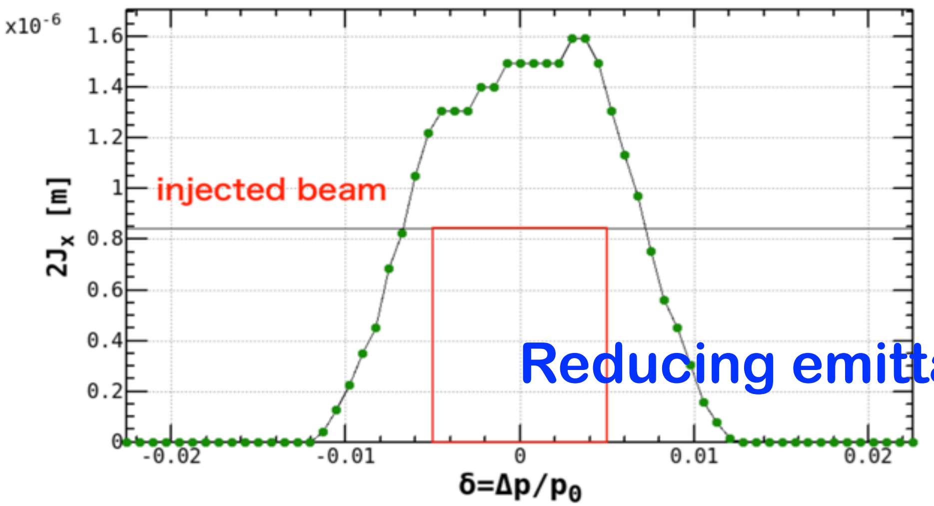


Y. Ohnishi — Dynamic Aperture for Injected Beam in LER

β_x^* = 80 mm / β_y^* = 1 mm

1704_80_1_A_YO4

norm. emittance : 180 μm / 30 μm



Ax: 8.42E-7 Ay: 3.83E-8 $\gamma\varepsilon_x$: 1.80E-4 $\gamma\varepsilon_y$: 3.00E-5

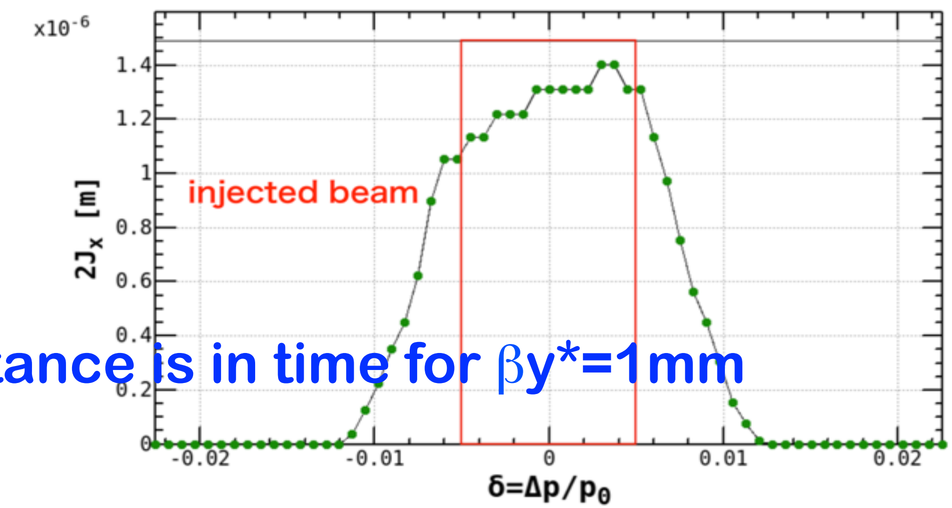
QCS aperture with collimators

Injection efficiency = 100 %

(6/Nov/2019)

(no machine error)

norm. emittance : 450 μm / 70 μm



Ax: 1.49E-6 Ay: 8.94E-8 $\gamma\varepsilon_x$: 4.50E-4 $\gamma\varepsilon_y$: 7.00E-5

QCS aperture with collimators

Injection efficiency = 86 %

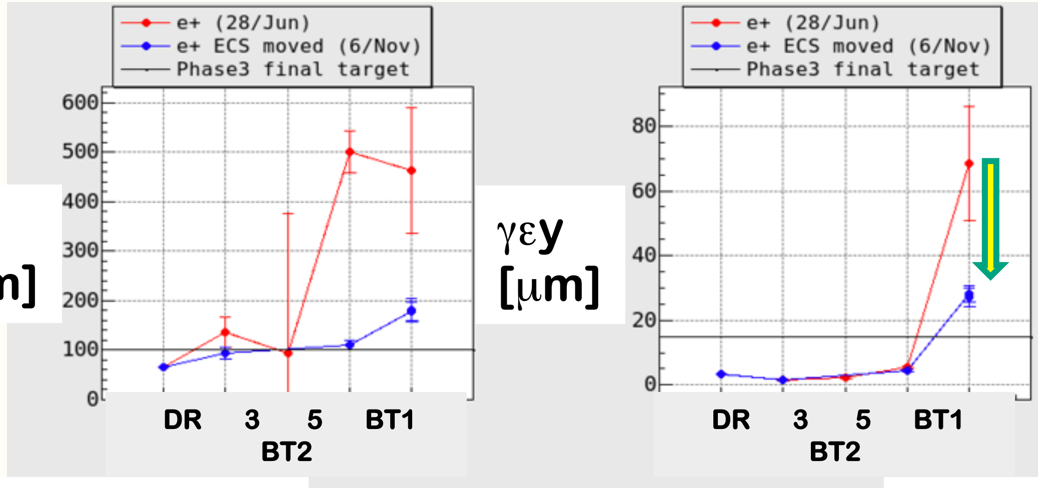
(28/Jun/2019)

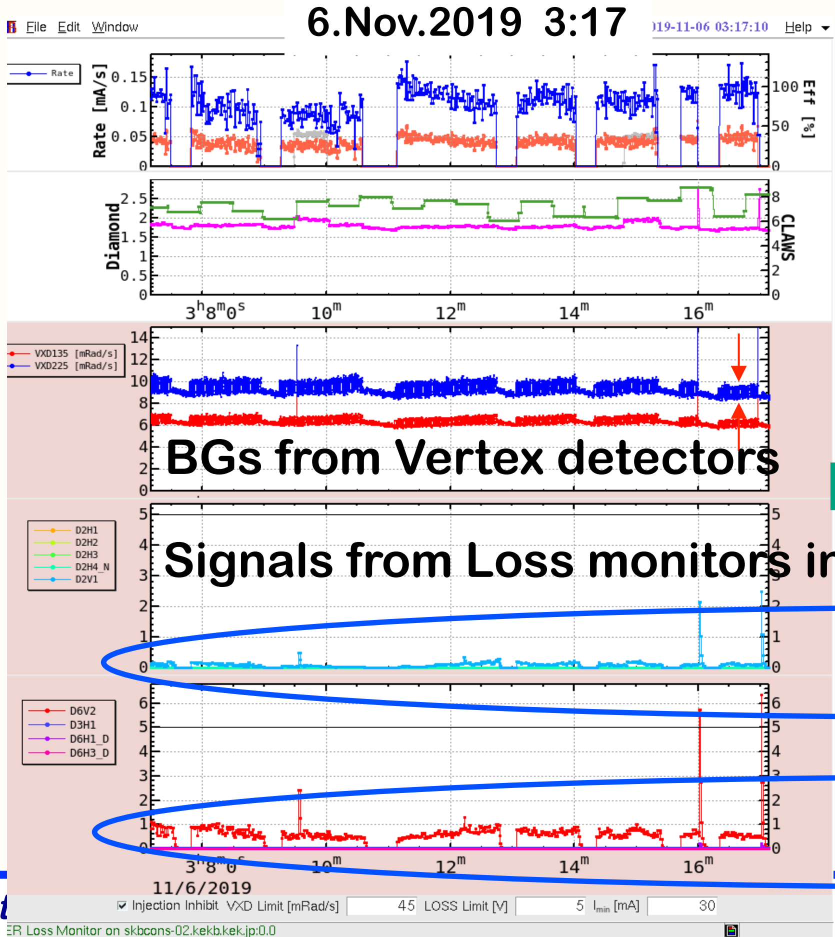
Before modification of ECS / BTp

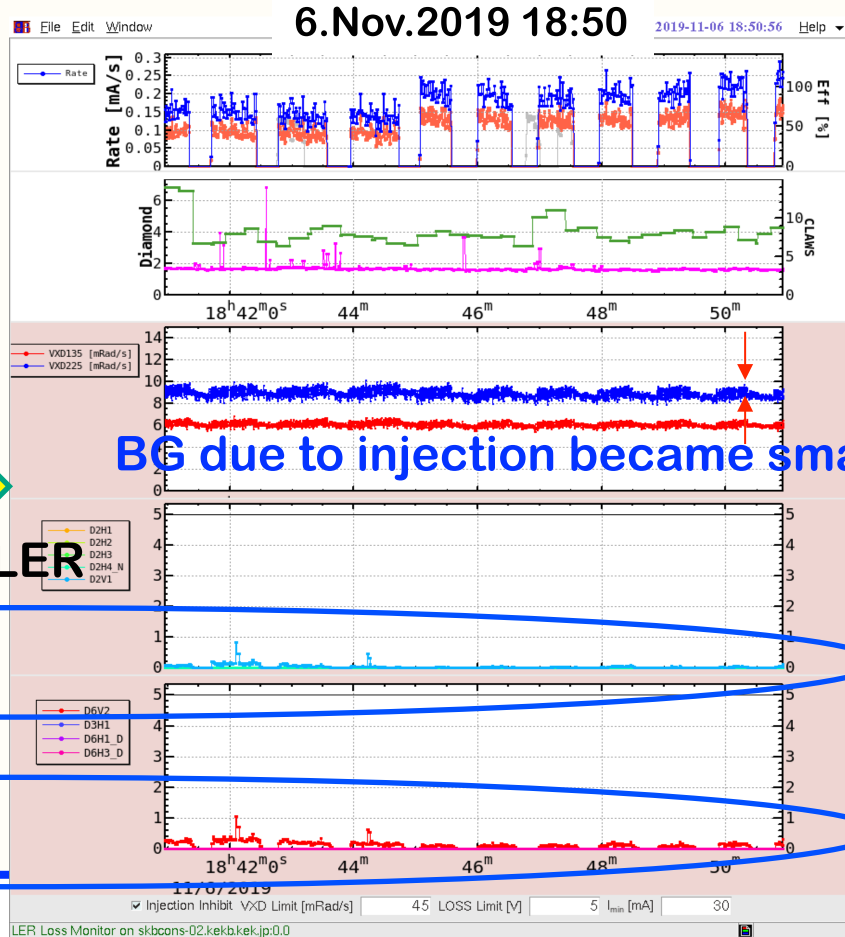
Reducing emittance is in time for βy*=1mm

LER

When the vertical emittance was improved



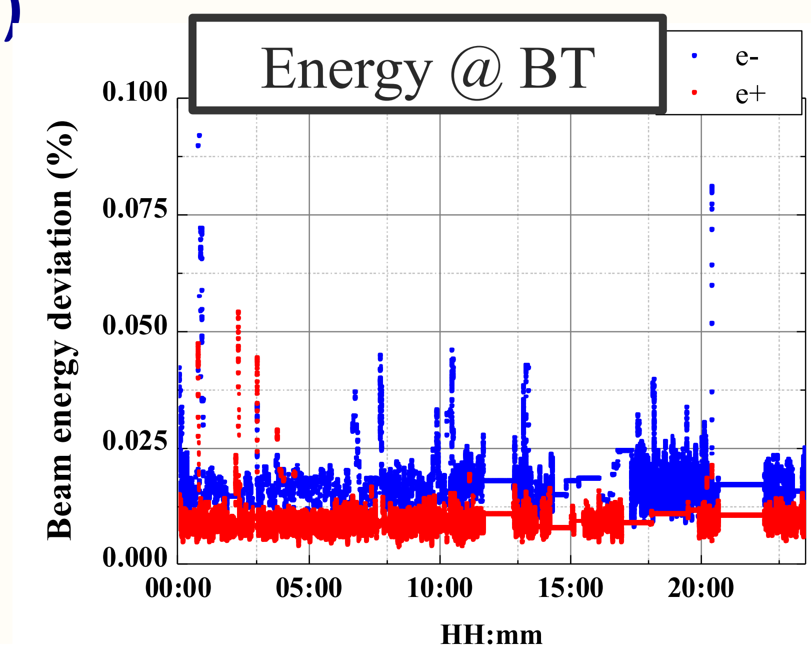


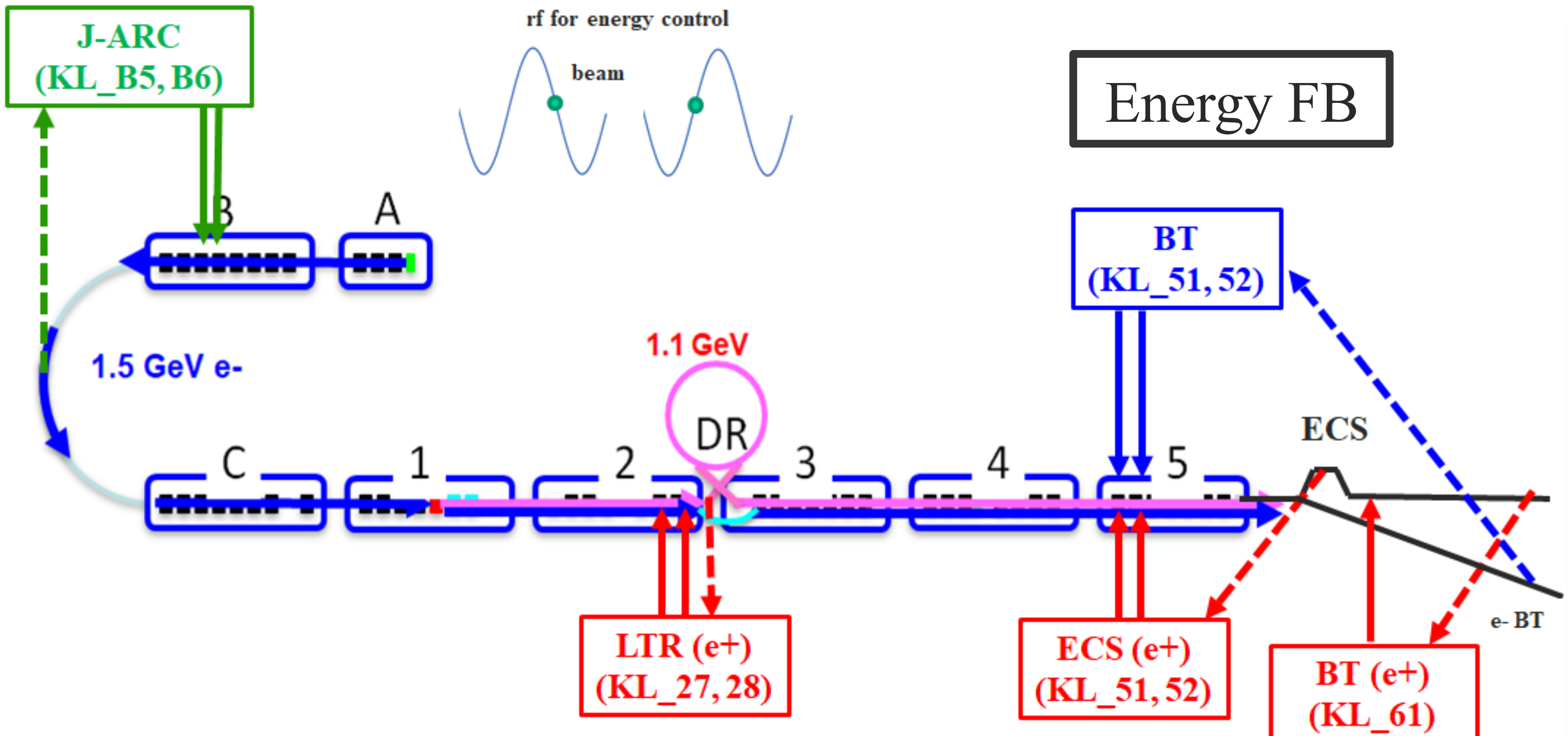


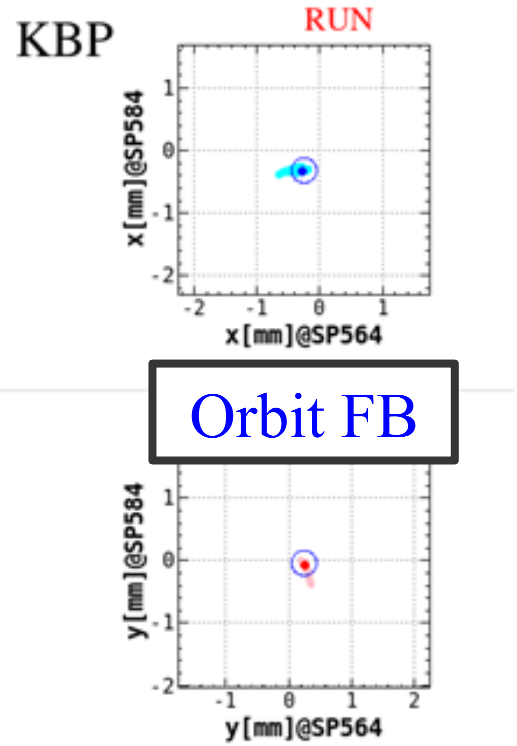
Beam Controls

Feedback loops

- **Energy feedback (J-ARC, LTR, ECS, BT) loops work fine.**
  - **Energy stability at BT line < 0.025%**
- **Orbit feedback at some locations.**
  - **Large drift (~ 1 mm) can be corrected within ~ 0.1 mm w/ feedback.**







2. Improvements of emittance growth

A) Residual dispersion

a. Dispersion correction

b. Residual dispersion at the acceleration for compression system

B) Abnormal skew magnetic field from bends

C) Emittance growth caused by jitters

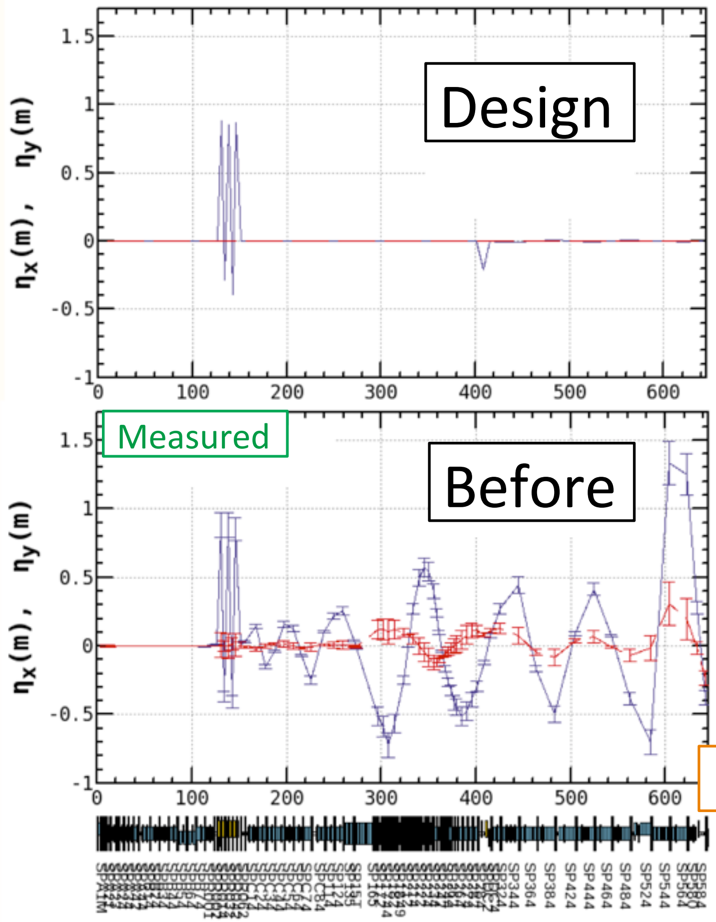
D) Other sources

- Wake field in the LINAC
- Radiation excitation in the e- BT line

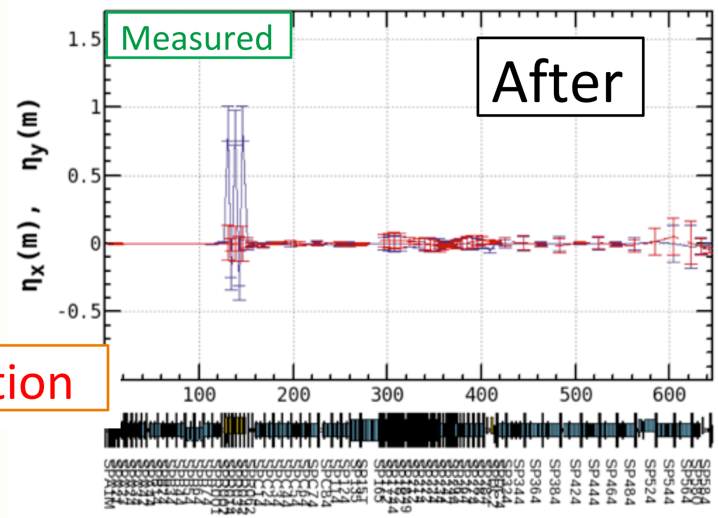
Residual Dispersion Function Correction

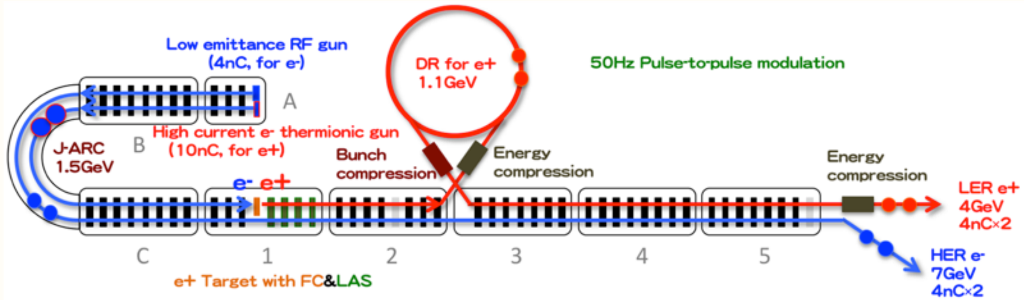
Y. Seimiya et al.

- Large residual dispersion function was generated at the 180-degree J–ARC, that caused beam instability.
- Dispersion correction by tuning the magnetic field of quadrupole magnets made residual dispersion function small enough.



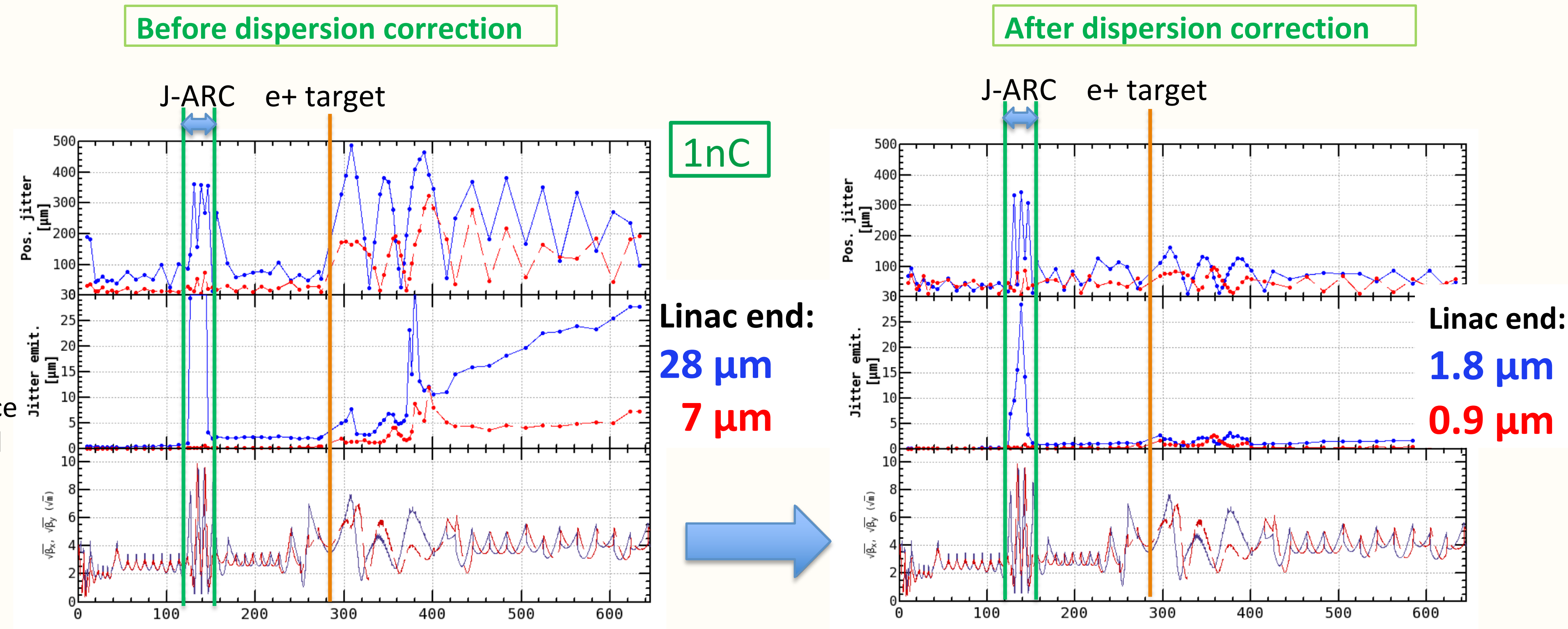
Dispersion correction





Phase Space Jitter Reduction

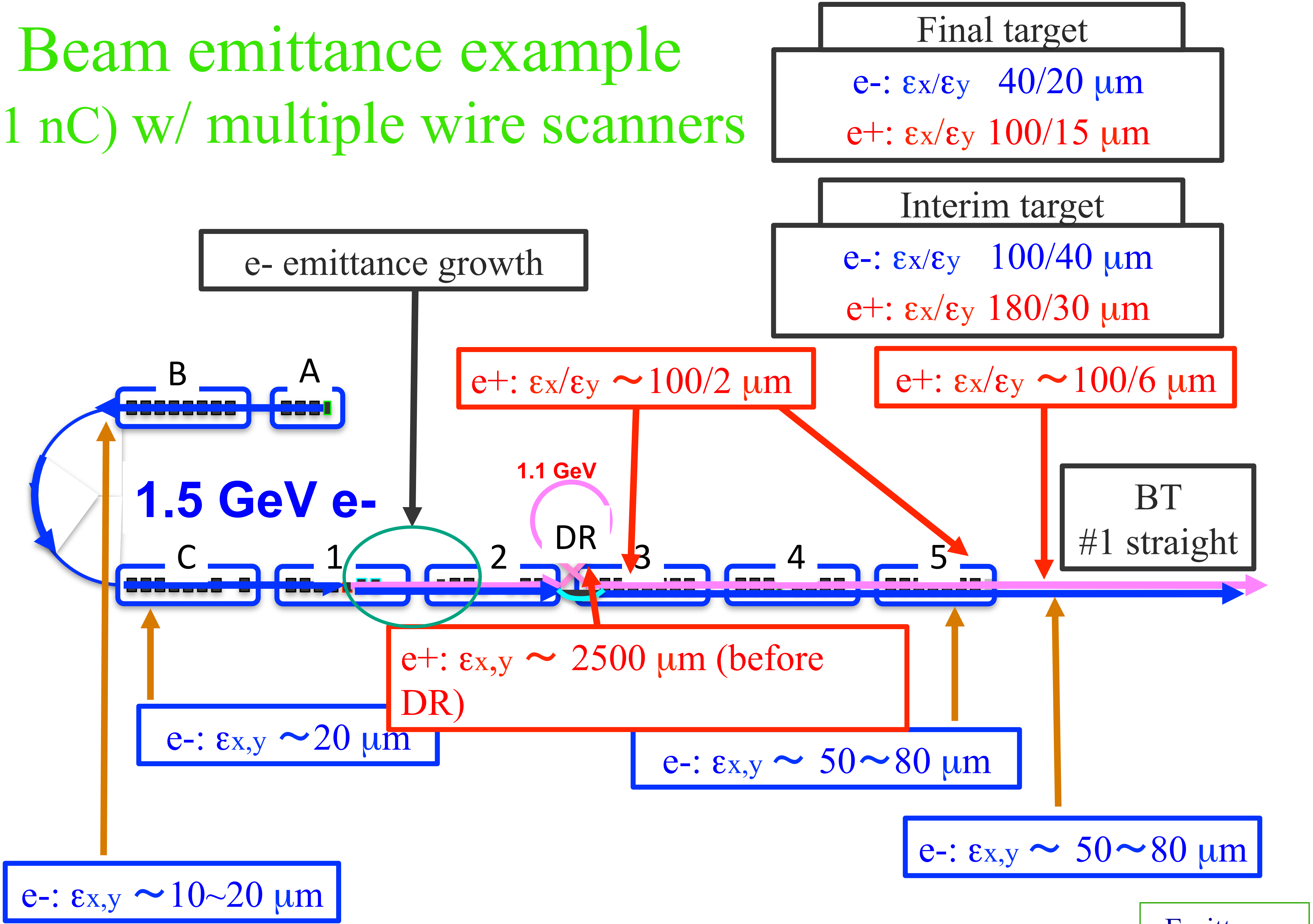
First figure shows the standard deviation of beam position. Second figure shows emittance growth induced by beam jitter.



Beam phase space jitter is reduced by dispersion correction.

- Small emittance growth still occurred from after the target after the correction.
- We should understand the source of the beam jitter to prepare for the high charged beam and for accidental jitter source which may occur at upstream.

Beam emittance example (~1 nC) w/ multiple wire scanners

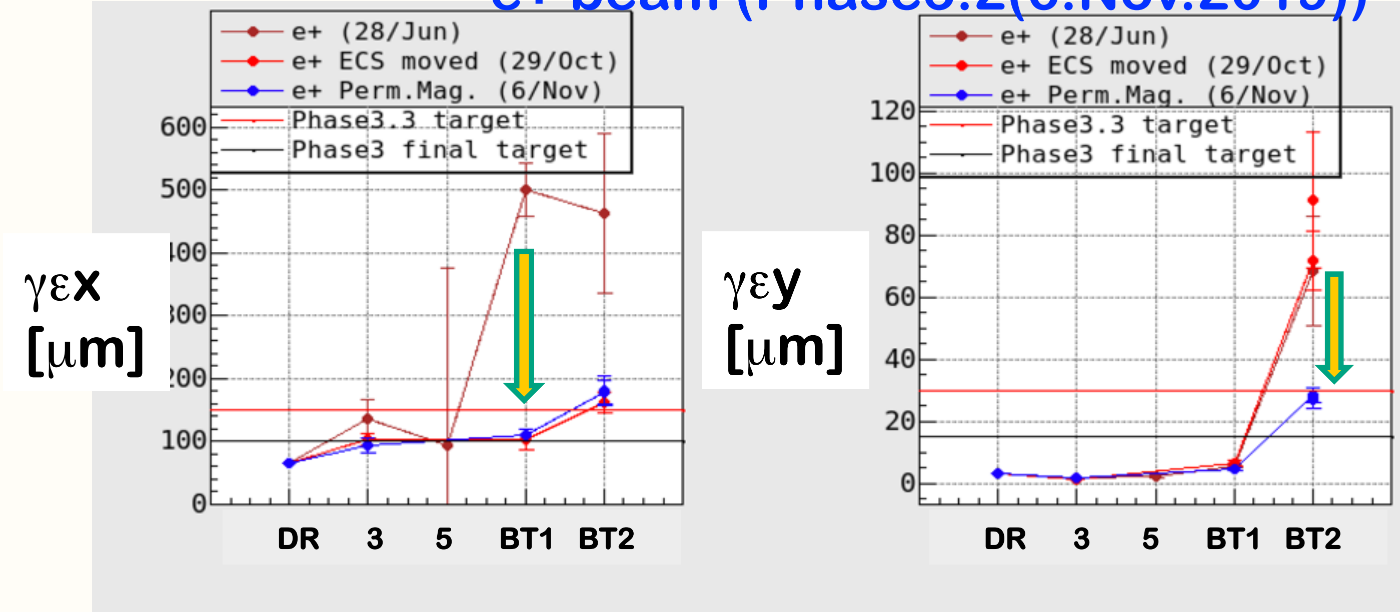


Emittance

Measured Emittance

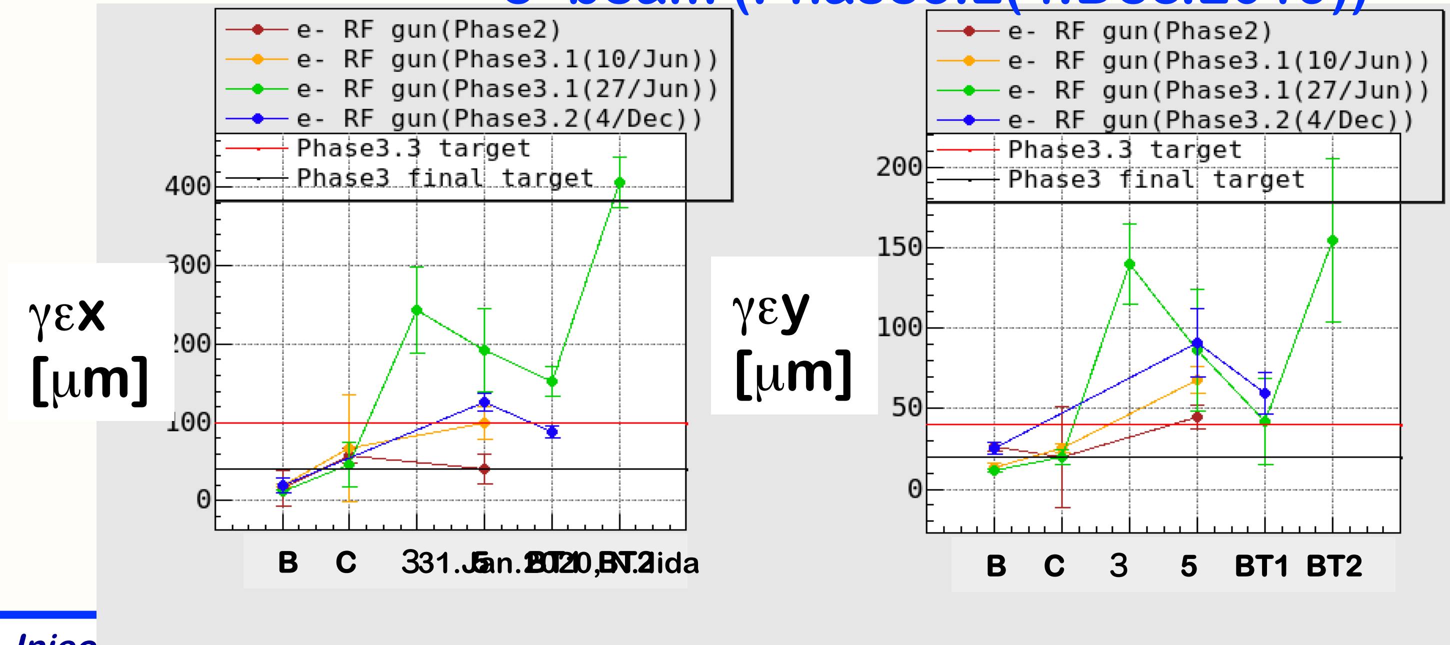
Phase3.3	e+	e-
$\gamma\varepsilon x$ [μm]	150	100
$\gamma\varepsilon y$ [μm]	30	40
σ_δ [%]	0.16(1σ)	0.1(1σ)

e+ beam (Phase3.2(6.Nov.2019))



DR → Sector 3、
BT1 → BT2、
Emittances increase
→Need study

e- beam (Phase3.2(4.Dec.2019))



C→Sector 3、
BT1→BT2、
Emittances increase
→Need study

A) Residual Dispersion in the BT line

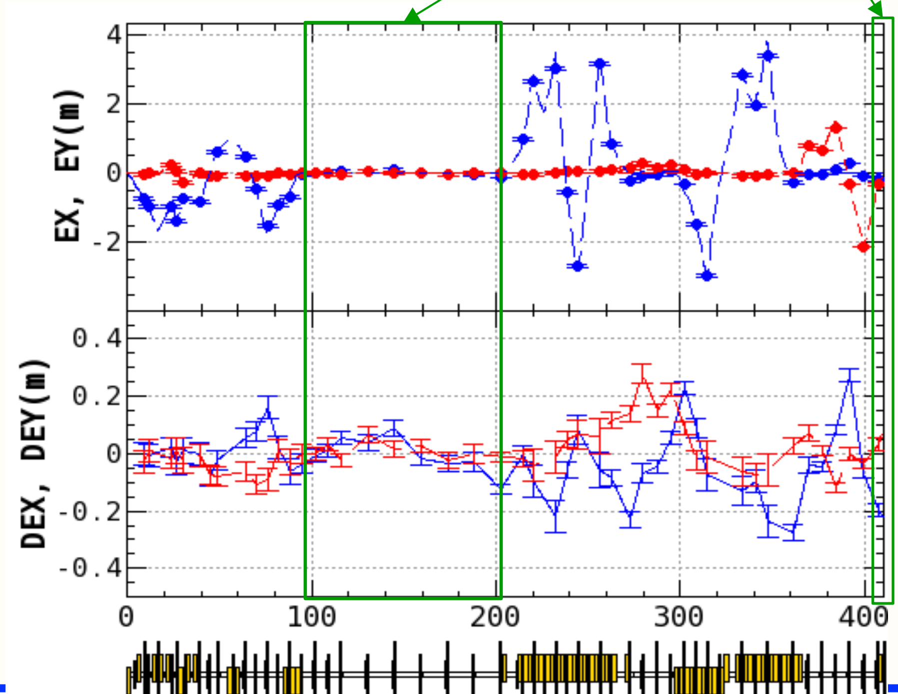
a. Dispersion function correction

Y. Seimiya

- The dispersion functions have been corrected for each BT ARC one by one.
- Non-negligible residual dispersion is still observed

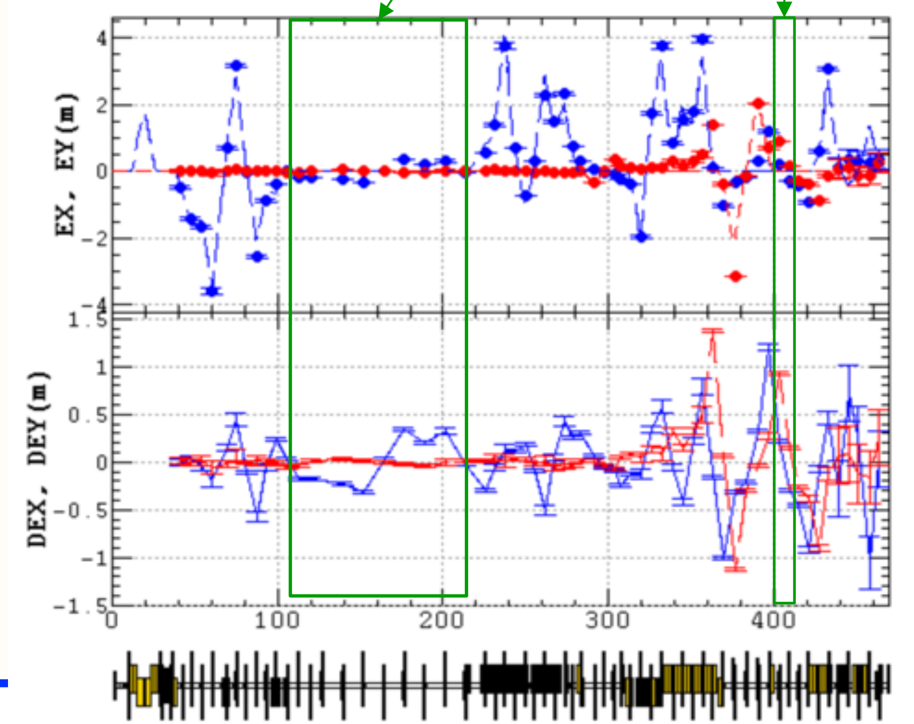
Straight line (BT1) Straight line (BT2)

BT for e-



Straight line (BT1) Straight line (BT2)

BT for e+



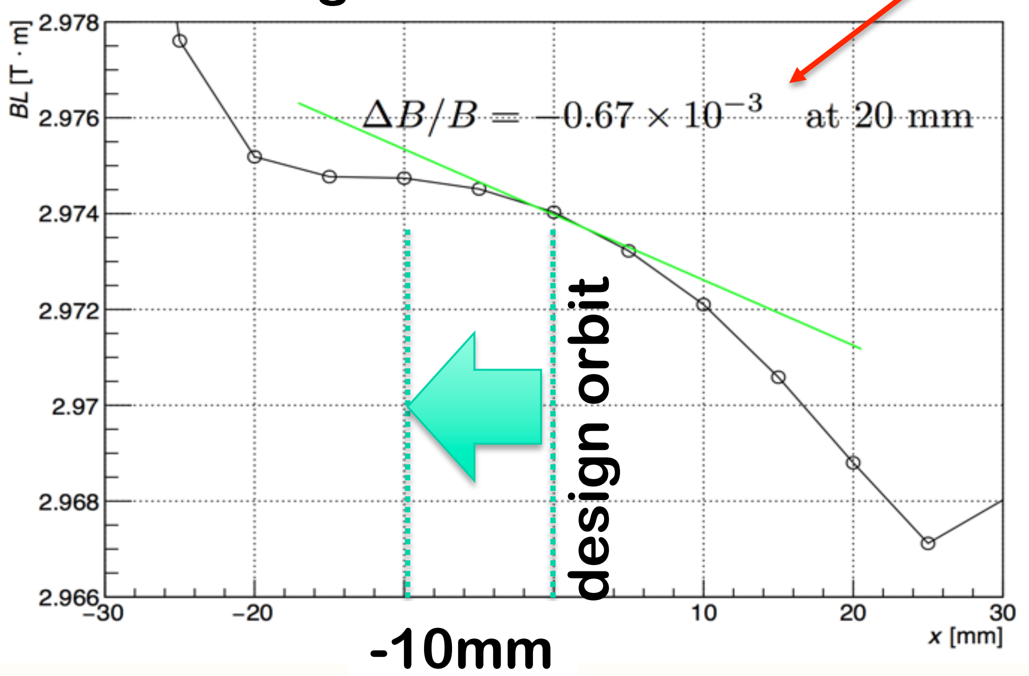
b. Residual dispersion at the acceleration structure for a compression system (cont'd)

- The bending magnets used in ECS/SY3 have quadrupole components.
  - The beam feels B' field passing through the design orbit in the bends, which makes dispersion leakage.
- By moving the bends about 10mm, the beam pass the area of small B'.

This can explain the measured dispersion leak

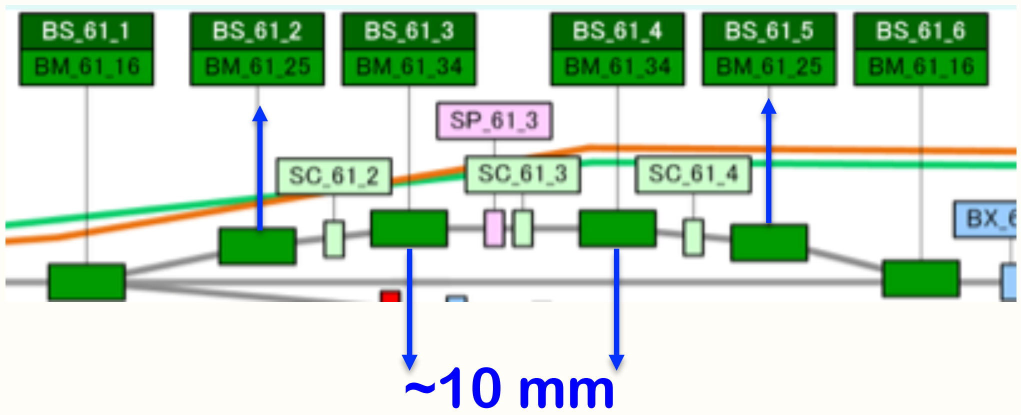
T. Mori

Magnetic field measurement



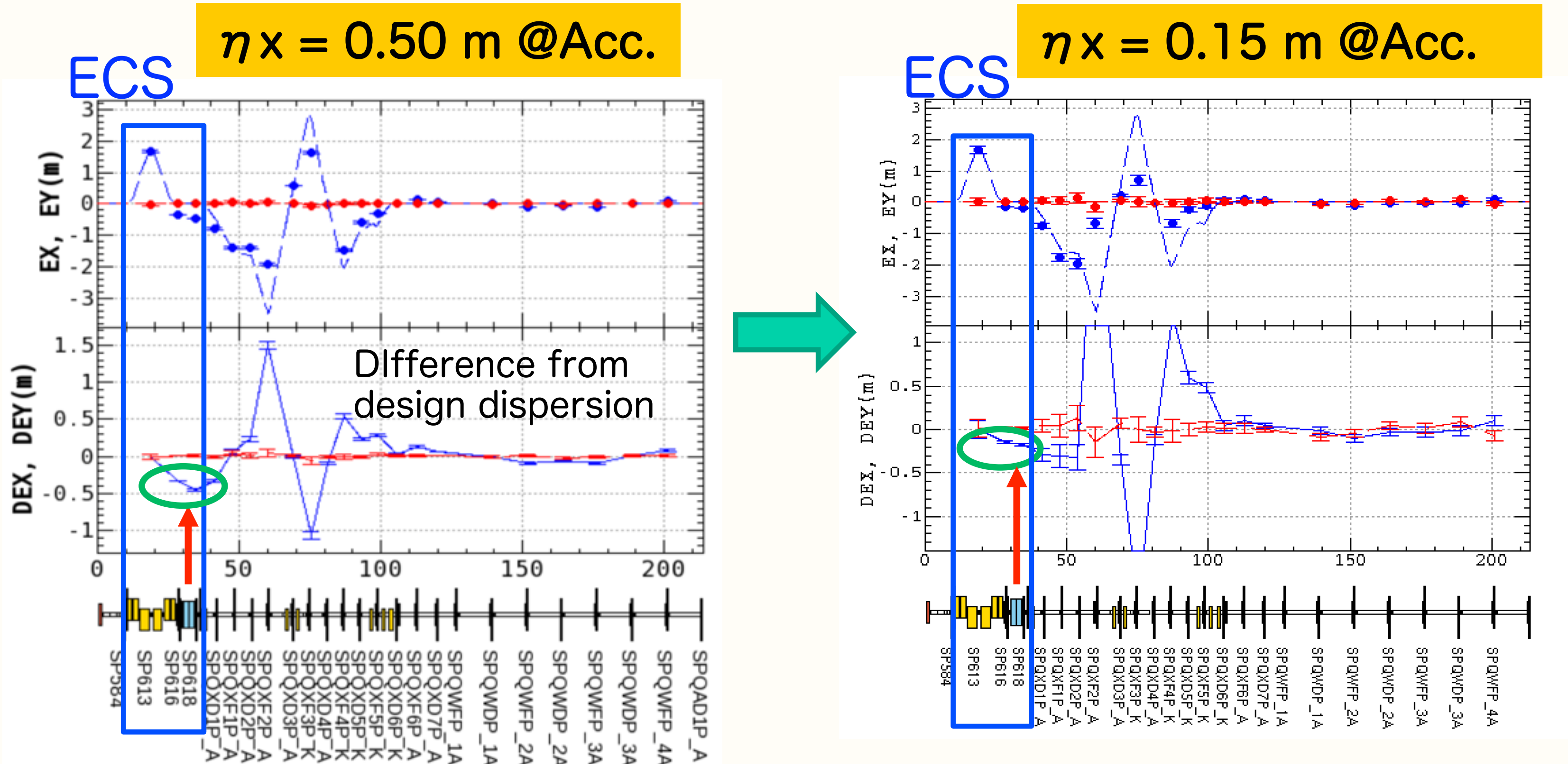
BL along the horizontal direction

T. Kamitani, H. Kakihara, T. Oogoe

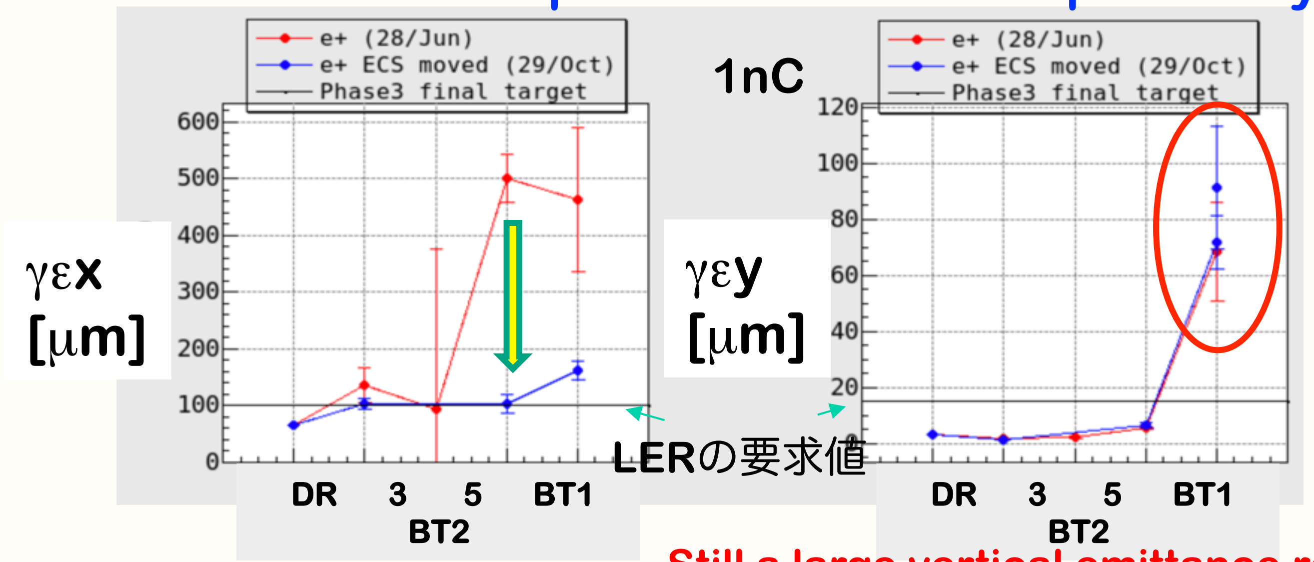


Bends were moved during sumer

Y. Seimiya



The horizontal dispersion has been improved by moving ECS bends.

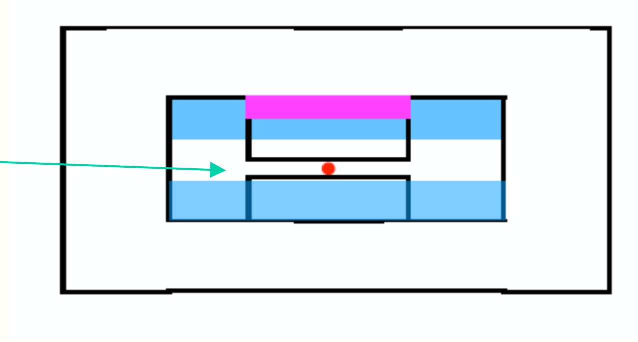


Still a large vertical emittance remained

Simulation

Since the energy of the e+ beam increased to 4 GeV **from 3.5GeV of the old KEKB**, the gap of **b**end narrowed **asymmetry**, **which** created an abnormal skew component in **the b**end.
However, this can only explain about one third of the measured **s**kew **q**uad component **of the beam.**
Anyway, try to correct.

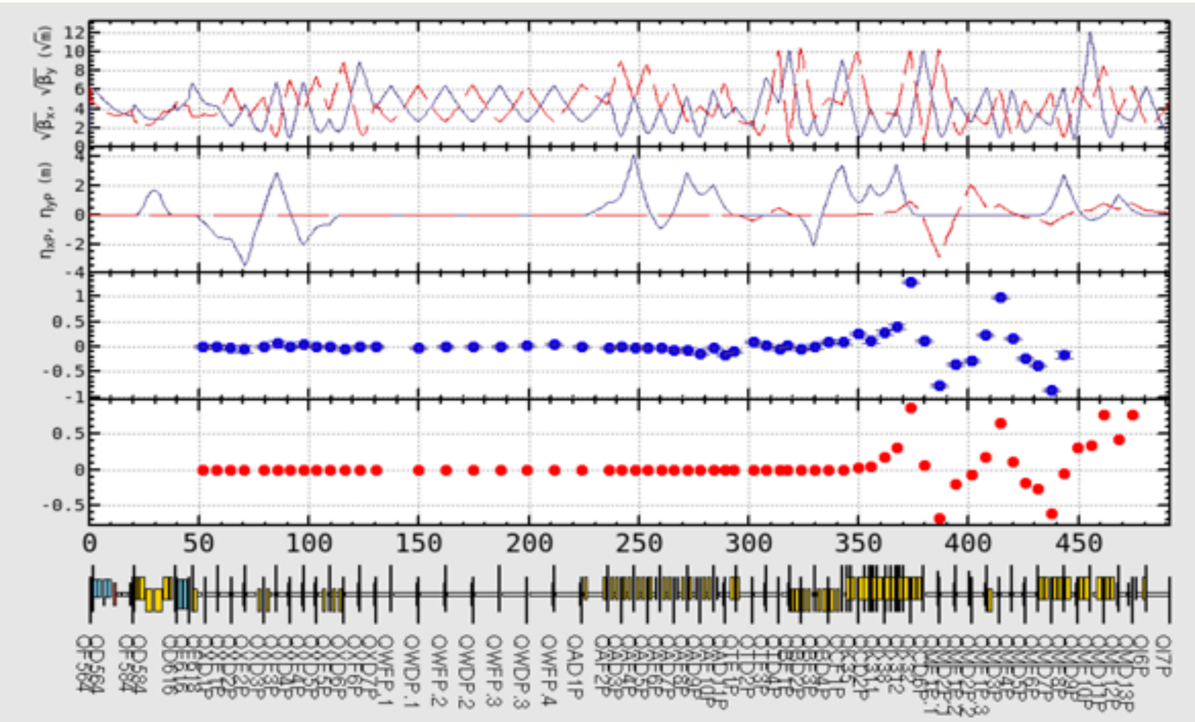
M. Kikuchi



It is considered that the vertical dispersion could be corrected with the skew quads with permanent magnets.

~1 kgauss

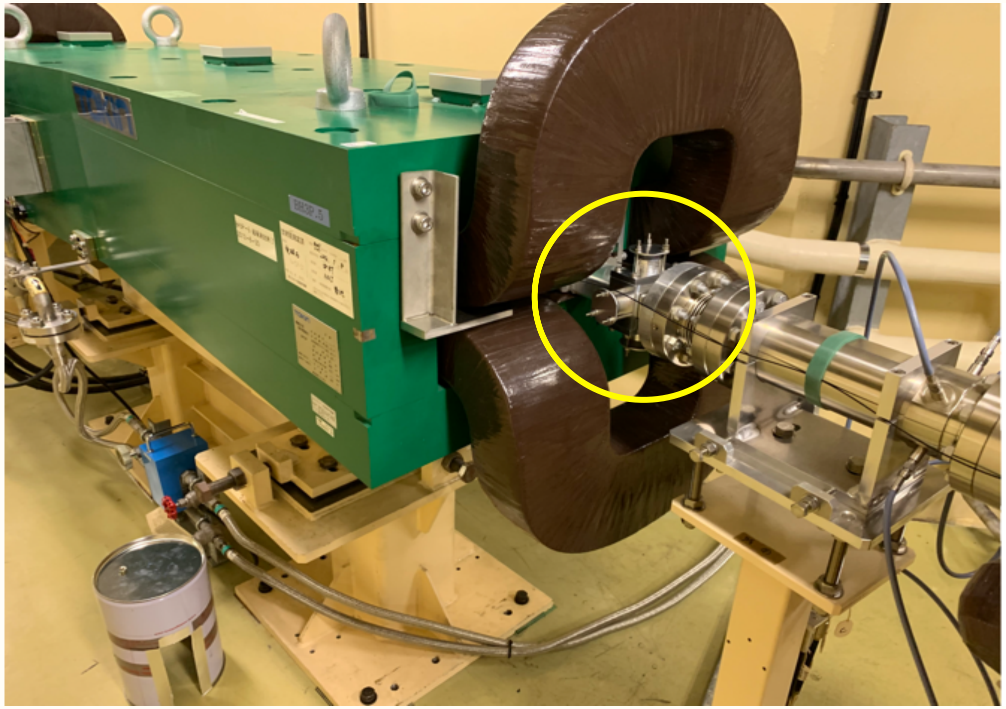
e+ beam

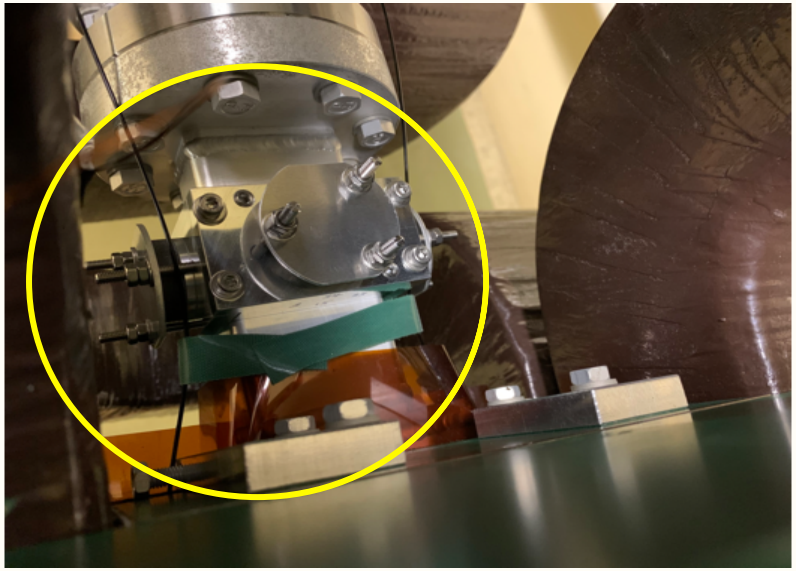


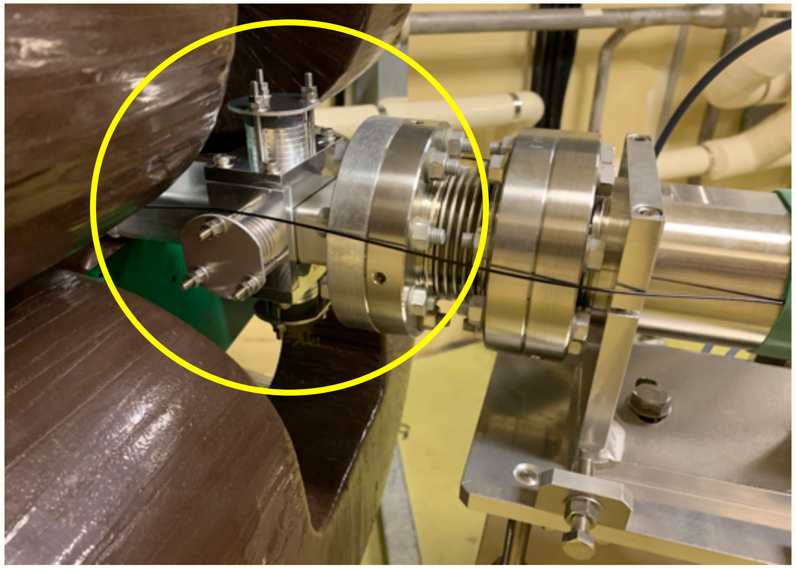
Measured vertical dispersion before SkewQ

Calculated vertical dispersion by the skew quads which are installed.

Good agreement !





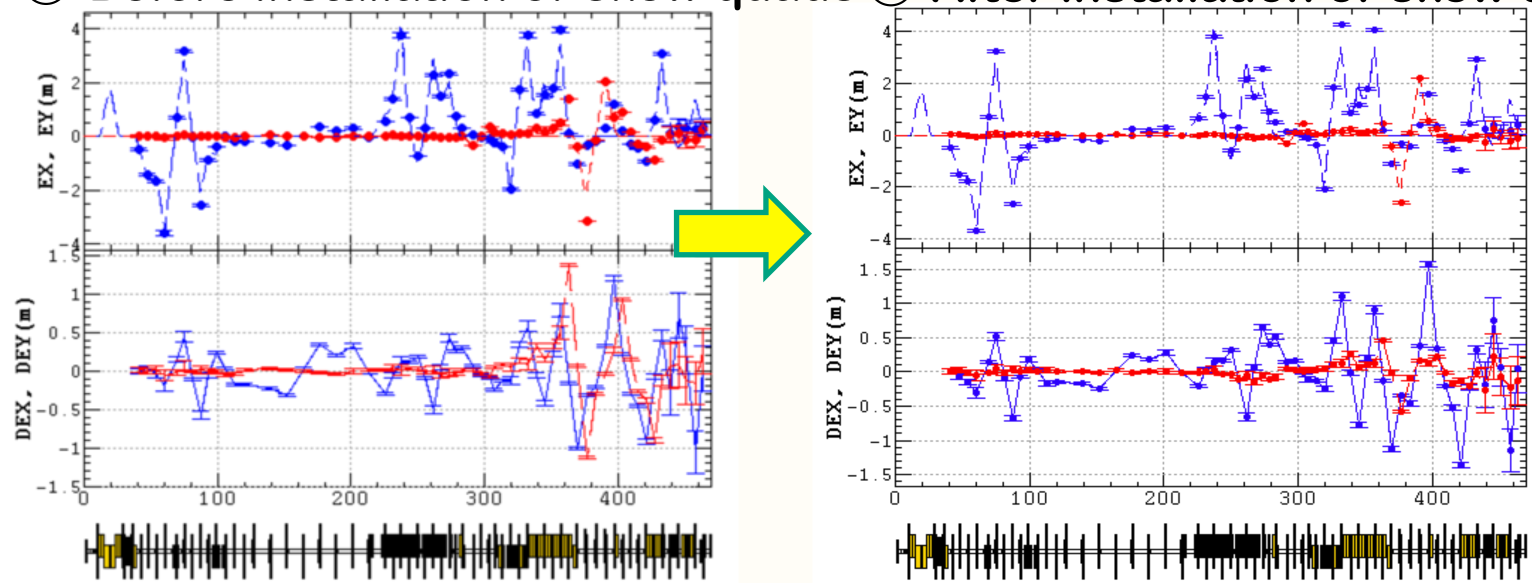


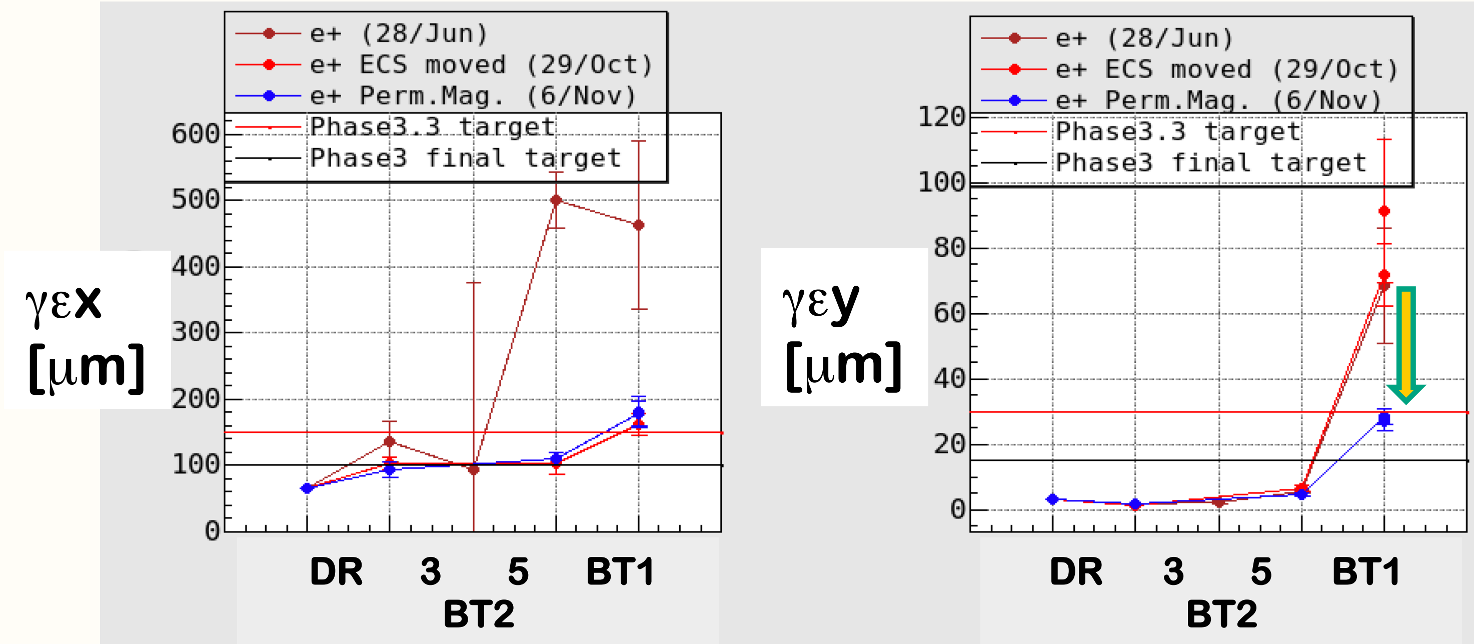
11 of 16 Skew Quads with permanent magnets were installed.

Measured Dispersion

Y. Seimiya

① Before installation of skew quads ② After installation of skew quads





Remaining SkewQuads will further improve the vertical emittance.

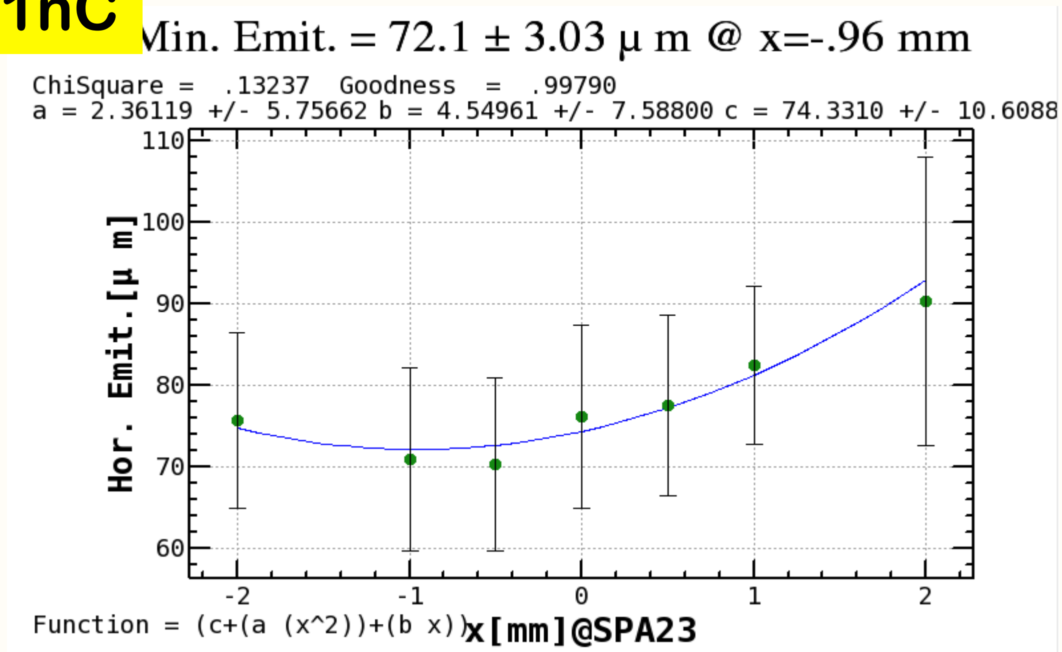
Y. Seimiya

Wakefield in Acceleration Structure

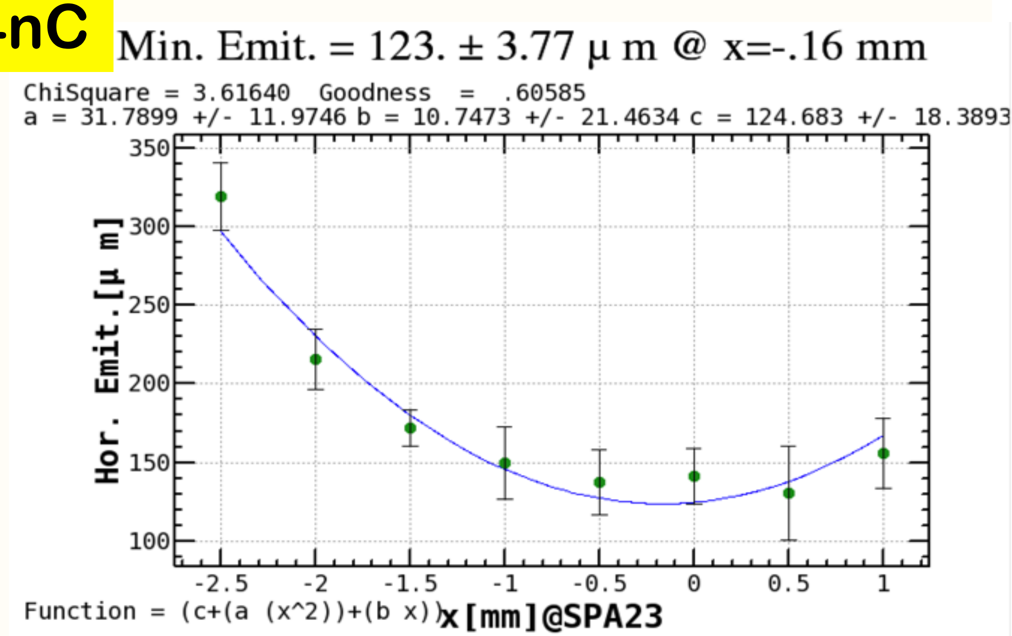
- Using a steering magnet, we searched an orbit so as to minimize emittance.
- Emittance highly depends on beam charge and orbit.
- Wake free steering will be performed using RF gun in the next run.

Thermionic gun

1nC



4nC



Beam abort caused by abnormal injection beam

A) Abnormal energy beam

B) Spike and injection beam

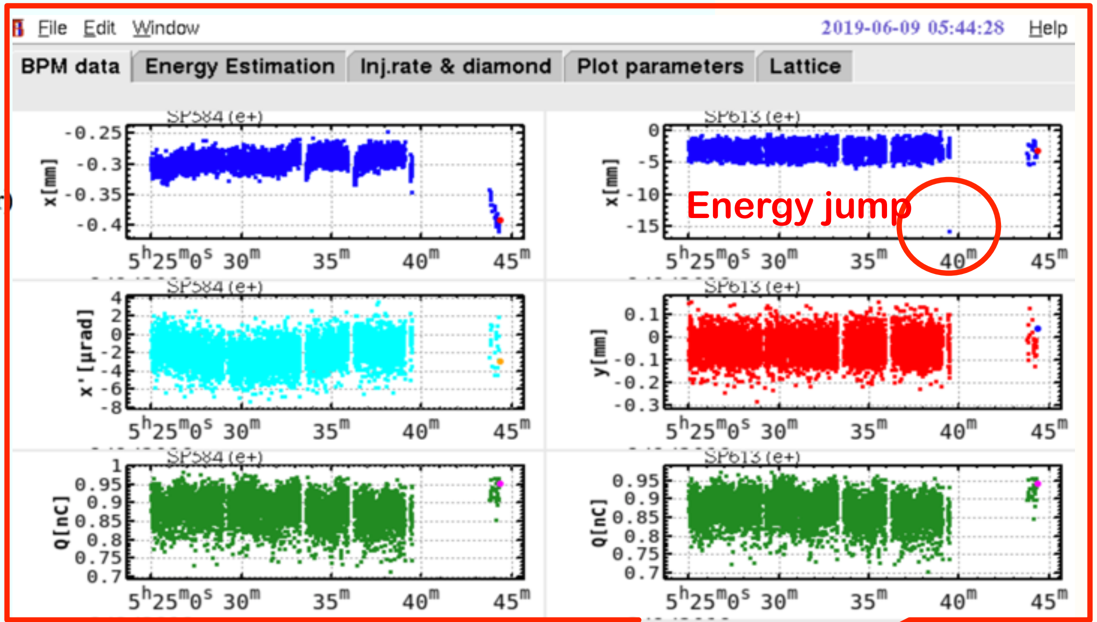
A) Lower or Higher energy injection beam

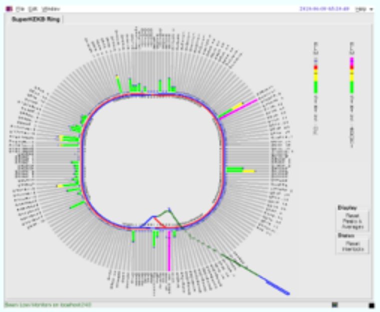
05:39:29 LER Beam Abort (659.9mA) LER 入射中

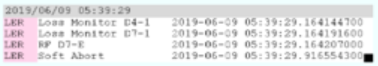
LER Abort Loss Monitor D4-1
LER Abort Loss Monitor D7-1
LER Abort RF D7-E
D05F REFLECT from 1-S
D05F REFLECT to CIR#3DL
Loss Monitor Abort BM_BLM:D07:ABORT1_2
LER Abort RF Software Abort
LER Abort Soft Abort
Loss Monitor Abort BM_BLM:D04:ABORT1_6 (D3H1 collimator)
D08E REFLECT from 2-S
D08B REFLECT from 2-S
D08B MT-DL INPOWER
D08A REFLECT from 2-S
D08E REFLECT from 1-S
D07A REFLECT from 1-S
D07B REFLECT from 1-S
D07C REFLECT from 2-S
D07E SQC ABORT TO RFOFF
D07E ARC COUPLER CAV#1-VAC

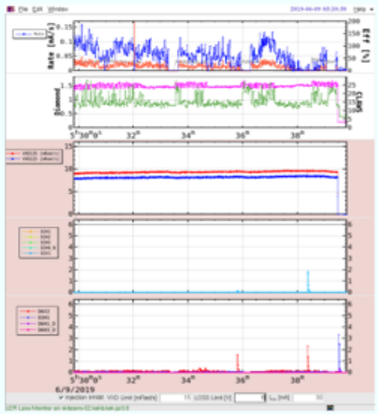
→ RF Recover、Loss Monitor Reset、Abort Reset

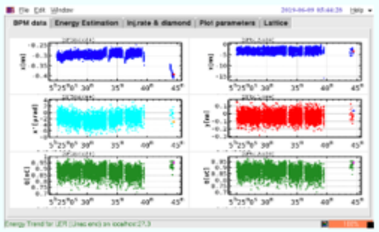
Operation log for SuperKEKB











Additonal information from LINAC

Injection beam just before abort can be monitored by,

Y. Seimiya, F. Miyahara

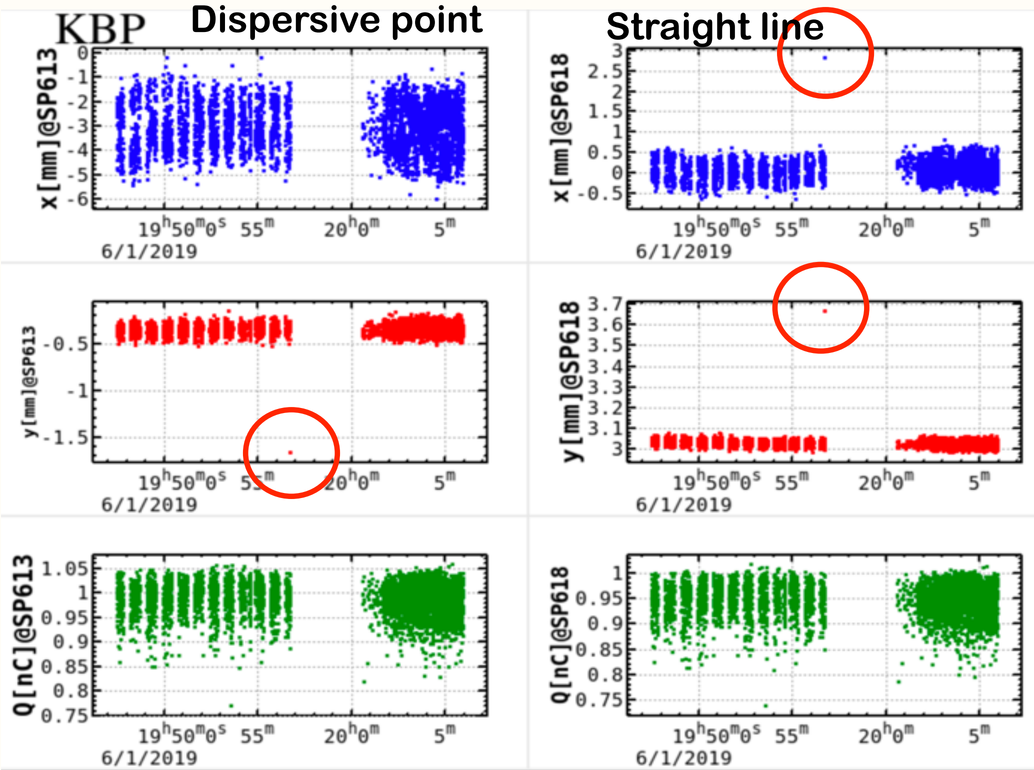
Fast beam position monitor(BPM) in LINAC

a. 1.Jun.2019 19:56

- LER D6V2 LM abort

No energy deviation

Orbit deviation

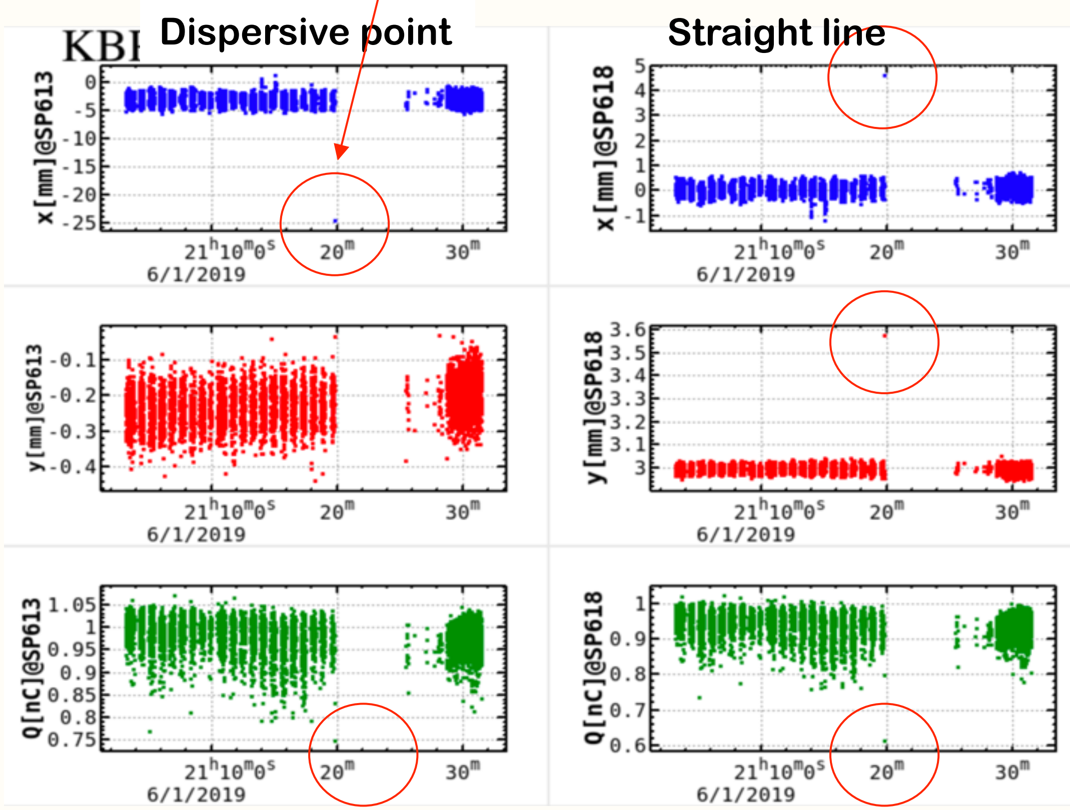


One station for the power supplies(PS) was set to 0 [A] due to a trigger missing of the PS.

b. 1.Jun.2019 21:19

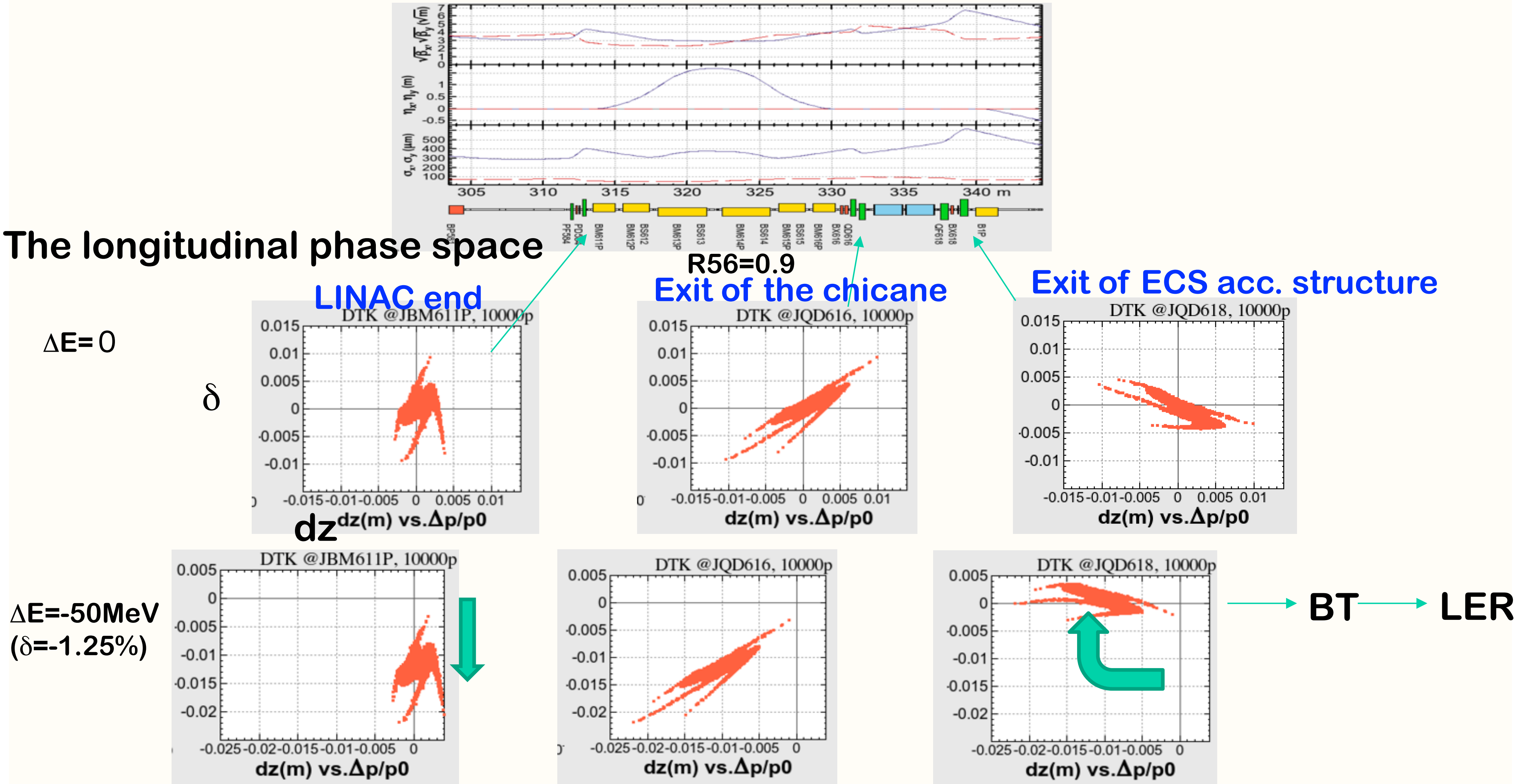
- LER D6V2 LM abort

Beam energy was 50 MeV lower.



The klystron 51 was down at the time. The estimation was -46.5 MeV which is consistent with the beam position.

Lower energy beam through the ECS



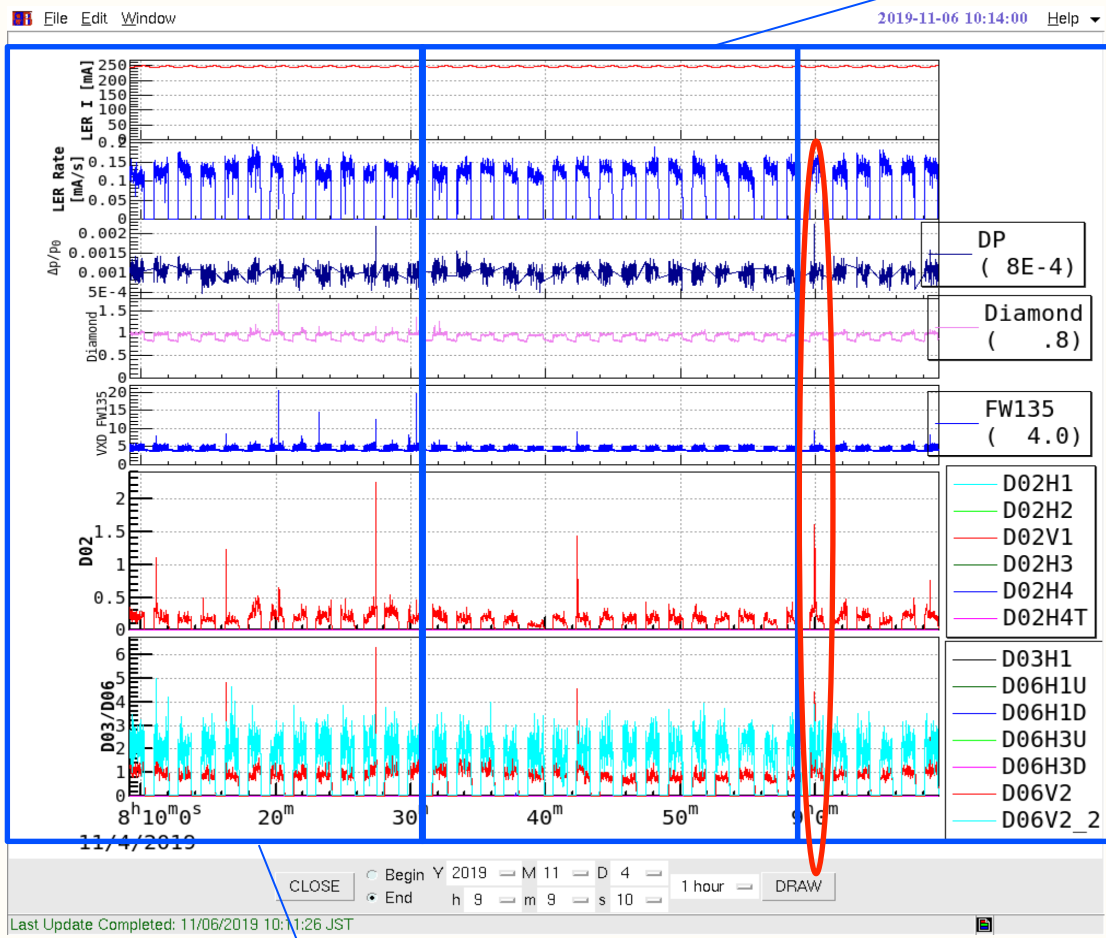
Since the ECS restores the beam energy, the beam can inject while being shifted in the time direction, which could cause a LER abort.

B) Spike and Injection beam

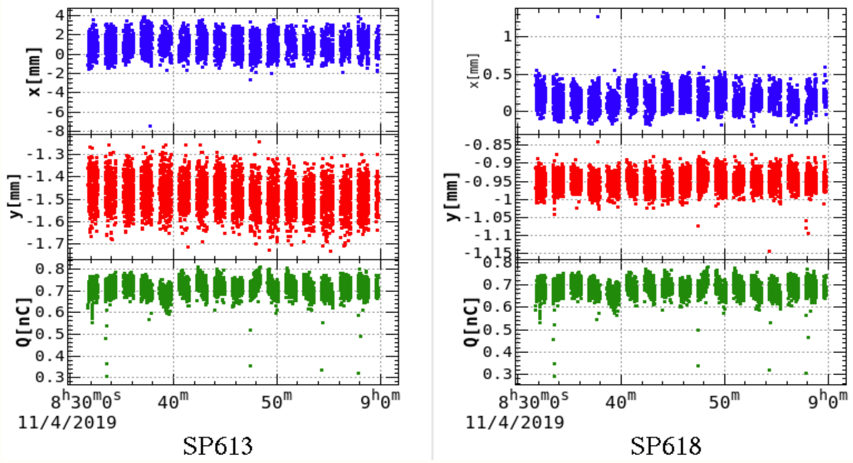
- Still mystery
- Injection beams sometimes have some correlation.
  - more detailed investigation is needed.
- Tunes in LER are also related.
- In smaller βy^*, the spikes increased.

Beam abort caused by abnormal injection beam

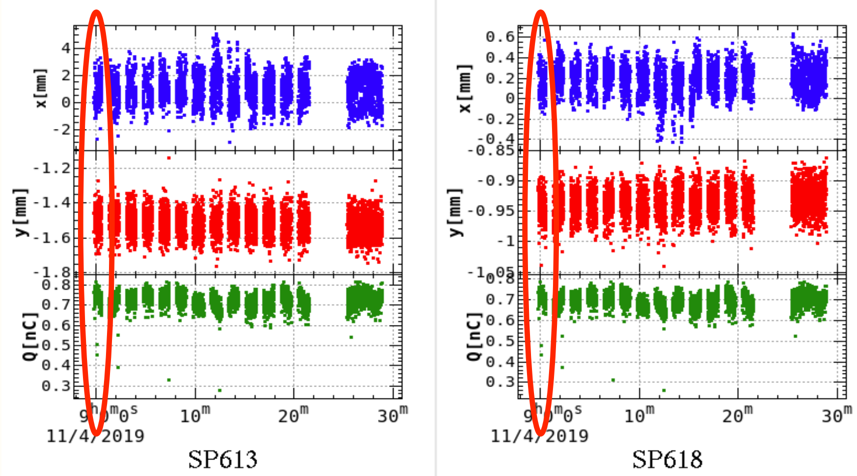
2019-11-04 , βy*=1mm



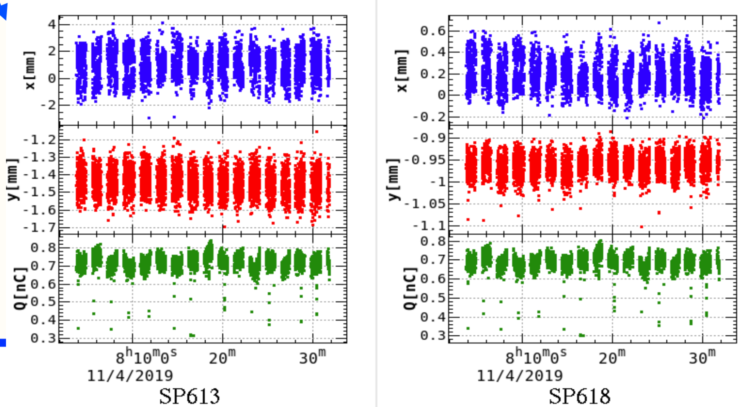
KBP-2019-11-04-08-31



KBP-2019-11-04-08-59



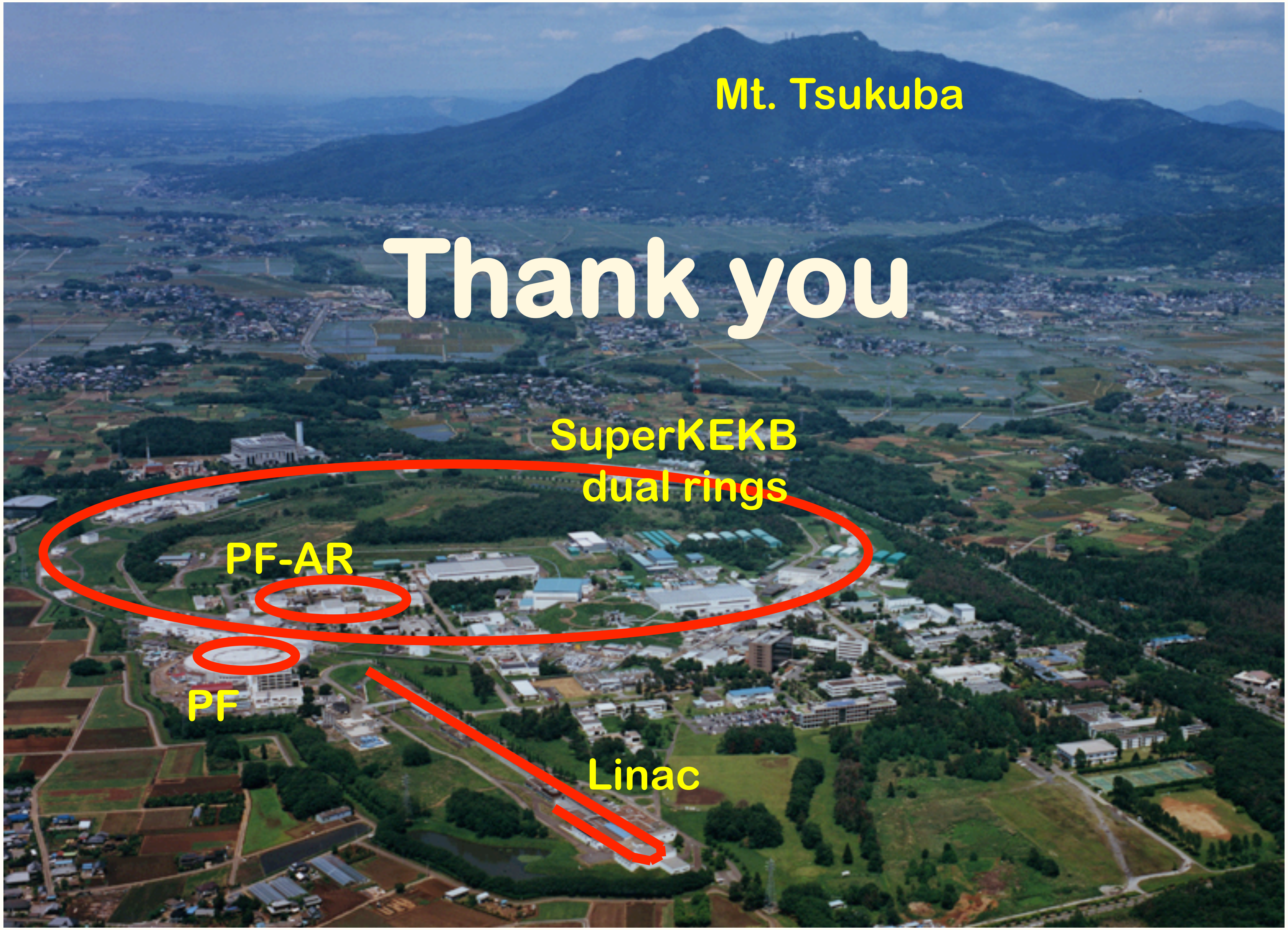
KBP-2019-11-04-08-03



Many spikes are observed.
Only one seems to be related to the LINAC orbit.

Summary

- Fire recovery, simultaneous top-up injections, RF-gun deployment, went well
- Beam sources and other subsystems are gradually upgraded
- Beam controls are being improved based on injection observations
- Further beam studies are indispensable balancing the resources and requirements in SuperKEKB complex


Mt. Tsukuba
Thank you
SuperKEKB
dual rings
PF-AR
PF
Linac