LINAC Status and Plans

Monday, 21th October 2019
B2GM
Accelerator Laboratory (5th)
Y. Seimiya

Contains

1. Introduction
2. New Findings of Injection Beam
    A) Emittance Growth
    B) Belle II Background by Injection Beam
    C) Beam Abort by Injection Beam
    D) Yield of Positron Beam
3. Recent Activity of LINAC
4. Plans

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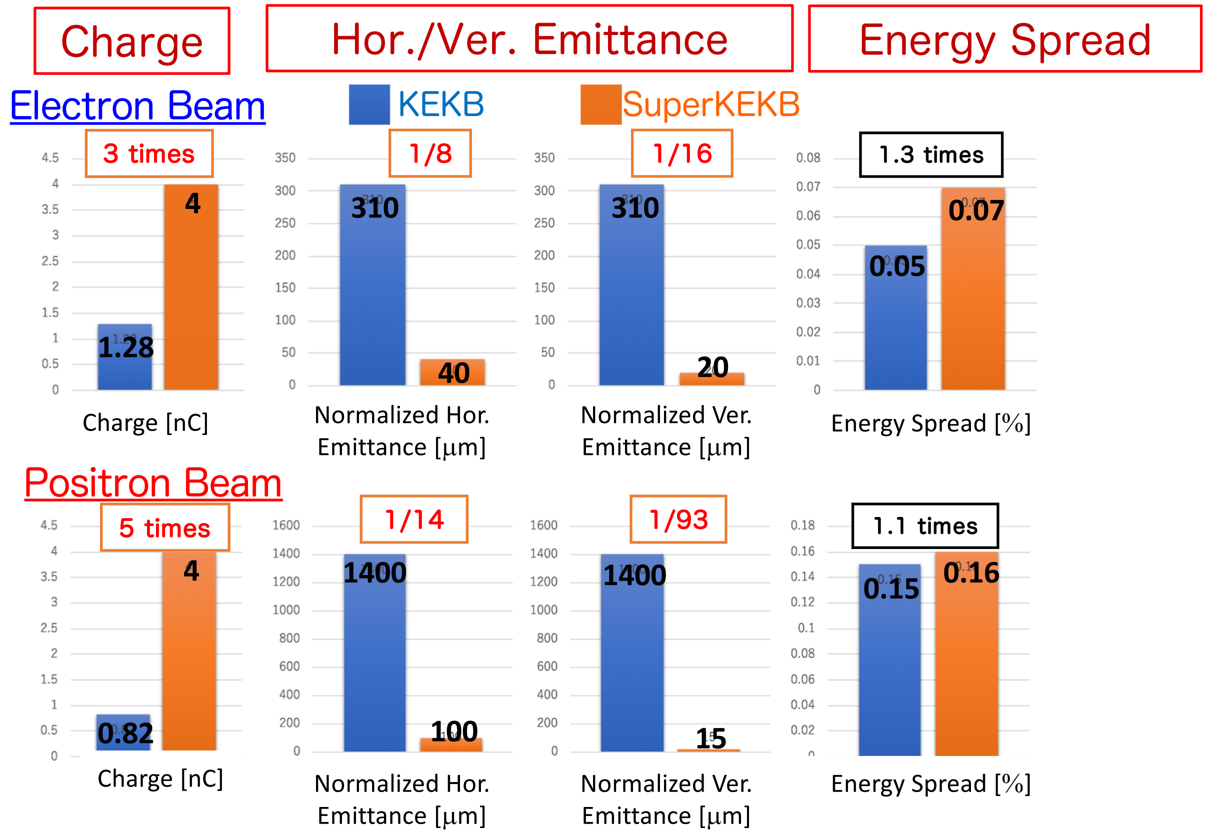
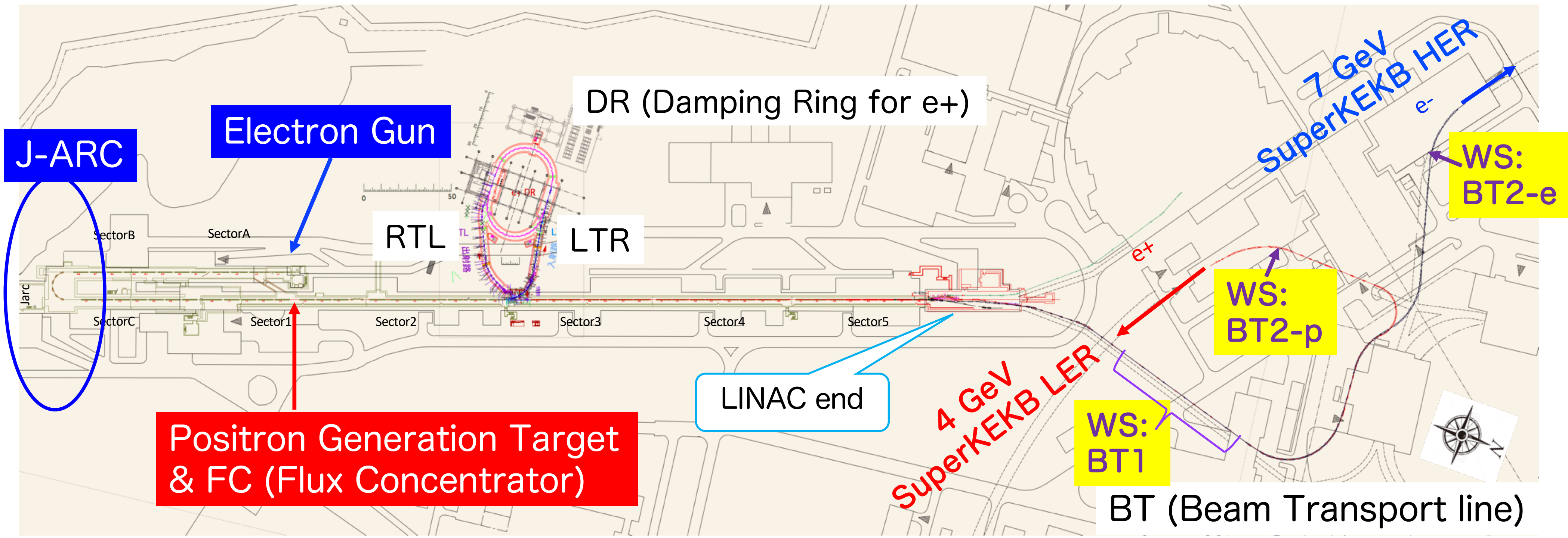
SuperKEKB comparison with KEKB

- Small emittance and high-intensity beam are required for injection beam.
- “Emittance ∝ charge squared”, 100 times higher performance is desired.



Footprint of LINAC and Beam Transport Line (BT)



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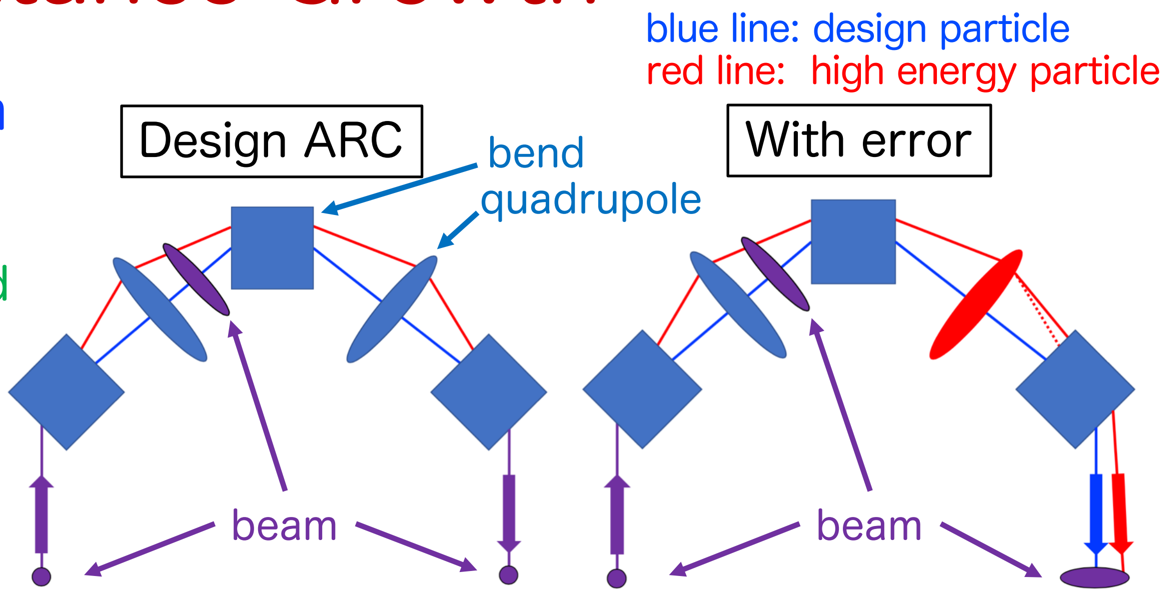
Main Reasons of Emittance Growth

◆Residual Dispersion of Momentum

- If there is magnetic error in a ARC, it can causes beam size blowup depended on energy spread after the ARC.
- Beam size blowup
  = energy spread x residual dispersion

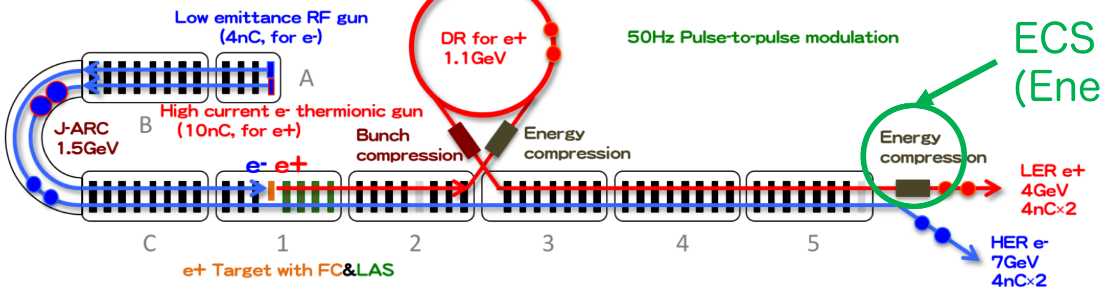


1. Residual dispersion increases emittance through energy spread.
2. If there is residual dispersion “in acceleration cavity”, it causes further serious emittance growth.
   (bunch length increases emittance through the residual dispersion -> z-dispersion)

➡ **In each case, emittance growth is reduced by suppression tuning of the residual dispersion.**

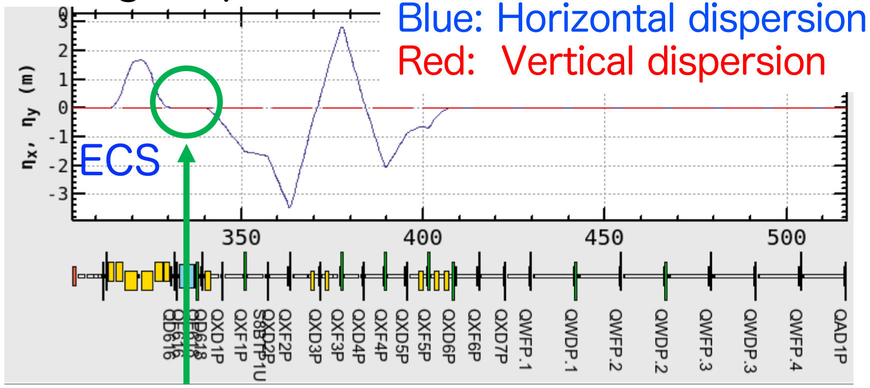
A) Emittance Growth

Residual Dispersion in ECS cavity.



ECS
(Energy Compression System)

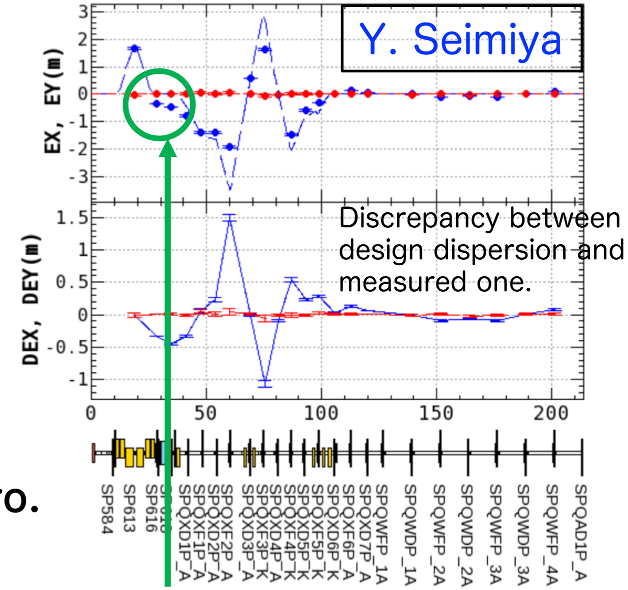
Design Optics



Blue: Horizontal dispersion
Red: Vertical dispersion

acceleration cavity

Dispersion Measurement



acceleration cavity

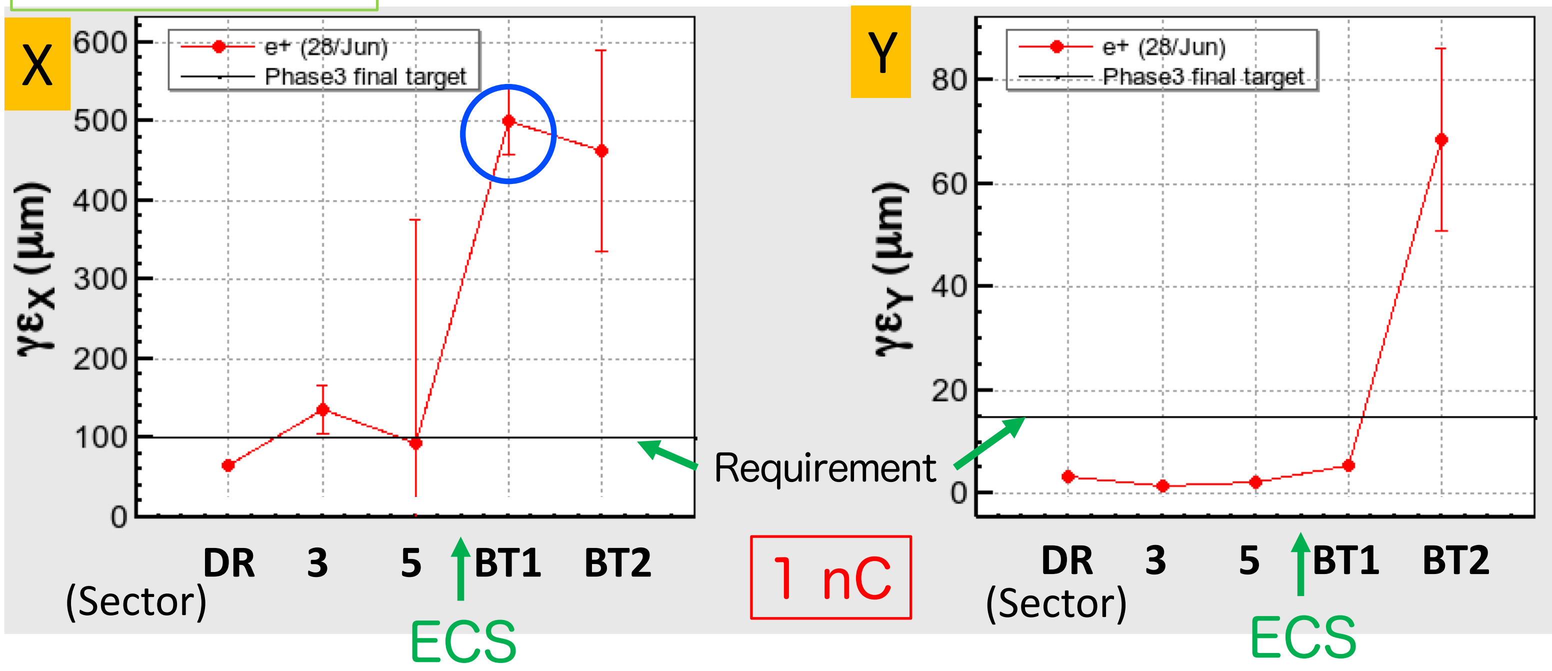
- In the design, dispersion in the cavity is zero.
- However, non-zero dispersion was measured in the cavity.

Emittance Measurement

- **Horizontal emittance became 5 times larger by ECS cavity with residual dispersion.**

N. Iida
M. Kikuchi
T. Mori

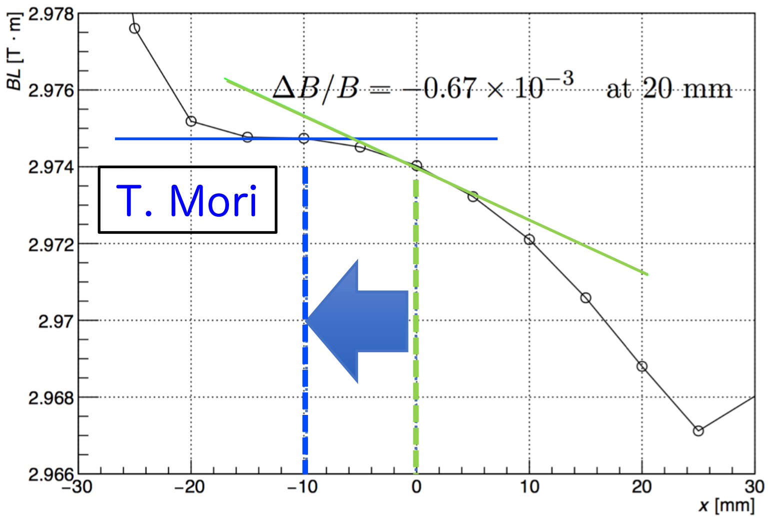
June 2019



Reason of the Residual Dispersion and the Countermeasure

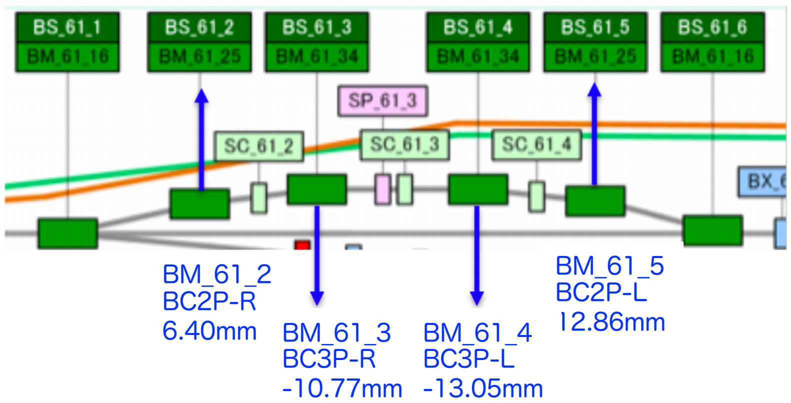
- It was found that beam passed through non-flat magnetic field.
- There is not quadrupole magnet in this ARC, we could not suppress the residual dispersion.
- We moved bending magnets so as beam passes through the flat field region.

Measured integrated magnetic field of bending magnet in ECS@SY3



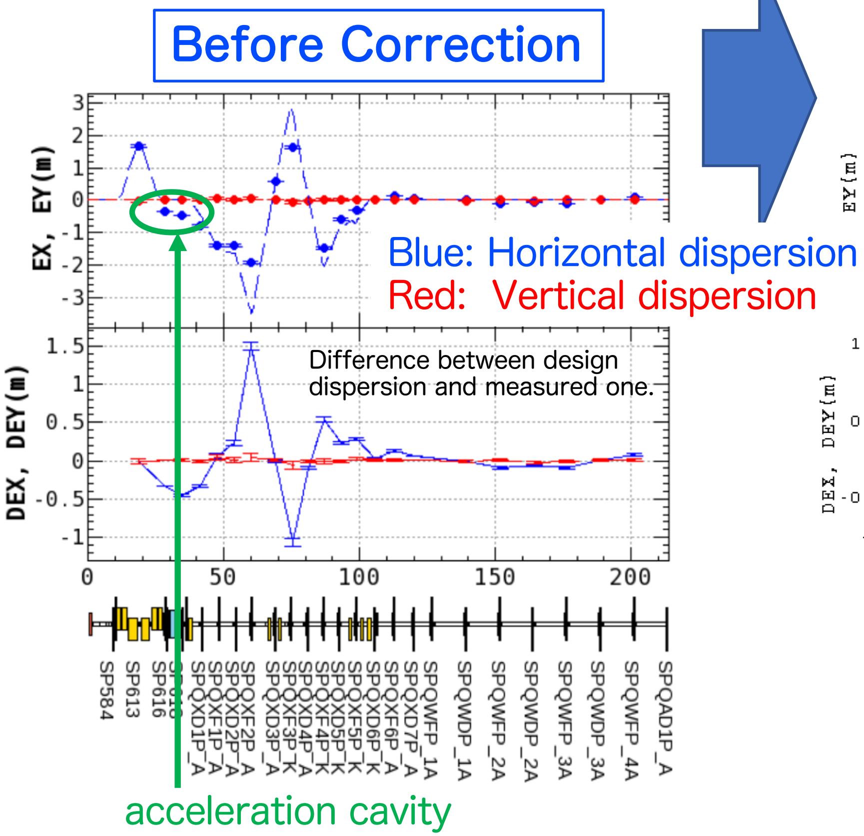
ECS

Many people

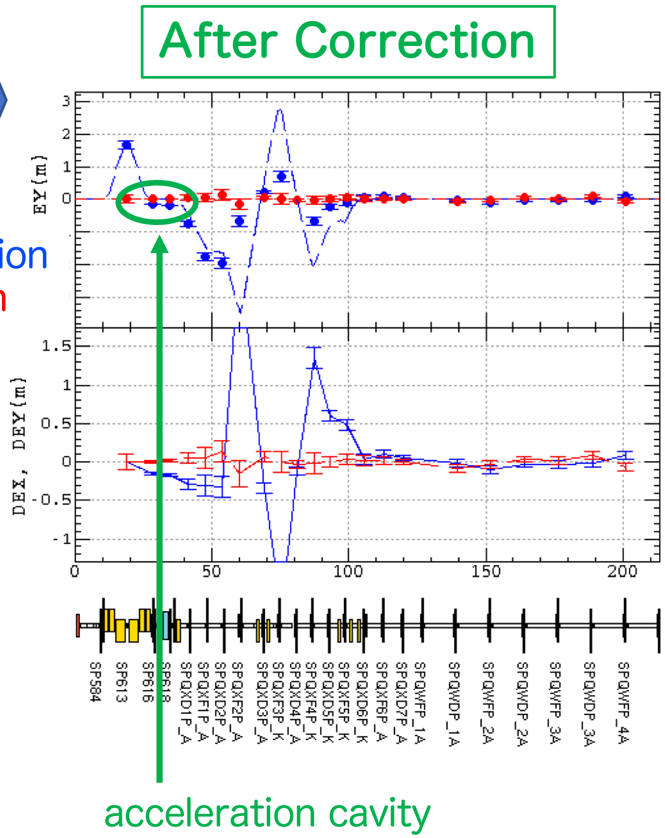


Improvement of Residual Dispersion

N. Iida
M. Kikuchi
Y. Seimiya



ηx = 0.50 m @cavity

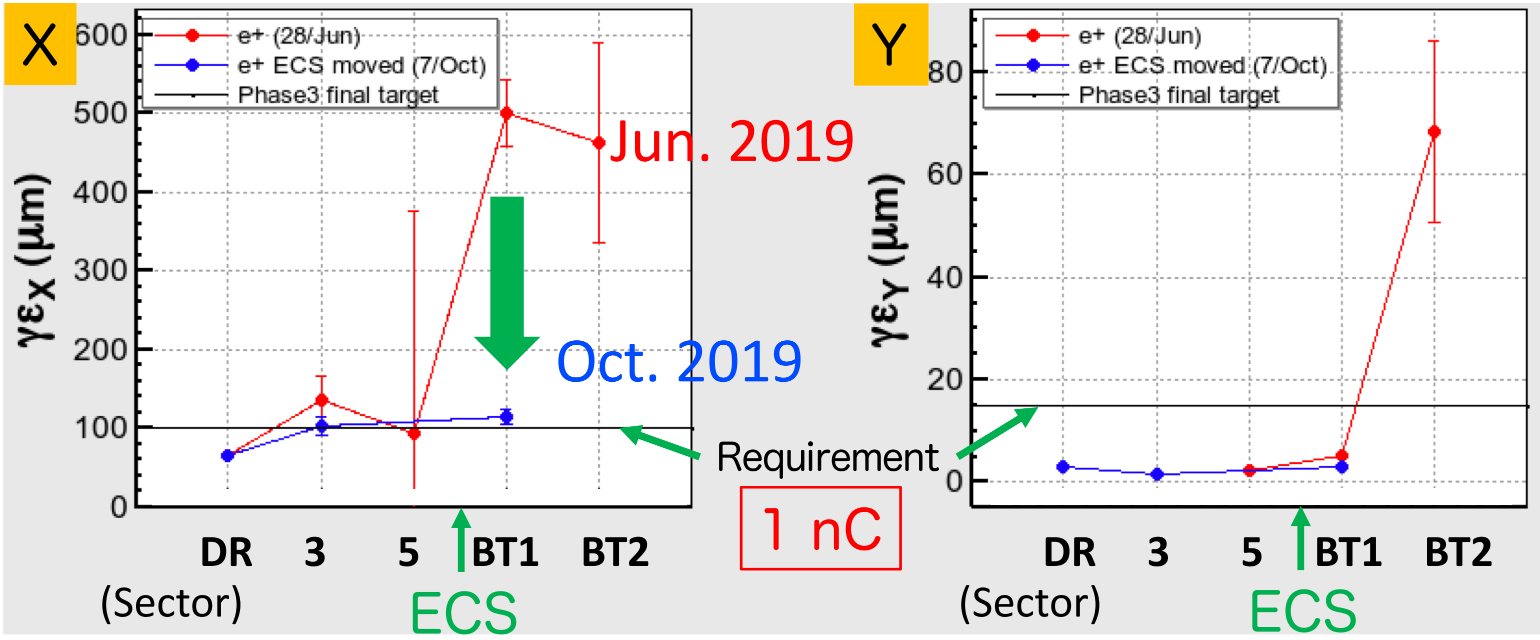


ηx = 0.15 m @cavity

Improvement of emittance (for LER beam)

- After the dispersion correction by bending magnet alignment, emittance growth by ECS cavity almost disappeared!
- Vertical emittance increases between BT1 and BT2. One of the main reasons is vertical residual dispersion in BT.

N. Iida
M. Kikuchi
T. Mori



A) Emittance Growth

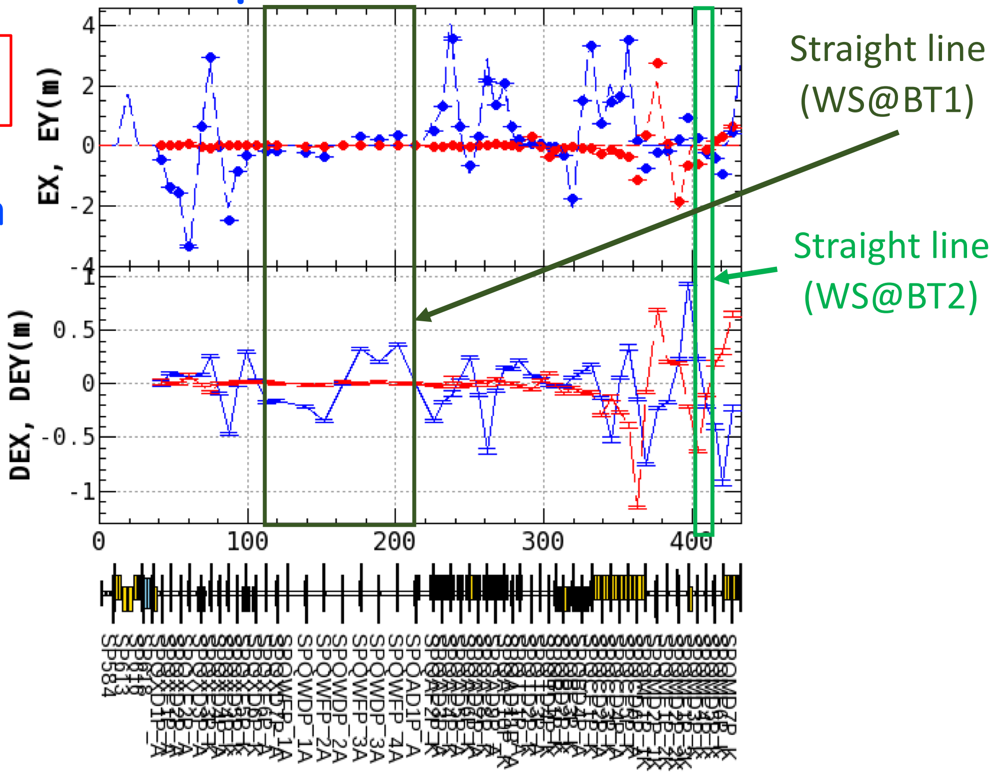
Residual Dispersion in BT

- Non-negligible residual dispersion was observed.
- We should minimize the residual dispersion at the BT end.
- Additional skew quadrupole magnets will be installed to reduce vertical residual dispersion.

N. Iida
M. Kikuchi
Y. Seimiya

BT for e+

Blue: Horizontal dispersion
Red: Vertical dispersion



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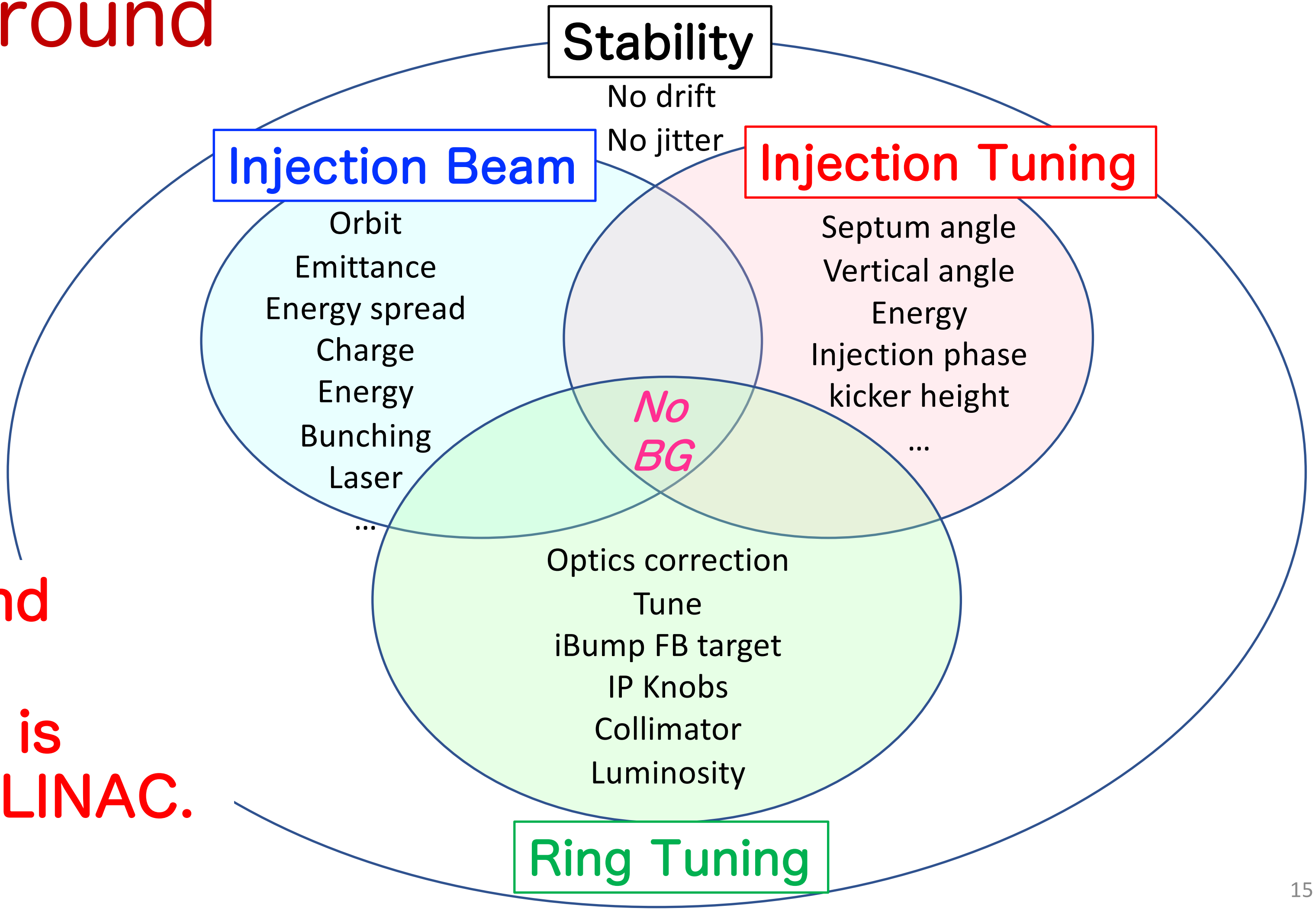
Background



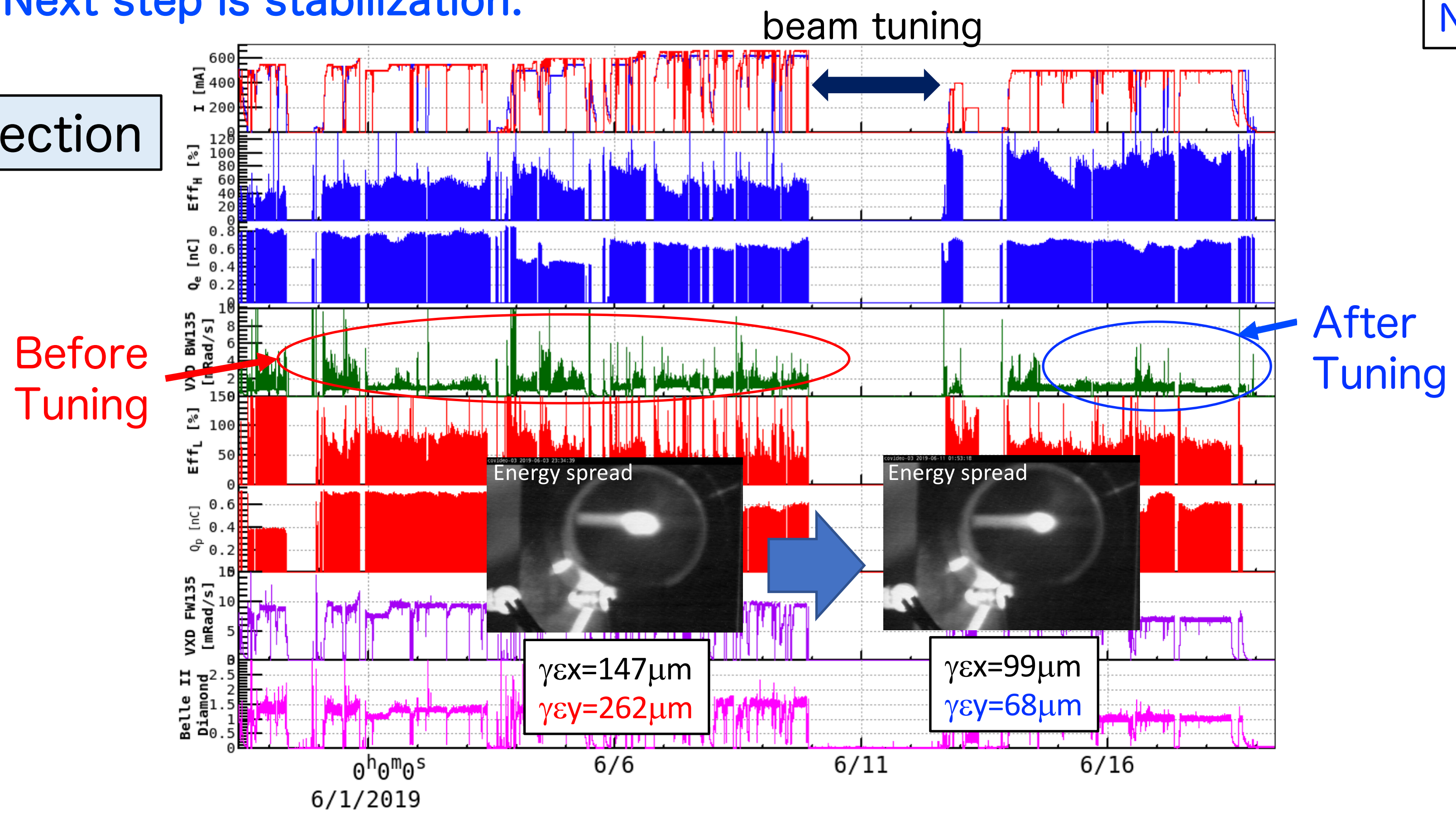
High quality and stable beam transportation is necessary for LINAC.

Background reduction by tuning of injection beam

- Orbit, energy spread, and emittance tuning were performed.
- By injection beam tuning, background was reduced.
- Next step is stabilization.

M. Yoshida
N. Iida

HER injection



For injection beam stabilization

TBI: To be introduced

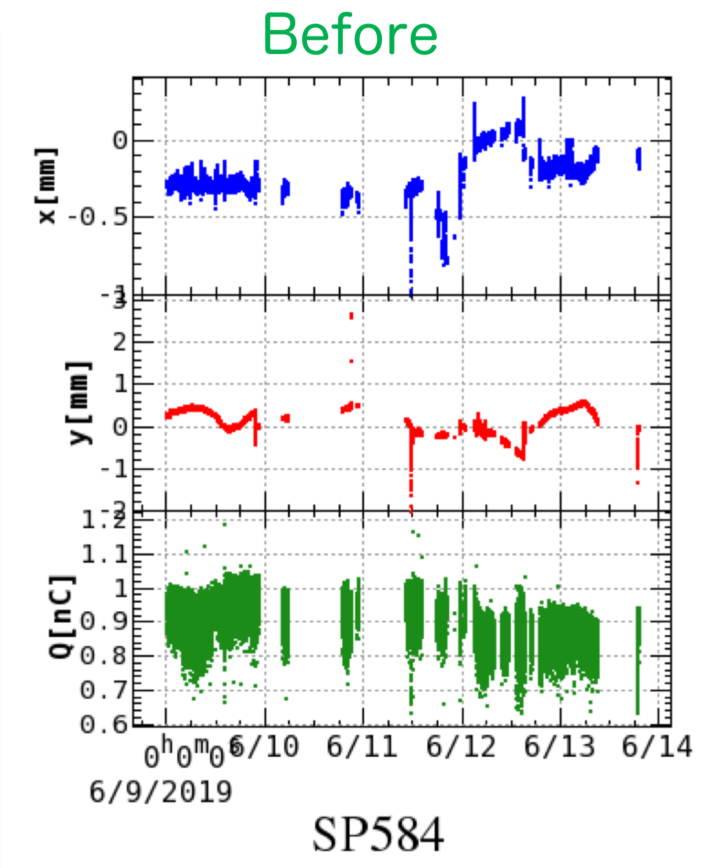
Many people

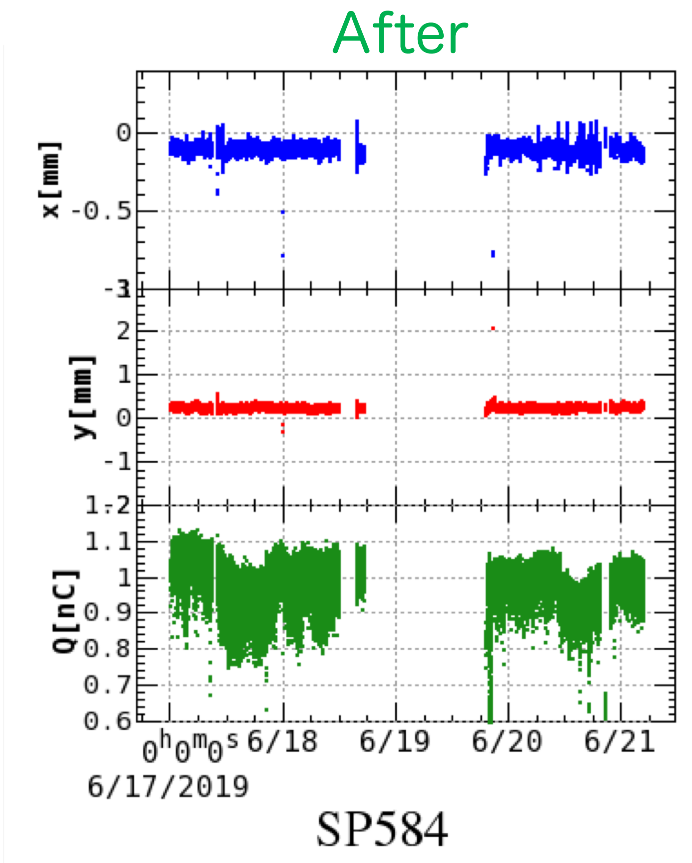
	Tool	Place	Achievement	Feedback
Energy	Energy feedback	Jarc, DR, BT	○	○
Energy spread	Sub Harmonic Buncher 1 (SHB1) for LER beam	Thermionic Gun	○	―
	SHB2		TBI	―
	RF Phase monitor	LINAC	○	TBI
	RF Induced wave monitor	LINAC	△	―
	OctoPos BPM monitor	Jarc	△	TBI
		BT	TBI	TBI
	Temperature control	LINAC	△	
Orbit	Orbit feedback	LINAC + BT	―	○
	Offset injection	LINAC	TBI	TBI
Orbit jitter	Pulsed magnet PS	Sector 3-5	○	―
Energy jitter	Energy knob phase	Sector B, 2, 5	△	―
	RF phase	LINAC	△	―
Injection phase	FB of Master oscillator	LINAC and MR	○	○
Emittance	e- RF gun	RF Gun	△(stability)	TBI
	e+ DR	DR	○	―
	Wire scanner	LINAC, BT	○	―
		End of BT	△	―

Orbit Feedback

- An example of orbit FB (Shown BPM place in the LINAC end)
- Orbit FB is operated correctly.

Y. Seimiya





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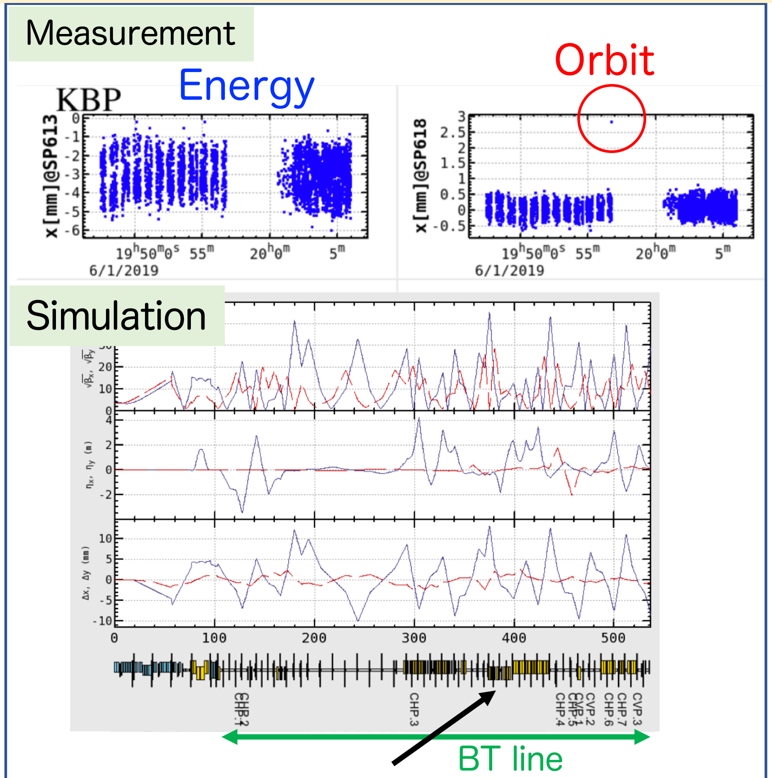
C) Beam Abort by Injection Beam

- Sometimes abnormal injection beam induces beam abort.

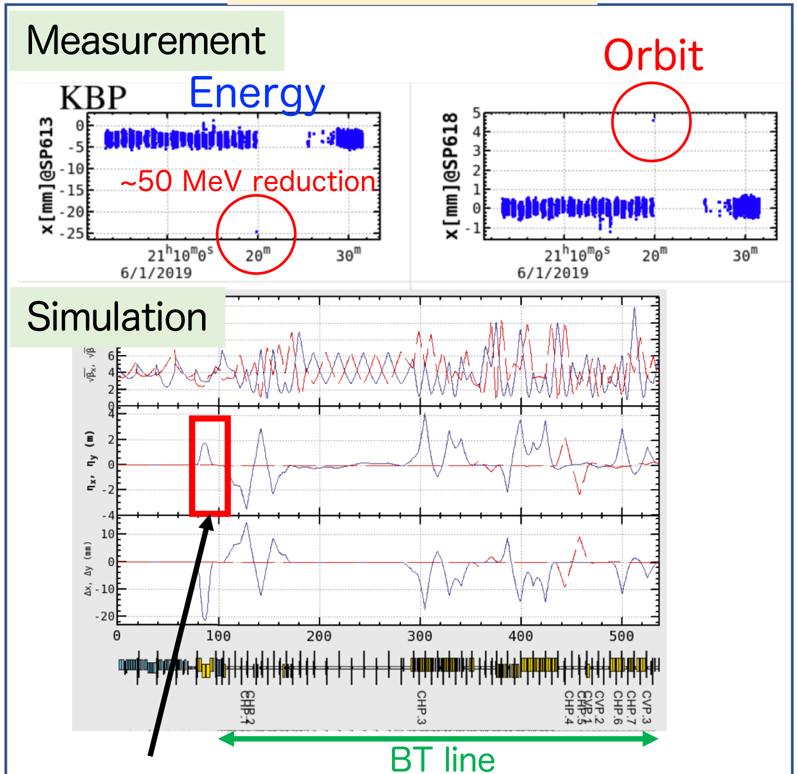
Y. Seimiya
F. Miyahara

Trigger Missing of Pulsed Magnet



Collimators in the BT could cut the beam of the abnormal orbit.

Klystron Down



New collimator installation is planned.

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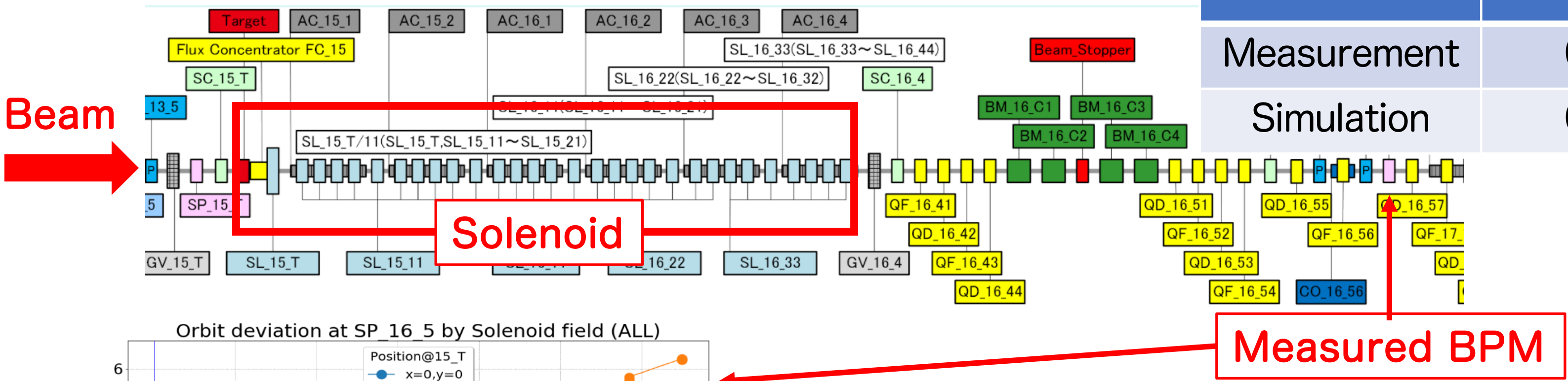
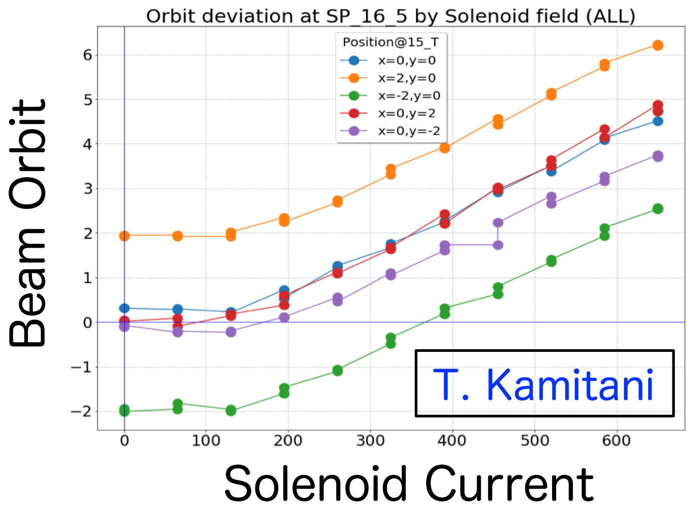
D) Yield of Positron Beam

- Measured positron yield is 30% less than simulated one.
- Non-axisymmetric field component were observed by electron beam deflection.
- This could cause e+ beam loss.

	Yield
Measurement	0.26
Simulation	0.34



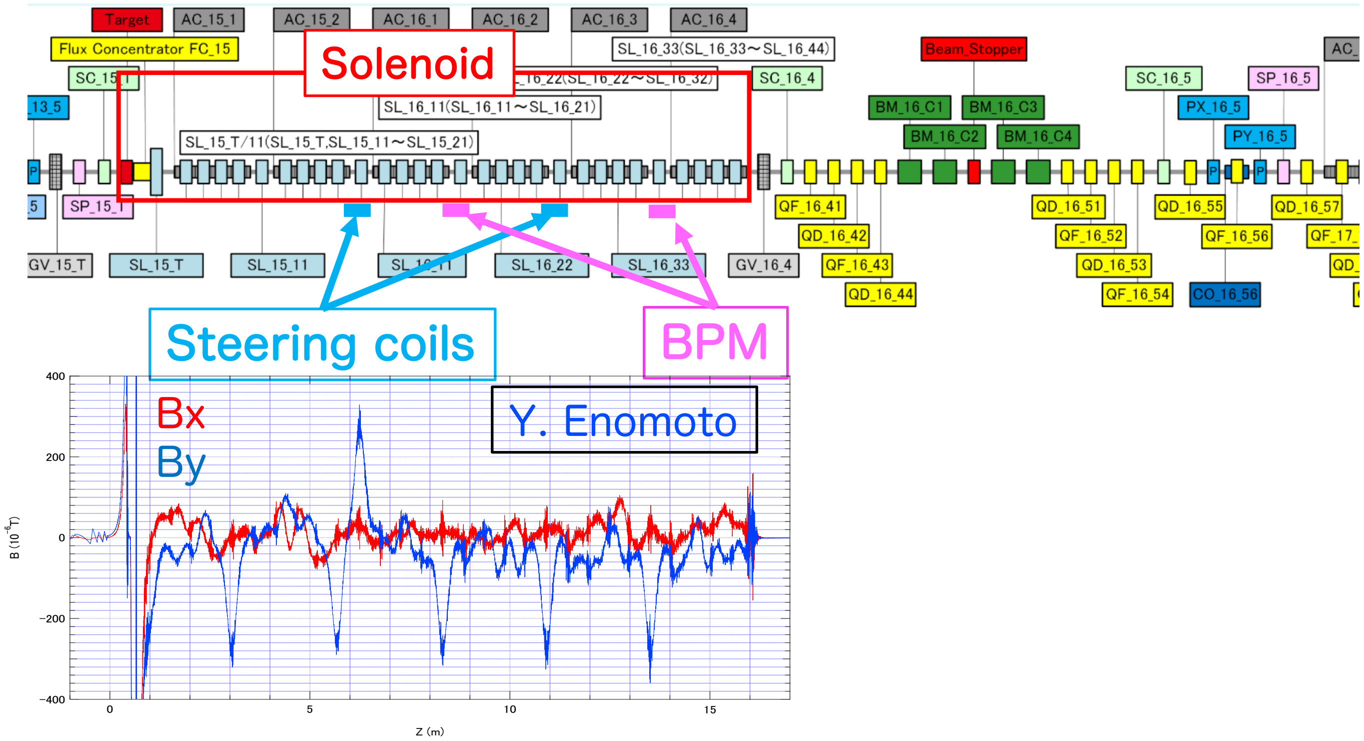


Solenoid magnetic field is tilt!

D) Yield of Positron Beam

Countermeasure of the Positron Yield Problem

- For understanding the phenomena and controlling beam orbit, we are planning to install orbit correction coils and BPMs.
- Detailed field distribution is being evaluated, including return yokes and structures (Fe) around solenoid.



Next Tasks

A) Emittance Growth
- Tuning to reduce the residual dispersion.
- At BT for e+, additional skew quadrupole magnets will be installed to reduce vertical residual dispersion.

B) Background by Injection Beam
- Emittance and energy spread tuning.
- RF phase FB is being introduced for stable energy spread.

C) Ring Abort by Injection Beam
- To stop abnormal beams, installation of collimators is planned in this winter for HER and in the next summer for LER, respectively.

D) Yield of Positron Beam
- We are planning to install orbit correction coils and BPMs in the next summer.

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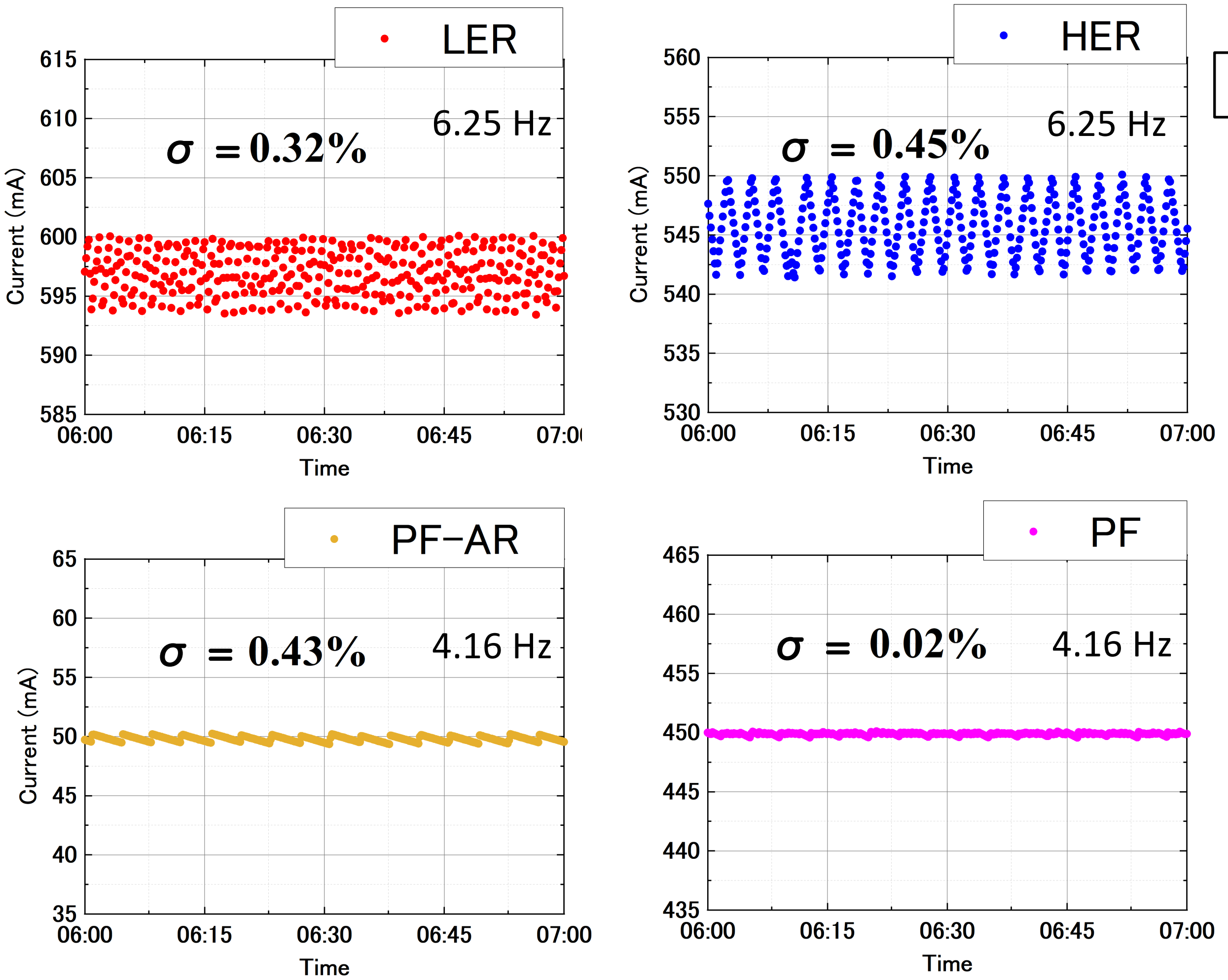
3. Recent Activity of LINAC

- 4 ring simultaneous top-up injection
- Long-term continuous operation of RF gun
- Completion of recovery from fire accident
- Main works in this summer shutdown.
  - RF gun
    - Vacuum exhaust of laser waveguide.
    - New air conditioning and insulation in laser hut.
    - Laser line preparation of RF gun for backup.
  - Beam line
    - Alignment
    - Mover installation for acceleration unit girder. (4 units)
  - Monitor
    - Installation of additional high resolution profile monitors. (OTR, YAG)

4 Ring Simultaneous Top-Up Injection



Many people

Contains

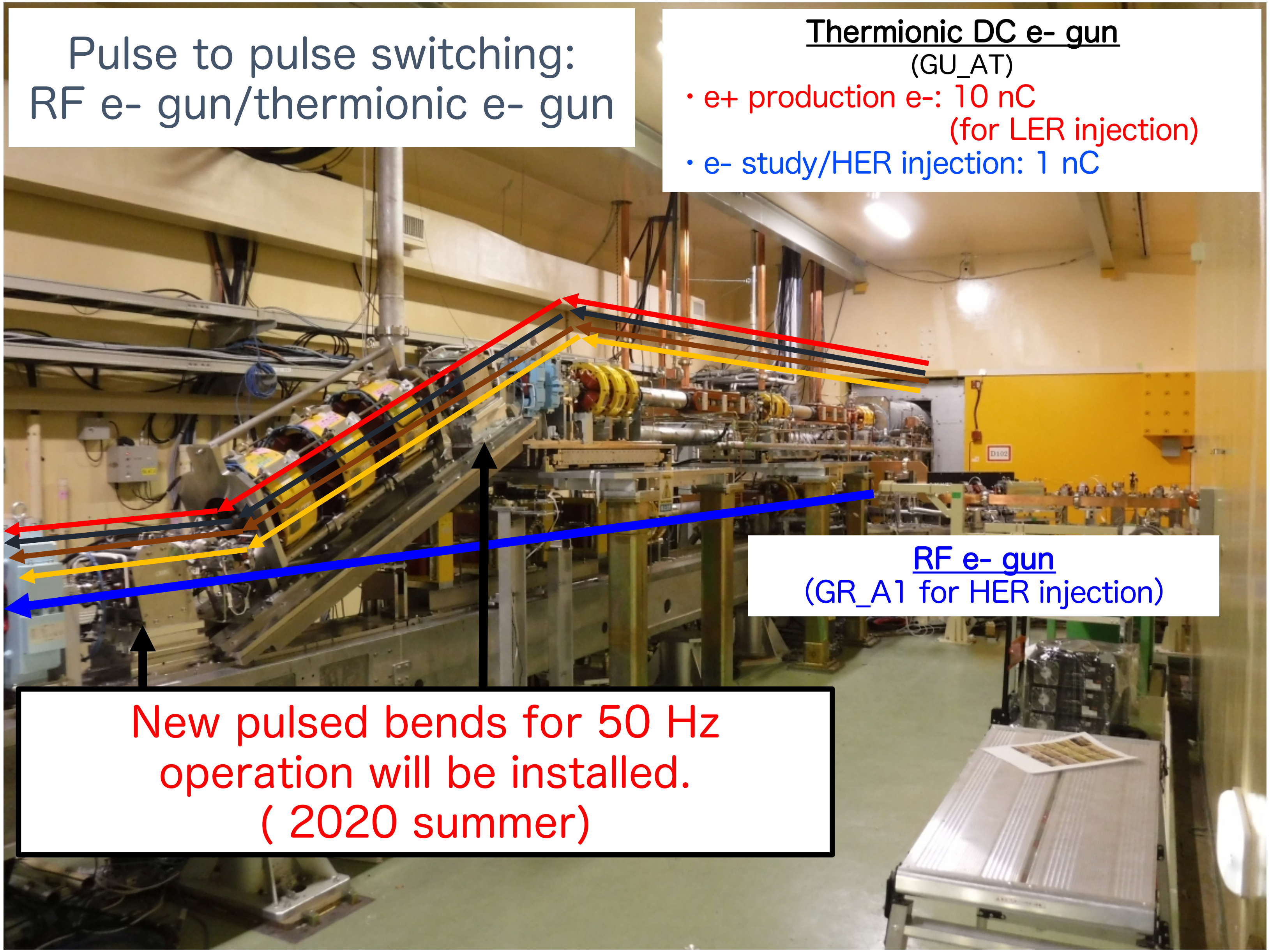
Plans

This Winter

- HER/LER 2 bunch injection
- Additional skew quadrupole magnets installation in e+ BT
- Collimator installation for HER

Next Summer

- Collimator installation for LER
- Installation of orbit correction coils and BPMs at e+ capture section
- New FC installation
  → e+ charge increase
- New pulsed bending magnet in merger line installation and new laser for RF gun installation
  → 50 Hz single beam operation


Pulse to pulse switching:
RF e- gun/thermionic e- gun
Thermionic DC e- gun
(GU_AT)
・e+ production e-: 10 nC
(for LER injection)
・e- study/HER injection: 1 nC
RF e- gun
(GR_A1 for HER injection)
New pulsed bends for 50 Hz
operation will be installed.
(2020 summer)

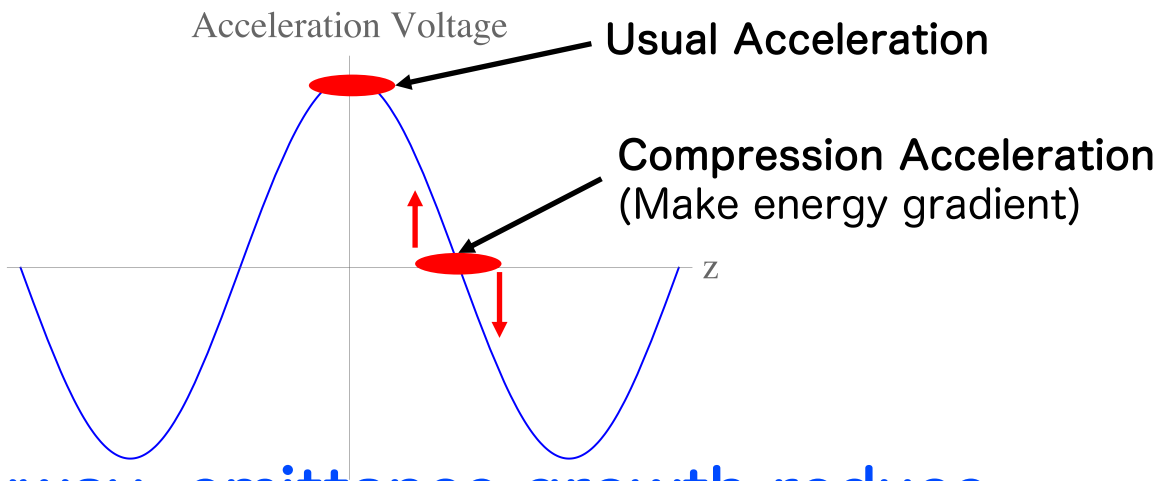
Thank you for your attention!

back up

Main Reasons of Emittance Growth

◆Residual Dispersion

1. If there is Residual Dispersion after ARC, energy spread increases beam size through residual dispersion.
2. **If there is Residual Dispersion in compression acceleration cavity, bunch length increases beam size through residual dispersion.**



➡ **Anyway, emittance growth reduce if dispersion is suppressed.**

Countermeasures

A) Emittance Growth

- Tuning to reduce the residual dispersion.
- At BT for e+, additional skew quadrupole magnets will be installed to reduce vertical residual dispersion.

B) Background by Injection Beam

- Emittance and energy spread tuning.
- Orbit FB and RF phase FB.

C) Ring Abort by Injection Beam

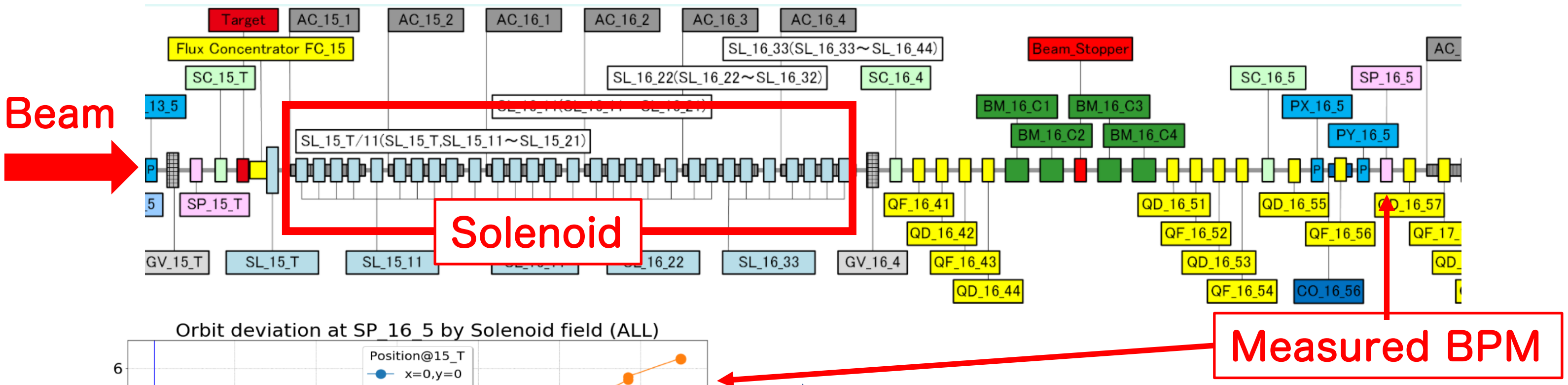
- To stop abnormal beams, installation of collimators is planned.

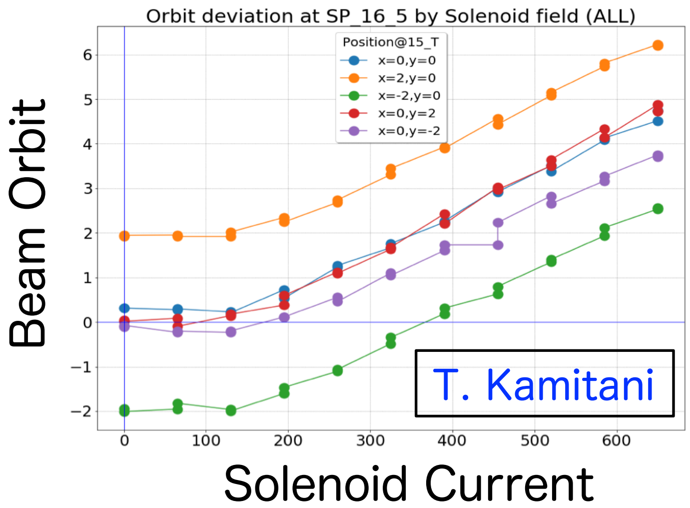
D) Yield of Positron Beam

- We are planning to install orbit correction coils and BPMs.
- 2 bunch operation, primary e- increase, beam loss reduction, field of flux concentrator increase.

D) Yield of Positron Beam

- Measured positron yield is 30% less than simulated one.
- Non-axisymmetric field component were observed by electron beam deflection.



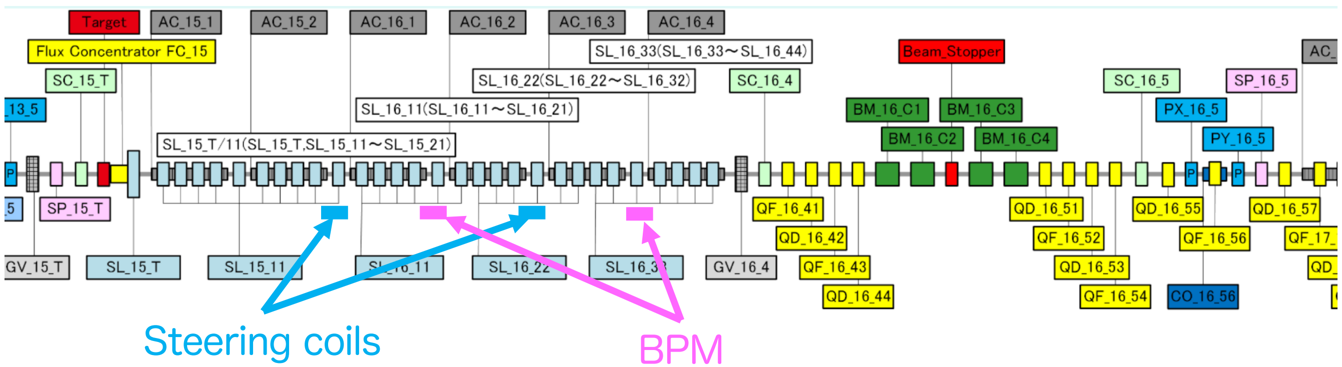


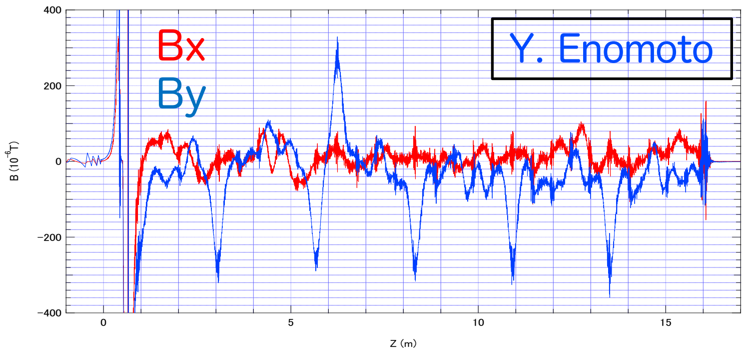
Solenoid magnetic field is tilt!

- First we checked beam pass through beam line straightly by turning off all magnet between BPMs.
- If solenoid tilt physically, there is 20 mm misalignment. This is unreal.

Countermeasure of the Positron Yield Problem

- For understanding the phenomena and controlling beam orbit, we are planning to install ST coils and BPMs in next summer.
- Detail simulation, which includes return yoke and structure (Fe) around solenoid, is performing now. (Y. Enomoto)





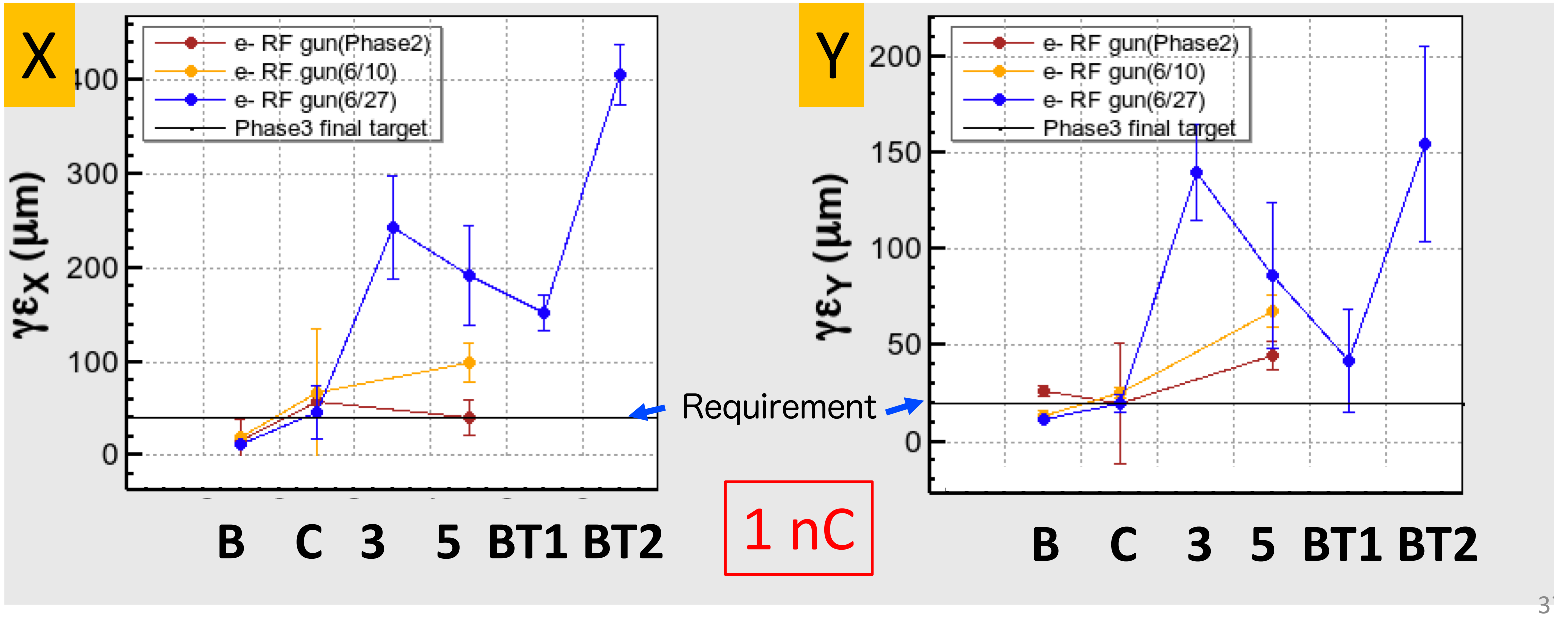
Possible causes:

- In DC solenoid, return yoke and supports of the acceleration cavity brake symmetry against of the solenoid axis.
- Though wires of DC solenoid is thick, current do not flow symmetry against of the solenoid axis.
- Bridge coil's shape has asymmetry and material of the return yoke has problem (magnetic field is saturated).

Emittance Measurement（for HER)

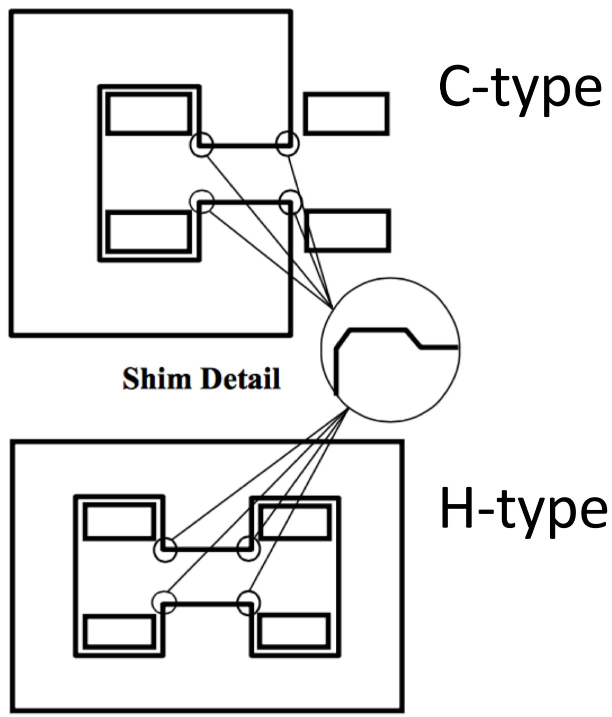
- Emittance was worse than Phase 2, because tuning time was limited by fire accident.
- It seems that wakefield by beam cause emittance growth from sector C to sector 5.
- To reduce tuning time, we are preparing automatic emittance minimized program.

N. Iida
M. Kikuchi
T. Mori



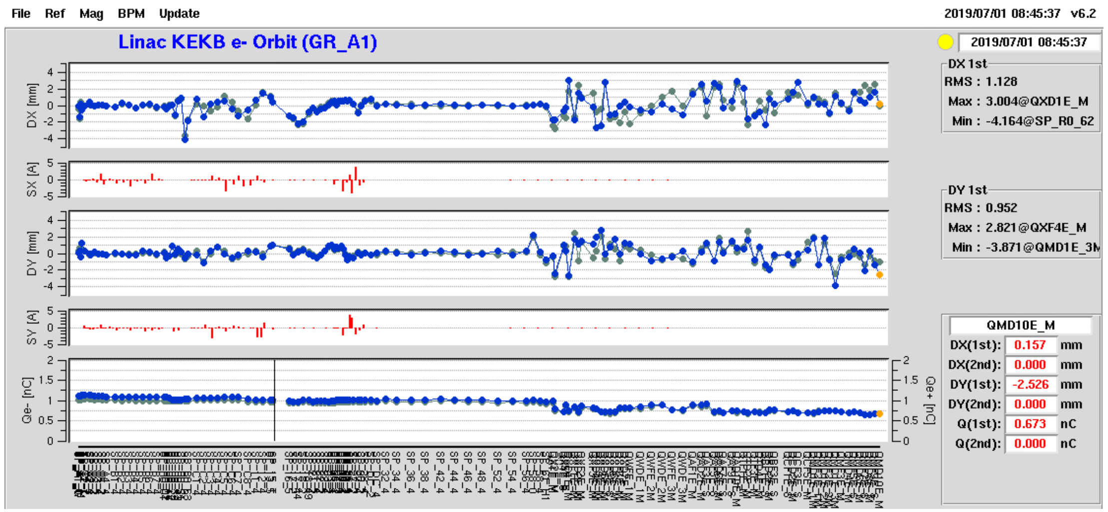
Ununiform magnetic field of bending magnet

- There are two type of bending magnet.
- One is C-type, the other is H-type.
- C-type's magnetic gap is easier to shrunk by own magnetic field than that of H-type.
- By the shrunk gap, ununiform magnetic filed is generated.

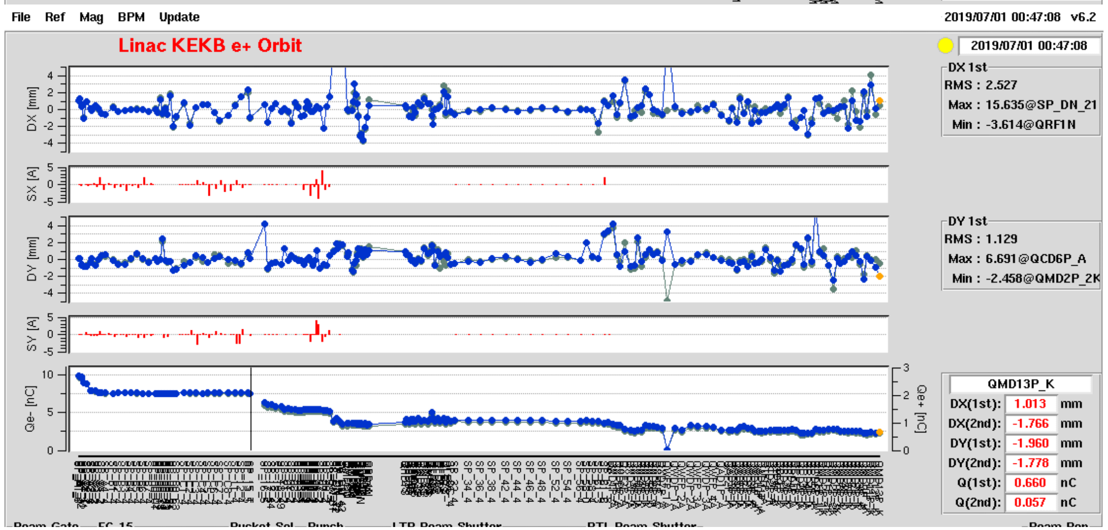


Typical Charge in Phase 3

Beam for HER
 1 nC @Linac end
 0.7 nC @BT end



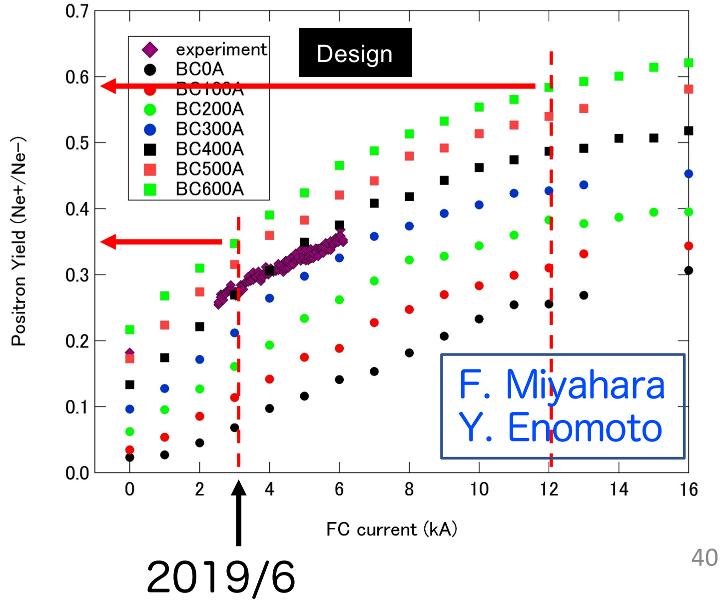
Beam for LER
 1 nC @Linac end
 0.7 nC @BT end



Positron Charge at some point

	primary e- (nC)	FC (kA)	Yield (simulation)	Yield比 (measured/ simulated)	e+ (nC) @before LTR	e+ (nC) @Linac end	e+ (nC) @BT end
2019/6	7.5	3	0.34	0.7	1.5 （measured）	1 （measured）	0.7 （measured）
Ideal case except charge loss	10	12	0.58	1	4.9 (extrapolation)	3.2 (extrapolation)	2.3 (extrapolation)

It is necessary to reduce beam loss.



Other Sources of Emittance Growth

Candidates of emittance growth in LINAC or BT.

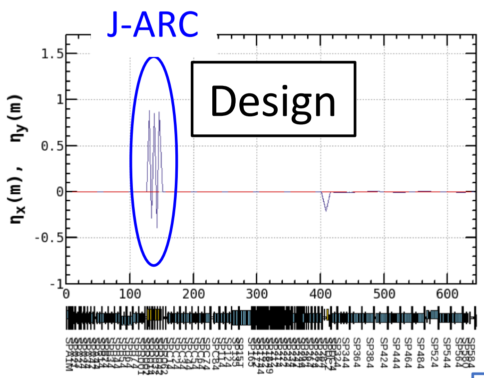
1. Beam Phase Space Jitter
   - The emittance that includes beam phase space jitter, called as effective emittance, must be satisfy the SuperKEKB requirement.

2. Wakefield in Acceleration Structure
   - Wakefield, generated by a head of bunch, kicks its own tail.
   - Thus if the beam is off-centered in the structure, the transverse wakefield increases beam emittance.

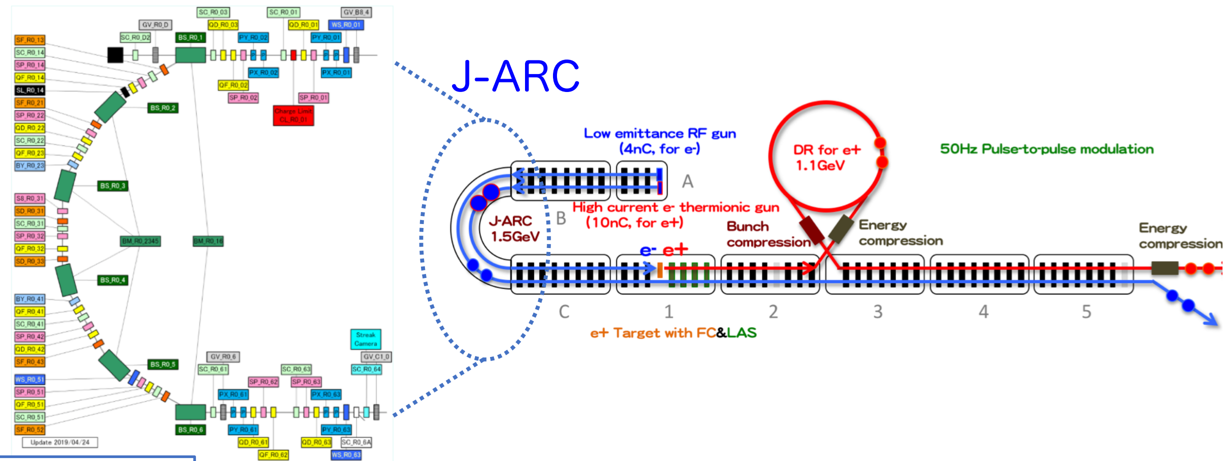
3. Radiation Excitation
   - Radiation excitation effect on emittance is proportional to both Lorenz gamma to the fifth power and inverse of curvature radius to the third power.
   - Especially, electron beam (7 GeV) is strongly affected by the radiation excitation effect.

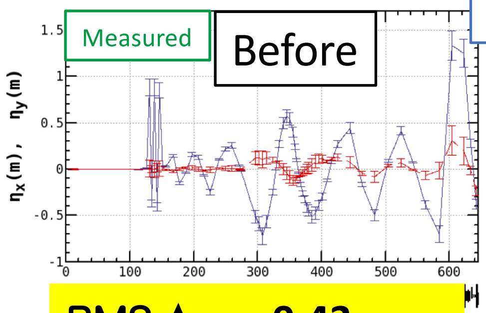
A) Residual Dispersion in LINAC

- Large residual dispersion had been observed at the J-ARC before dispersion correction.
- By tuning the strength of quadrupole magnets, residual dispersion became small.



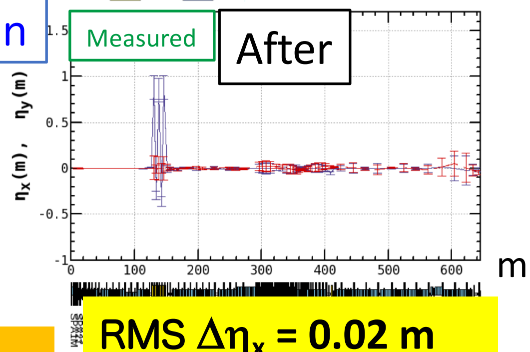
$$x = \eta \frac{\Delta p}{p} = \eta\delta$$





Thermionic gun

Dispersion correction



RMS $\Delta\eta_x$ = 0.43 m
$\gamma\beta\varepsilon_x$ = 187 ± 27 μm

$\Delta\gamma\beta\varepsilon_x$ = -47 μm

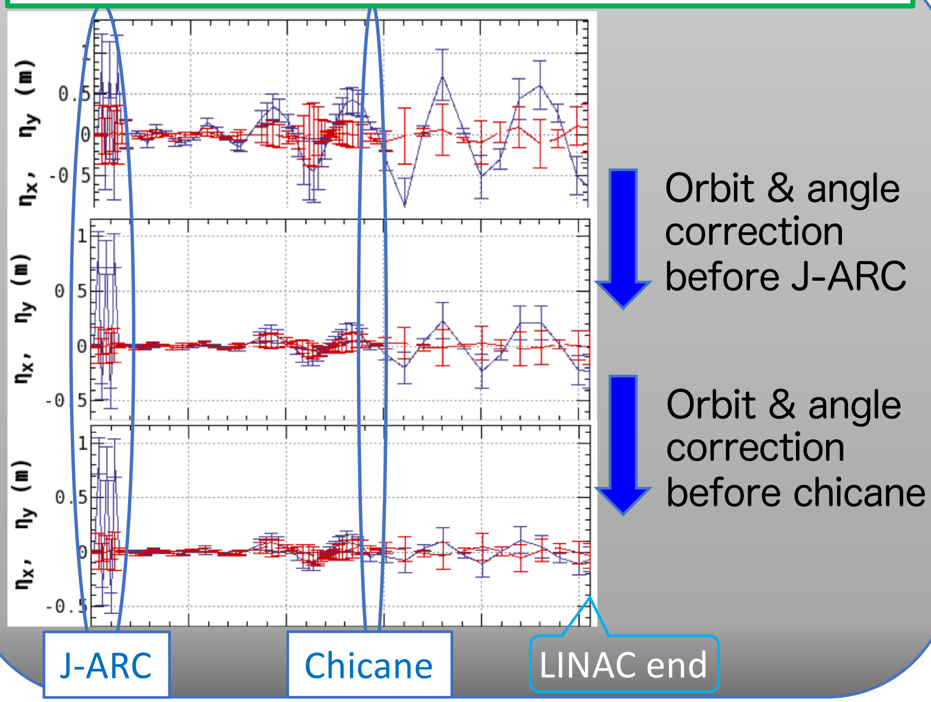
RMS $\Delta\eta_x$ = 0.02 m
$\gamma\beta\varepsilon_x$ = 140 ± 33 μm

A) Other sources of Residual Dispersion

- Both orbit and angle of a beam which pass through bending magnets.
- Orbit displacement at quadrupole magnets that have a large strength creates a sizable dispersion.
- Orbit of a beam which pass through sextupole magnets.

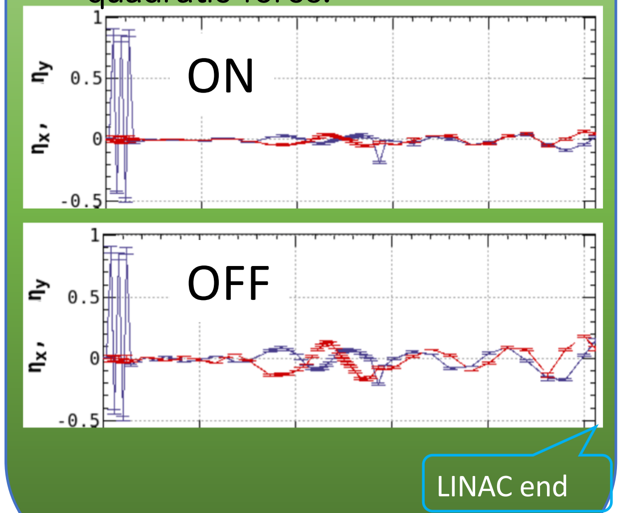
To keep residual dispersion minimized, orbit feedback is necessary.

Dependence between orbit+angle and dispersion



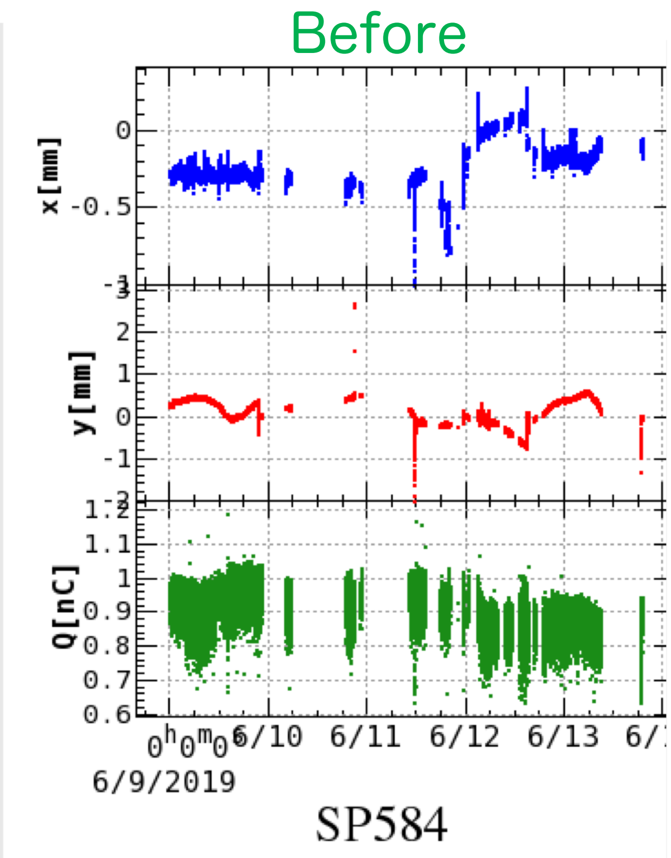
Effect of sextupole magnets

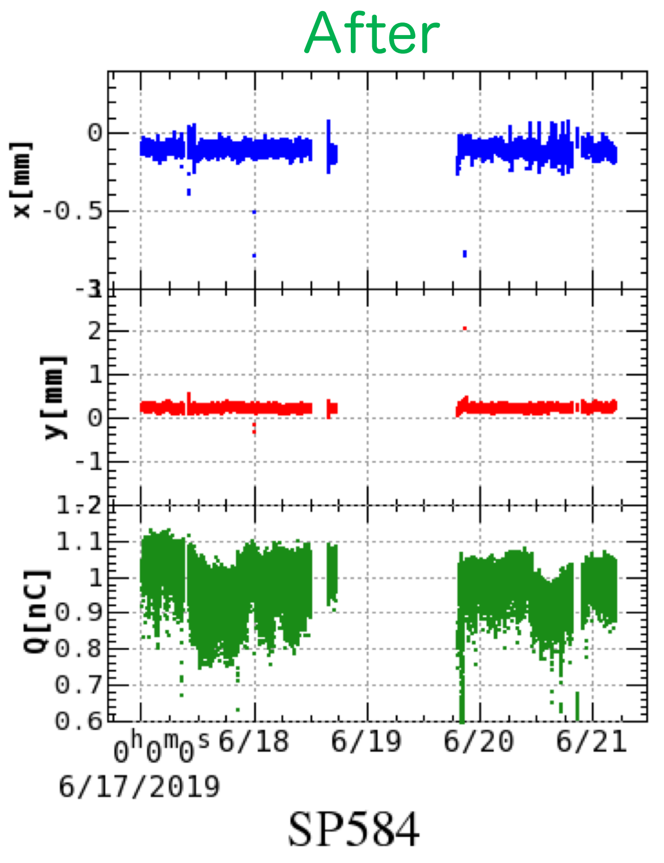
- There are 6 sextupole in J-ARC.
- Orbit displacement cause quadratic force.



A) Orbit Feedback

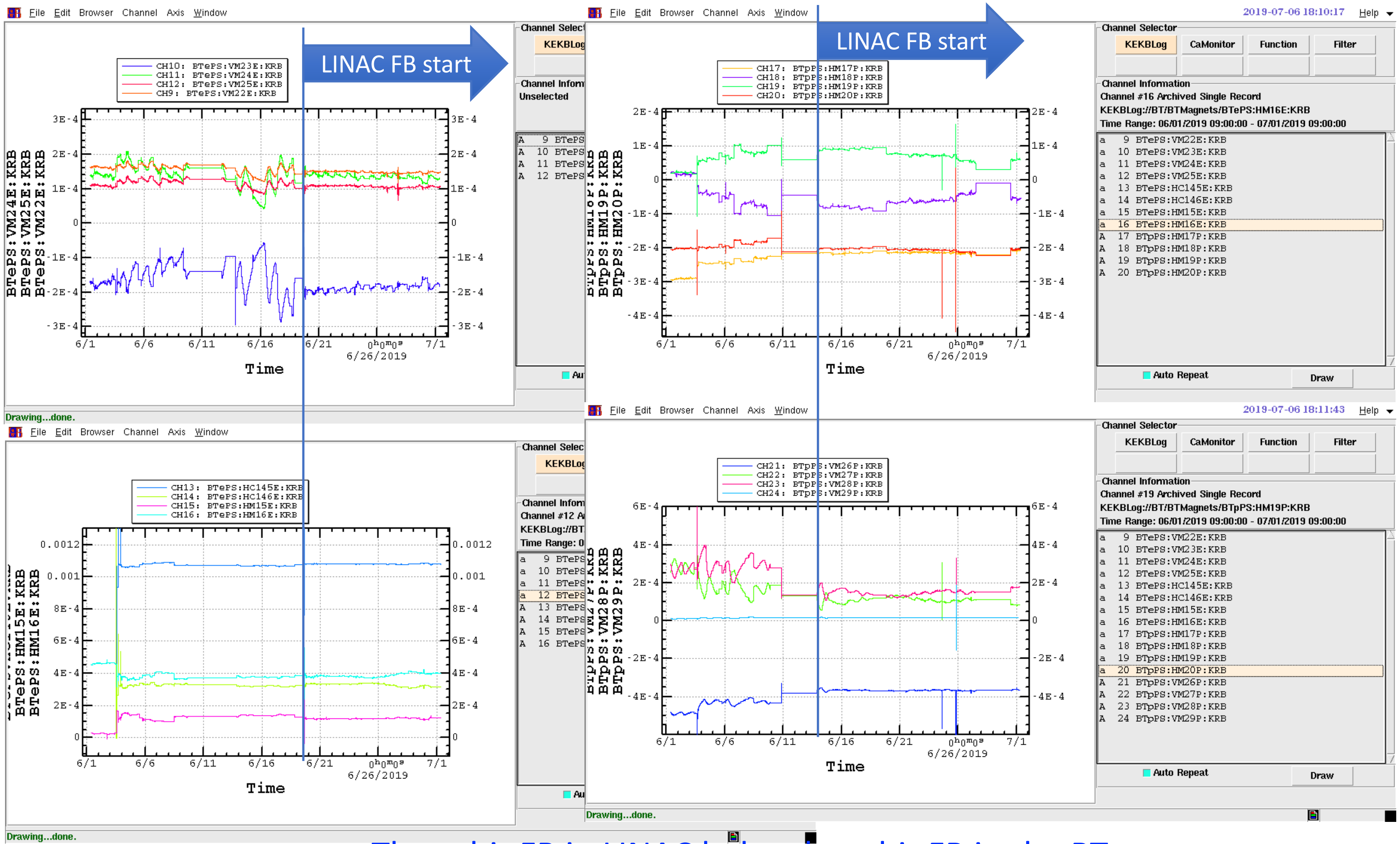
- An example of orbit FB (Shown BPM place in the LINAC end)
- Orbit FB at the end of LINAC was operated correctly.
- Orbit FB of J-ARC upstream will be performed next run.





A) Residual Dispersion

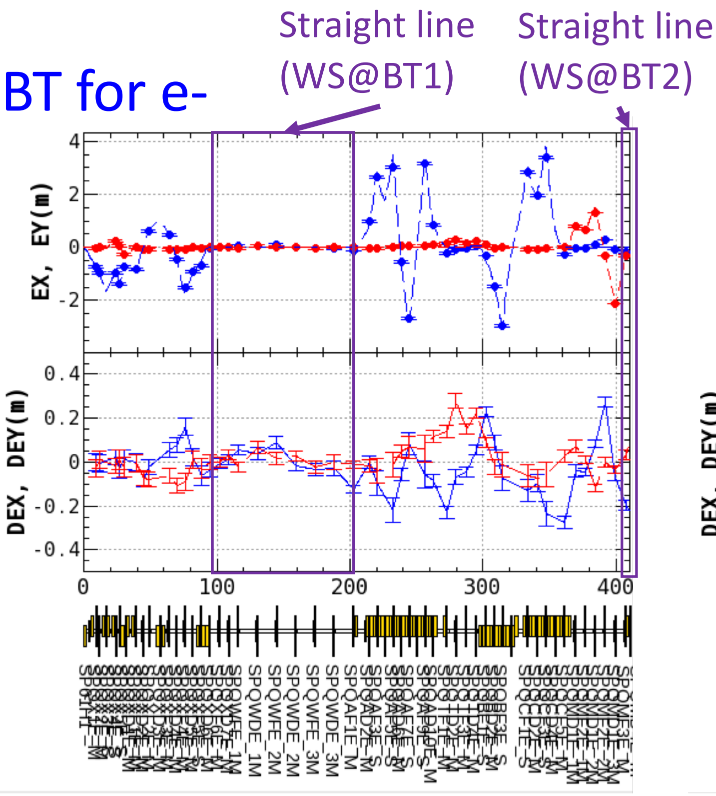
A) Magnet used in the orbit FB at the end of BT

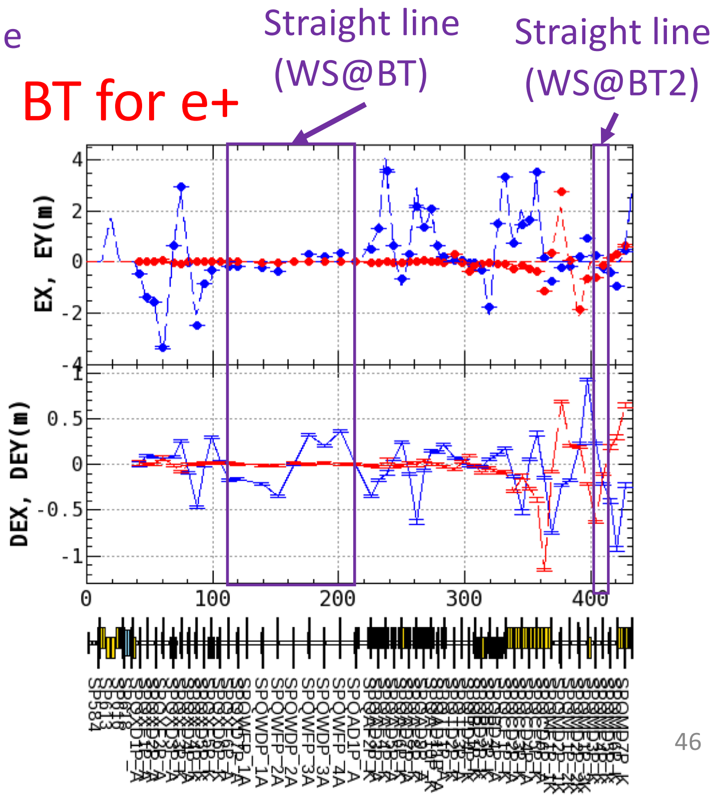


The orbit FB in LINAC helps thr orbit FB in the BT.

A) Residual Dispersion at BT line

- We had corrected dispersion of each BT ARC one by one.
- After that dispersion of the BT overall was measured changing the beam energy.
- Non-negligible residual dispersion was still observed.
- We will minimize Δη and Δη' at the end of BT in the autumn run.





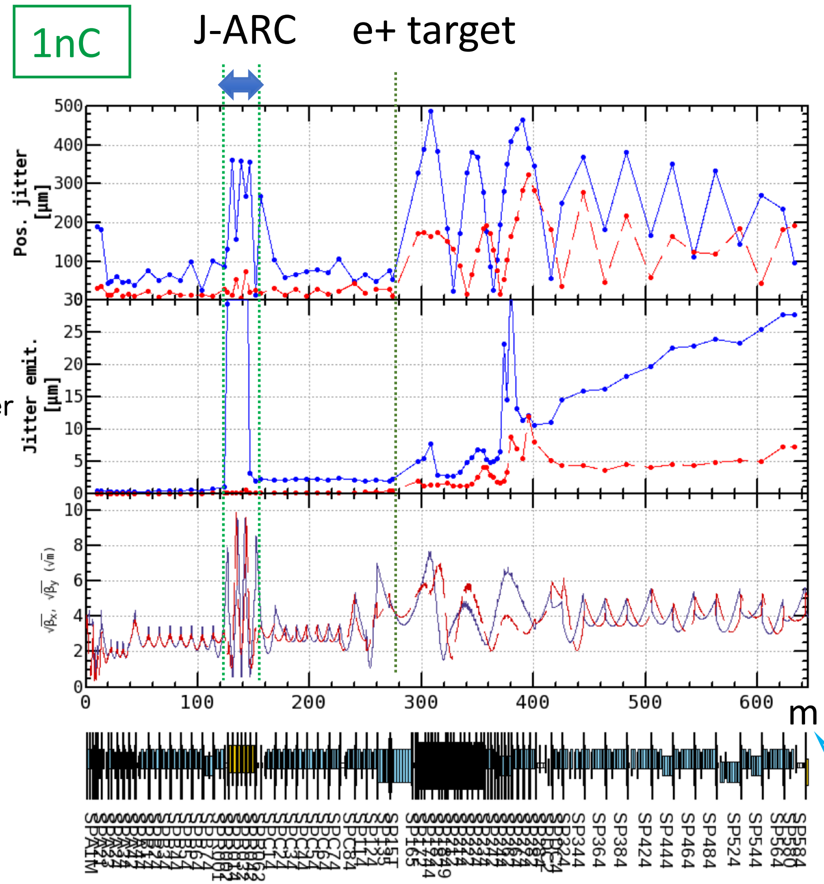
B) Beam Phase Space Jitter

- In 2018, large orbit jitter was measured (1000 shots).
- Emittance estimated from beam jitter, called jitter emittance, was not negligible.

Orbit jitter (RMS)

Emittance growth converted from beam jitter

Design beta function



	Phase 3 final
Bunch charge (nC)	4
Emit. @BT end (γβε) (μm)	40/20 (Hor./Ver.)

Linac end:
28/7 μm
(Hor./Ver.)

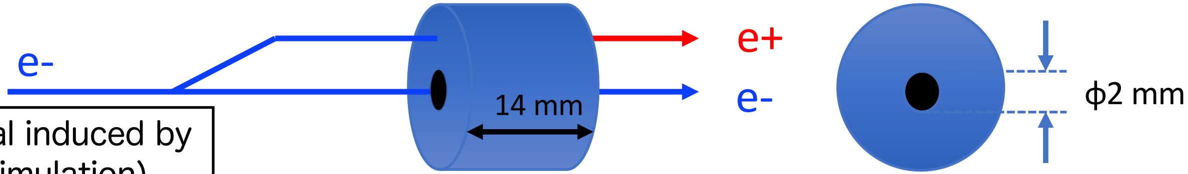
$$\epsilon_{eff} = \sqrt{\epsilon_0^2 + \epsilon_j^2 + 2\epsilon_0\epsilon_j B_{jmag}} \geq \epsilon_0 + \epsilon_j$$

B_{jmag} (≧1) express amount of mismatching between beam optics and the jitter optics.

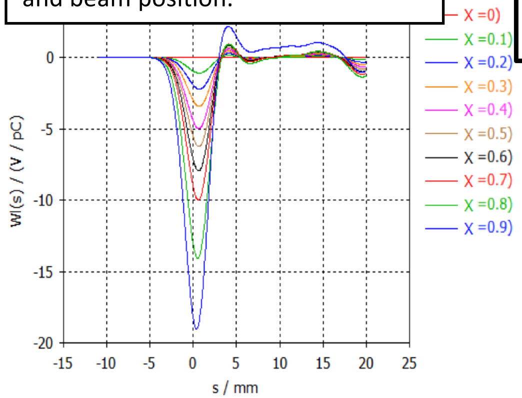
LINAC end

B) Wakefield effect and Beam Phase Space Jitter

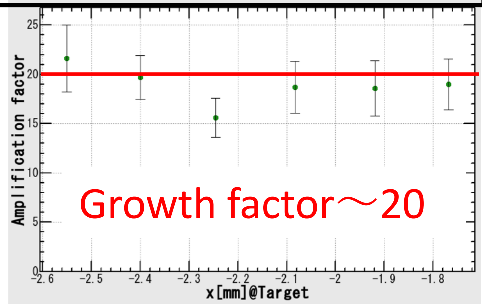
- Electron beam straightly pass through the positron generation target hole, whose diameter is 2 mm.
- We suspected wakefield effect as a orbit jitter source.



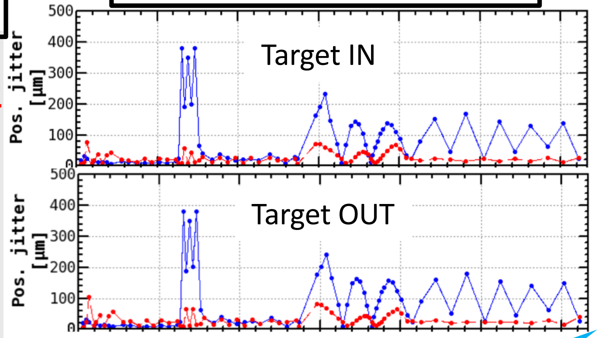
wake potential induced by target hole (simulation)
Color differences show differences of distance between center of hole and beam position.



From the beam position before and after target, amplification factor are derived.



Comparison of orbit jitter



LINAC end

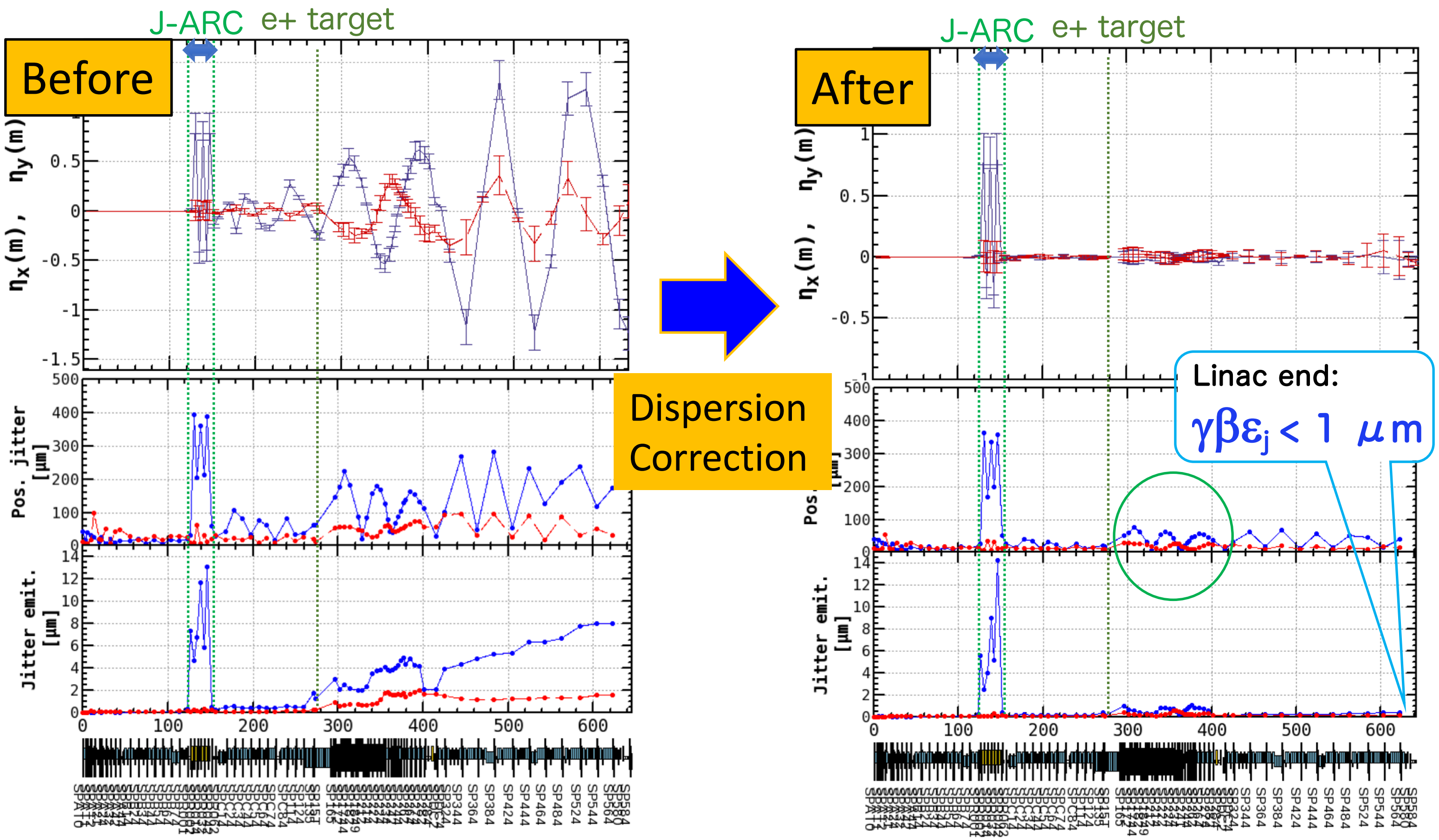
Growth factor of beam phase space jitter:

$$R_j = \frac{\beta \Delta y'}{\Delta y} = \frac{Q}{E_0} k_{\mathrm{T}} \beta_y$$ < 0.1@1nC << Measured growth factor

Wakefield effect of target hole is negligibly small.

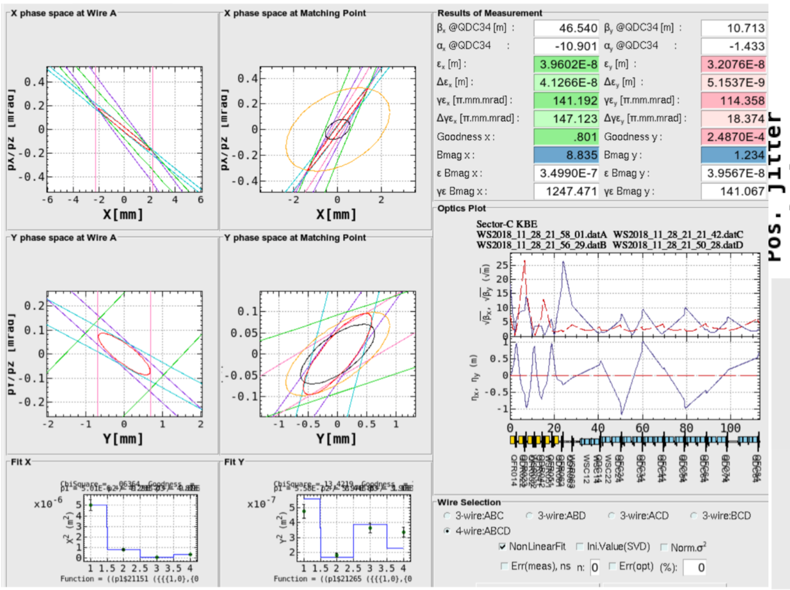
B) Dispersion and Beam Phase Space Jitter

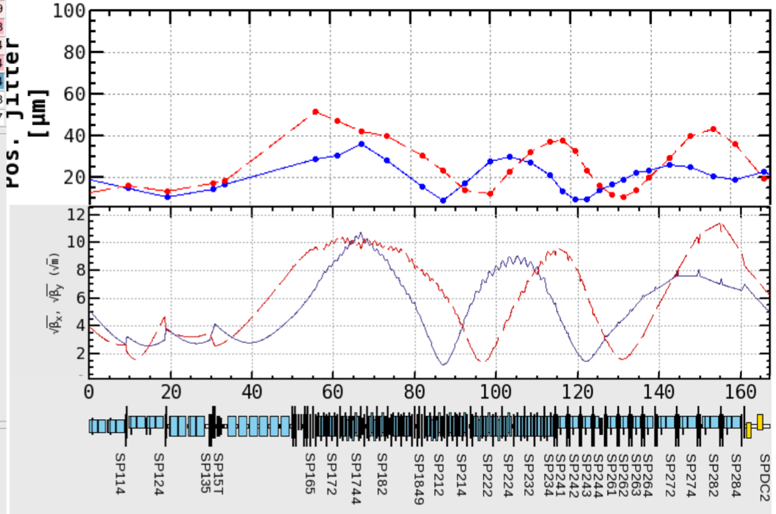
- We focus on dispersion which convert to orbit jitter through energy jitter.
- By dispersion correction, jitter emittance become less than 1 μm.



B) β Function and Orbit Jitter

- Remain orbit jitter can be explained by β function.
- Using Twiss parameters measured by WS at C sector, β function near target is derived.
- β function is highly correlated with orbit jitter.
- We conclude that large orbit jitter sources are mainly both residual dispersion and β function.

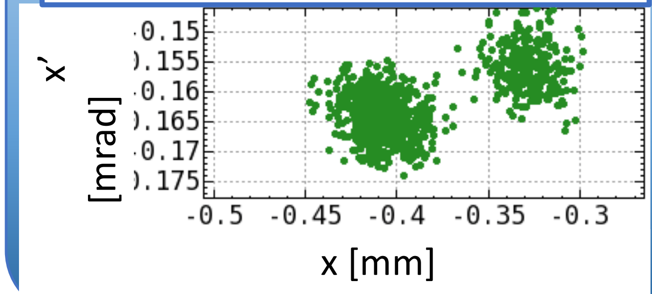




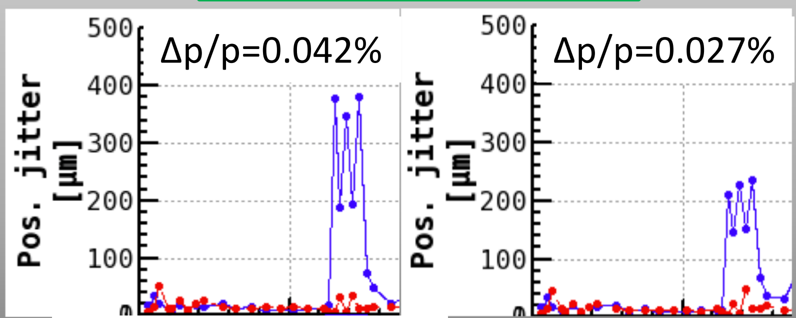
B) Other Sources of Beam Phase Space Jitter

- By further investigation, we found that following items were sometimes sources of jitter. Pulse magnet and RF phase jitter was almost resolved by person in charge.
- To identify the jitter source, monitoring beam jitter is important.

Binarization of Pulse Magnet



Slope of RF phase



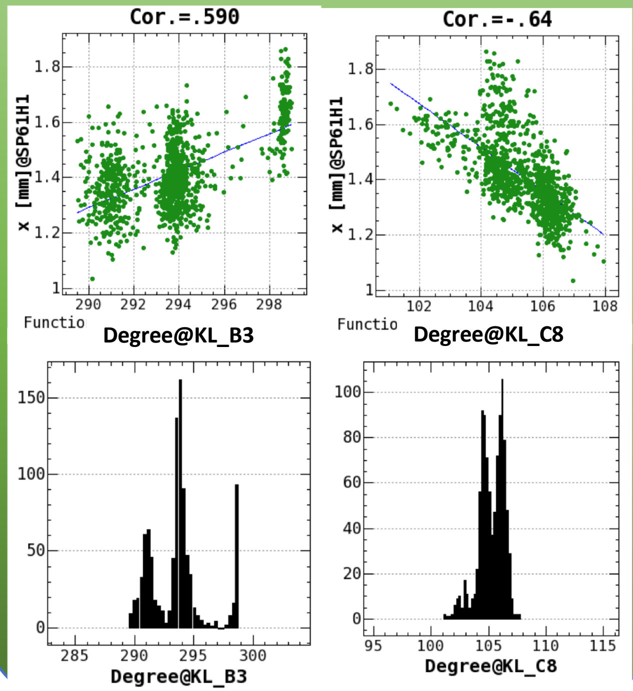
Near zero cross phase

Near crest phase

If RF phase is near zero cross, energy jitter is enlarged by the slope of phase.

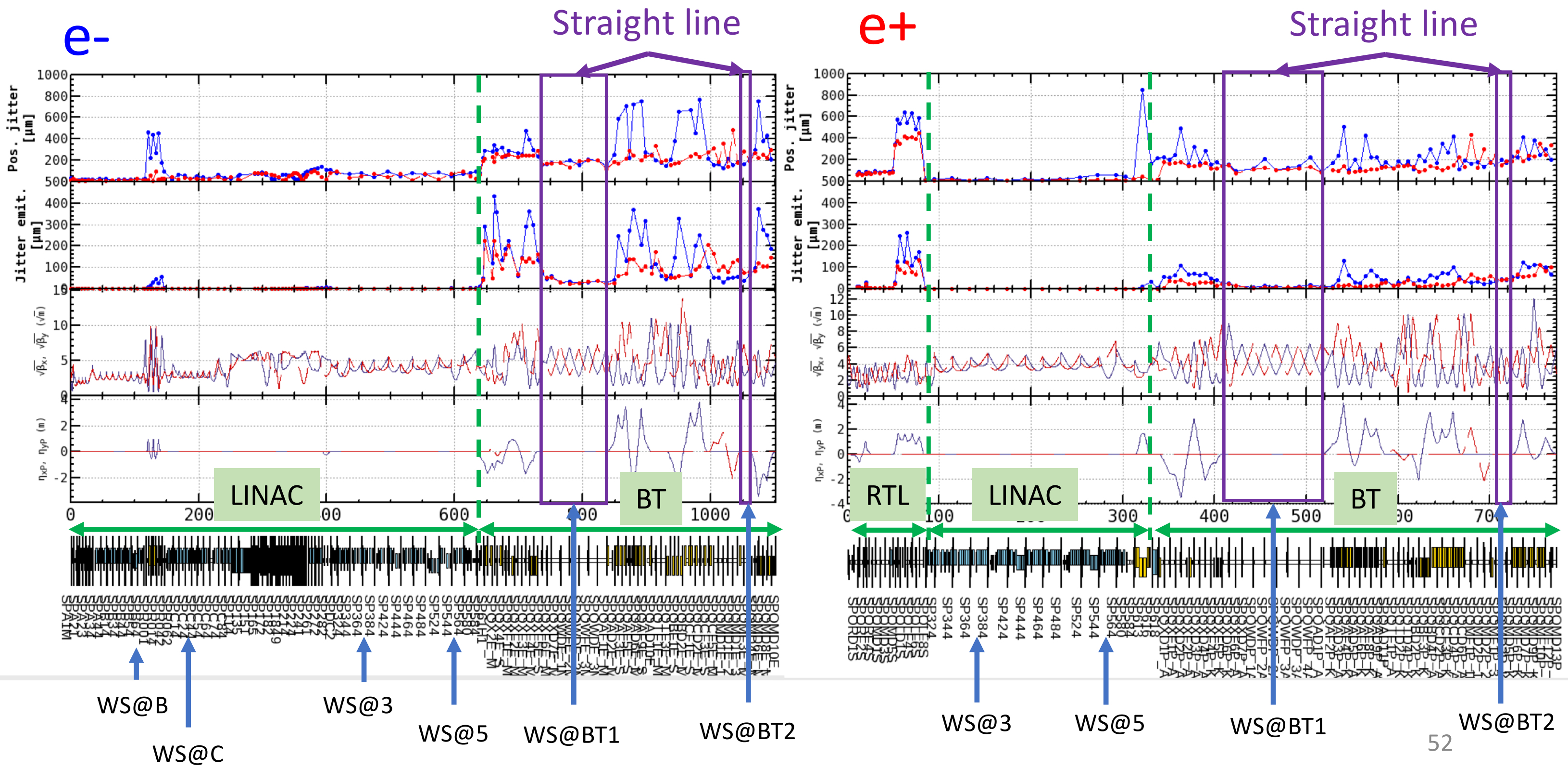
Three valued RF phase

Large RF phase jitter cause orbit jitter.



B) Beam Phase Space Jitter at BT line

- In the RTL and BT, orbit jitter is much larger than that in LINAC, partly because BPM resolution is poor.
- Orbit jitter of first straight line in BT is about ~150 μm@1σ. This value is probably BPM resolution.
- Assumed that calculated jitter emittance at the first straight line came from BPM resolution, jitter emittance at second straight line is estimated as following:
  - e- beam: $\gamma\beta\varepsilon_{jx}/\gamma\beta\varepsilon_{jy}$ @BT end ~ 40/50 μm
  - e+ beam: $\gamma\beta\varepsilon_{jx}/\gamma\beta\varepsilon_{jy}$ @BT end ~ 30/30 μm
- High resolution BPM is strongly desirable at BT. An upgrade of some BPMs for higher resolution is planned.

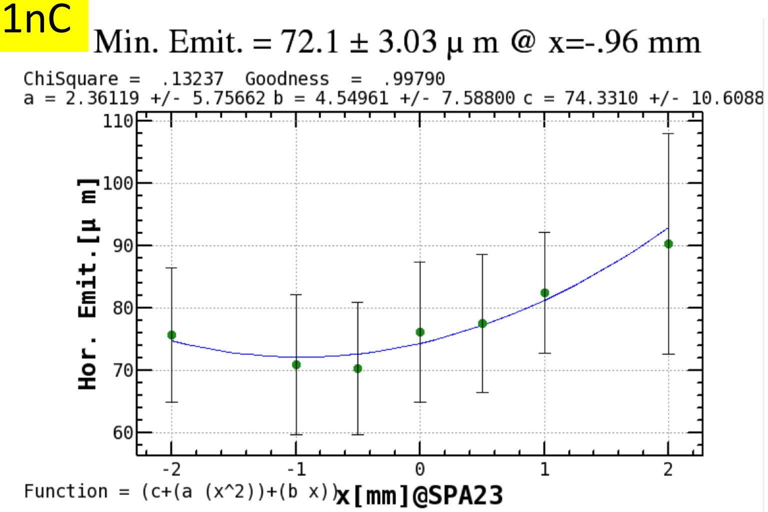


C) Wakefield in Acceleration Structure

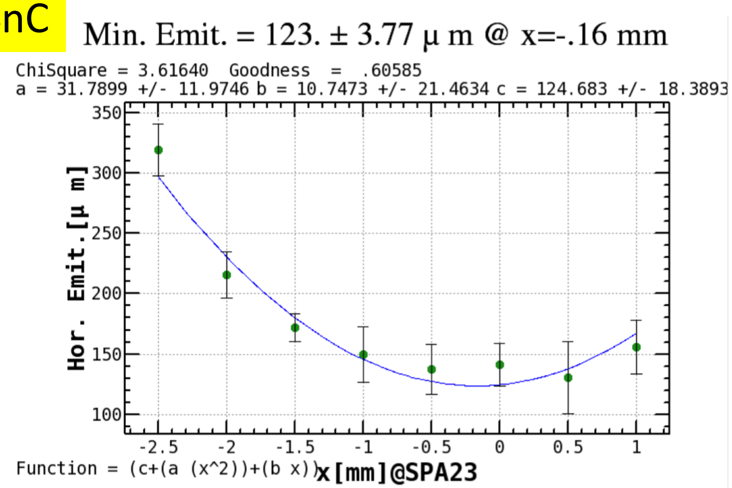
- Using a steering magnet, we searched an orbit so as to minimize emittance.
- Emittance highly depends on beam charge and orbit.
- Wake free steering will be performed using RF gun in the next run.

Thermionic gun

1nC



4nC



E) Emittance growth induced by radiation excitation in BT

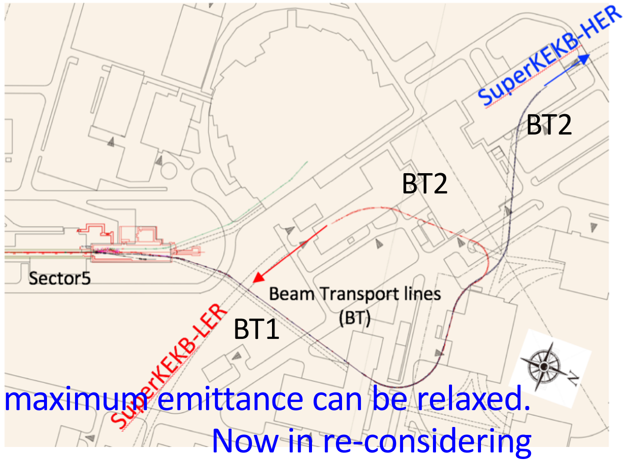
Theoretical emittance growth induced by radiation excitation:

$$\Delta\epsilon = \frac{55}{48\sqrt{3}}\frac{\hbar r_e}{mc}\gamma^5\int\frac{H}{\rho^3}ds \quad \propto \gamma^5, 1/\rho^3$$

Particle tracking simulation was performed from the end of LINAC to the end of BT.

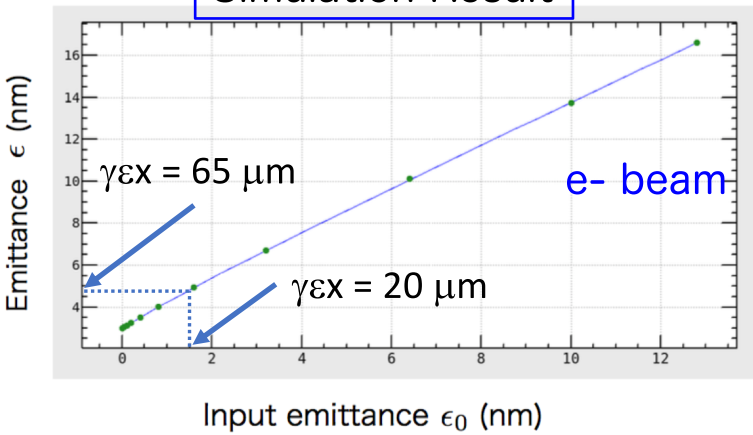
Simulation	Initial particles	With Radiation	Phase-III final requirement
e- (7 GeV) $\gamma\beta\varepsilon_x$ [μm]	20	65	40
e+ (4 GeV) $\gamma\beta\varepsilon_x$ [μm]	64	74	100

-> The maximum emittance can be relaxed. Now in re-considering



M. Kikuchi

Simulation Result



- Radiation excitation has little dependence on initial emittance.
- By the radiation excitation, emittance growth of e-/e+ beam is about 48/10 μm.
- The beam size at the injection septum is 0.31 mm, assuming βx = 20 m. The required injection aperture is still dominated by the septum width of 2.5 mm. Although the emittance growth due to synchrotron radiation is very big, it plays only a minor role on the injection aperture itself.