Emittance Preservation

SuperKEKB review
July 9th, 2019
Y. Seimiya
for Emittance Preservation Task Force Group

Iida gives this presentation instead of Seimiya-san who has sudden illness.

SuperKEKB Review in 2018

R8.1: Perform several further analyses to identify the sources of beam jitter as detailed in the following recommendations.

- R8.2: The analysis should include the calculation and study of the Bmag term, which characterizes mismatch in the optics functions. Expand the formulae to include this term.
- R8.3: Calculate the normalized position jitter amplitude to remove the effect of t he beam optics.
- R8.4: Compare the normalized jitter amplitude and its evolution to the beam loss locations and an aperture model.
- R8.5: Determine the frequency contents of the beam position jitter. In case that dominant frequencies in the position jitter are found correlate them to possible technical sources.
- R8.6: Perform a quantitative analysis of energy jitter, dispersion and observed be am position jitter to see what part of the position jitter can be explained by energy jitter and what fraction remains unexplained.
- R8.7: Perform a careful and rigorous study on the timing jitter of the RF trigger and the gun trigger, which might explain the observed energy jitter.
- R8.8: In case that further wakefield studies are performed, investigate the position-dependent direct wakefield kick in linear order, which should be measurable for strong wakefields, as they are required for creating beam position jitter.

We partly answer about green items in my slide. Purple items have not been preformed yet. We will investigate purple items as soon as possible.

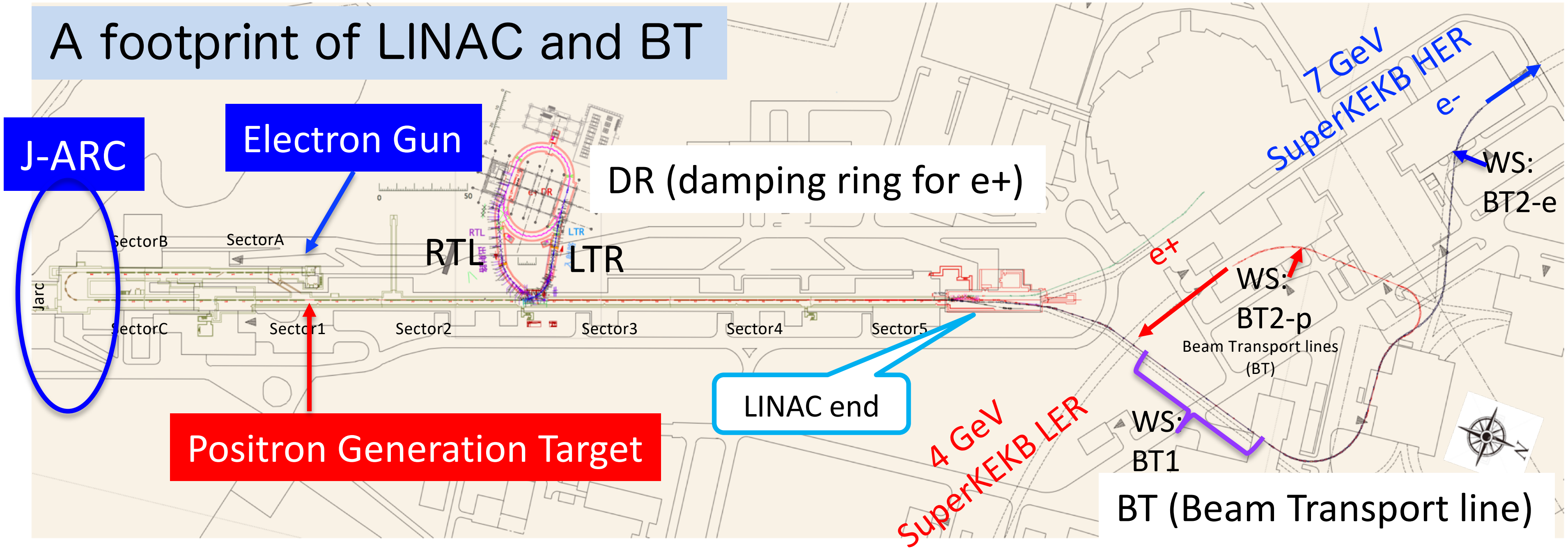
Outline

1. Requirement for SuperKEKB
2. Sources of Emittance Growth
   A) Residual Dispersion
   B) Beam Phase Space Jitter
   C) Wakefield in Acceleration Structure
   D) Acceleration of Beam with Dispersion
   E) Radiation Excitation
3. Results of Emittance Measurement
4. Summary

1. Requirement for SuperKEKB

- For the e-/e+, initial emittance is at RF gun/extraction line of DR.
- We have to realize the high quality beam transportation to main ring without emittance growth as far as possible.
- Otherwise, injection rate is worse and luminosity can not reach the target value.

	Phase 3 (Mar. 2019 –) final	
Beam	e+	e–
Bunch charge (nC)	4	4
Initial Emit. (γβε) (μm)	DR: 64/0.8 (Hor./Ver.)	RF gun: 10/10 (Hor./Ver.)
Emit. @BT end (γβε) (μm)	100/15 (Hor./Ver.)	40/20 (Hor./Ver.)
Energy spread	0.16%	0.07%



2. Sources of Emittance Growth

Candidates of emittance growth in LINAC or BT.

A) Residual Dispersion
  - Through the residual dispersion, the energy spread converts to the beam size.

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

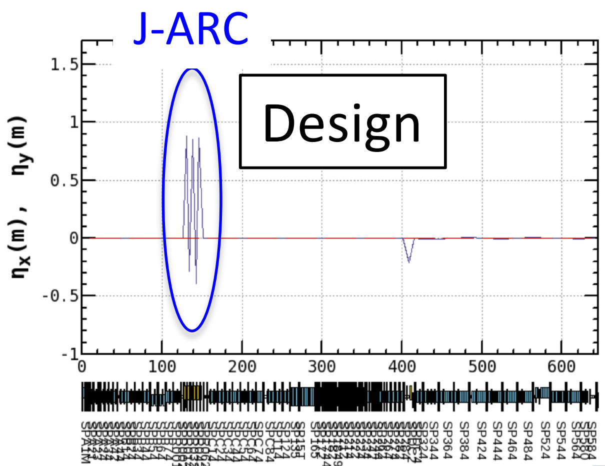
C) Wakefield in Acceleration Structure
  - Wakefield, generated by a head of bunch, kicks its own tail.
  - Thus if the beam is off-centered in the structure, the transverse wakefield increases beam emittance.

D) Acceleration of Beam with Dispersion
  - If a beam, which has dispersion, is accelerated by acceleration cavity with off-phase, the energy deviation converts to betatron oscillations and causes emittance growth.

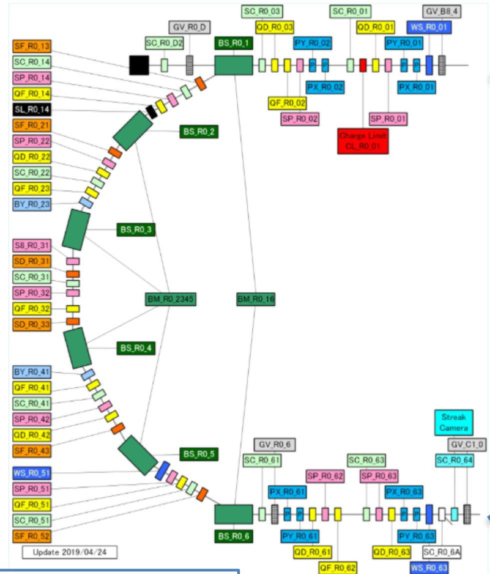
E) Radiation Excitation
  - Radiation excitation effect on emittance is proportional to both Lorenz gamma to the fifth power and inverse of curvature radius to the third power.
  - Especially, electron beam (7 GeV) is strongly affected by the radiation excitation effect.

A) Residual Dispersion in LINAC

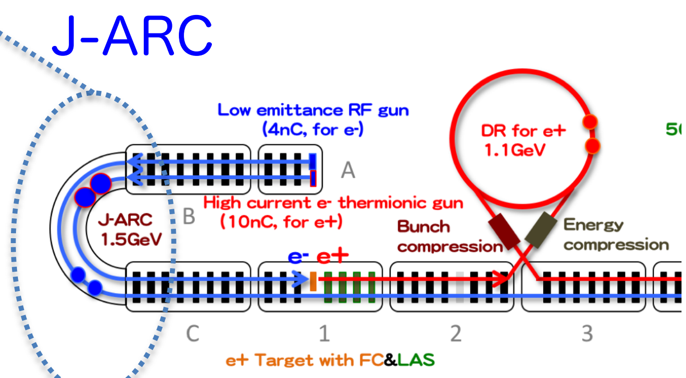
- Large residual dispersion had been observed at the J-ARC before dispersion correction.
- By tuning the strength of quadrupole magnets, residual dispersion became small.

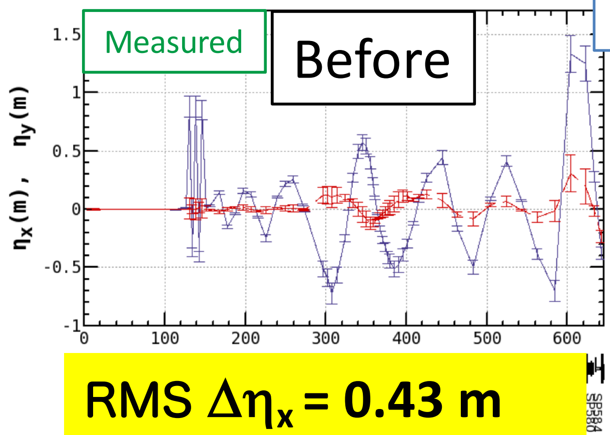


$$x = \eta \frac{\Delta p}{p} = \eta\delta$$



J-ARC





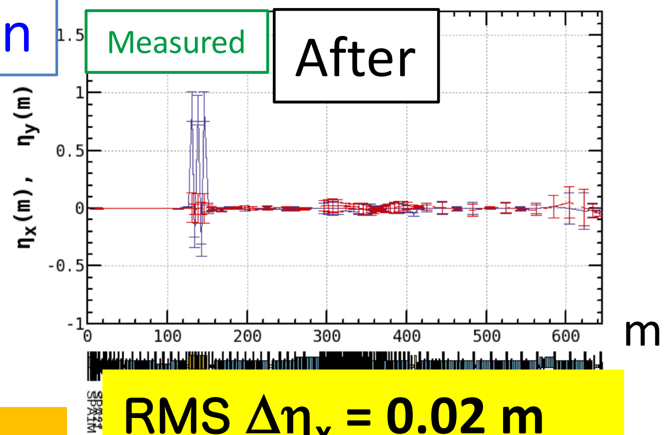
RMS $\Delta\eta_x$ = 0.43 m

$\gamma\beta\varepsilon_x$ = 187 ± 27 μm

Thermionic gun

Dispersion correction

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



RMS $\Delta\eta_x$ = 0.02 m

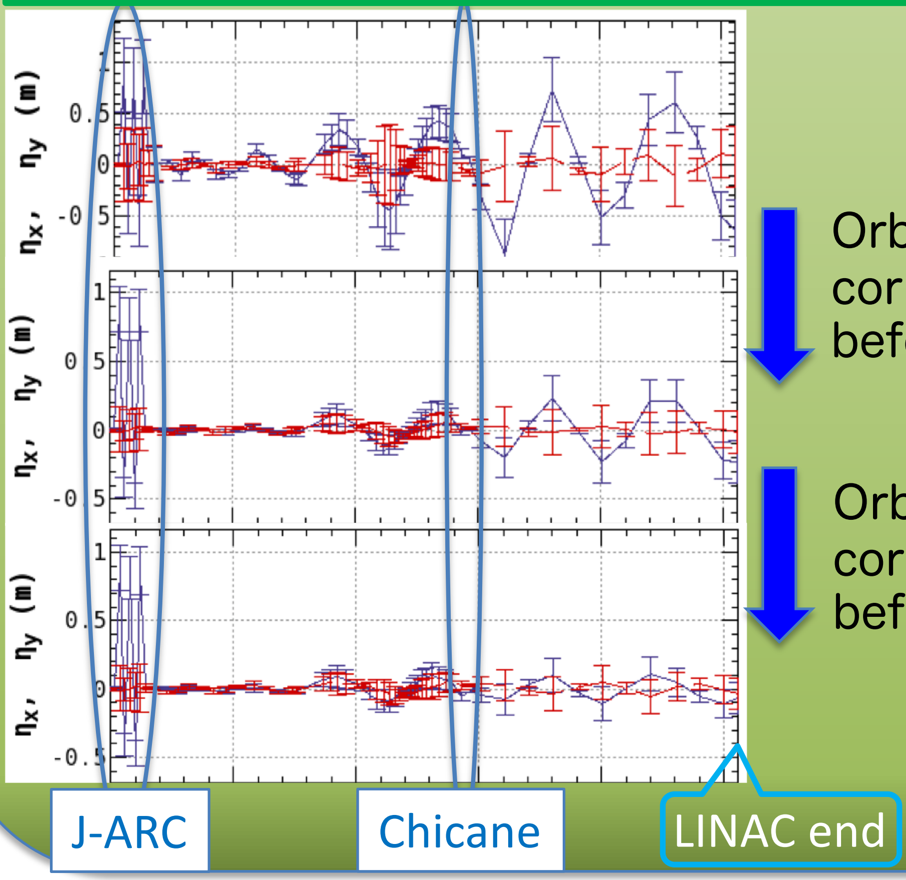
$\gamma\beta\varepsilon_x$ = 140 ± 33 μm

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

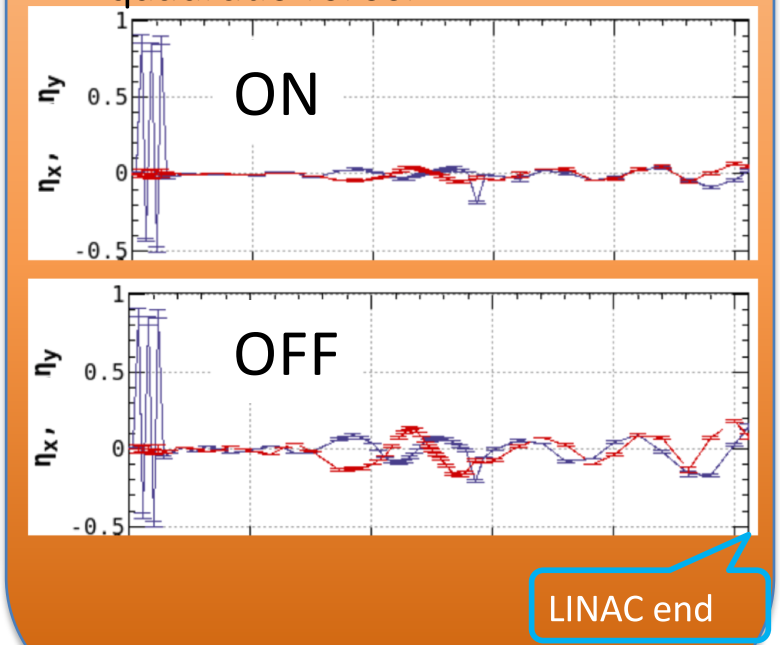


Orbit & angle correction before J-ARC

Orbit & angle correction before chicane

Effect of sextupole magnets

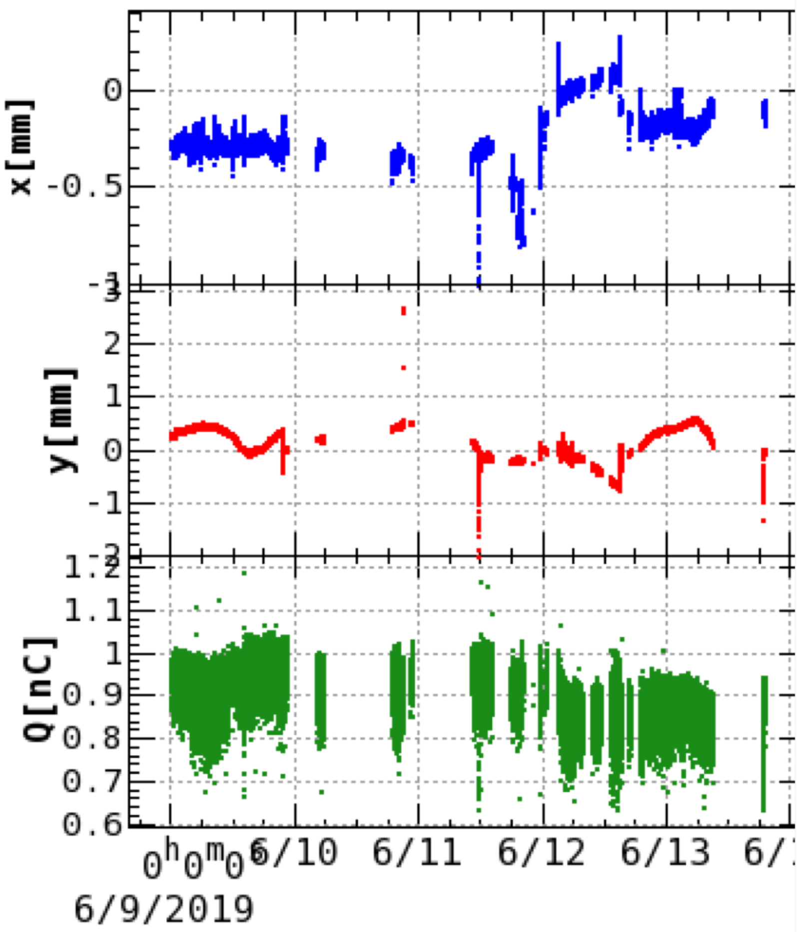
- There are 6 sextupole in J-ARC.
- Orbit displacement cause quadratic force.



A) Orbit Feedback

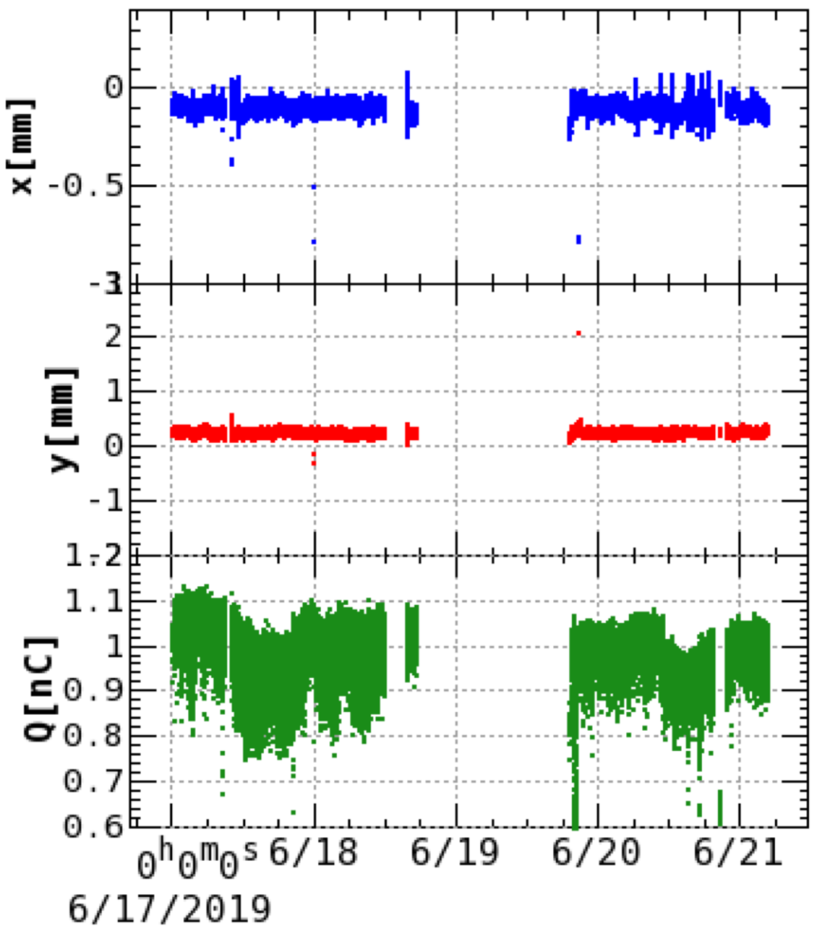
- An example of orbit FB (Shown BPM place in the LINAC end)
- Orbit FB at the end of LINAC was operated correctly.
- Orbit FB of J-ARC upstream will be performed next run.

Before



SP584

After



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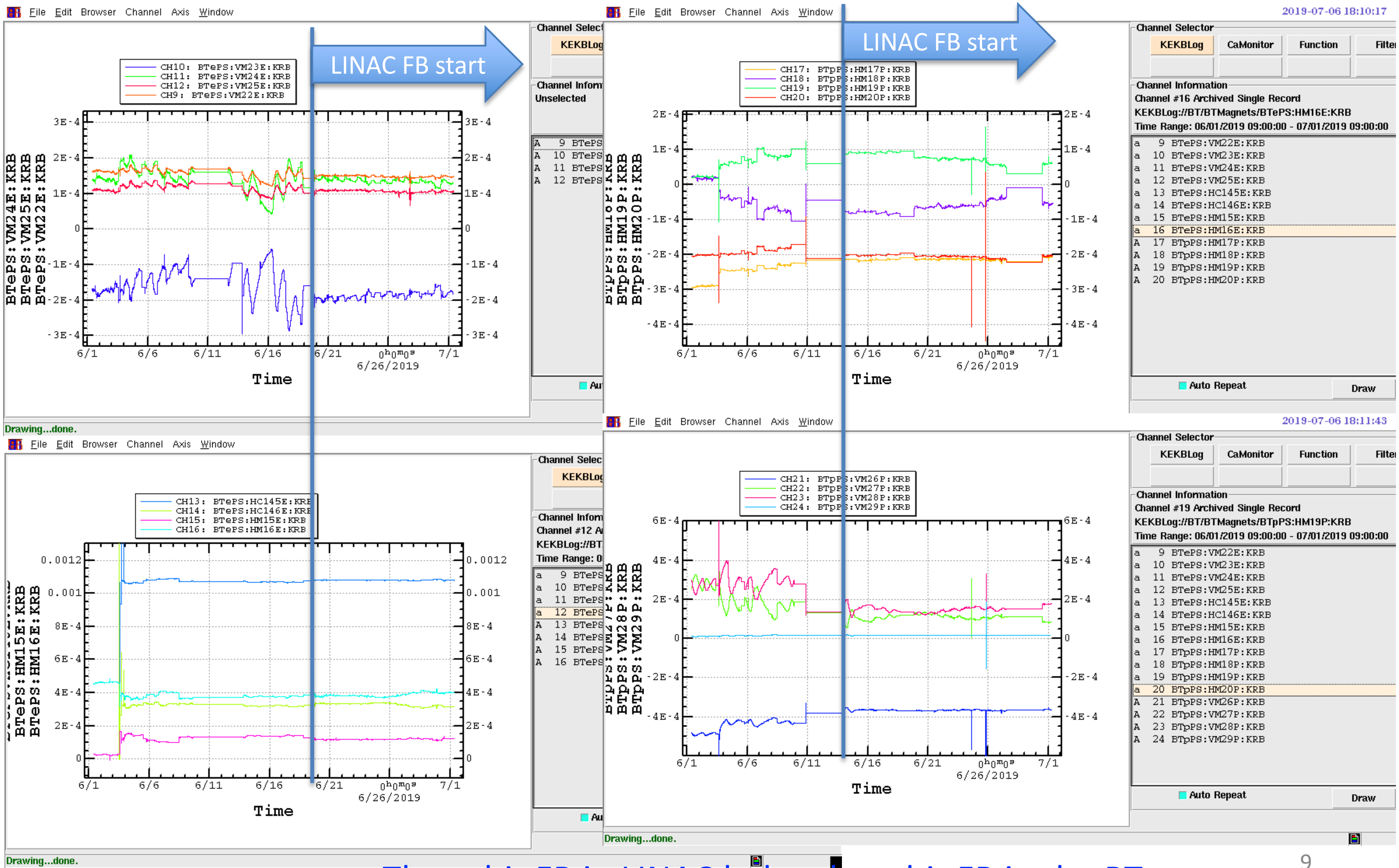
A) Residual Dispersion

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.

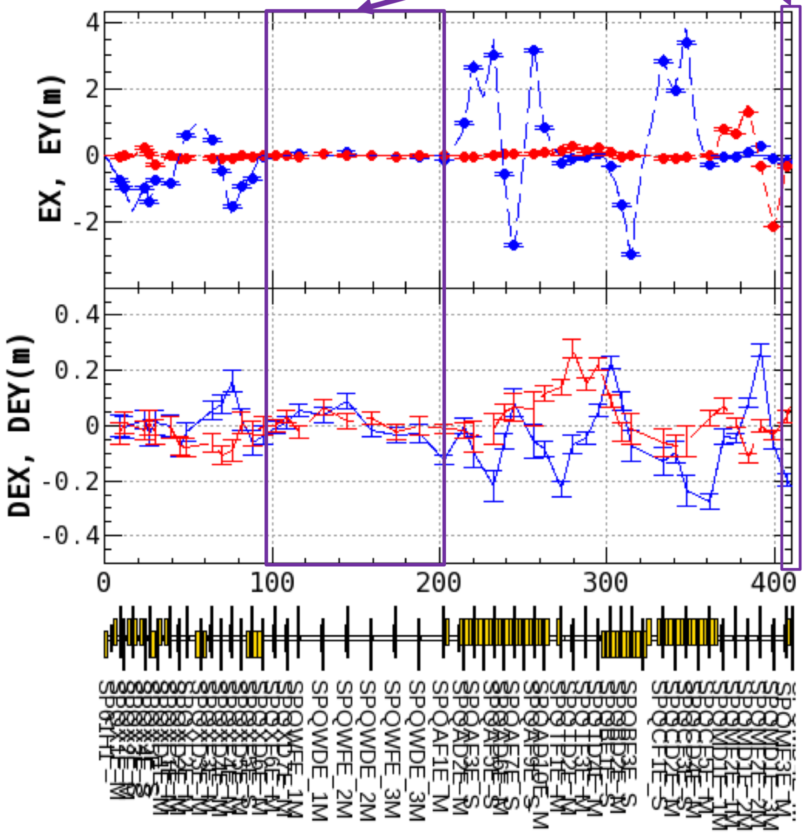
Straight line (WS@BT1)

Straight line (WS@BT2)

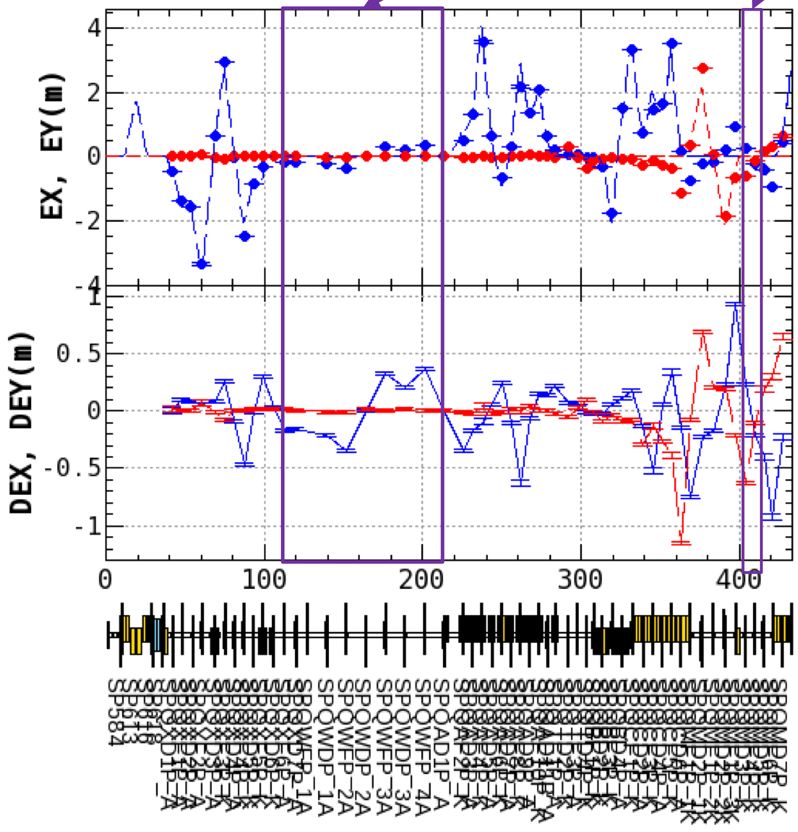
Straight line (WS@BT)

Straight line (WS@BT2)

BT for e-



BT for e+



2. Sources of Emittance Growth

Candidates of emittance growth in LINAC or BT.

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

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   - If a beam, which has dispersion, is accelerated by acceleration cavity with off-phase, the energy deviation converts to betatron oscillations and causes emittance growth.

E) 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.

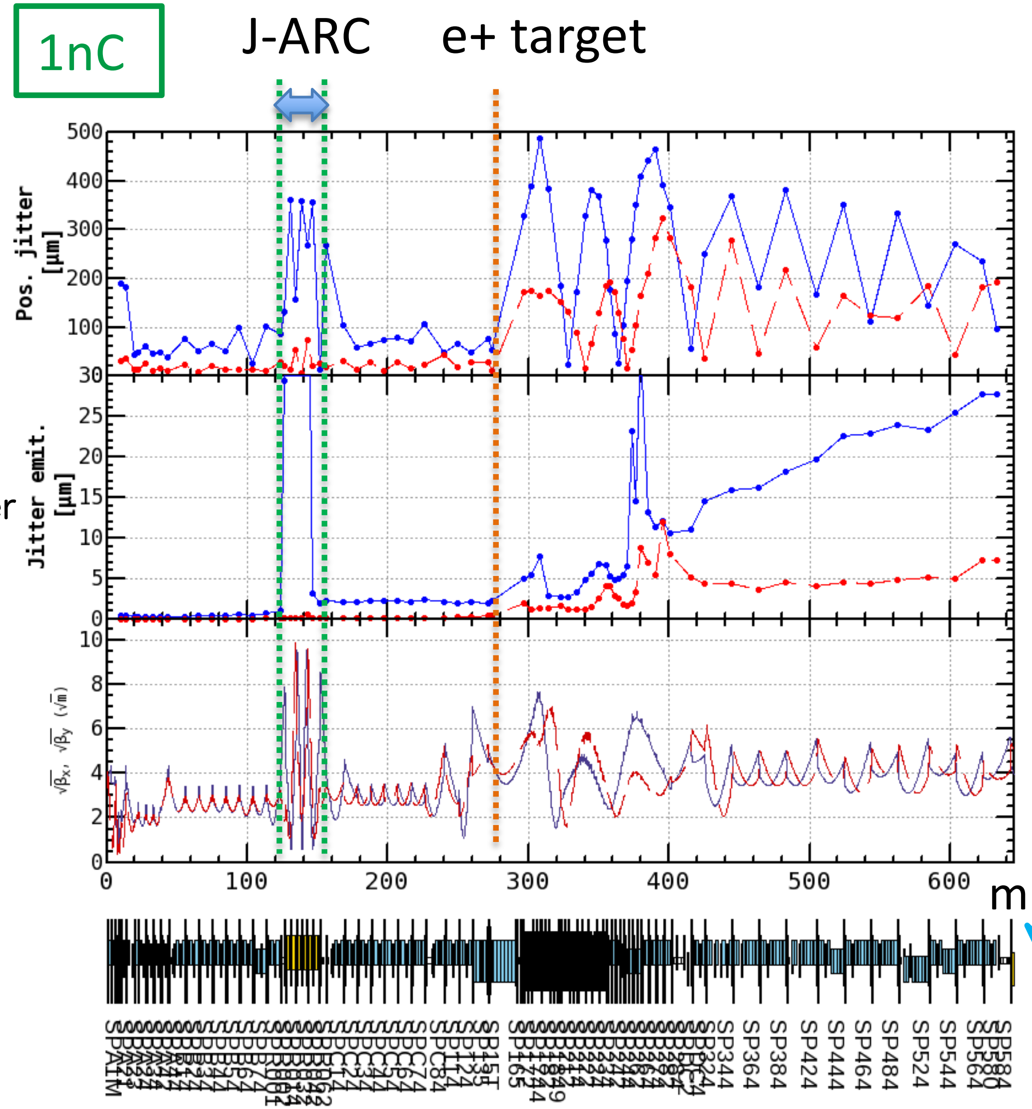
B) Beam Phase Space Jitter

- 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.)

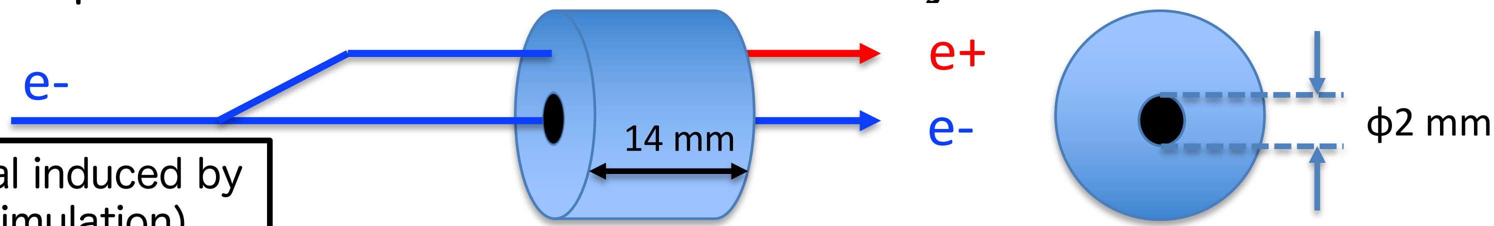
Linac end:
28/7 μm
(Hor./Ver.)

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

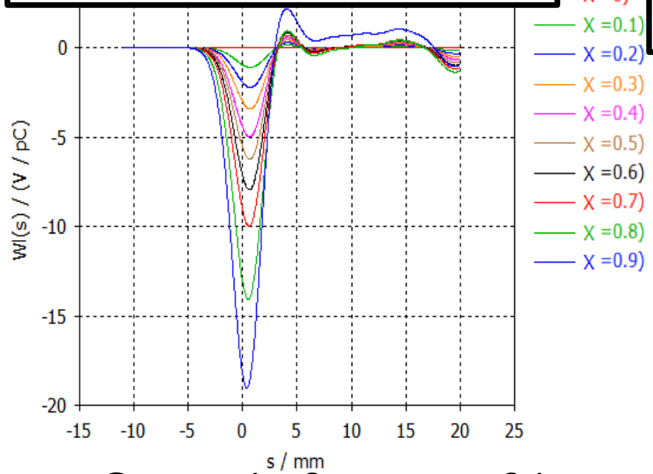
B_{jmag} (≧1) express amount of mismatching between beam optics and the jitter optics.

B) Wakefield effect and Beam Phase Space Jitter

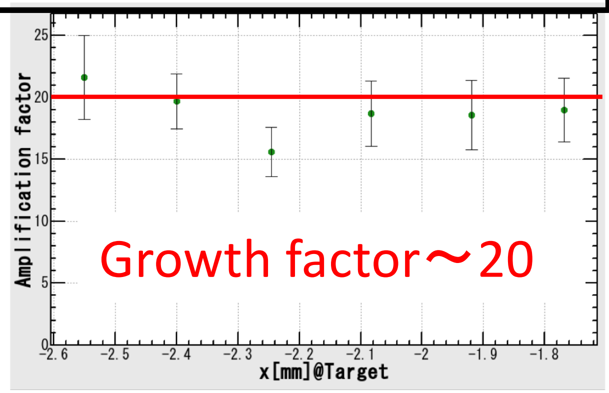
- Electron beam straightly pass through the positron generation target hole, whose diameter is 2 mm.
- We suspected wakefield effect as a orbit jitter source.



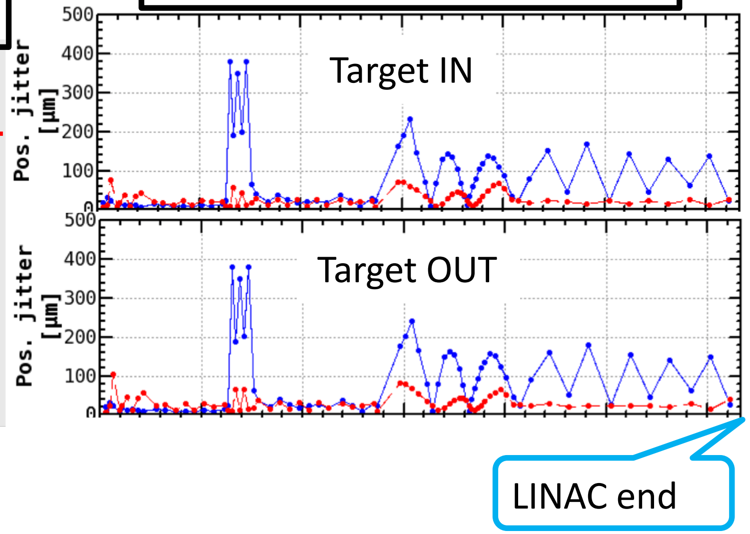
wake potential induced by target hole (simulation)
Color differences show differences of distance between center of hole and beam position.



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



Comparison of orbit jitter



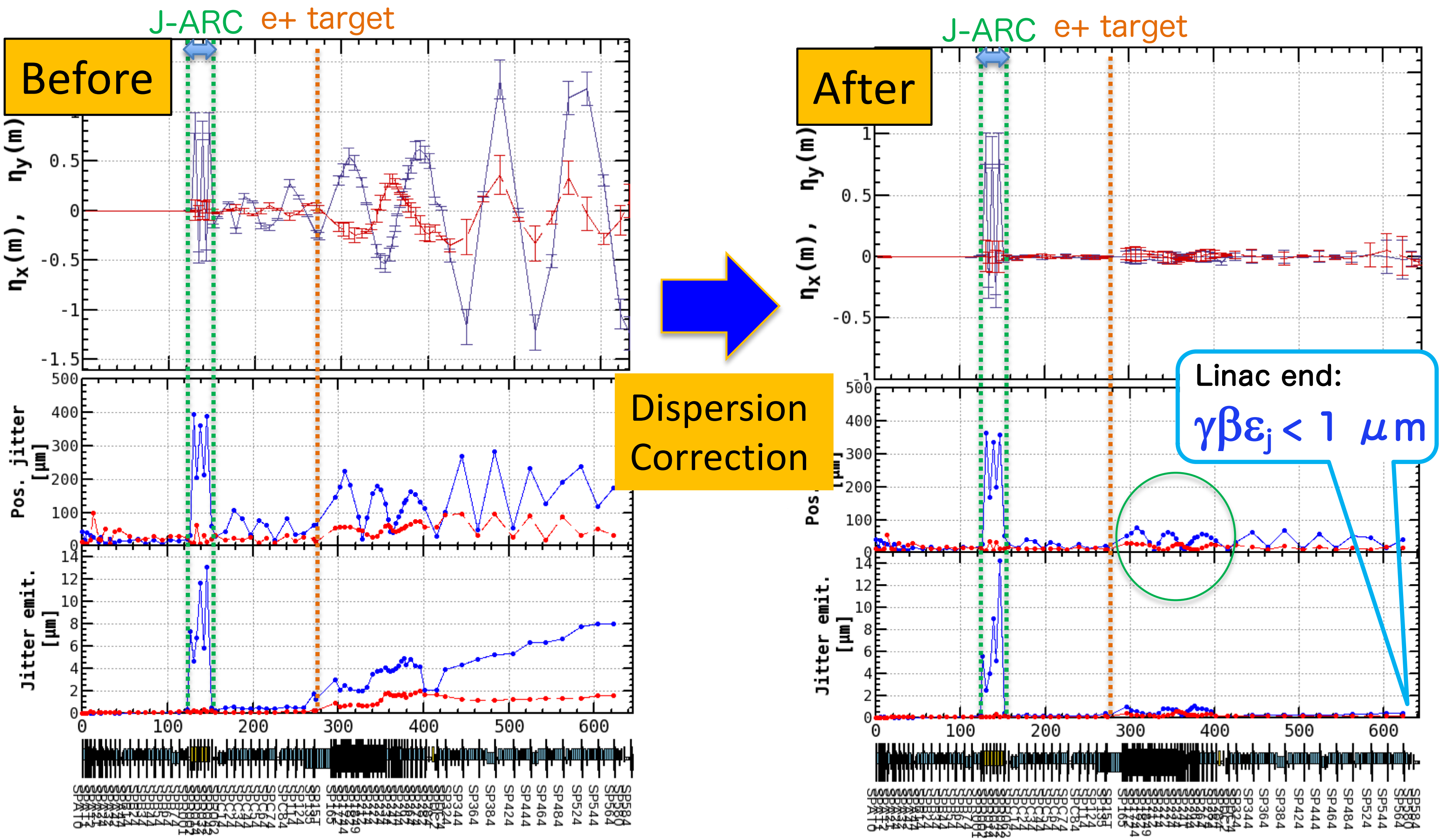
Growth factor of beam phase space jitter:

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

Wakefield effect of target hole is negligibly small.

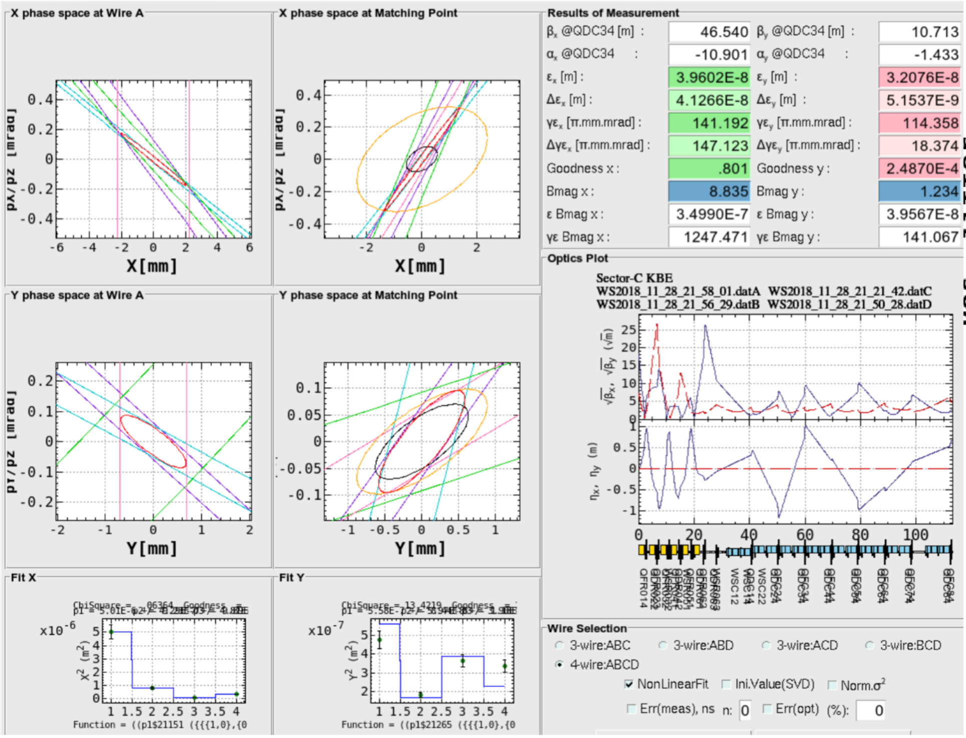
B) Dispersion and Beam Phase Space Jitter

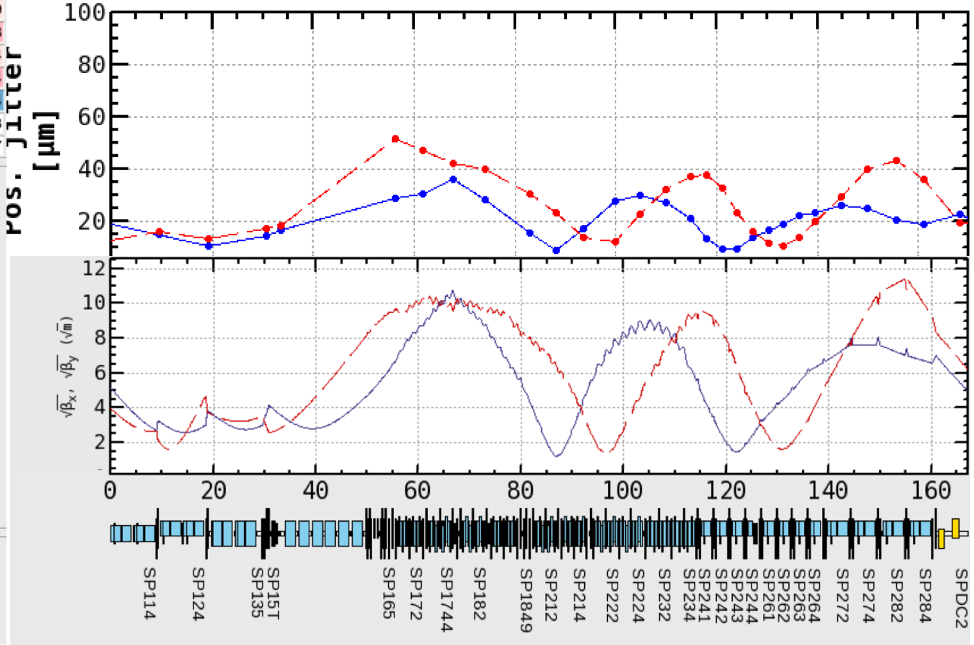
- We focus on dispersion which convert to orbit jitter through energy jitter.
- By dispersion correction, jitter emittance become less than 1 μm.



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.

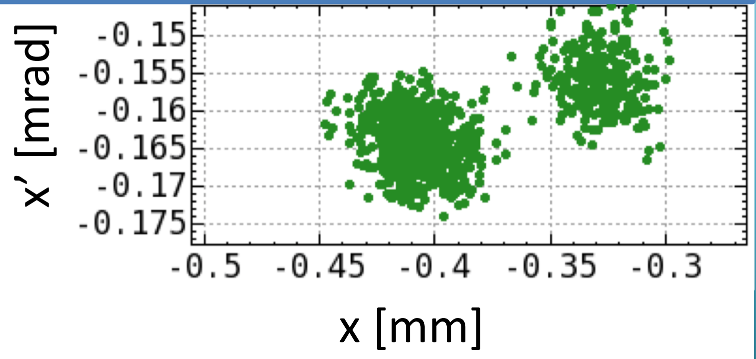




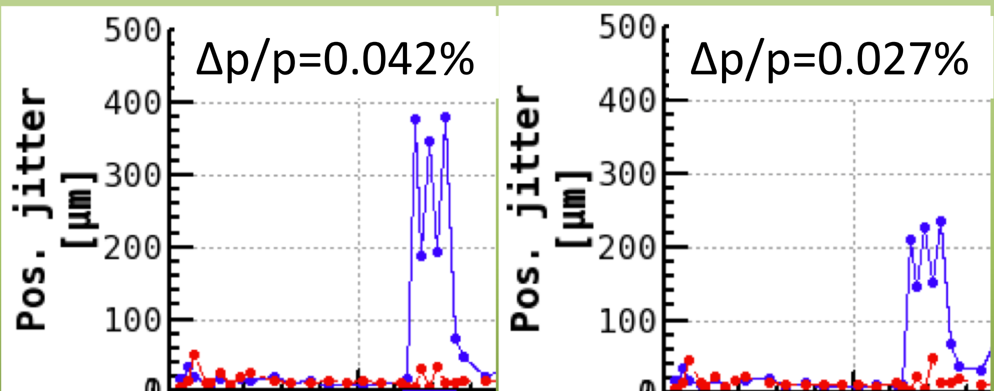
B) Other Sources of Beam Phase Space Jitter

- 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



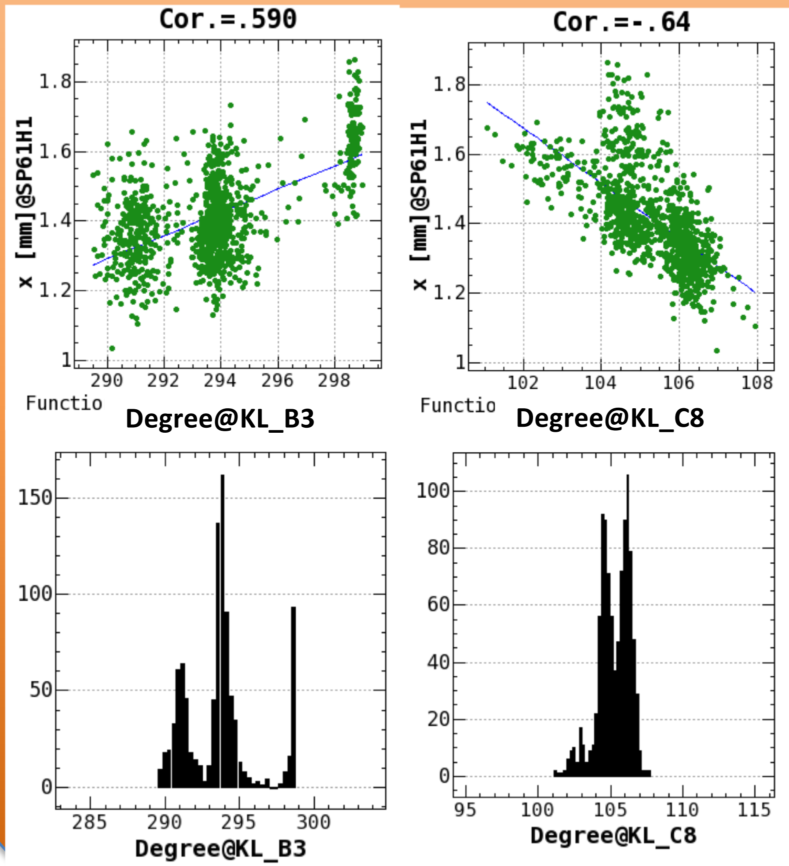
Near zero cross phase

Near crest phase

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

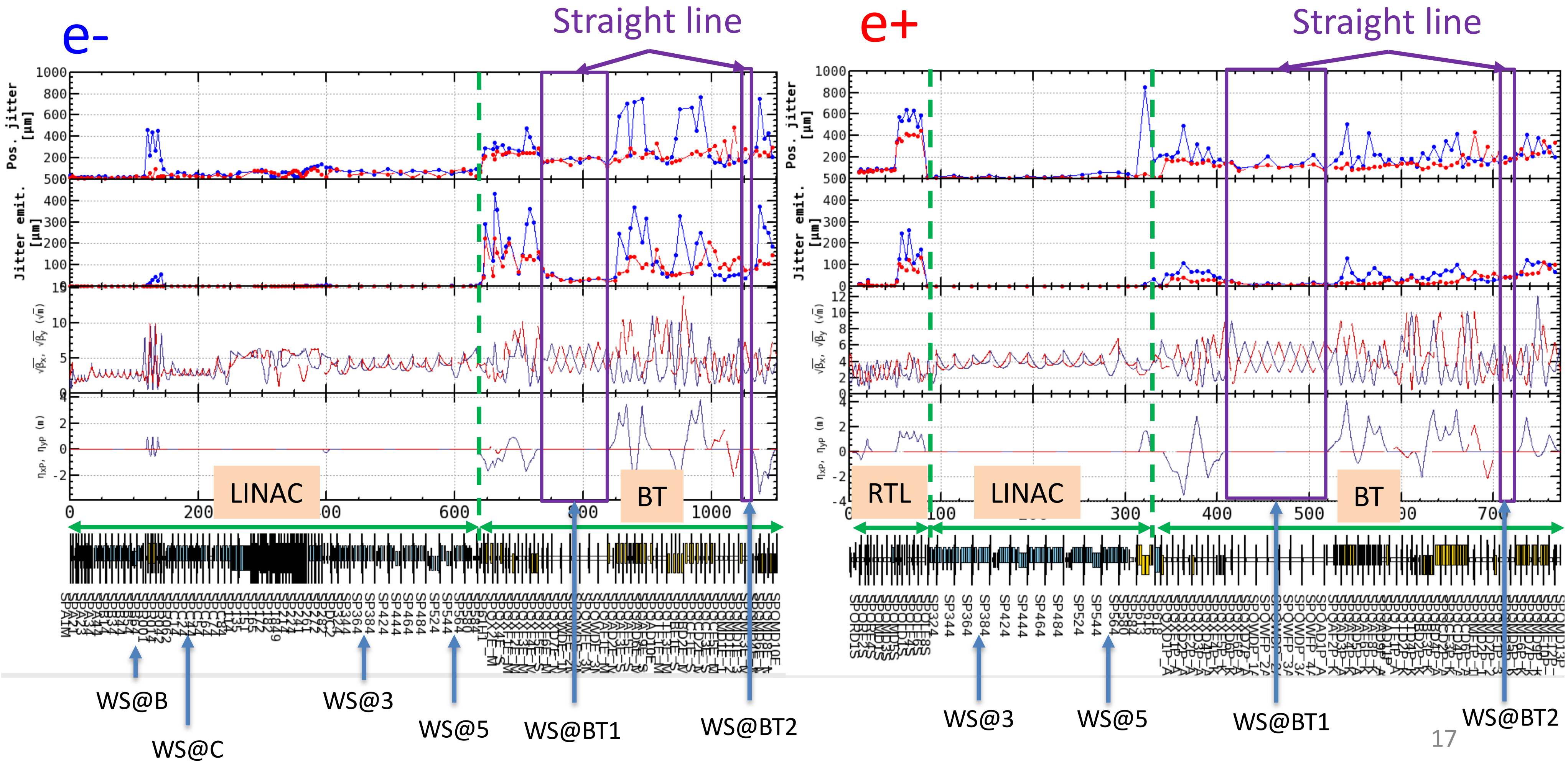
Three valued RF phase

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.



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   – If a beam, which has dispersion, is accelerated by acceleration cavity with off-phase, the energy deviation converts to betatron oscillations and causes emittance growth.

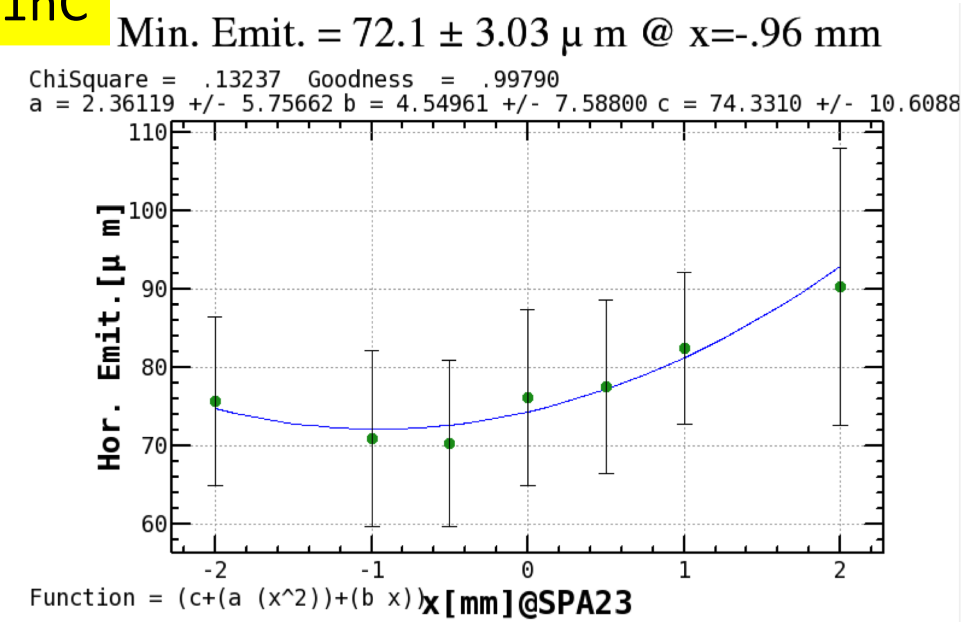
E) Radiation Excitation
   – Radiation excitation effect on emittance is proportional to both Lorenz gamma to the fifth power and inverse of curvature radius to the third power.
   – Especially, electron beam (7 GeV) is strongly affected by the radiation excitation effect.

C) Wakefield in Acceleration Structure

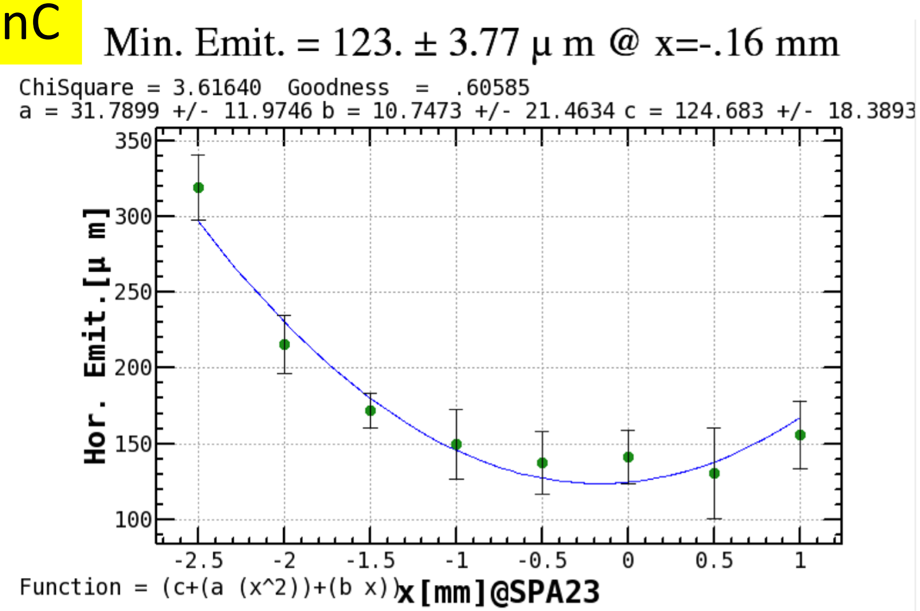
- Using a steering magnet, we searched an orbit so as to minimize emittance.
- Emittance highly depends on beam charge and orbit.
- Wake free steering will be performed using RF gun in the next run.

Thermionic gun

1nC



4nC



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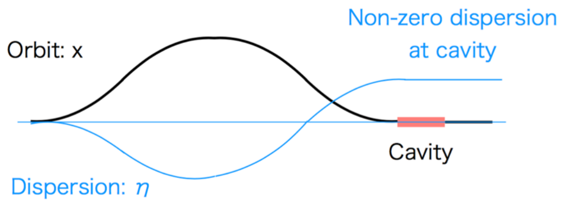
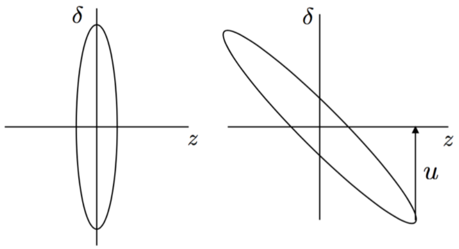
D) Acceleration of Beam with Dispersion

- If a beam, which has dispersion, is accelerated by RF cavity, $\eta\delta$ converts to betatron oscillations and causes emittance growth.
- From measured dispersion, the dispersion is leak to RF cavity in ECS of SY3

M. Kikuchi





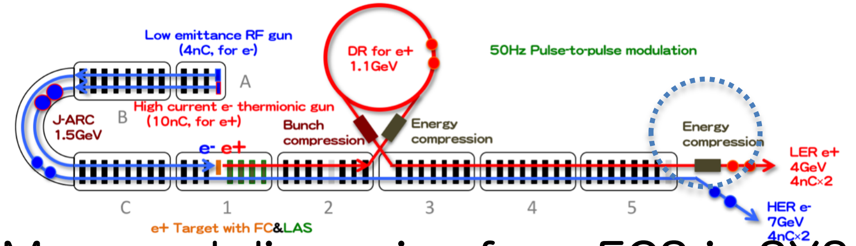
If the cavity has non-zero dispersion, a beam, gaining its energy depending on z, has net growth in the projected-emittance.

This is an analogue of the synchro-beta excitation at the cavity with non-zero dispersion in the ring.

$$\bar{\epsilon}^2 = \epsilon_0^2 + \epsilon_0 \left(\beta\eta'^2 + 2\alpha\eta\eta' + \gamma\eta^2\right) \langle u^2 \rangle$$

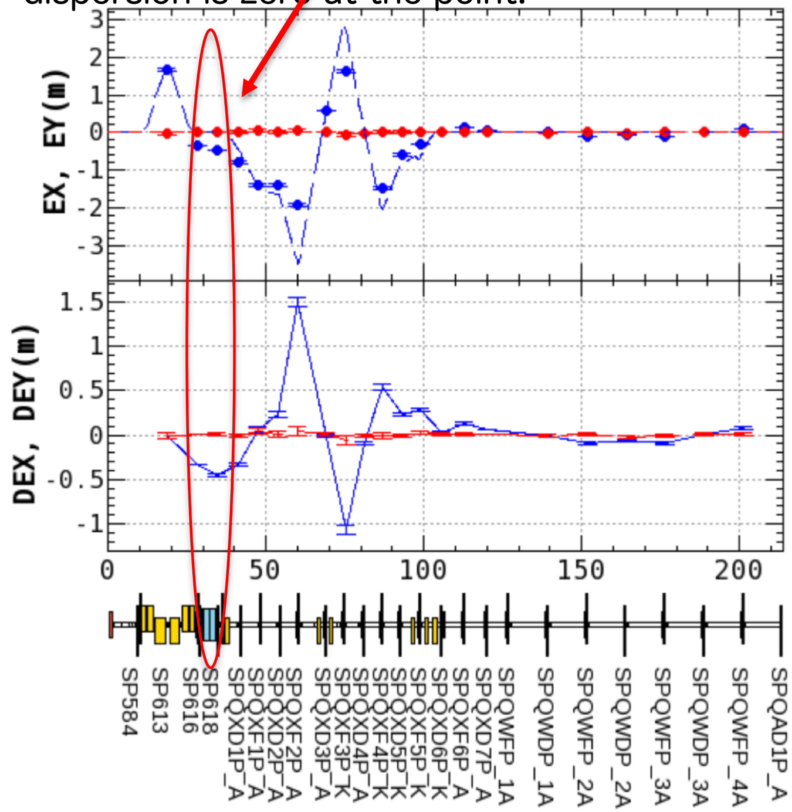
$$u = -vz \quad v = \frac{eV}{E_0}\frac{\omega_{rf}}{c}$$

Simulation result: $\dfrac{\epsilon}{\epsilon_0} \sim 2$



Measured dispersion from ECS in SY3.

There is dispersion at ECS cavity though design dispersion is zero at the point.



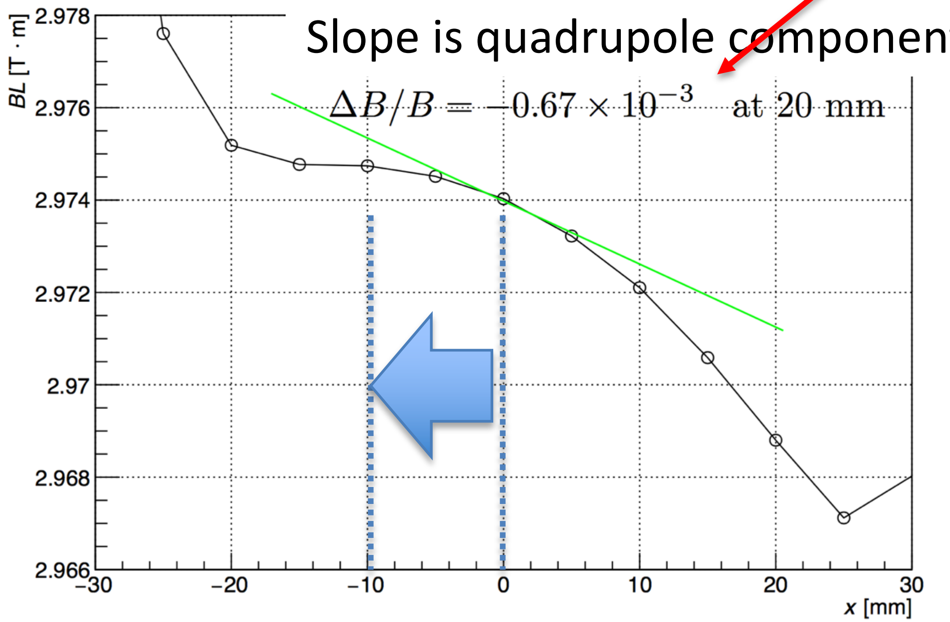
The bending magnets in ECS/SY3 have

D) Quadrupole component of bending magnet

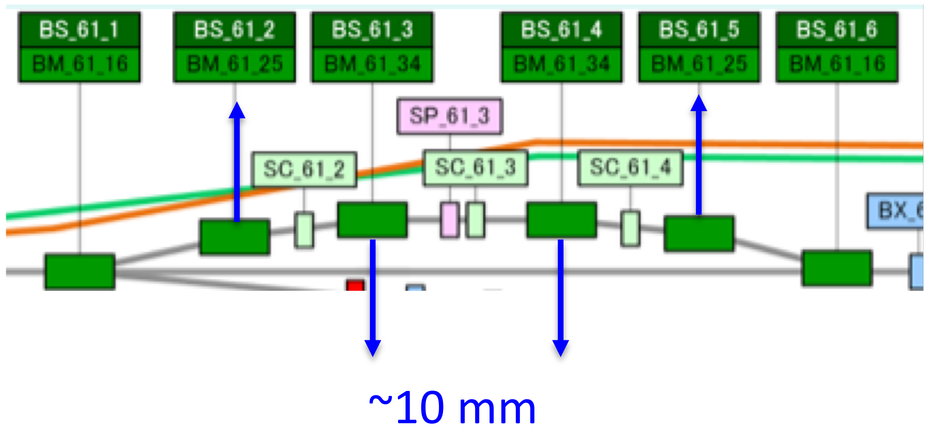
- BL measurement data shows that non-negligible quadrupole component of bending magnet exists.
- Assumed measured quadrupole component, simulation satisfy measured dispersion well.
- We will move the each bending magnet about 10 mm in this summer.
- If the qudrupole component still remained in autumn operation, we are also planning to installing a quad in the center of the chicane.

T. Mori

This can explaine the measured dispersion leak.



BL of bending magnet along to beam orbit



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- Radiation excitation effect on emittance is proportional to both Lorenz gamma to the fifth power and inverse of curvature radius to the third power.
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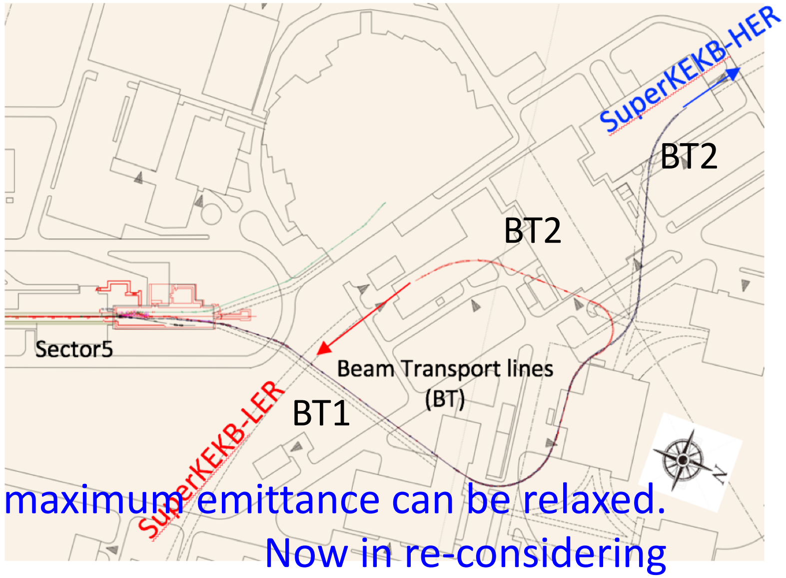
E) Emittance growth induced by radiation excitation in BT

Theoretical emittance growth induced by radiation excitation:

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



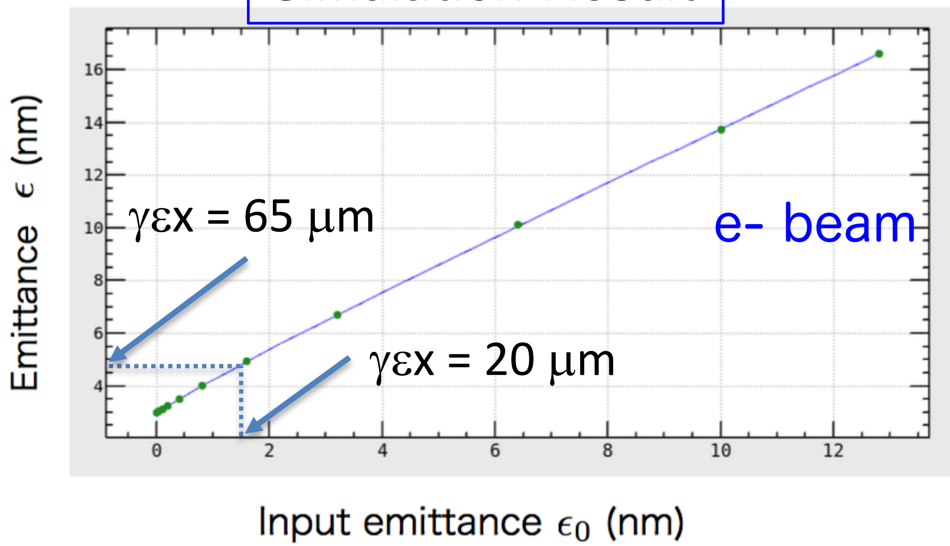
Particle tracking simulation was performed from the end of LINAC to the end of BT.

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.

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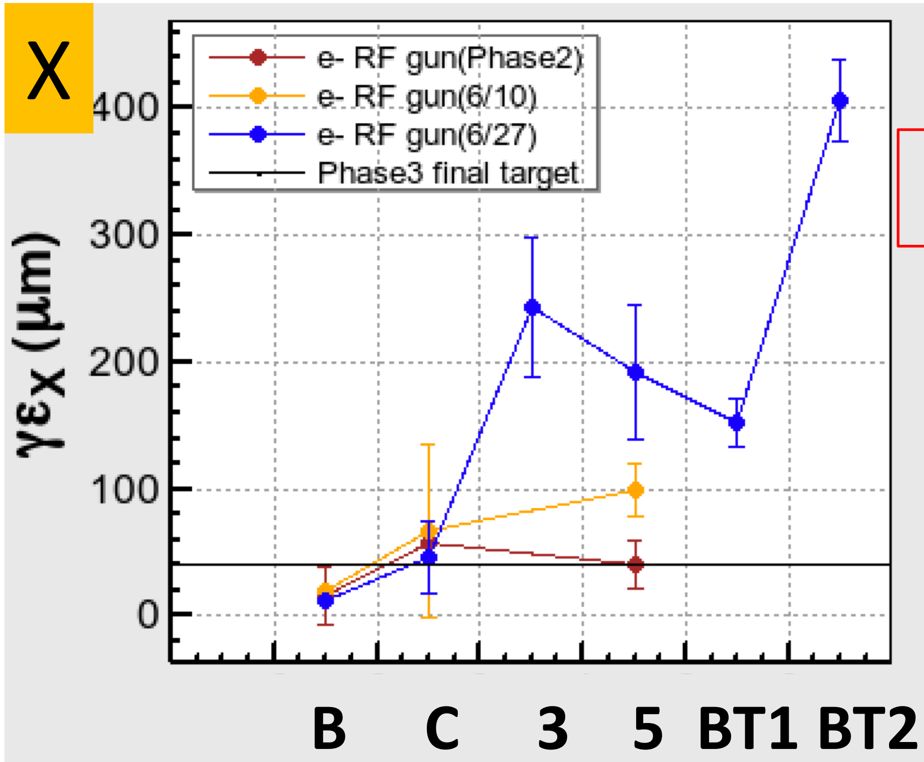
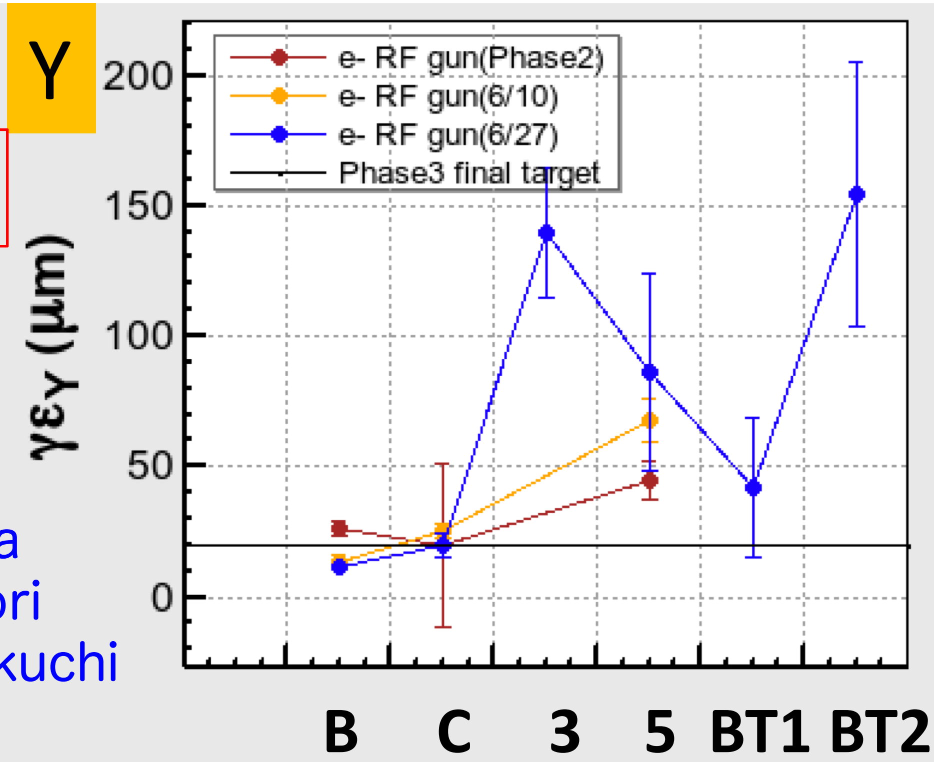
4. Summary

3. Results of Emittance Measurement (e-)

- Unfortunately, tuning time of the LINAC was seriously limited in Phase 3.
- Emittance in Phase 3 is worse than that in Phase 2.
- Though residual dispersion and jitter emittance is small in LINAC, emittance growth perhaps come from wakefield of cavity.
- Measured emittance at 27/Jun is worse than 10/Jun without special tuning.
- We hope that orbit FB, which start from 20/Jun, hold emittance quality.
- In the end of BT, emittance growth occurred. Vertical emittance can be explained by both residual dispersion and jitter emittance.
- It seems that measured horizontal emittance growth at BT2 is larger than that of both residual dispersion and jitter emittance. We are investigating this reason now.



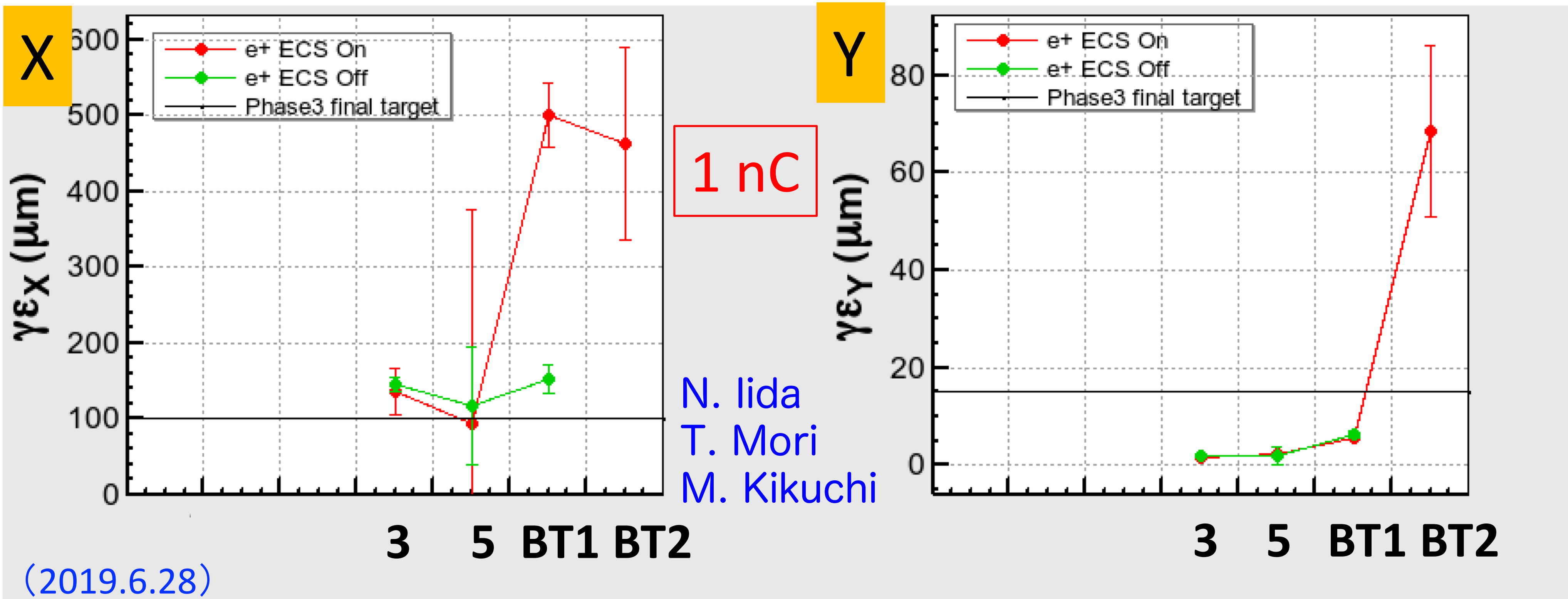
1 nC



N. Iida
T. Mori
M. Kikuchi

3. Results of Emittance Measurement (e+)

- In Phase 3, emittance growth was almost same as that in Phase 2.
- Emittance growth under ECS off was smaller than that under ECS on.
- Vertical emittance growth between BT1 and BT2 can be explained by residual dispersion and jitter emittance.
- While, ratio of the horizontal emittance at BT2 to that at sector 5 is about 4 though simulation result is 2. We are investigating this reason now.



SUMMARY

- In LINAC and BT, high charge and low emittance beam transportation is necessary for SuperKEKB project.
- Current main emittance growth sources are residual dispersion (beam phase space jitter), wakefield in acceleration cavity, and acceleration of beam with dispersion.

Countermeasure:

Residual dispersion:

- Minimize $\Delta\eta$ and $\Delta\eta'$ in the BT end.

Wakefield in acceleration cavity:

- For the main ring operation, tuning time of the LINAC was seriously limited. For stable low emittance transportation, continuous emittance measurement is strongly desirable. We will consider new diagnostic line at BT.
- Automatic orbit correction for minimizing emittance growth is also desirable. We will introduce such wake free steering program using a screen in the new line, for example.

Acceleration of beam with dispersion:

- The bending manets realignment and the quad installation in the ECS of SY3 are planned so as to cancel the quadrupole component of the bending magnet.

Back up

A) Residual dispersion in the DR extraction line

- This table shows values of residual dispersion before and after correction.
- Residual dispersion became smaller in both ARCs.
- In 1st ARC, residual dispersion is not still small enough.

Y. Seimiya,
N. Iida,
M. Kikuchi

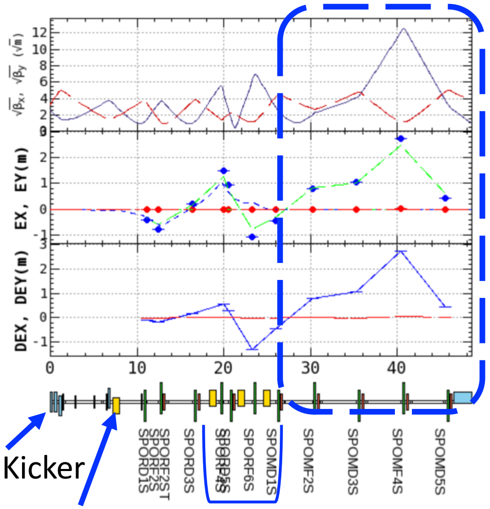
There are two ARCs in the DR extraction line.

e+	$\langle \eta x^2 \rangle^{1/2}$ [m]		$\langle \eta y^2 \rangle^{1/2}$ [m]		**Fudge Factor of Quad.**
Correction	Before	After	Before	After	[%]
2nd ARC	0.079	0.019	0.0094	0.0077	- 4.5
1st ARC	1.05	0.09	0.02	0.01	- 8.2

Need more study

Example: 1st ARC

Before

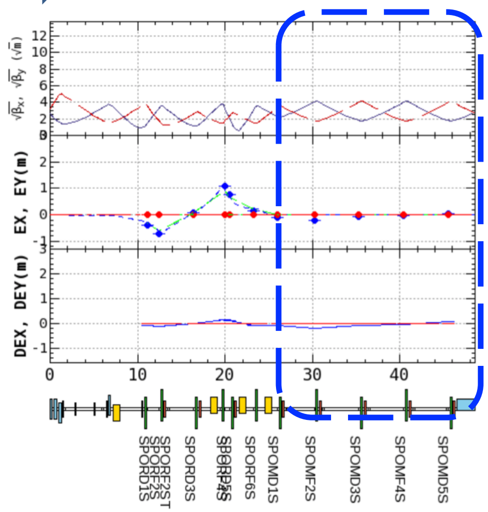


Extraction Kicker

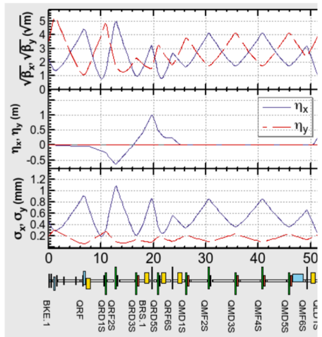
Extraction Septum

DC Bends

After dispersion correction



Optics of the extraction line



The third graph shows residual dispersion.
Blue is horizontal and red is vertical.

A) Residual dispersion and emittance growth

Emittance improvement by dispersion correction

e+ 0.7 [nC]	Residual Dispersion/Normalized Emittance			DR design emittance
	Before correction	After 2nd ARC correction	After 1st ARC correction	
$\langle \eta x^2 \rangle^{1/2}$ [m]	0.079	0.019		
	1.05		0.09	
$\gamma\beta\varepsilon x$ [μm]	293±44.5	192±22.4	126±8.2	64.3

- Horizontal emittance became less than half
- It is still twice as large as that of DR design.

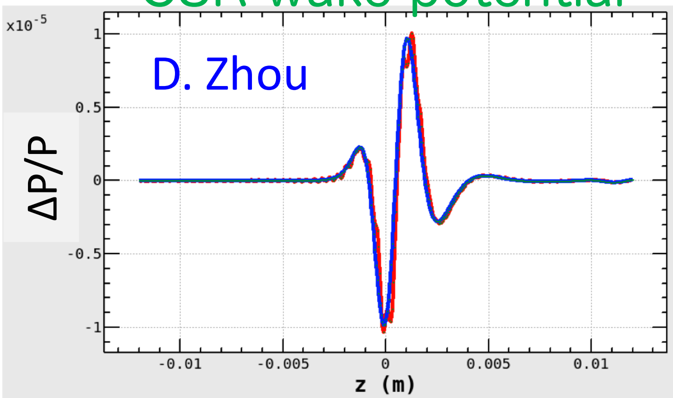
CSR calculation (depend on beam charge and bunch length)

CSR wake potential

x 10^{-5}

Theoretical

Analytical



$$W(z) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\omega Z(\omega)\psi(\omega)e^{-i\frac{\omega}{c}z}$$

Tracking Result

Charge [nC]	$\Delta\gamma\beta\varepsilon x/\gamma\beta\varepsilon x$
0.7	3.2 x 10^{-6}
4	3.1 x 10^{-5}

- CSR at RTL is negligible.

A) Residual dispersion in BT

- Until BT-Wire Scanner (WS) position, dispersion correction was done.
- In some ARC, dispersion correction is not finished. → Continue to Phase-III

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M. Kikuchi

As a same manner, we corrected dispersion in each ARC of BT.

This table shows residual dispersion before and after correction for e- and e+ beam.

These ARC names are listed from the upstream of the beam line.

e-	$\langle \eta x^2 \rangle^{1/2}$ [m]		$\langle \eta y^2 \rangle^{1/2}$ [m]		Quadの Fudge Factor
Correction	Before	After	Before	After	[%]
Slope1	0.13	0.11	0.05	0.01	1.0～5.9
BTe Arc#0	0.11	0.02	0.01	0.02	0～6.7
BTe Arc#1	0.102	0.038	0.029	0.036	2.37
BTe Arc#2&3	0.066	0.029	0.037	0.034	2.52
Slope2	0.104	0.091	0.192	0.015	3.55
BTe Arc#4					2.17

e+	$\langle hx^2 \rangle^{1/2}$ [m]		$\langle hy^2 \rangle^{1/2}$ [m]		Quadの Fudge Factor
Correction	Before	After	Before	After	[%]
LTR Arc#1	0.037	0.018	0.019	0.016	-3.3, -2.4
RTL Arc#1	0.079	0.019	0.0094	0.0077	- 4.5
RTL Arc#2	1.05	0.021	0.02	0.01	- 8.2
BTp Arc#0	0.27	0.02	0.01	0.03	-26～12.9
BTp Arc#1	0.037	0.047	0.126	0.102	2.5
Slope1	0.011		0.029		2.5
BTp Arc#2&3	0.123	0.029	0.253	0.313	2.5～5.1
Slope 2	0.012	0.012	0.324	0.017	3.4
BTp Arc#4					2.5

BT-WS placed

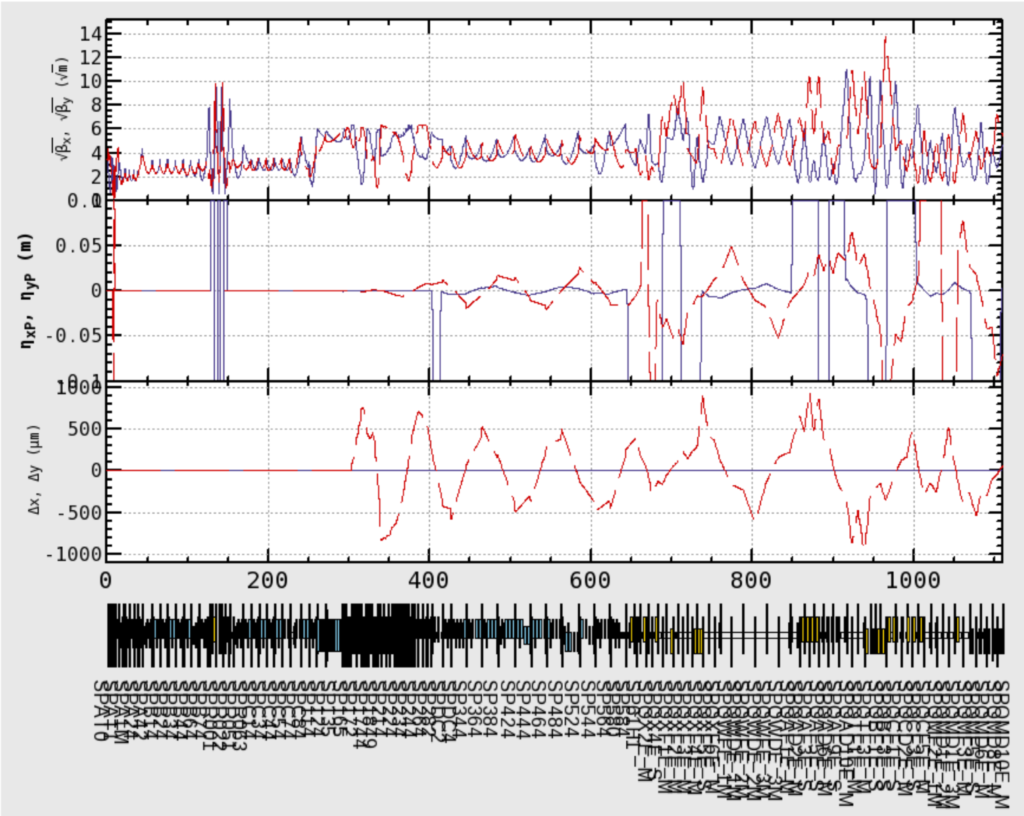
Inj. point to MR

BT-WS placed

Inj. point to MR

A) Dispersion induce by ST

-1A@PY172, PY182、0.5A@PY184



- Dispersion generated by ST is less than 0.05 m.
- The dispersion affect to beam size less than 1%.

B) Effective emittance

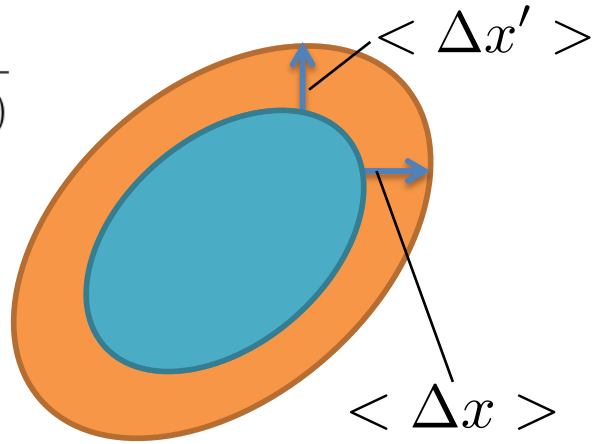
- Effective emittance, design emittance, emittance growth by beam jitter :

$$\epsilon_{eff} = \sqrt{< (x+\Delta x)^2 >< (x'+\Delta x')^2 > - < (x+\Delta x)(x'+\Delta x') >^2}.$$

$$\epsilon_0 = \sqrt{< x^2 >< x^2 > - < xx' >^2},$$

$$\epsilon_j = \sqrt{< \Delta x^2 >< \Delta x^2 > - < \Delta x \Delta x' >}.$$

- Effective emittance can be described by design emittance and emittance growth included by beam phase space jitter,



Nominal emittance

Emittance growth by beam jitter

$$\begin{aligned}\epsilon_{eff} &= \sqrt{\epsilon_0^2 + \epsilon_j^2 + \epsilon_0(\gamma_0 < \Delta x^2 > + 2\alpha_0 < \Delta x \Delta x' > + \beta_0 < \Delta x^2 >)} \\ &= \sqrt{\epsilon_0^2 + \epsilon_j^2 + 2\epsilon_0\epsilon_j(\frac{\gamma_0\beta - 2\alpha_0\alpha + \beta_0\gamma}{2})} \\ &= \sqrt{\epsilon_0^2 + \epsilon_j^2 + 2\epsilon_0\epsilon_j B_{mag}} \quad \geq \epsilon_0 + \epsilon_j\end{aligned}$$

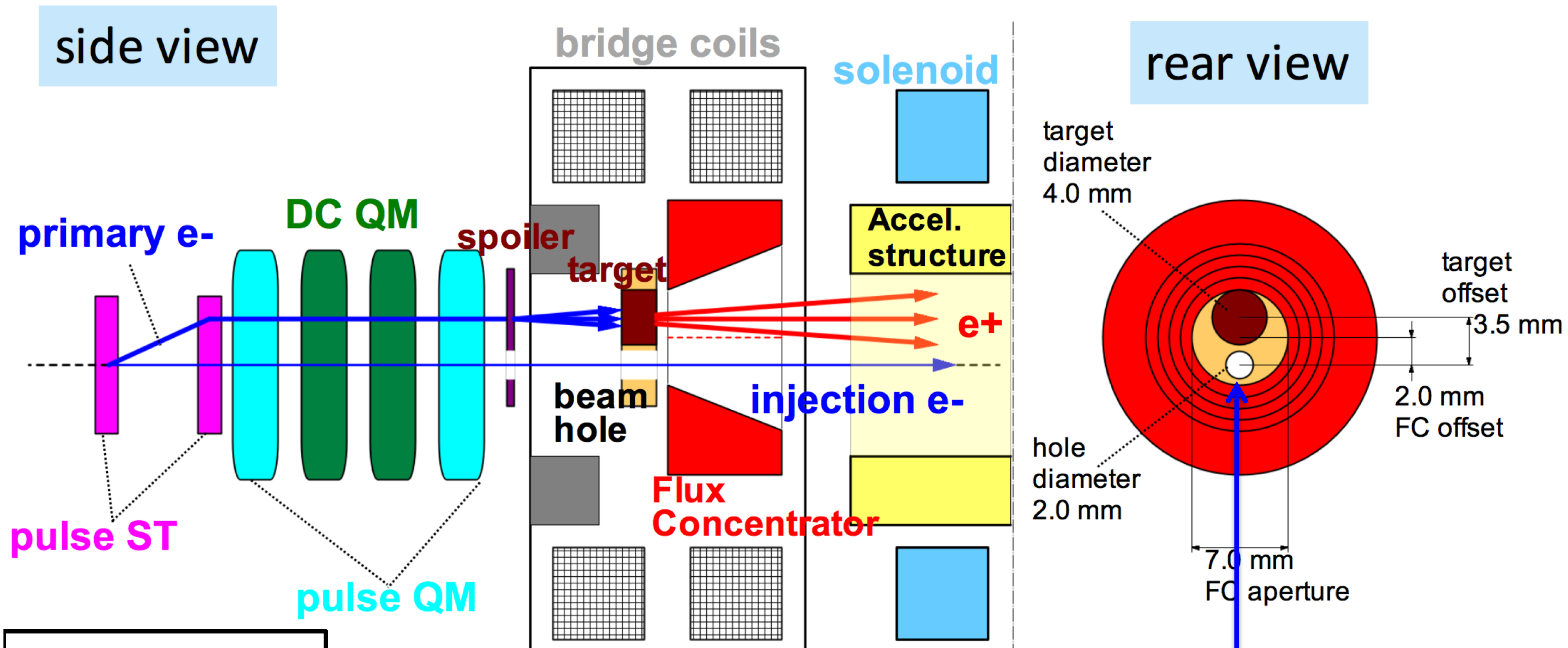
- B_{mag} (≧1) express amount of mismatching between beam optics and the jitter optics. (Not between beam optics and the design optics.) If matching is perfect, B_{mag}=1.

$$B_{mag} = \frac{1}{2}(\gamma_0\beta - 2\alpha_0\alpha + \beta_0\gamma) = \frac{1}{2}\left[\frac{\beta}{\beta_0} + \frac{\beta_0}{\beta} + \left(\alpha_0\sqrt{\frac{\beta}{\beta_0}} - \alpha\sqrt{\frac{\beta_0}{\beta}}\right)^2\right] \geq 1$$

- Once beam position and transfer matrix between two BPMs is identified, we can derive beam angle.

B) Positron generation target

- As jitter source, components around target is suspected.
- Schematic layout of component around target.



T. Kamitani slide

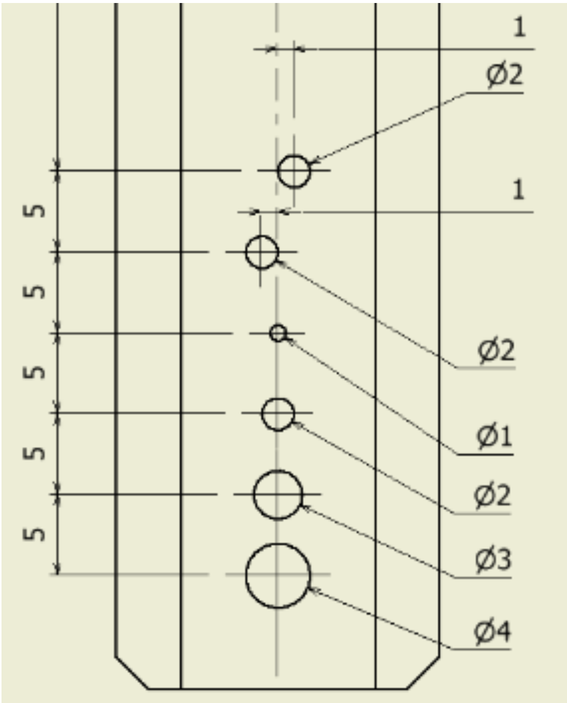
Target hole for electron beam

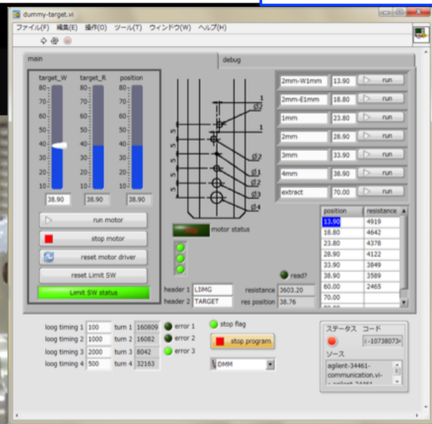
- Electron beam straightly pass through the positron generation target hole, which diameter is 2 mm.

B) Dummy Target

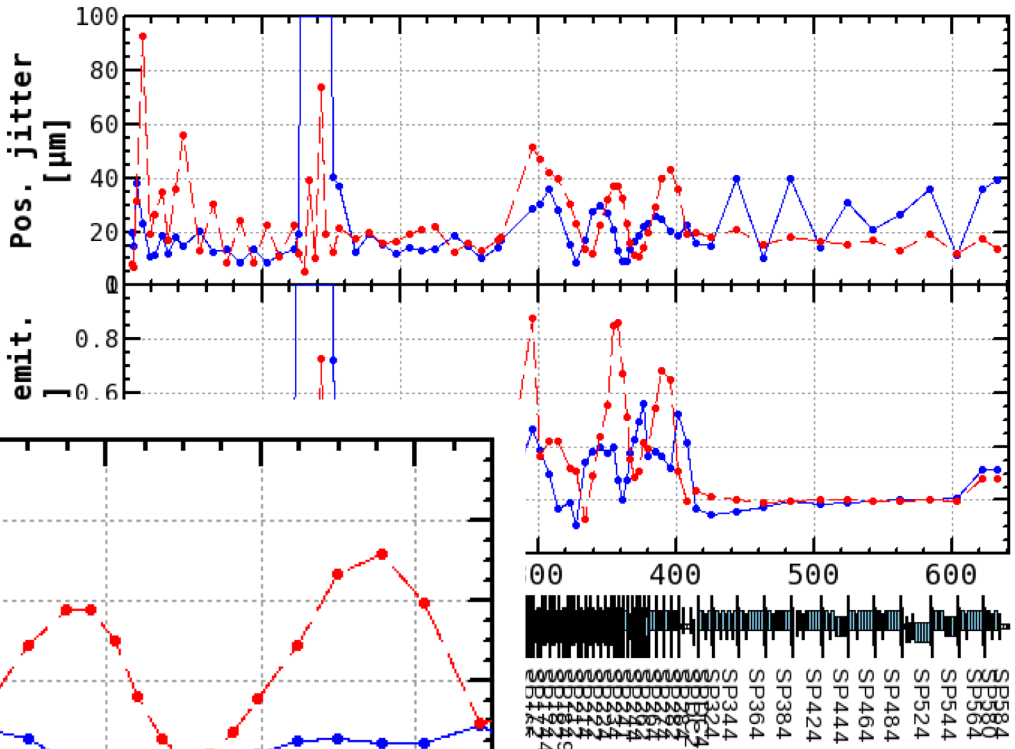
- To reveal beam jitter source directly, we temporally replaced the target to dummy target with several hole, which had different diameter.
- In autumn 2018, we studied the target hole effect on beam jitter.

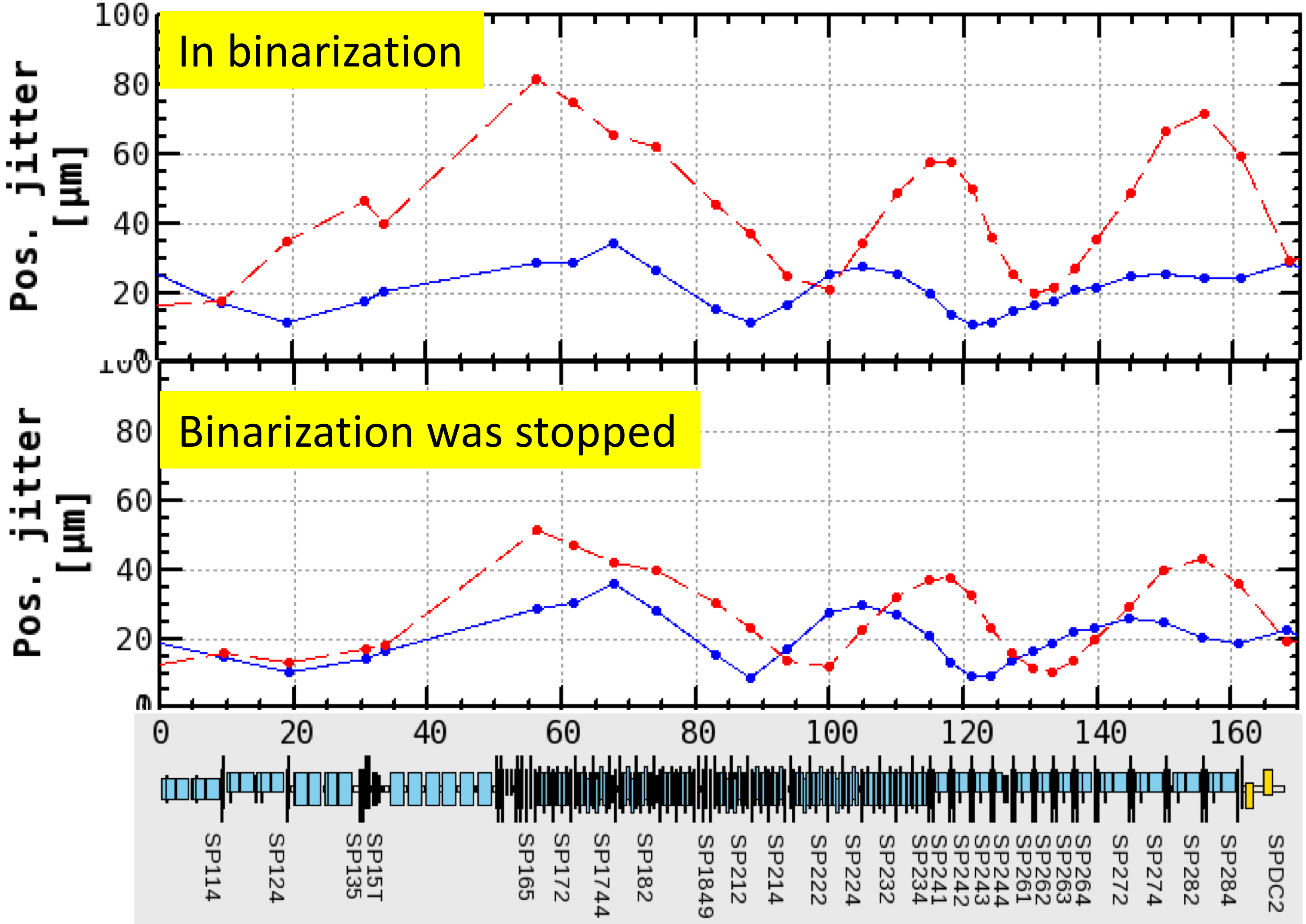
Y. Enomoto et al.



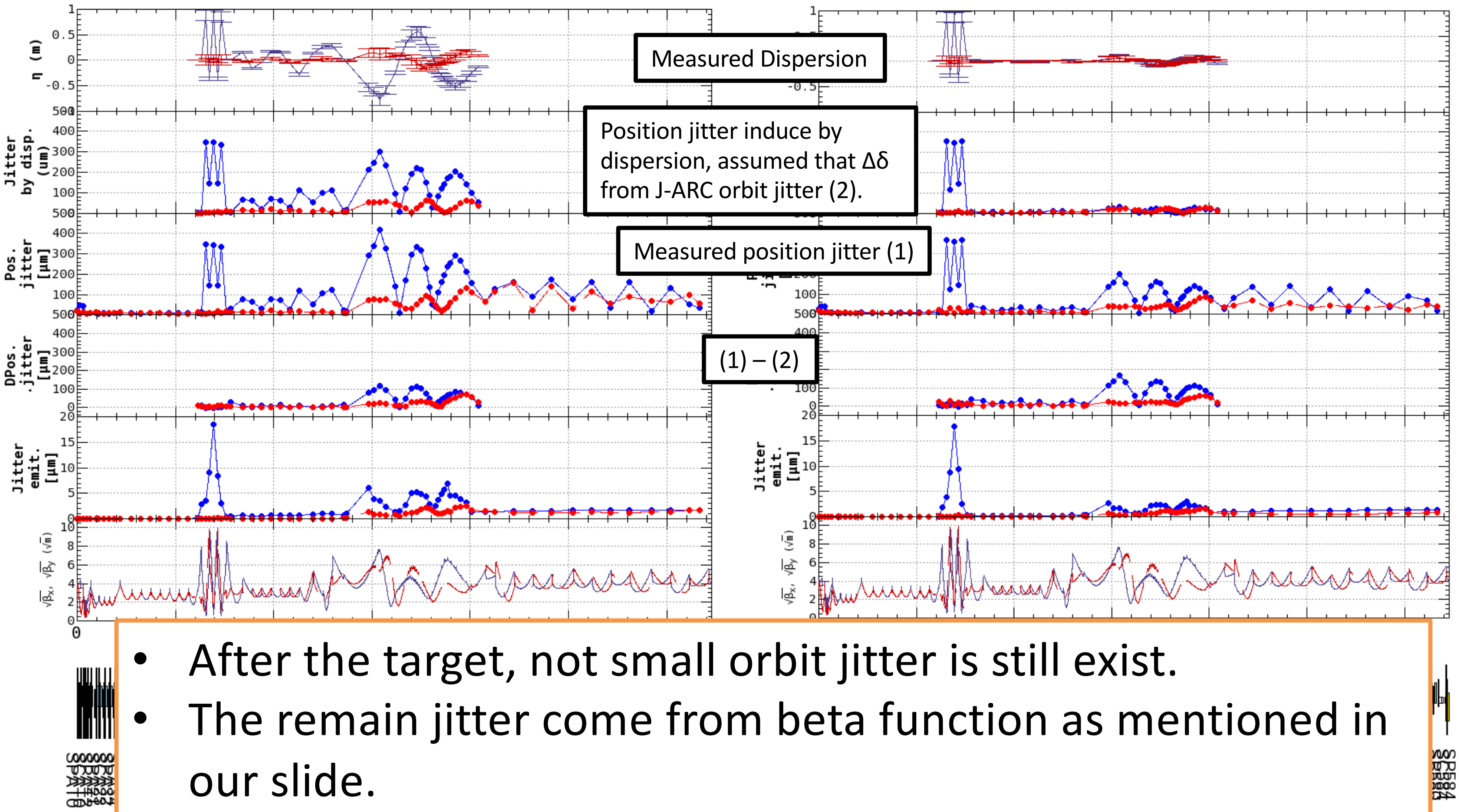




B) Binarization effect of pulse ST



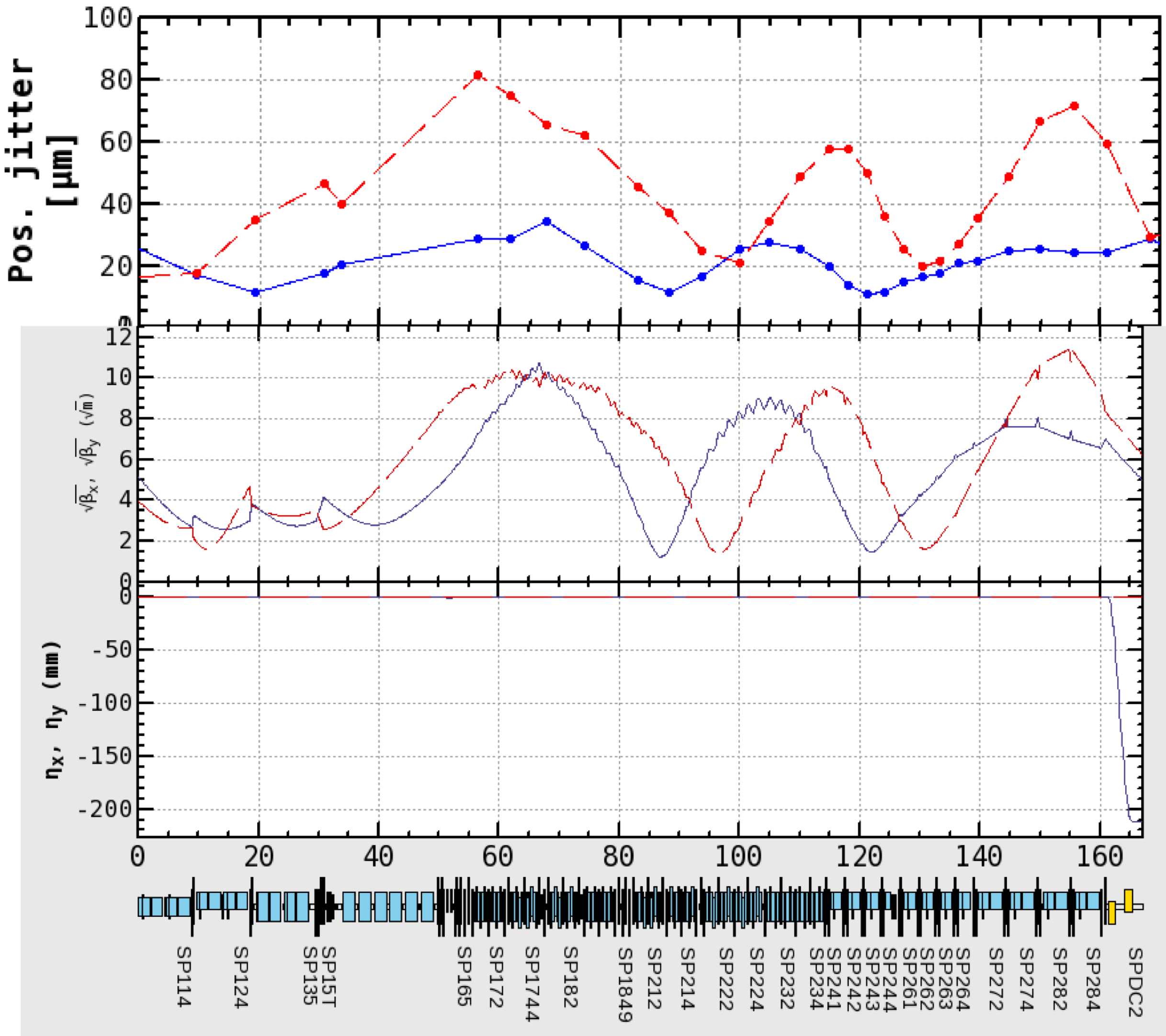


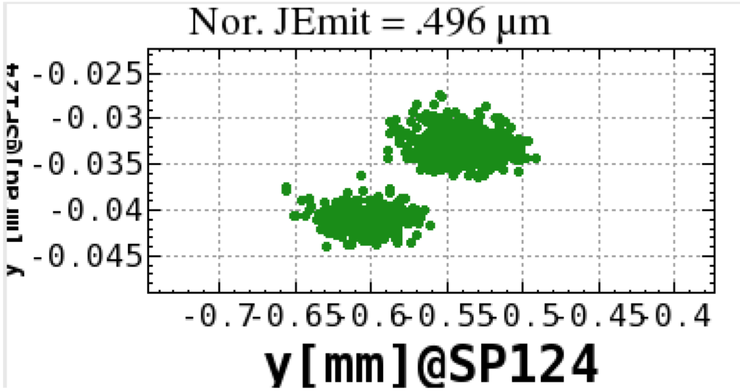
B) Dispersion effect on position jitter

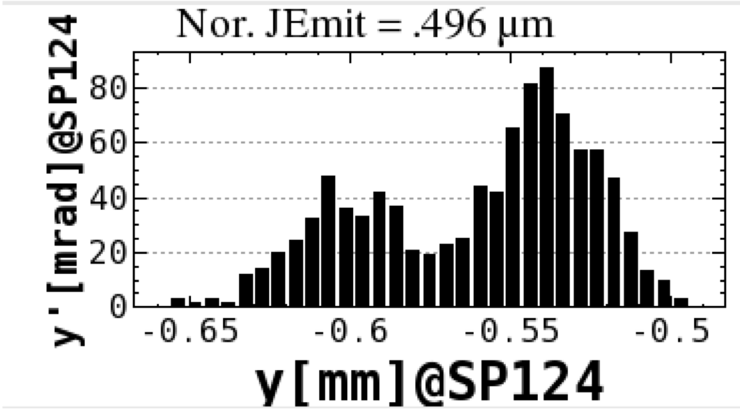


- After the target, not small orbit jitter is still exist.
- The remain jitter come from beta function as mentioned in our slide.

B) Orbit jitter and beta function

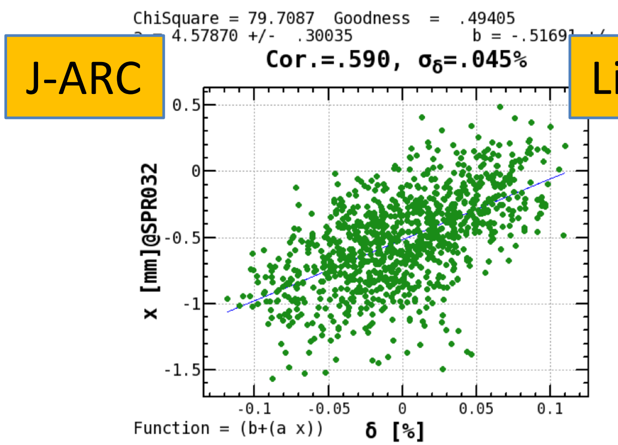


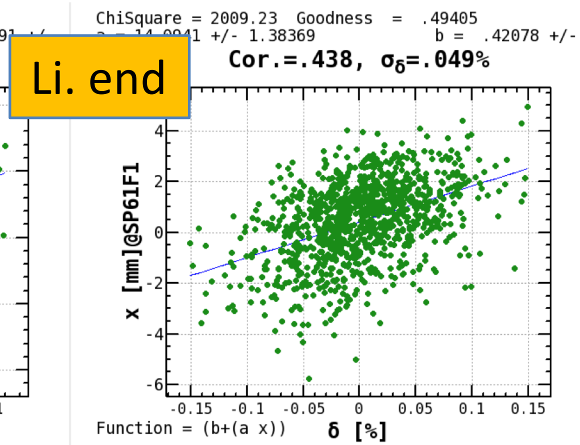


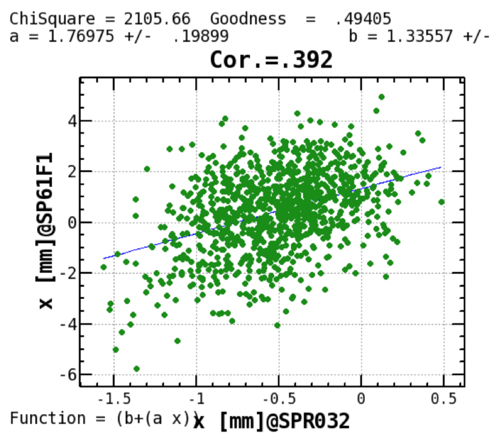


B) RF Phase Jitter and Energy Jitter

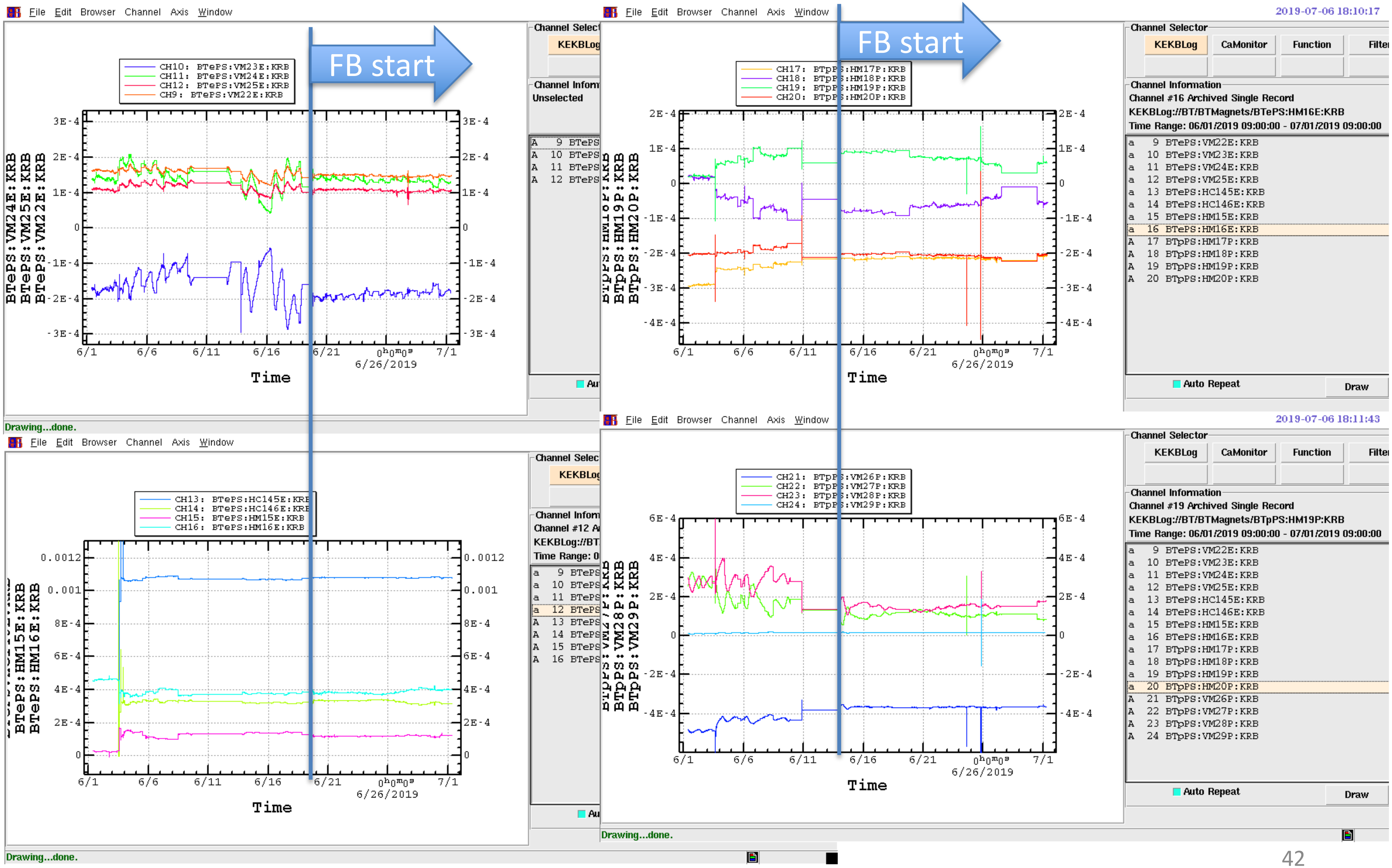
- Using RF monitor, energy jitter from RF phase was derived.
- 1000 shots, 15 minutes.
- Significant correlation can be seen at both J-ARC and LINAC end.
- Mainly the dependence come from RF zero cross phase as mentioned in our slide.







B) Orbit FB at BT



C) Simulation for minimizing emittance growth induced by wakefield in acceleration structure

Particle tracking simulation was performed to evaluate this emittance growth.
Simulation conditions:

- Measured misalignments of acc. structure and quadrupole magnet were used.
- Aris diameter of acc. structure is about 20 mm.

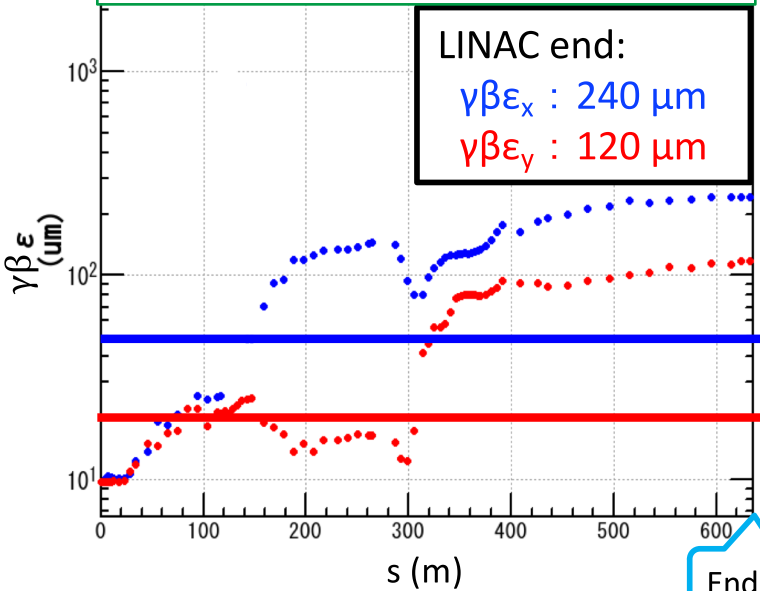
- $\gamma\beta\varepsilon_{inj}$ = 10 μm
- σ_z = 1.3 mm
- σ_δ = 0.4%
- Q = 5 nC

Phase-III requirement:
Horizontal : — (＜50 μm)
Vertical : — (＜20 μm)

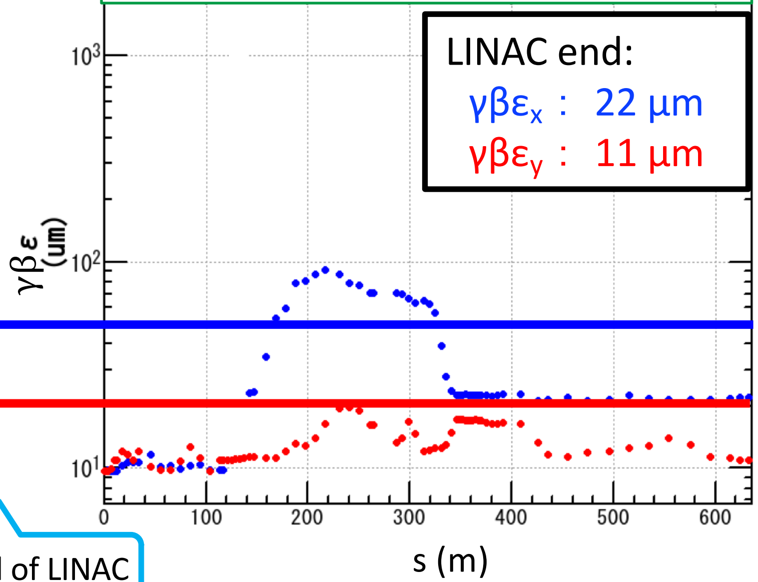
Blue and red dot show horizontal and vertical emittance, respectively.

Blue and red line shows horizontal and vertical requirement of Phase-III.

After orbit displacement is minimized



After emittance is minimized at the end of LINAC

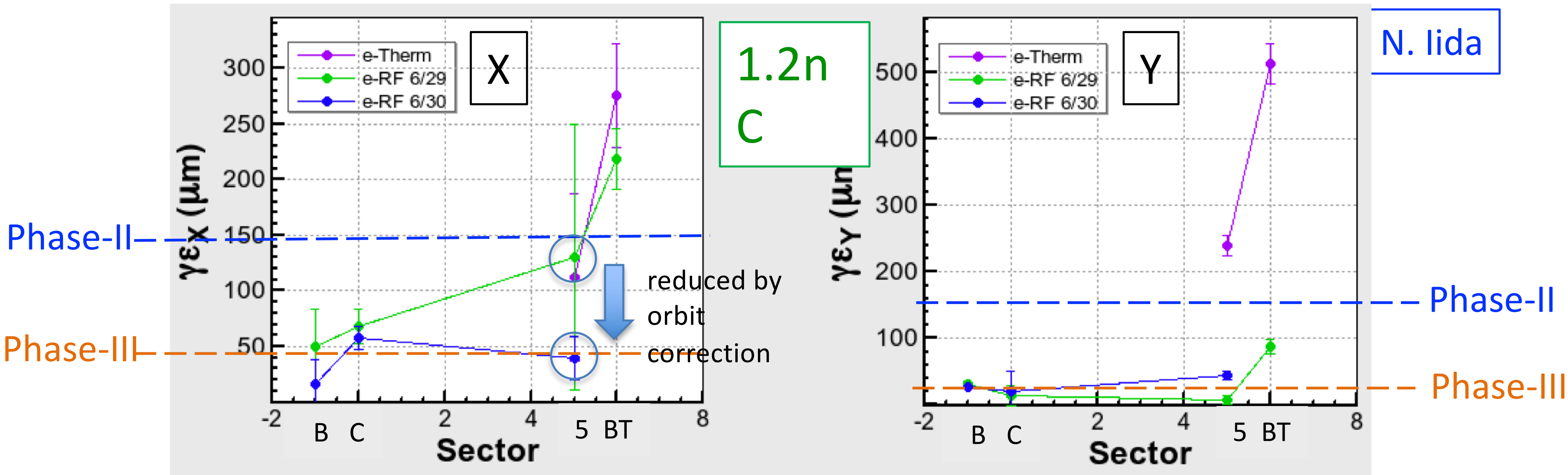


End of LINAC

By the orbit correction for minimizing emittance growth, requirement of Phase-III can be satisfied.

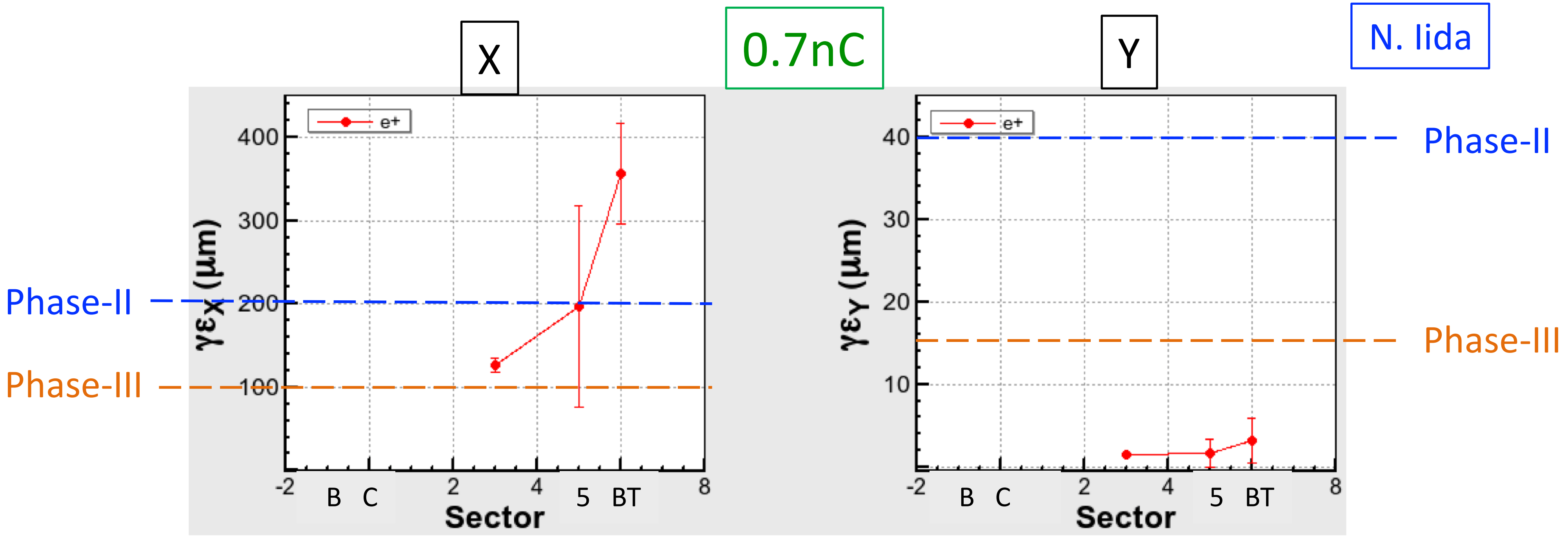
Emittance measurement (e-) in Phase 2

- Left and right figure show horizontal and vertical emittance measured at each sector, respectively.
- Green and blue plot show emittance of beam generated by RF gun.
- Manual orbit correction was done so as to reduce the orbit distortion. By this correction, emittance was reduced.
- In Phase-II, the requirement of e- emittance at the end of LINAC was satisfied.
- However, emittance was increased in BT though dispersion correction was done.
- This growth is not caused by radiation excitation because BT-WS is placed around the start of BT.



Emittance measurement (e+) in Phase 2

- In Phase-II, the requirement of e+ emittance at the end of LINAC was also satisfied.
- However, e+ emittance was also increased in BT though dispersion correction was done.
- Investigations for this emittance growth source in BT are under going.



ex) Single-bunch effects: Longitudinal: CSR

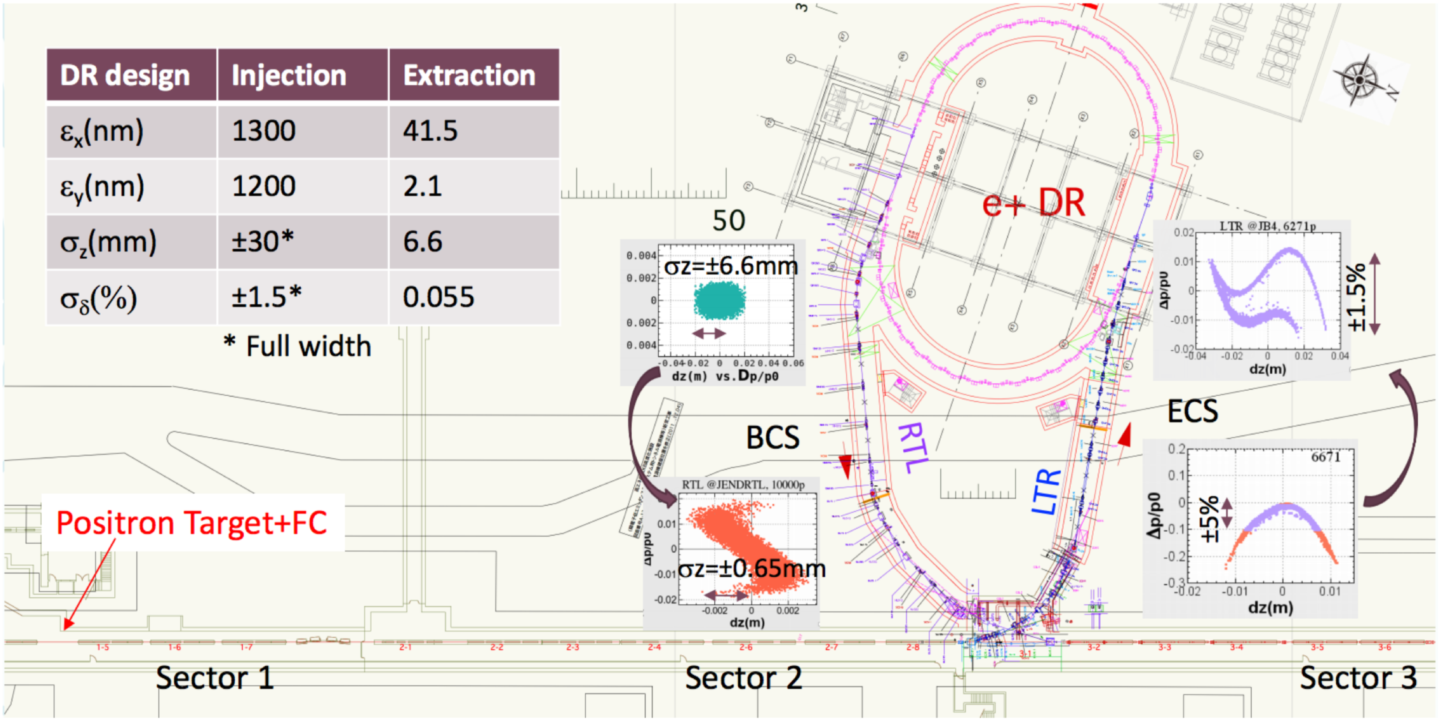
➤ **CSR at RTL of SuperKEKB**

D. Zhou

- **Dependence between BCS acceleration voltage (Vrf) and CSR effect**

DR design	Injection	Extraction
ε_x(nm)	1300	41.5
ε_y(nm)	1200	2.1
σ_z(mm)	±30*	6.6
σ_δ(%)	±1.5*	0.055

* Full width



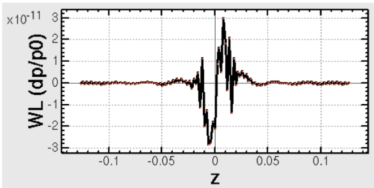
ex) Single-bunch effects: Longitudinal: CSR

➤ **Tracking with CSR: (Vrf=21.5 MV, Q=0.7 nC, Nbin=128)**

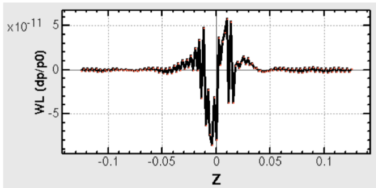
- **Np=1e6, GCUT=5**

D. Zhou

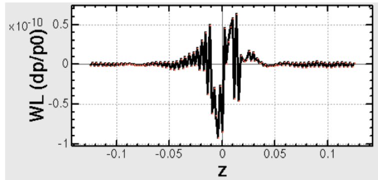
BSE1



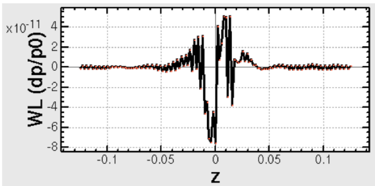
BRS.1



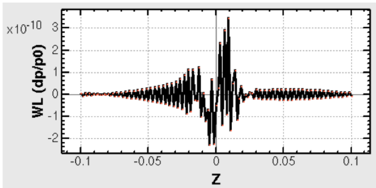
BRS.2



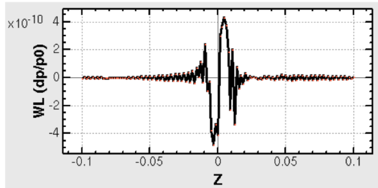
BRS.3



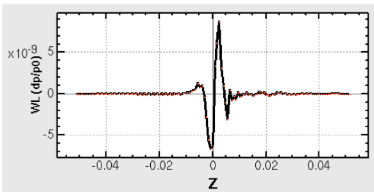
BL1S.1



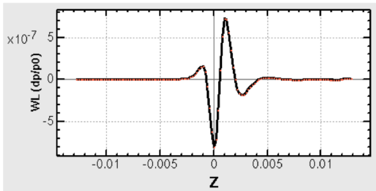
BL1S.2



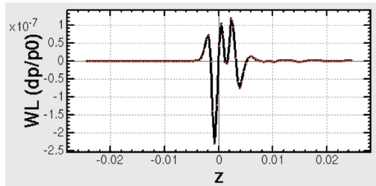
BL2S.1



BL2S.2



BL2S.3



ex) Single-bunch effects: Longitudinal: CSR

Np=1e6

D. Zhou

- **Vrf=0. MV:**
  - **W/O CSR, $\gamma\varepsilon_x$ = 91.484 nm**
  - **With CSR, $\gamma\varepsilon_x$ = 91.484 nm@4nC**

- **Vrf=21.5 MV:**
  - **W/O CSR, $\gamma\varepsilon_x$ = 91.563 nm**
  - **With CSR, $\gamma\varepsilon_x$ = 91.566 nm@4nC**

- **Vrf=23. MV:**
  - **W/O CSR, $\gamma\varepsilon_x$ = 91.577 nm**
  - **With CSR, $\gamma\varepsilon_x$ = 91.583 nm@4nC**

ex) Very Rough Estimation of CSR

N. Iida

Handbook of Accelerator Physics and Engineering
3rd Printing

Coherent synchrotron radiation (CSR): [23]- [25] Bunch moves in free space on a circle of radius R; $k \ll \gamma^3/R$. See Sec.2.5.12.	$\frac{Z_0^{\parallel}}{L} = \frac{Z_0}{2 \cdot 3^{1/3}\pi}\Gamma\left(\frac{2}{3}\right)\left[\frac{ik}{R^2}\right]^{1/3}$	$\frac{W_0'}{L} = -\frac{Z_0 c}{2 \cdot 3^{4/3}\pi R^{2/3}}\frac{1}{z^{4/3}}$
	$\Gamma(2/3) \approx 1.3541$. Note: non-zero wake for test particle *ahead* of driving particle. $W_0'(0^+)/L \approx 0.1 Z_0 c\gamma^4/R^2$. This is also used to approximate effect at high k for beam in beam pipe; shielded (suppressed) for $k \lesssim R^{1/2}b^{-3/2}$.	

$k=1/\sigma_z=150\text{~}1000 << \gamma^3/R=2.9e9$

$$Z_{\parallel}(k) = \frac{1}{c}\int_0^{\infty} dz W_{\parallel}(z)e^{-ikz}$$

$$= \frac{Z_0}{2\pi}\frac{e^{i\pi/6}}{3^{1/3}}\Gamma\left(\frac{2}{3}\right)\frac{k^{1/3}}{R^{2/3}} \qquad (2)$$

Z0=377
R=3.35m
sz=1~7mm
L=0.7938m
cc=1nC,
E=1.1GeV
I=cc/σz*c

dE=Z(k)L*I/E
dεx=(ηx*dE)^2/βx
Δγεx=Sum∑ dεx)i=0.81μm < 40μm

ex) Very Rough Estimation of Resistive Wall

N. Iida

Handbook of Accelerator Physics and Engineering

Resistive Wall:[1] pipe length L, wall thickness t, conductivity σ_c, skin depth $\delta_{\rm skin}$.	$\frac{Z_m^\parallel}{L}=\frac{\omega}{c}\frac{Z_m^\perp}{L}=\frac{Z_0c/(\pi b^{2m})}{[1+{\rm sgn}(\omega)i](1+\delta_{m0})bc\sqrt{\frac{\sigma_c Z_0 c}{2\lvert\omega\rvert}}-\frac{ib^2\omega}{m+1}+\frac{imc^2}{\omega}}$ $t\gg\delta_{\rm skin}=\sqrt{2c/(\lvert\omega\rvert Z_0\sigma_c)},\quad \lvert\omega\rvert\gg c\chi/b,\quad \chi=1/(Z_0\sigma_c b)$	
For $t\gg\delta_{\rm skin}$ and $b/\chi\gg\lvert z\rvert\approx c/\lvert\omega\rvert\gg b\chi^{1/3}$.	$Z_m^\parallel=\frac{\omega}{c}Z_m^\perp$ $Z_m^\parallel=\frac{1-{\rm sgn}(\omega)i}{1+\delta_{0m}}\frac{L}{\pi\sigma_c\delta_{\rm skin}b^{2m+1}}$	$W_m=-\frac{c}{\pi b^{m+1}(1+\delta_{m0})}\sqrt{\frac{Z_0}{\pi\sigma_c}}\frac{L}{\lvert z\rvert^{1/2}}$ $W_m'=-\frac{c}{2\pi b^{m+1}(1+\delta_{m0})}\sqrt{\frac{Z_0}{\pi\sigma_c}}\frac{L}{\lvert z\rvert^{3/2}}$
For $t\ll\delta_{\rm skin}$ or very low freq., and $b/\chi\gg\lvert z\rvert\approx c/\lvert\omega\rvert\gg\sqrt{bt}$.	$\frac{Z_0^\parallel}{L}=-\frac{iZ_0t\omega}{2\pi bc},\quad \frac{Z_1^\perp}{L}=-\frac{iZ_0t}{\pi b^3}$	$\frac{W_0'}{L}=-\frac{Z_0tc}{2\pi b}\delta'(z),\quad \frac{W_1}{L}=-\frac{Z_0tc}{\pi b^3}\delta(z)$

dE=(Z0/L)*L*I/E

dεx=(ηx*dE)^2/βx

Δγεx=Sum∑ dεx)i=0.0012μm << 40μm

Z0=377
R=3.35m
sz=1~7mm
L=0.7938m
cc=1nC,
E=1.1GeV
I=cc/σz*c
m=0