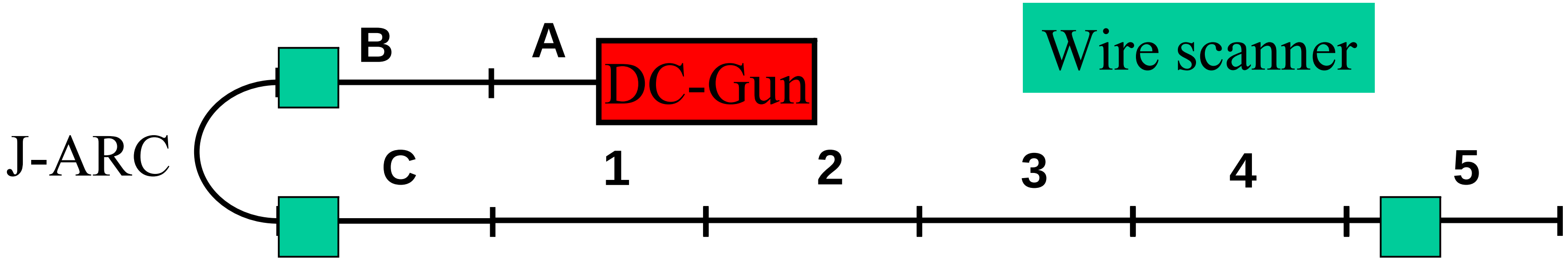
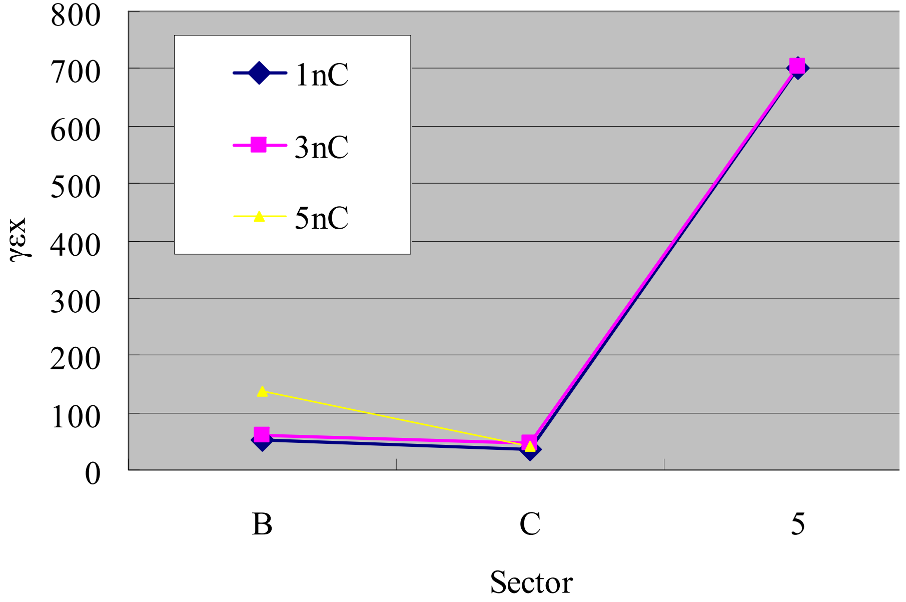
Emittance Preservation in Linac

2011.02.07 Super KEKB Review

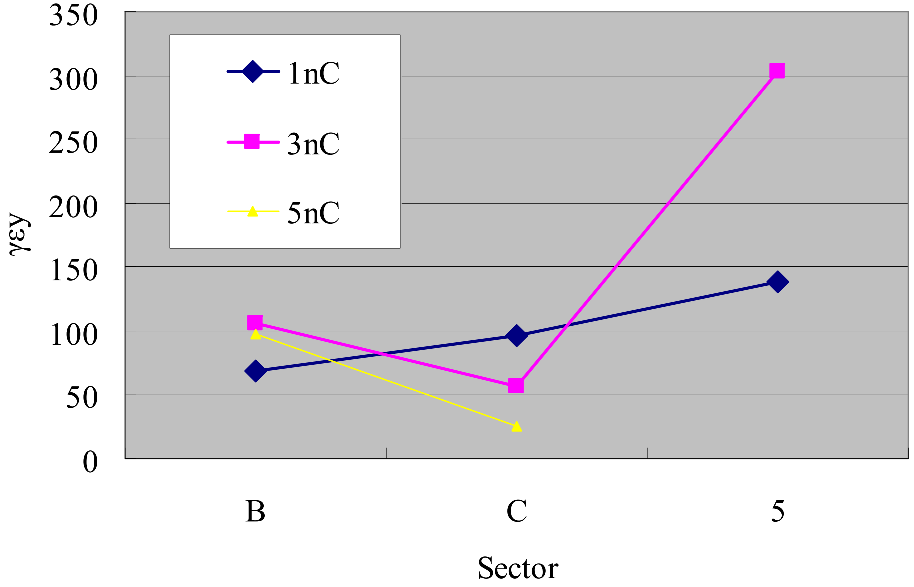
Emittance Measurement @2009.07.01



Horizontal Emittance



Vertical Emittance



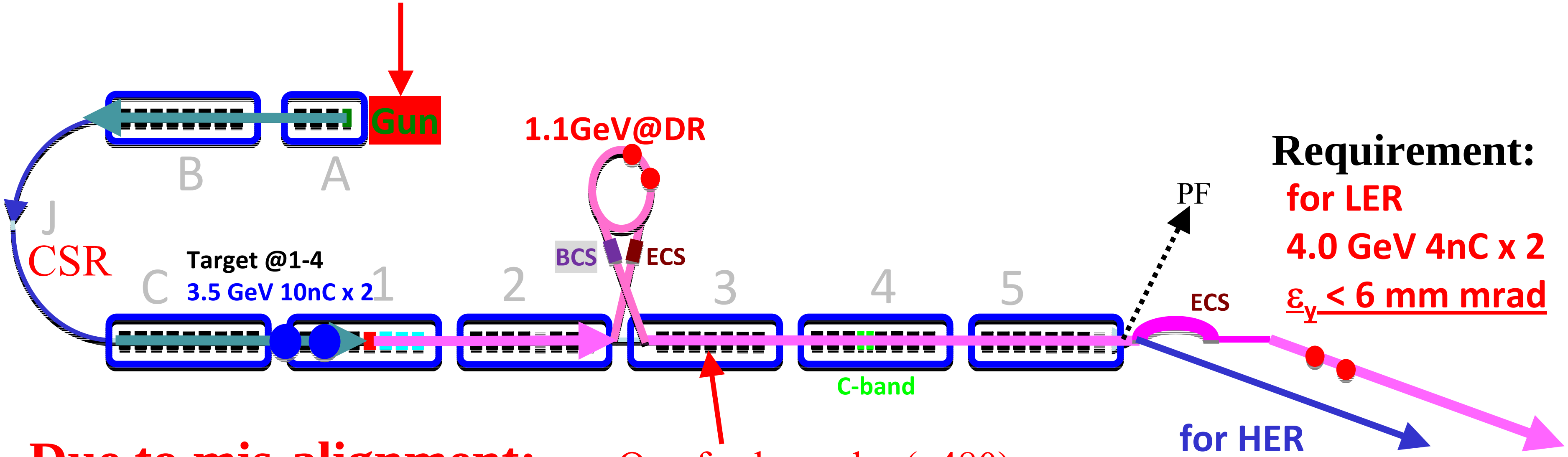
Initial emittance looks low considering ϕ16 big cathode.

Problem is emittance growth. ⇨ Machine study from 2010/10

Overview of emittance source and growth

Longer bunch can reduce space charge effect inside RF-Gun and also CSR at J-ARC.

Current charge & emittance:
e^- :1 nC, 300 mm mrad
e^+ :1 nC, 2100 mm mrad



Requirement:
for LER
4.0 GeV 4nC x 2
ε_y < 6 mm mrad

Due to mis-alignment:
- Dispersion
- Short range wakefield

One feed coupler (x480) causes of RF emittance.
($\Delta\gamma\varepsilon$ ~ 1.2 mm mrad is estimated)

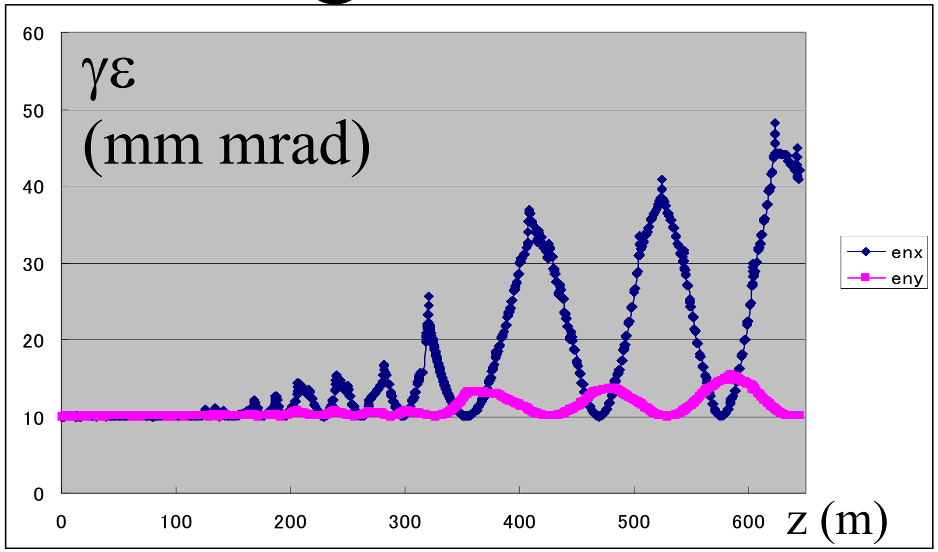
for HER
7.0 GeV 5nC x 2
ε_y < 20 mm mrad

Apparent emittance growth due to Dispersion and Short Range Wakefield

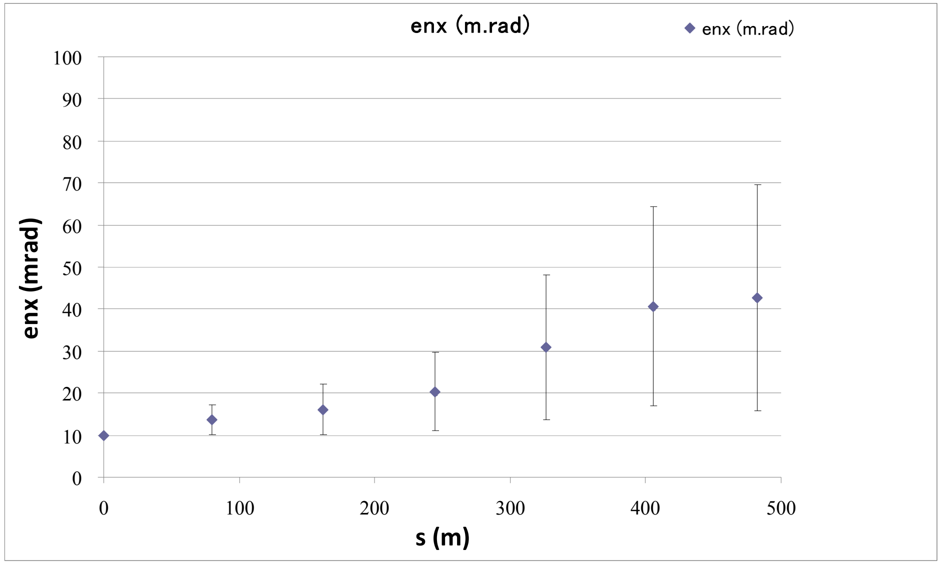
- Mis-alignment : σ_x=0.5 mm
- Initial emittance = 10 mm mrad

– δ_p : 0.1 %, σ_z : 1mm

Dispersion
(only from ηx)



[Short Range Wakefield]
- Charge : 5 nC



Emittance Compensation ⇔ Alignment

Alignment tolerance:

becomes severe without compensation

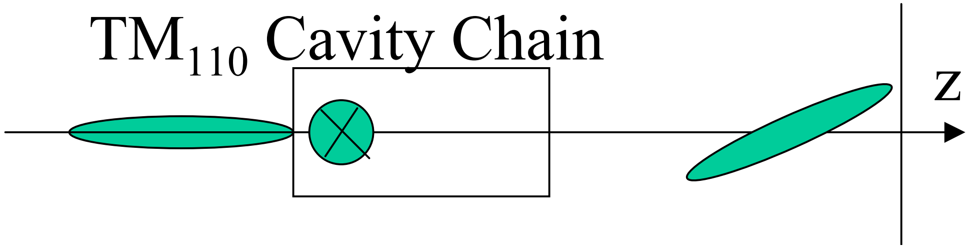
=> Compensation is required.

should be determined by second order effect and compensation error.

→ Machine & simulation study of emittance source.

- Dispersion : compensated in BT line.
- Short range wakefield : Initial offset
  → Monitoring using RF-Deflector is required.
- RF Emittance : RF-Deflector can compensate
- CSR : longer bunch length.

RF-Deflector => bunch slice emittance


TM_{110} Cavity Chain

Machine study

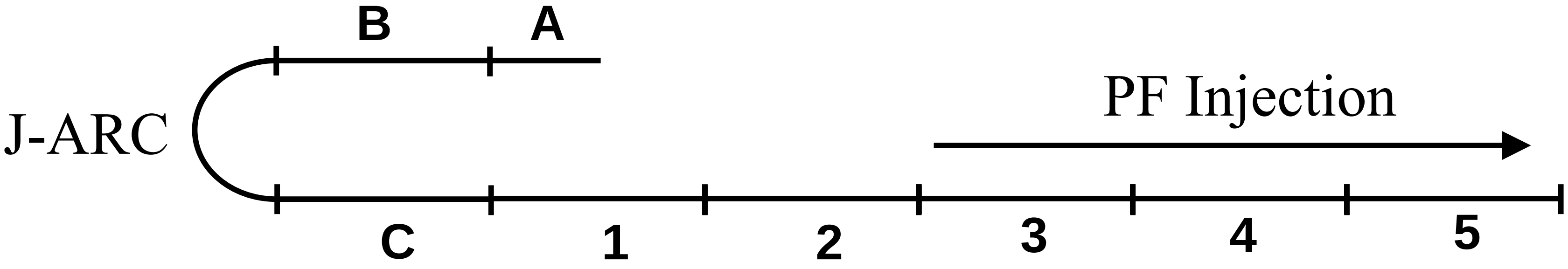
from 2010.10

Machine study

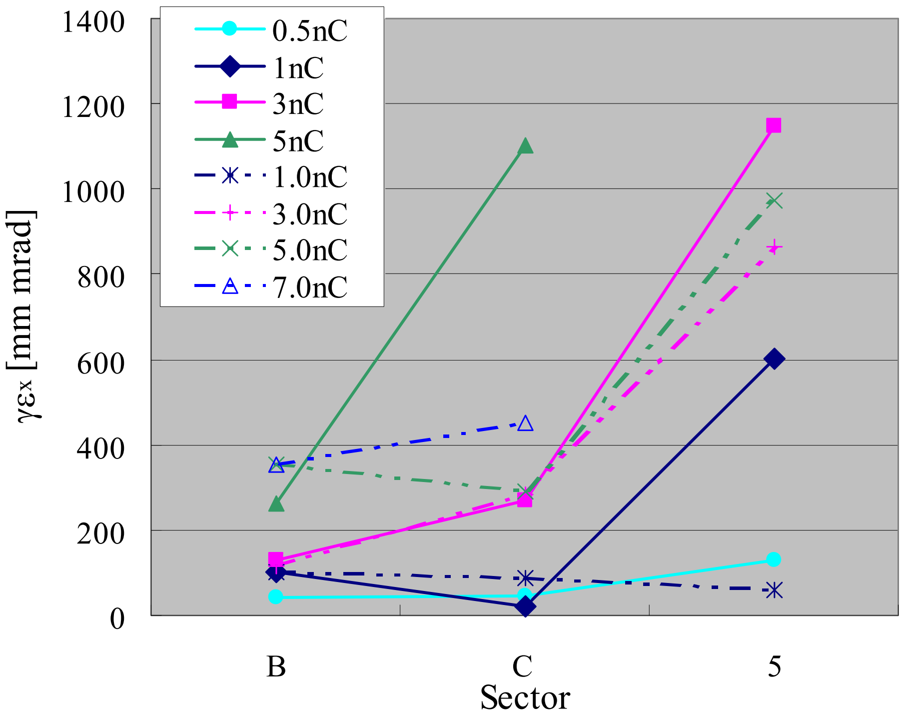
- Emittance growth measurement
  - Charge dependence
  - Optics dependence
- R_{16}, R_{36} measurement
- Response orbit measurement

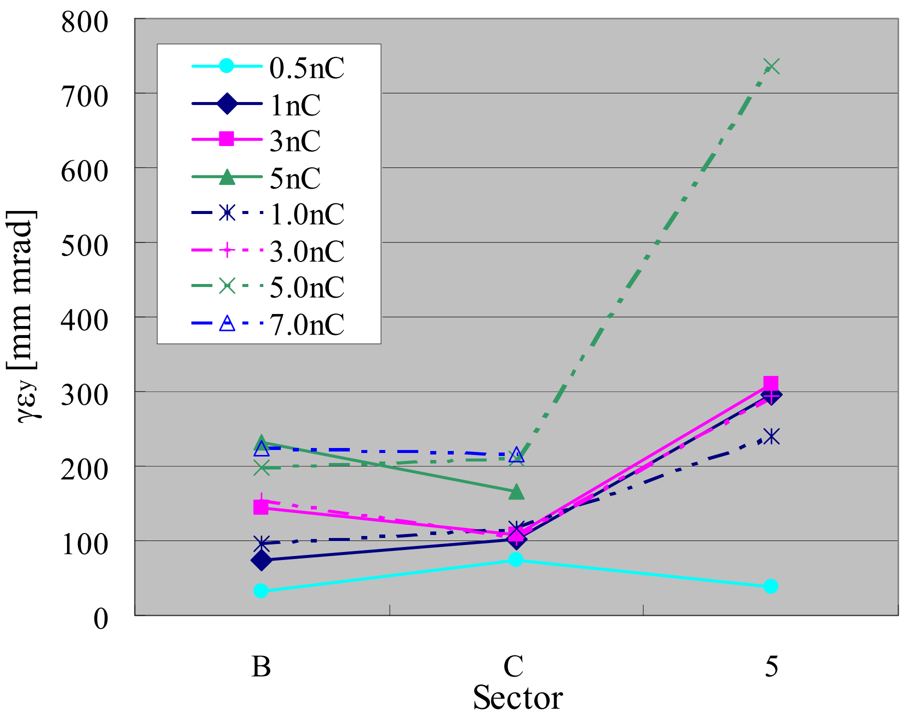
  → Beam based alignment

  → Dispersion calculation



Emittance measurement



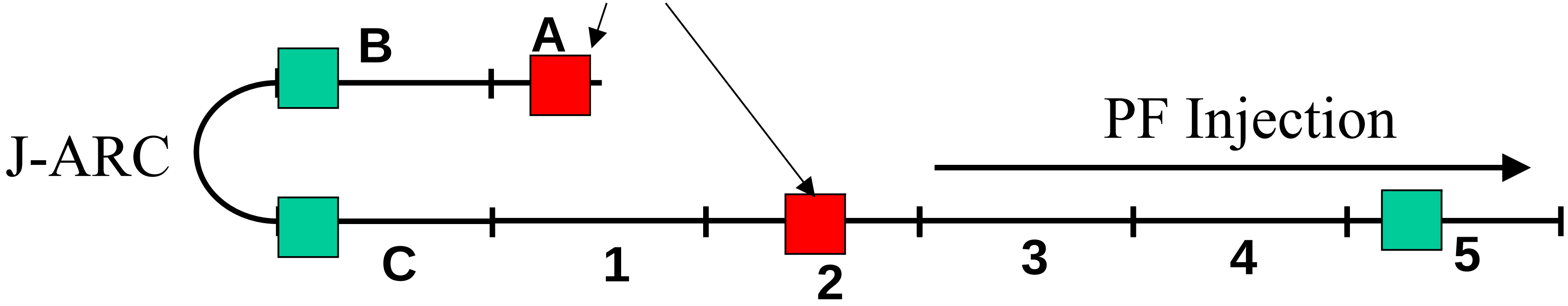


Emittance measurement

Improvement of emittance measurement will be required:

- Optimize phase advance during PF injection.
  => Use injection intervals to change Q-magnets.
- RF-gun installation to obtain lower emittance.

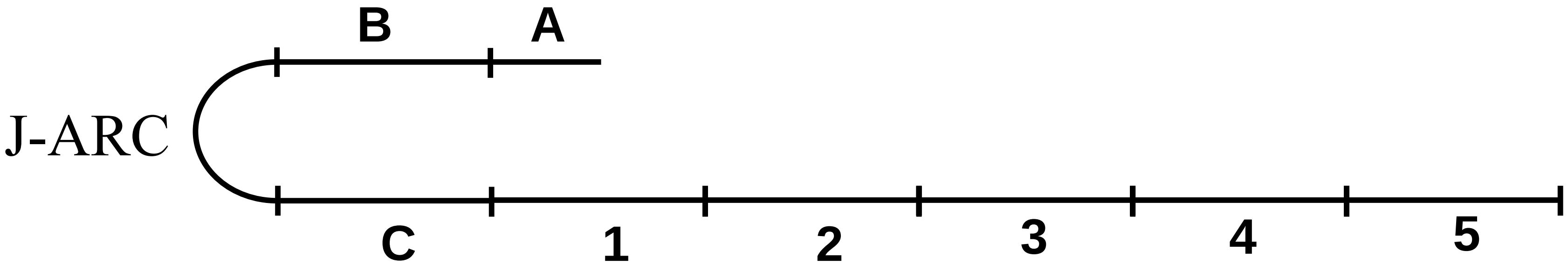
Wire scanner should install more:



Dispersion (R_{16}, R_{36})

- Emittance growth was observed at 1 nC.
- Large dispersion was measured at sector 5.
- Dispersion leak from J-ARC is small by comparing energy change before and after ARC section
- 3～5 sector has small dispersion

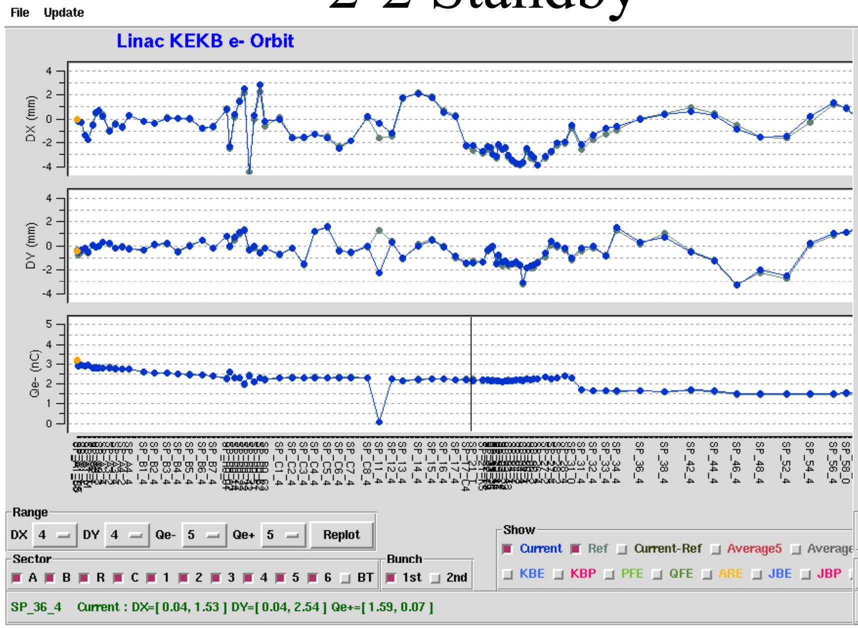
  → Determine the dispersion source



Horizontal Dispersion
(One by one unit standby)

- 1-7 to 2-2 has horizontal dispersion source

2-2 Standby



Range: DX 4, DY 4, Qe- 5, Qe+ 5

Sector: ☒ A ☒ B ☒ R ☒ C ☒ 1 ☒ 2 ☒ 3 ☒ 4 ☒ 5 ☒ 6 ☐ BT

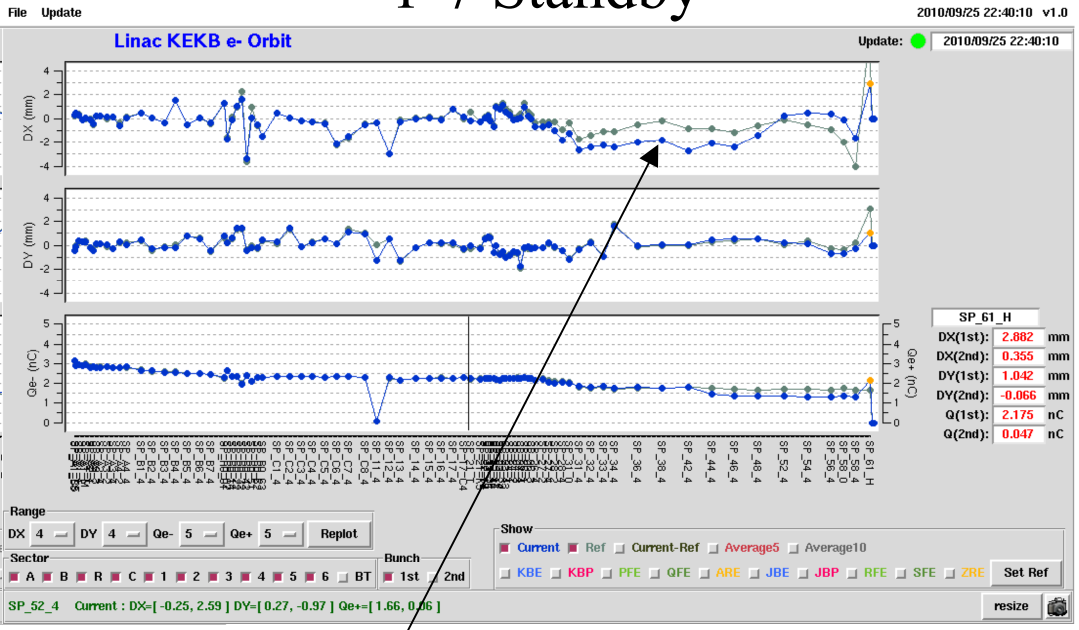
Bunch: ☒ 1st ☐ 2nd

Show: ☒ Current ☒ Ref ☐ Current-Ref ☐ Average5 ☐ Average

☐ KBE ☐ KBP ☐ PFE ☐ QFE ☐ ARE ☐ JBE ☐ JBP

SP_36_4 Current : DX=[0.04, 1.53] DY=[0.04, 2.54] Qe+=[1.59, 0.07]

1-7 Standby



Update: 2010/09/25 22:40:10

SP_61_H

DX(1st): 2.882 mm

DX(2nd): 0.355 mm

DY(1st): 1.042 mm

DY(2nd): -0.066 mm

Q(1st): 2.175 nC

Q(2nd): 0.047 nC

Range: DX 4, DY 4, Qe- 5, Qe+ 5

Sector: ☒ A ☒ B ☒ R ☒ C ☒ 1 ☒ 2 ☒ 3 ☒ 4 ☒ 5 ☒ 6 ☐ BT

Bunch: ☒ 1st ☐ 2nd

Show: ☒ Current ☒ Ref ☐ Current-Ref ☐ Average5 ☐ Average10

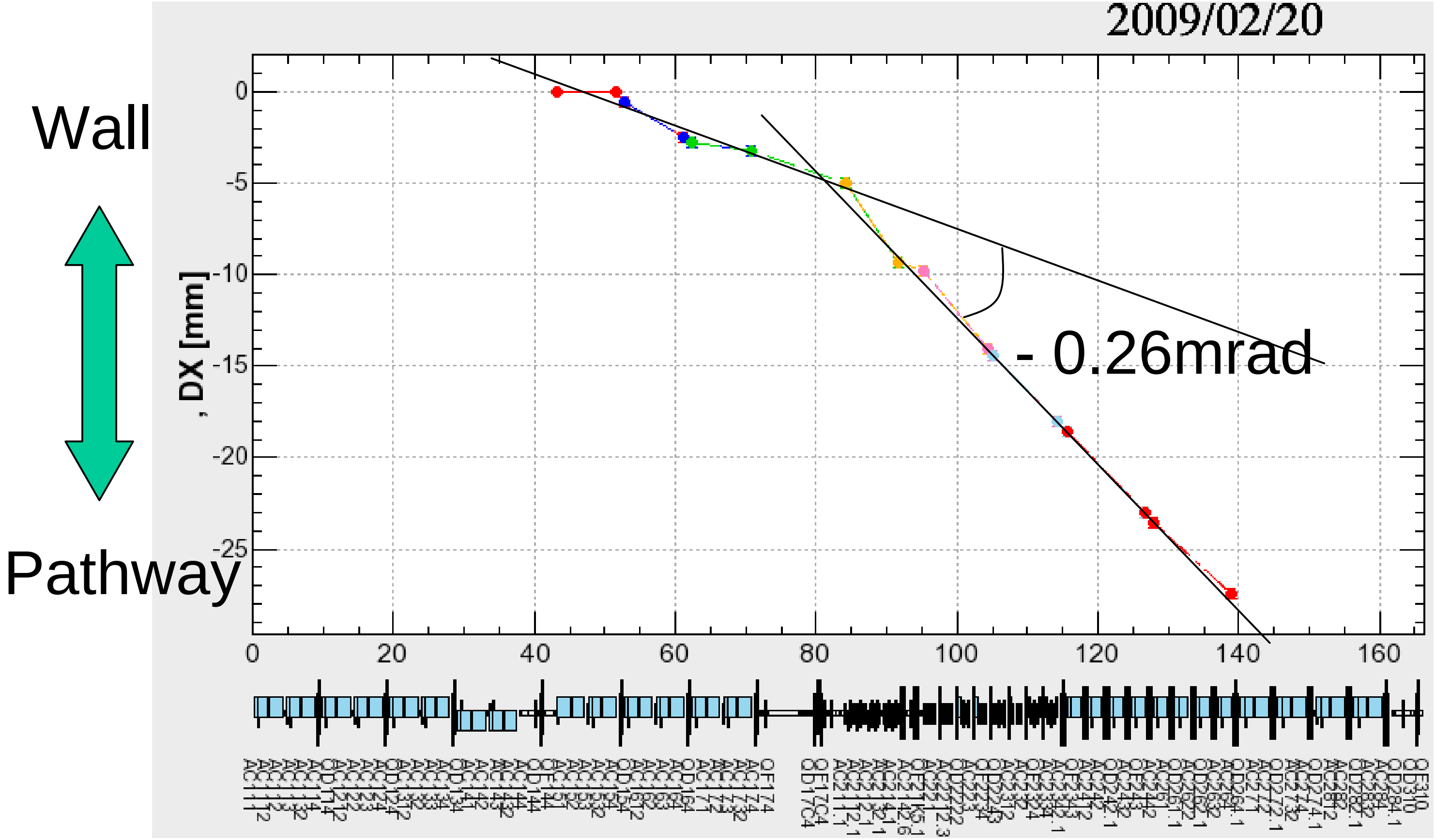
☐ KBE ☐ KBP ☐ PFE ☐ QFE ☐ ARE ☐ JBE ☐ JBP ☐ RFE ☐ SFE ☐ ZRE

SP_52_4 Current : DX=[-0.25, 2.59] DY=[0.27, -0.97] Qe+=[1.66, 0.06]

$\Delta p = 140$ MeV ($p=4$ GeV) → $R_{16} = 50$ mm

➡ Kink at 2-1 was observed before.

Kink of 2-1


2009/02/20

Wall

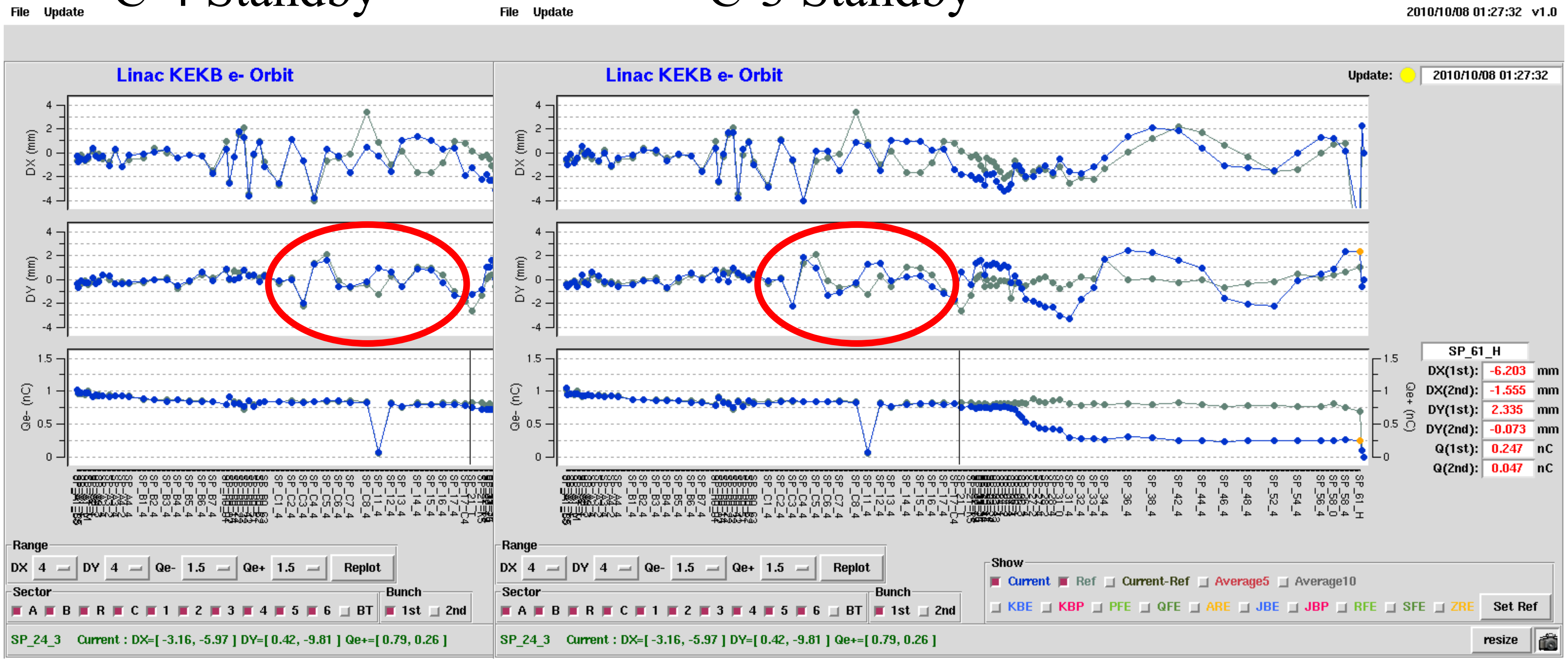
Pathway

- 0.26mrad

Vertical Dispersion
(One by one standby)

C-4 Standby

C-3 Standby



SP_61_H
DX(1st): -6.203 mm
DX(2nd): -1.555 mm
DY(1st): 2.335 mm
DY(2nd): -0.073 mm
Q(1st): 0.247 nC
Q(2nd): 0.047 nC

SP_24_3 Current : DX=[-3.16, -5.97] DY=[0.42, -9.81] Qe+=[0.79, 0.26]

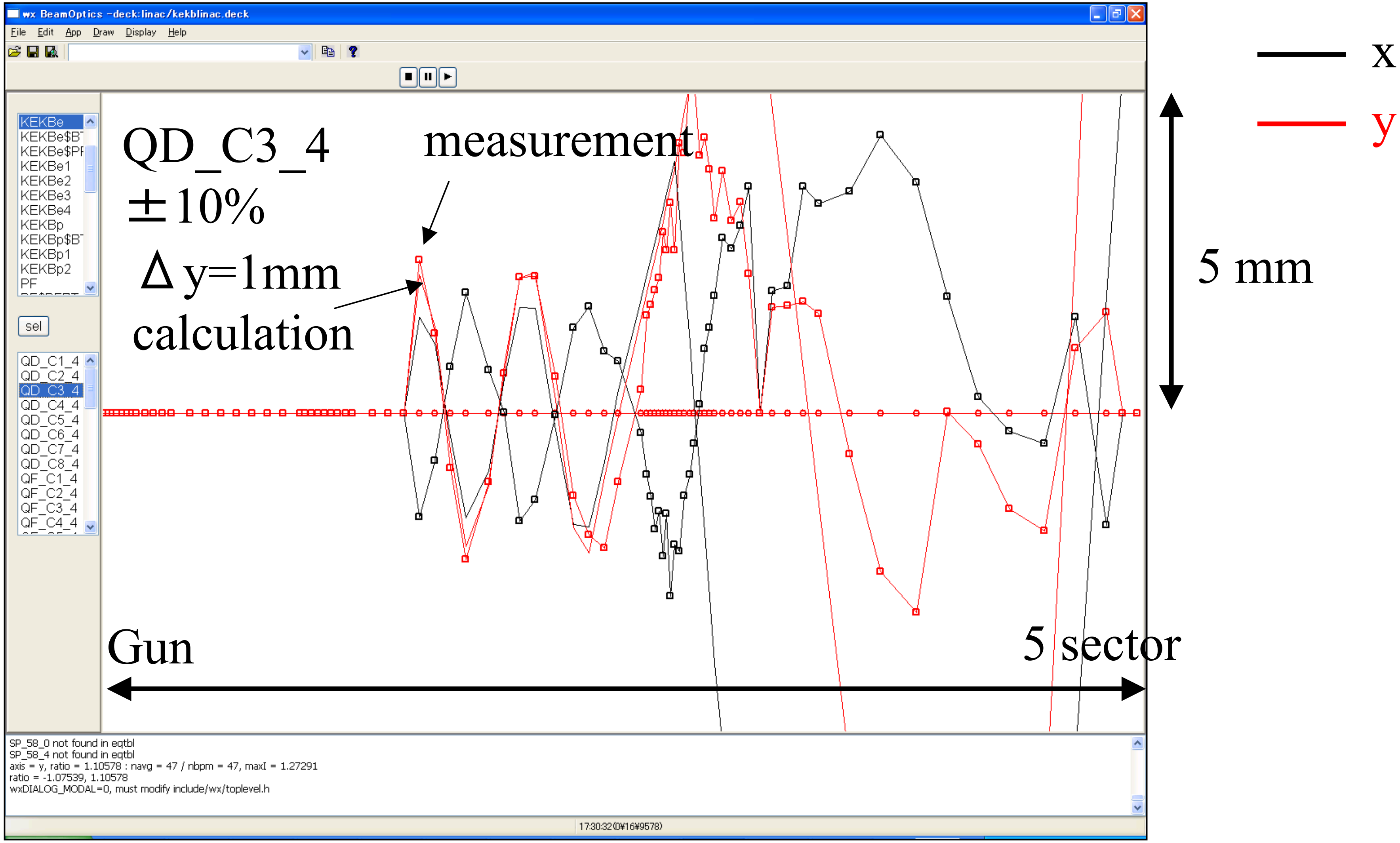
SP_24_3 Current : DX=[-3.16, -5.97] DY=[0.42, -9.81] Qe+=[0.79, 0.26]

→ Building connection between C3 and C4 unit causes 1 mm mis-alignment.

Dispersion source is almost found, but so large dispersion (200mm)

Response measurement

- All magnets : Q, Steering, Sextupole



QD_C3_4

±10%

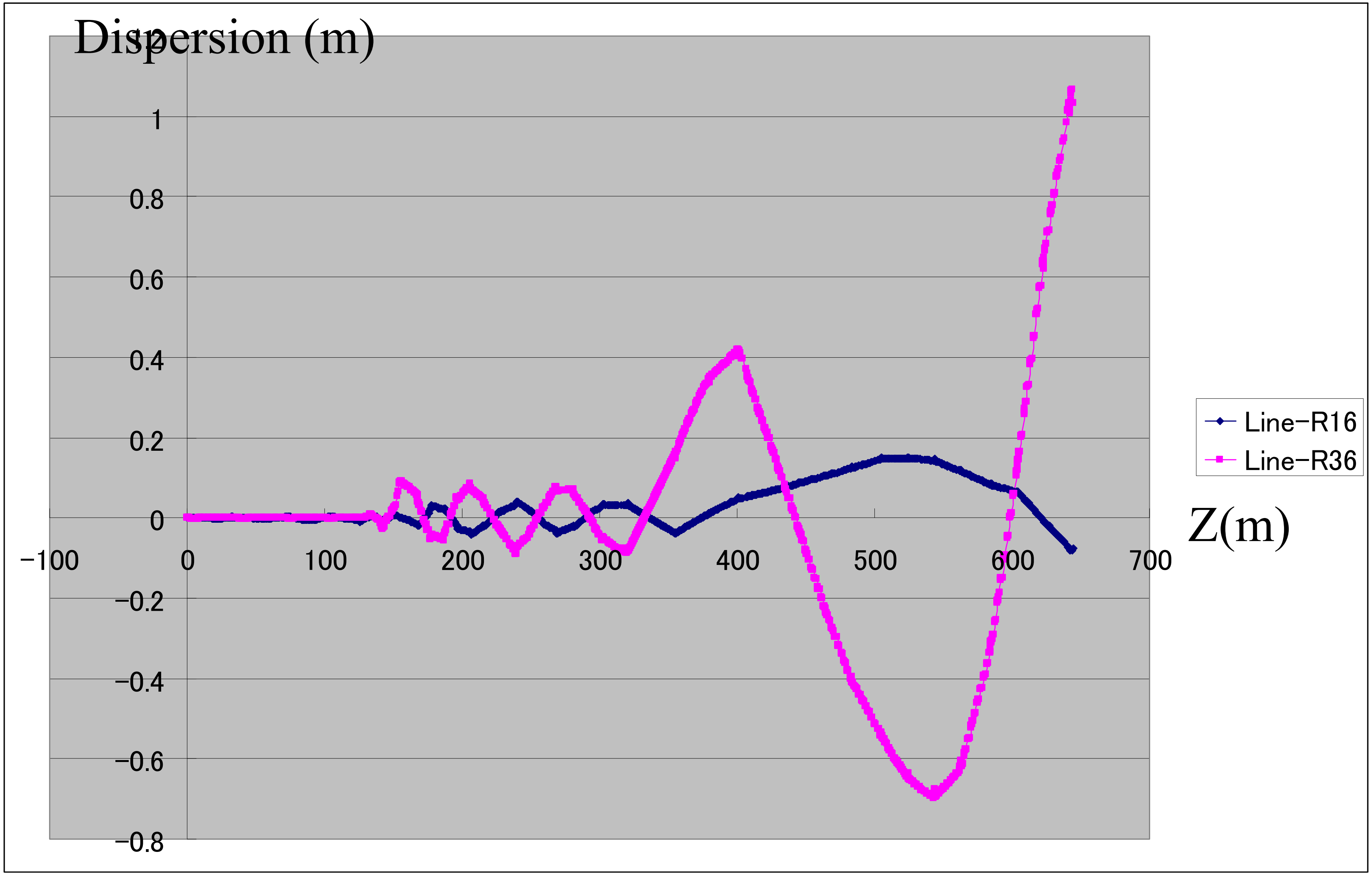
Δy=1mm

measurement

calculation

```
SP_58_0 not found in eqtbl
SP_58_4 not found in eqtbl
axis = y, ratio = 1.10578 : navg = 47 / nbpm = 47, maxI = 1.27291
ratio = -1.07539, 1.10578
wxDIALOG_MODAL=0, must modify include/wx/toplevel.h
```

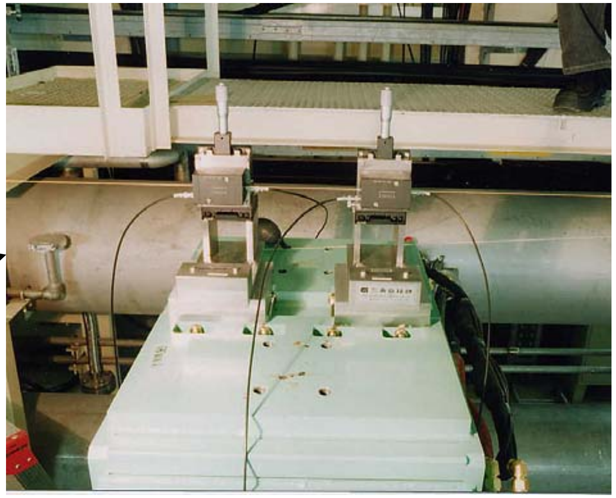
Calculated dispersion from response measurement



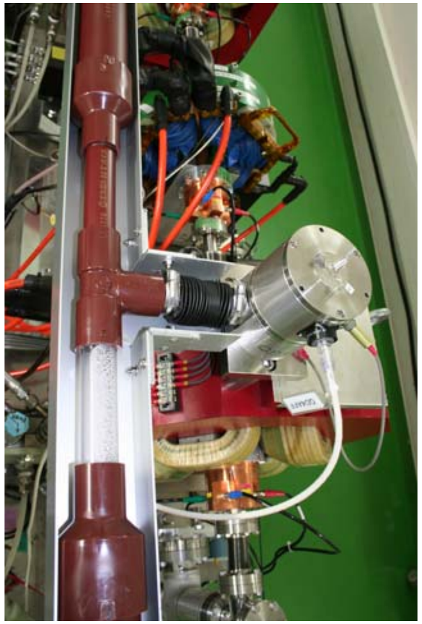
Emittance preservation and compensation

Alignment

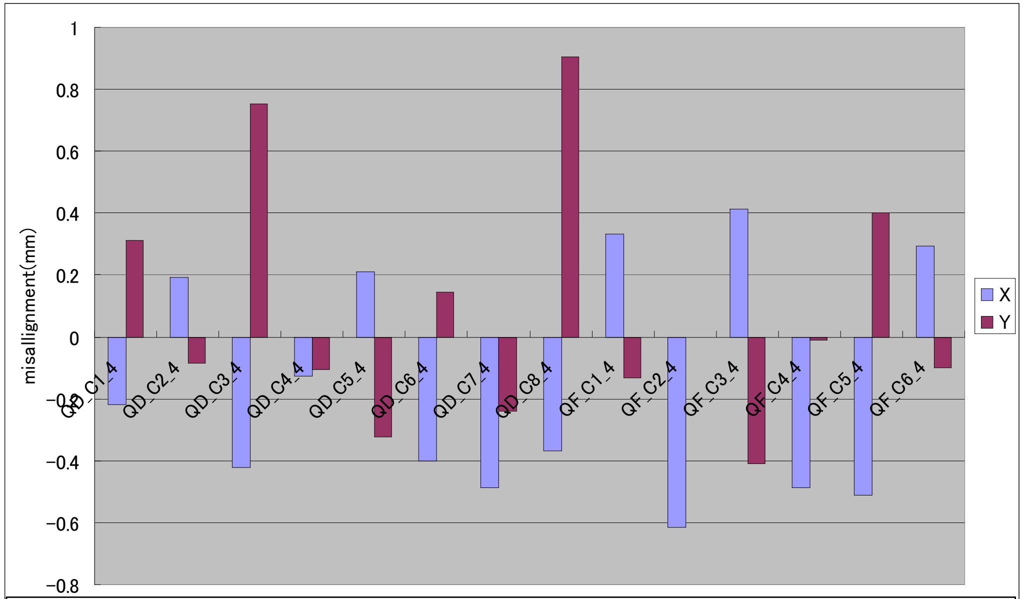
- Conventional alignment
  - Wire positioning for horizontal
  - Hydraulic leveling for vertical
- Beam based alignment
  - Response from all magnets
- Laser alignment
  - R&D for continuous measurement.



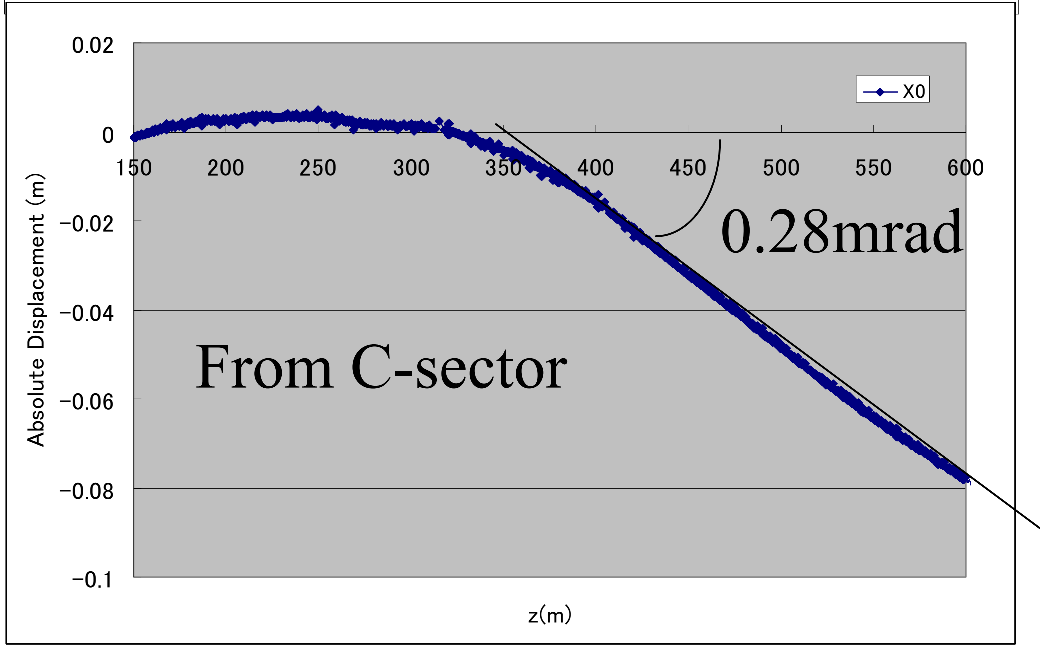
2011.04 => Alignment

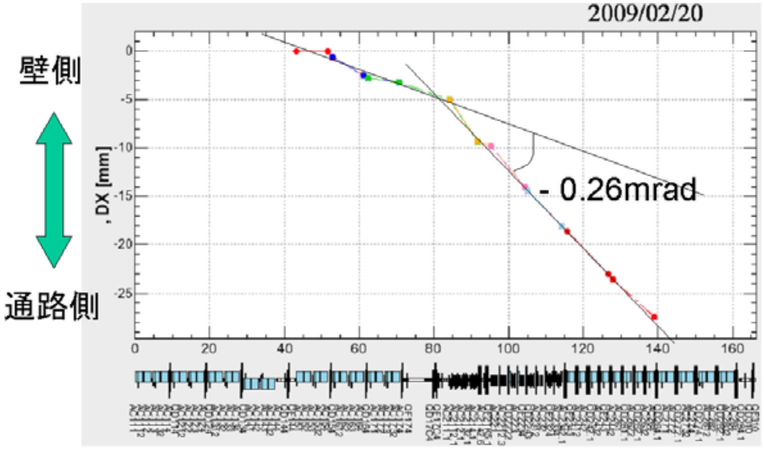


Beam based alignment

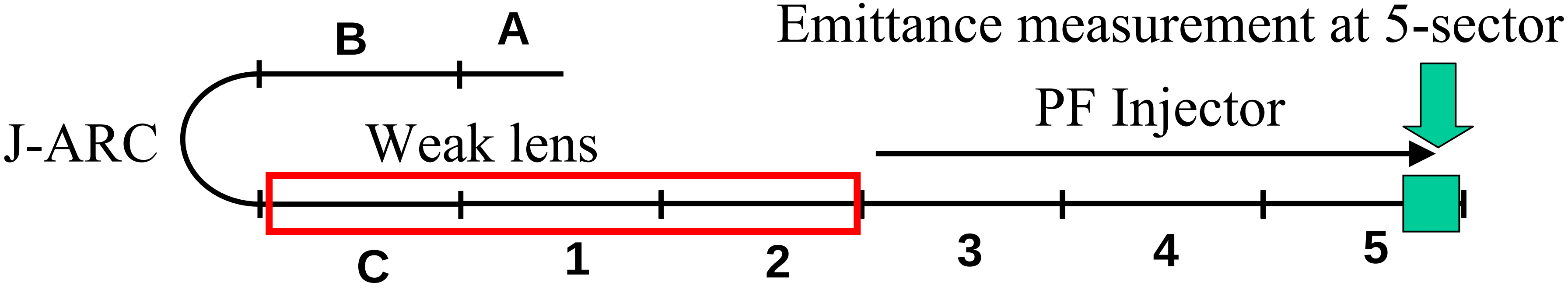


C-sector





Dispersion reduction (Weak lens)

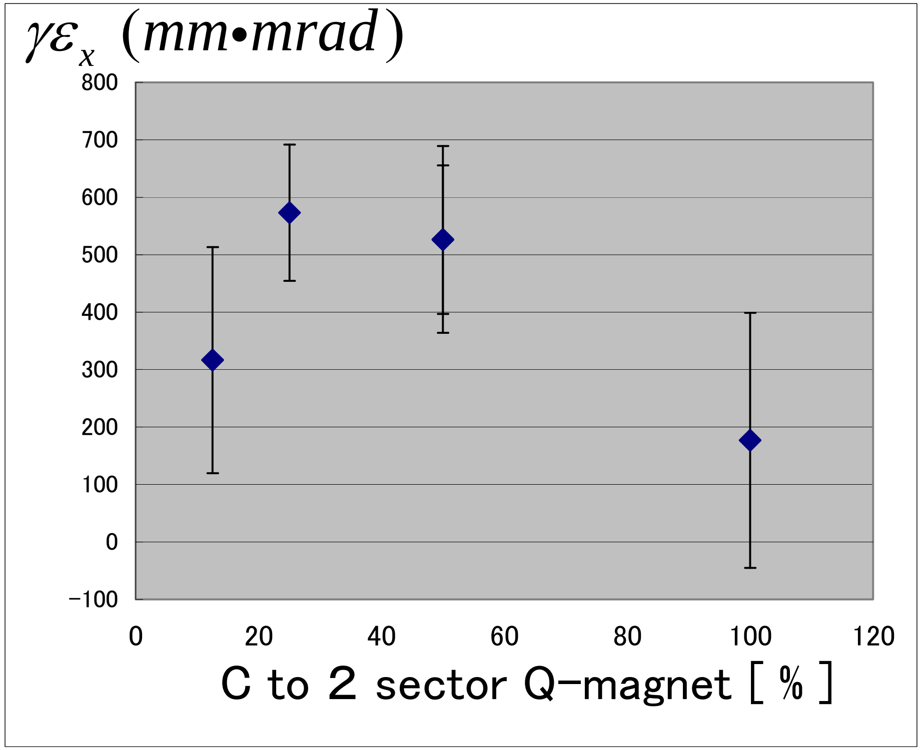


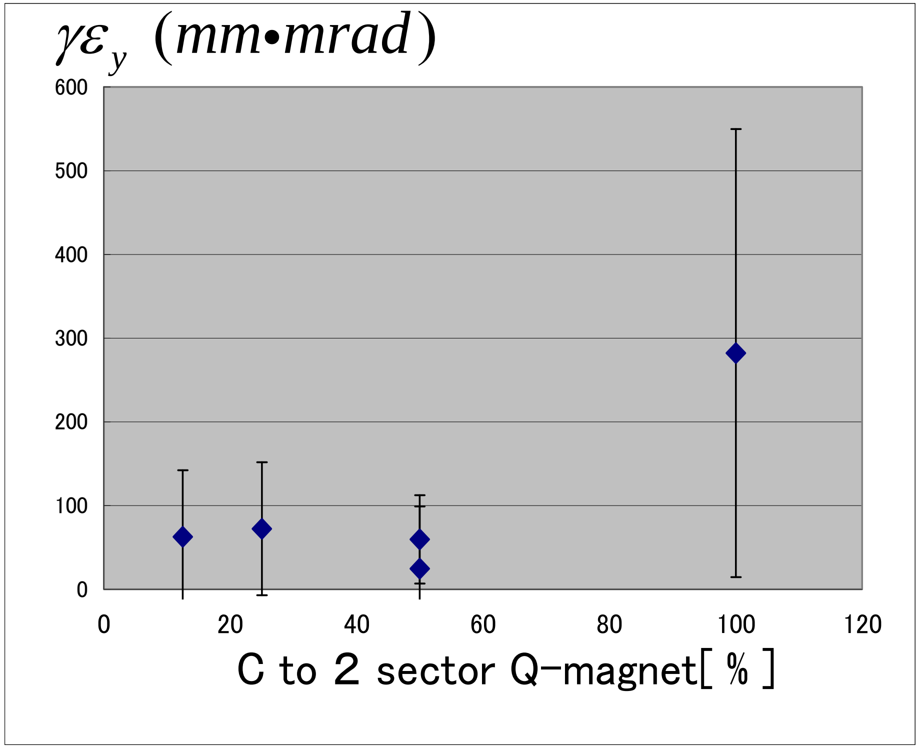
Emittance measurement at 5-sector

J-ARC

Weak lens

PF Injector

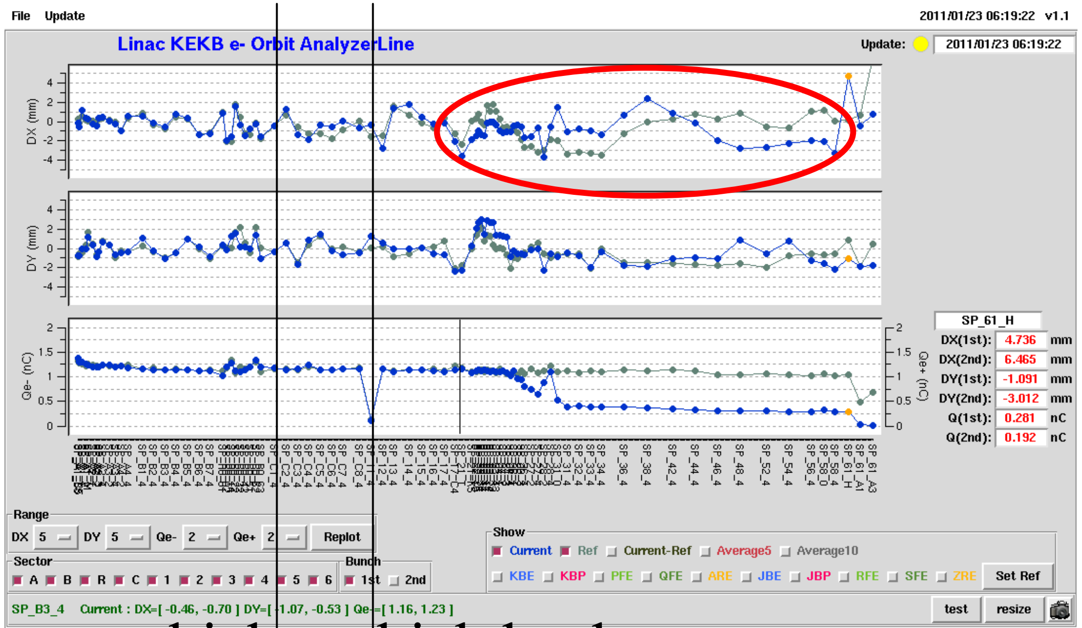




Kink at 2-1 is dominant ?

Quadrupole mis-alignment may be dominant.

Dispersion compensation by beam orbit



2011/01/23 06:19:22 v1.1

Linac KEKB e- Orbit AnalyzerLine

Update: 2011/01/23 06:19:22

SP_61_H

DX(1st): 4.736 mm

DX(2nd): 6.465 mm

DY(1st): -1.091 mm

DY(2nd): -3.012 mm

Q(1st): 0.281 nC

Q(2nd): 0.192 nC

Range: DX 5 DY 5 Qe- 2 Qe+ 2

Sector: ☒ A ☒ B ☒ R ☒ C ☒ 1 ☒ 2 ☒ 3 ☒ 4 ☒ 5 ☒ 6

Bunch: ☒ 1st ☐ 2nd

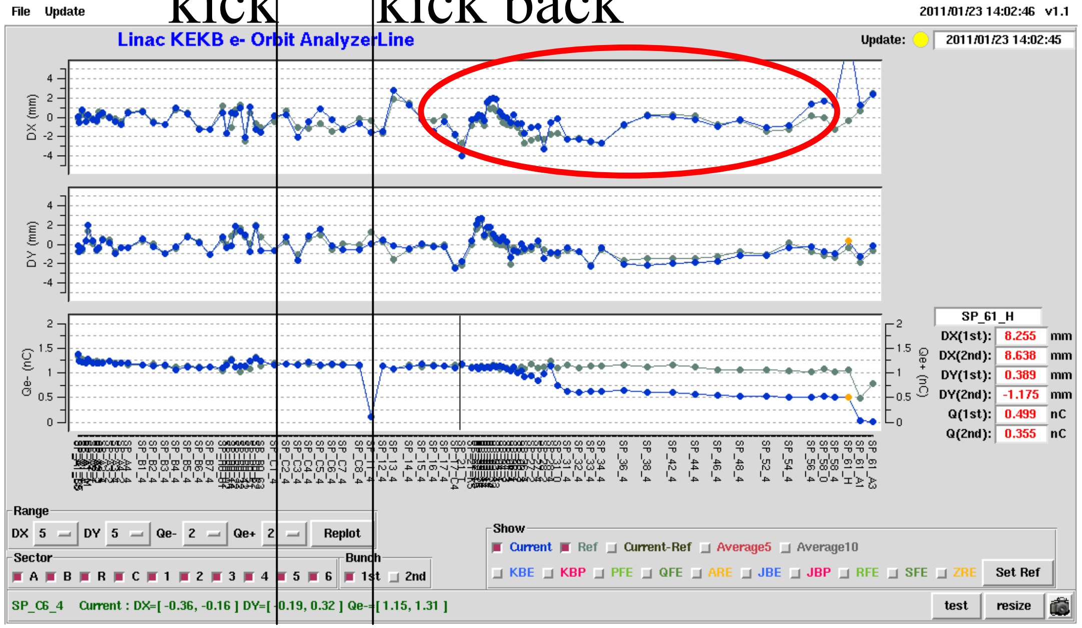
Show: ☒ Current ☒ Ref ☐ Current-Ref ☐ Average5 ☐ Average10

☐ KBE ☐ KBP ☐ PFE ☐ QFE ☐ ARE ☐ JBE ☐ JBP ☐ RFE ☐ SFE ☐ ZRE

SP_B3_4 Current : DX=[-0.46, -0.70] DY=[-1.07, -0.53] Qe-=[1.16, 1.23]

kick

kick back



2011/01/23 14:02:46 v1.1

Linac KEKB e- Orbit AnalyzerLine

Update: 2011/01/23 14:02:45

SP_61_H

DX(1st): 8.255 mm

DX(2nd): 8.638 mm

DY(1st): 0.389 mm

DY(2nd): -1.175 mm

Q(1st): 0.499 nC

Q(2nd): 0.355 nC

Range: DX 5 DY 5 Qe- 2 Qe+ 2

Sector: ☒ A ☒ B ☒ R ☒ C ☒ 1 ☒ 2 ☒ 3 ☒ 4 ☒ 5 ☒ 6

Bunch: ☒ 1st ☐ 2nd

Show: ☒ Current ☒ Ref ☐ Current-Ref ☐ Average5 ☐ Average10

☐ KBE ☐ KBP ☐ PFE ☐ QFE ☐ ARE ☐ JBE ☐ JBP ☐ RFE ☐ SFE ☐ ZRE

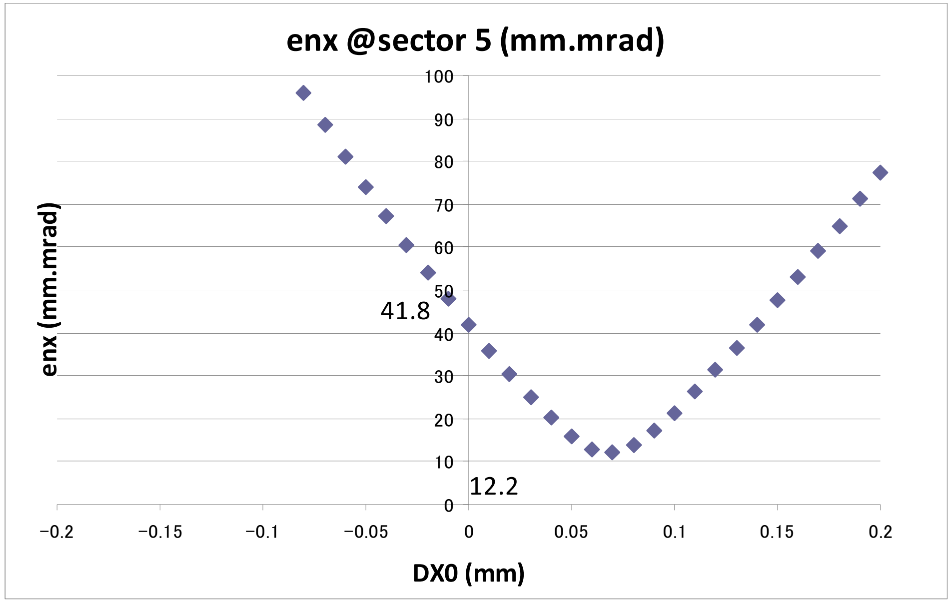
SP_C6_4 Current : DX=[-0.36, -0.16] DY=[-0.19, 0.32] Qe-=[1.15, 1.31]

Reference (green line)

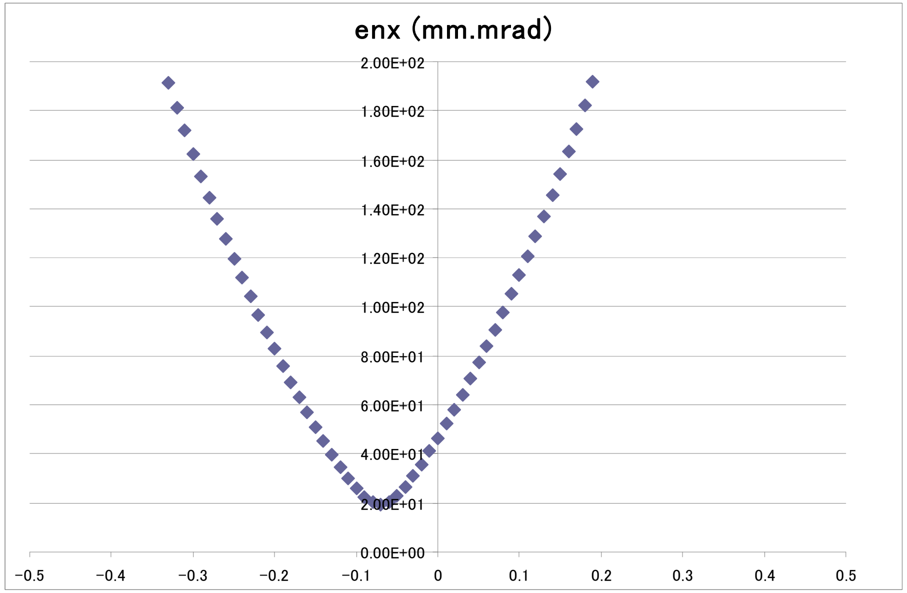
C-1 Standby (blue line)

Short range wakefield
(simulated using ELEGANT)

Charge : 5 nC
Mis-alignment : σ_x=0.5mm
Initial emittance = 10 mm mrad
δ_p : 0.1 %, σ_z : 1mm



Initial offset (mm)



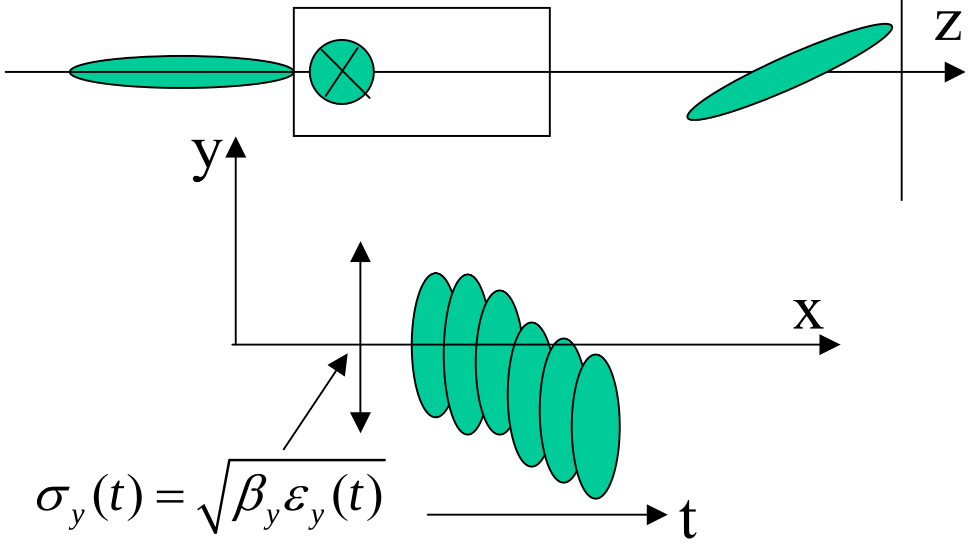
Initial offset (mm)

Beam diagnostic station

RF-Deflector => Longitudinal slice observation.

- Compensation of RF-Emittance
- Measurement of short range wakefield => Initial offset

X-band TM_{110} Cavity Chain



$$\sigma_y(t) = \sqrt{\beta_y \varepsilon_y(t)}$$

$$\Delta x_{screen} = \sqrt{\beta_{deflector}\beta_{screen}}\left(\frac{eV_{deflector}\omega_{RF}\Delta t}{E_{beam}}\right)\sin\left(\phi_{deflector\to screen} = \frac{\pi}{2}\right)$$

$$\sigma_x = \sqrt{\beta_{screen}\varepsilon_{screen}}$$

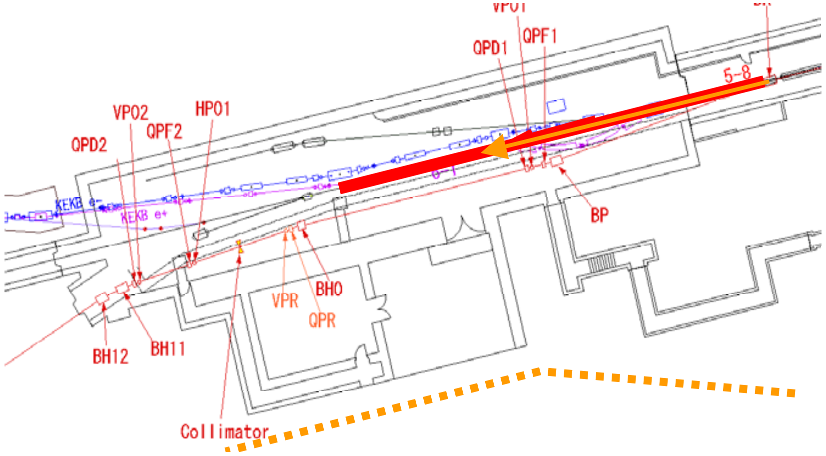
$$\Delta x_{\mathrm{screen}} / \sigma_x = \sqrt{\frac{\beta_{deflector}}{\varepsilon_{screen}}}\left(\frac{eV_{deflector}\omega_{RF}\Delta t}{E_{beam}}\right)$$

$V_{deflector} = 20MV,\ \ f_{RF} = 2.856GHz,\ \Delta t = 1ps,\ \ \beta_{deflector} = 10m$

$\rightarrow \Delta x_{\mathrm{screen}} / \sigma_x = 4$

$V_{deflector} = 50MV,\ \ f_{RF} = 11.424GHz,\ \Delta t = 1ps,\ \ \beta_{deflector} = 10m$

$\rightarrow \Delta x_{\mathrm{screen}} / \sigma_x = 40$



Placed at 3rd switch yard

Summary and plan for machine study

FY2010:

- Improvement for machine study:
  - Agreement of measured and simulated optics.
  - Emittance measurement.
  - Continuous machine study during PF injection.
- Dispersion:
  - Both of measurement and simulation are proceeding.
  - Determine cancellation method as soon as possible.
- Determine alignment tolerance by simulation.

FY2011:

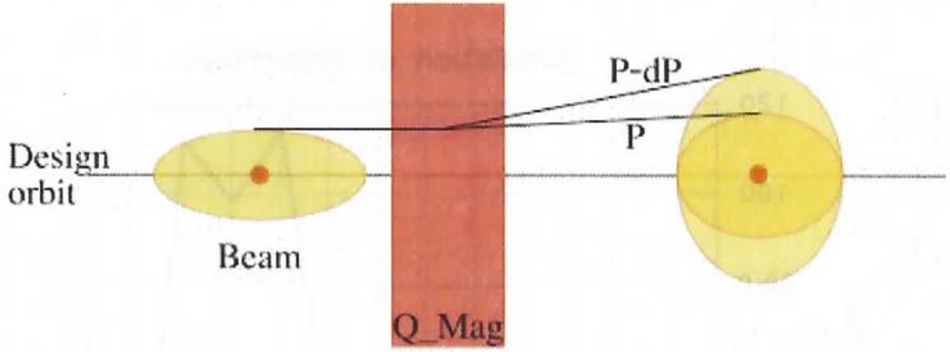
- Alignment (Beam-based & Conventional method)
- Installation of RF-Gun.
  => Emittance measurement using lower emittance beam
- Development of RF-Deflector
  to measure short range wakefield and compensate RF emittance
  => Install by FY2012
- Installation of wire scanner.

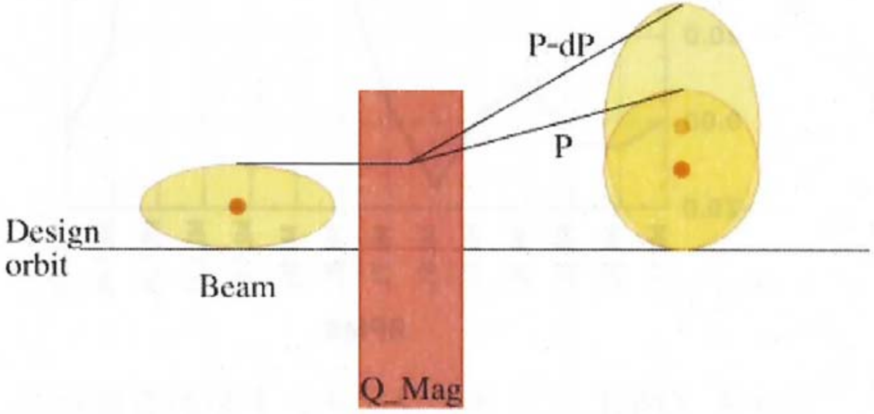
Plan to SuperKEKB injection

- Final Target:
  - Multi-line beam optics control software development
  - Continuous emittance preservation corresponding to emittance measurement during operation.
- Emittance preservation
  - Research for emittance growth
    - Dispersion (Yoshida, Iida)
    - RF emittance (Matsumoto, Yoshida)
    - Short range wakefield (Zang, Sato, Iida(e^+), Yoshida)
    - CSR (Zang, Yoshida)
  - Hardware development for beam diagnostics and compensation
    - X-band RF deflector (Matsumoto, Yoshida)
    - 3rd switch yard – Beam diagnostic station (Sato, Yoshida)
    - Q-magnet with active mover
    - Pulse steering (Kamitani)
  - Alignment
    - Beam based alignment(Yoshida), Laser alignment(Suwada) / Wire + Water pipe (Sugawara)

Appendix:
Emittance source

Apparent emittance growth caused by dispersion





$$K = \frac{eg}{p},\ dx = \frac{dp}{p}\eta_x$$

$$\eta'(s) = 0$$

$$\Delta\varepsilon_{dispersion} = \sqrt{\langle p_x^2\rangle\langle x^2\rangle - \langle p_x x\rangle^2} - \varepsilon_0 = \sqrt{\left(\varepsilon_0\beta_x + (\eta\delta)^2\right)\left(\varepsilon_0\gamma_x + (\eta'\delta)^2\right) - \left(\varepsilon_0\alpha_x + \eta\eta'\delta^2\right)^2} - \varepsilon_0$$

$$(\alpha = 0,\ \beta\gamma = 1 \rightarrow \gamma = \frac{1}{\beta})$$

$$\approx \frac{\eta(s)^2\,\delta(s)^2}{2\langle\beta\rangle} \quad \delta(s): \text{energy spread}$$

$$\delta \sim 0.1\%,\ \beta \sim 50m$$

$$\gamma\Delta\varepsilon \sim 0.016\,mm\cdot mrad\ (for\ \ \eta \sim 10\,mm)$$

$$\gamma\Delta\varepsilon \sim 6.4\ mm\cdot mrad\ (for\ \eta \sim 200mm)$$ <= measured value

$$x(s_B) = R_{11}x(s_A) + R_{12}x'(s_A) + R_{16}\delta(s_A)$$

$$\delta(s_B) = \delta(s_A)\quad for\ given\ acceleration\ phase$$

$$\delta(s_B) = \frac{p(s_A)}{p(s_A)+\Delta p}\delta(s_A)\quad for\ a\ part\ of\ energy\ change$$

$$\begin{pmatrix} R_{11} & \cdots & R_{16} \\ \vdots & \ddots & \vdots \\ R_{61} & \cdots & R_{66} \end{pmatrix}\begin{pmatrix} x \\ \vdots \\ \delta \end{pmatrix}$$

RF emittance caused by coupler of accelerating structure

- Dipole, Quadrupole 2～5 × 10^{-5}

$$E_z = E_0 \sin(\omega t) \sum a_n r^n \cos n\varphi$$

$$\Delta\varepsilon_1 = \frac{eE_0 L}{2m_e c^2 \pi} a_1 \sigma_y \sigma_z$$

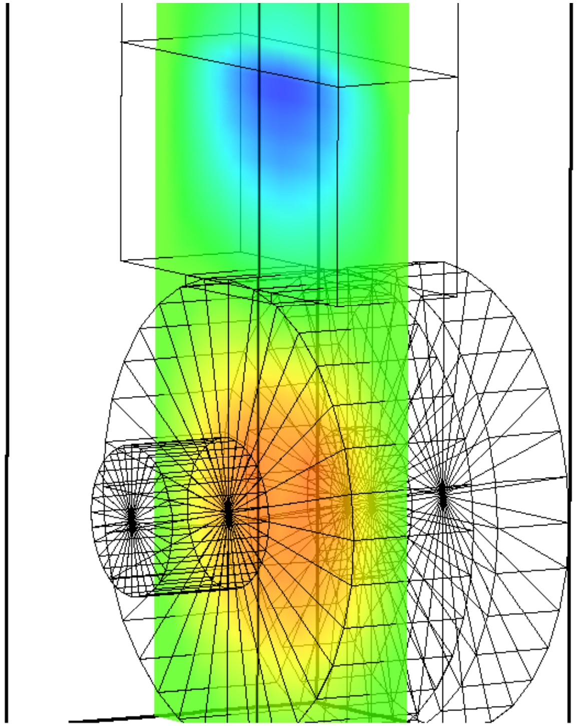
$$\Delta\varepsilon_2 = \frac{eE_0 L}{2m_e c^2 \pi} 2a_2 \sigma_y{}^2 \sigma_z$$

$$E_0 = 17MV/m,\ \ L = 35mm,$$

$$\sigma_y = 2mm,\ \ \sigma_z = 3mm = 10\,ps$$

$$a_1 = 5\times 10^{-5},\ \ 480cell$$

$$\to \Delta\varepsilon_1 = 80\,nm \ \to\ \gamma\Delta\varepsilon = 1.2\ mm\bullet mrad$$



a_1 was determined by simulation

Short Range Wakefield

$$\frac{d}{ds}\left(\gamma(s)\frac{d}{ds}x(z,s)\right)+\left(\frac{2\pi}{\lambda(s)}\right)^2\gamma(s)x(z,s)=\frac{e^2N_e}{m_0c^2}\int_z^\infty\rho(z')W_t^\delta(z'-z,s)x(z',s)dz'$$

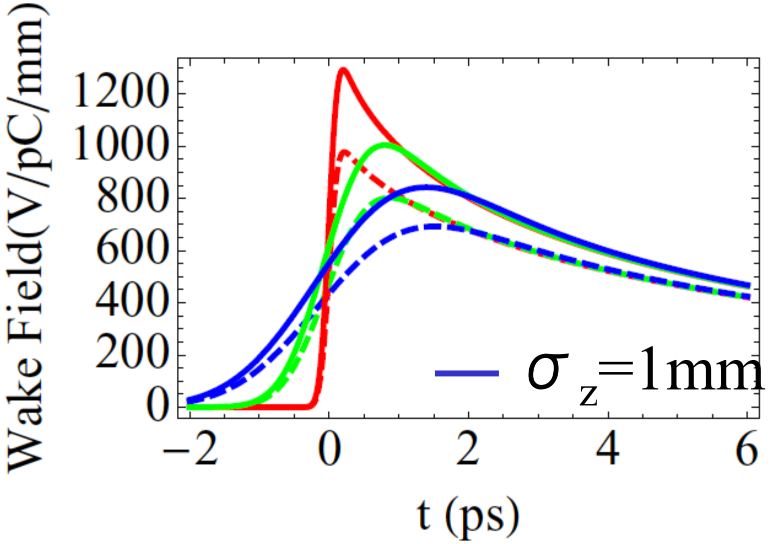
$$W_t(s)=\int\rho(s')W_t^\delta(s-s')ds' \propto \frac{\sqrt{\sigma_z}}{a^3}$$

$$\gamma\Delta\varepsilon_x=\frac{\langle x_{alignment}\rangle^2 L\langle\beta\rangle}{2\gamma(0)G_f}\left(\frac{e^2N_eW_t(z)}{m_0c^2}\right)^2,\quad \gamma(s)=\gamma(0)\left(1+G_fs\right)$$

$$\sigma_z\sim 10\,ps=3mm,\ \langle x_{alignment}\rangle=0.1mm,\ q=5\,nC,\ W_t^\delta(z)=z\times3\times10^{15}\,V/C/m^2$$

$$\gamma(0)=4000,\ G_f=0.01\ \text{(from C sector)}$$

$$\gamma\Delta\varepsilon_x=2.9\,mm\cdot mrad$$

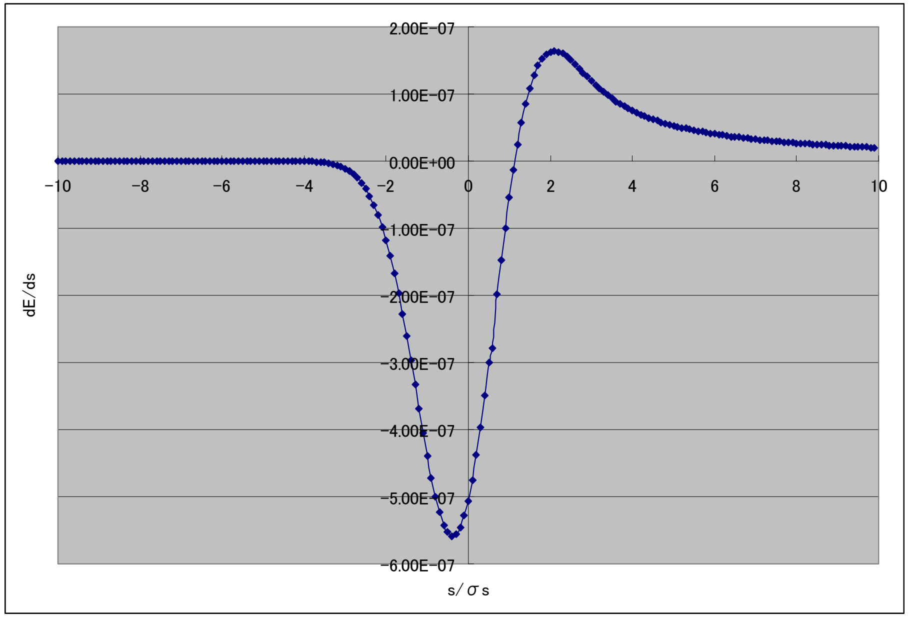


CSR (ARC section)

$$\frac{dE(s)}{ds} = -\frac{1}{\sqrt{2\pi}} \frac{2qe}{\sqrt[3]{3R^2\sigma_z^4}} \int_{-\infty}^{\frac{z}{\sigma_z}} dx \frac{-xe^{-\frac{x^2}{2}}}{\sqrt[3]{\frac{z}{\sigma_z} - x}}$$

$$\sqrt{\left\langle \theta_{rad}{}^2 \right\rangle} \sim \frac{1}{\gamma} \sqrt[3]{\frac{3\sigma_z}{R}}$$

$$= 0.03\, mrad$$



Emittance growth is calculated similar to Dispersion

$$\varepsilon = \sqrt{\left(\varepsilon_0\beta_x + \left(\frac{W\Delta E_{rms}}{E_0}\right)^2\right)\left(\varepsilon_0\gamma_x + \left(\frac{W'\Delta E_{rms}}{E_0}\right)^2\right) - \left(\varepsilon_0\alpha_x + WW'\left(\frac{\Delta E_{rms}}{E_0}\right)^2\right)^2}$$

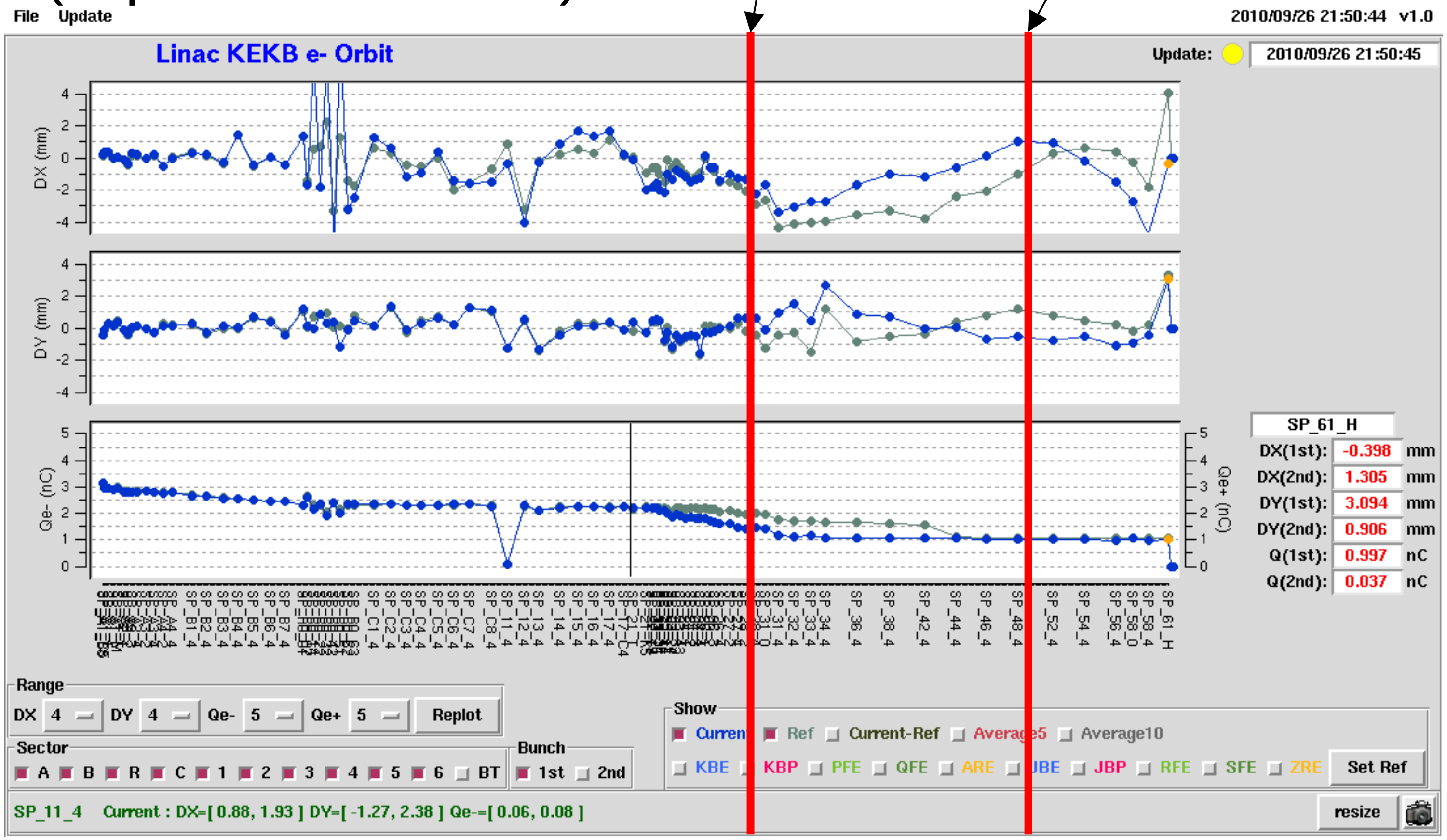
$$= 1.2\ nm$$

$$\gamma\varepsilon = 0.02\ mm \bullet mrad$$

Dispersion (change energy by ARC)

r0_kbe 1.6092 → 1.6249 GeV

($\Delta p = 0.0153$ GeV)



R_{16}= 53 mm

R_{16} = 210 mm

Linac KEKB e- Orbit

2010/09/26 21:50:44 v1.0

Update: 2010/09/26 21:50:45

SP_61_H		
DX(1st):	-0.398	mm
DX(2nd):	1.305	mm
DY(1st):	3.094	mm
DY(2nd):	0.906	mm
Q(1st):	0.997	nC
Q(2nd):	0.037	nC

Range: DX 4, DY 4, Qe- 5, Qe+ 5

Sector: ☒ A ☒ B ☒ R ☒ C ☒ 1 ☒ 2 ☒ 3 ☒ 4 ☒ 5 ☒ 6 ☐ BT

Bunch: ☒ 1st ☐ 2nd

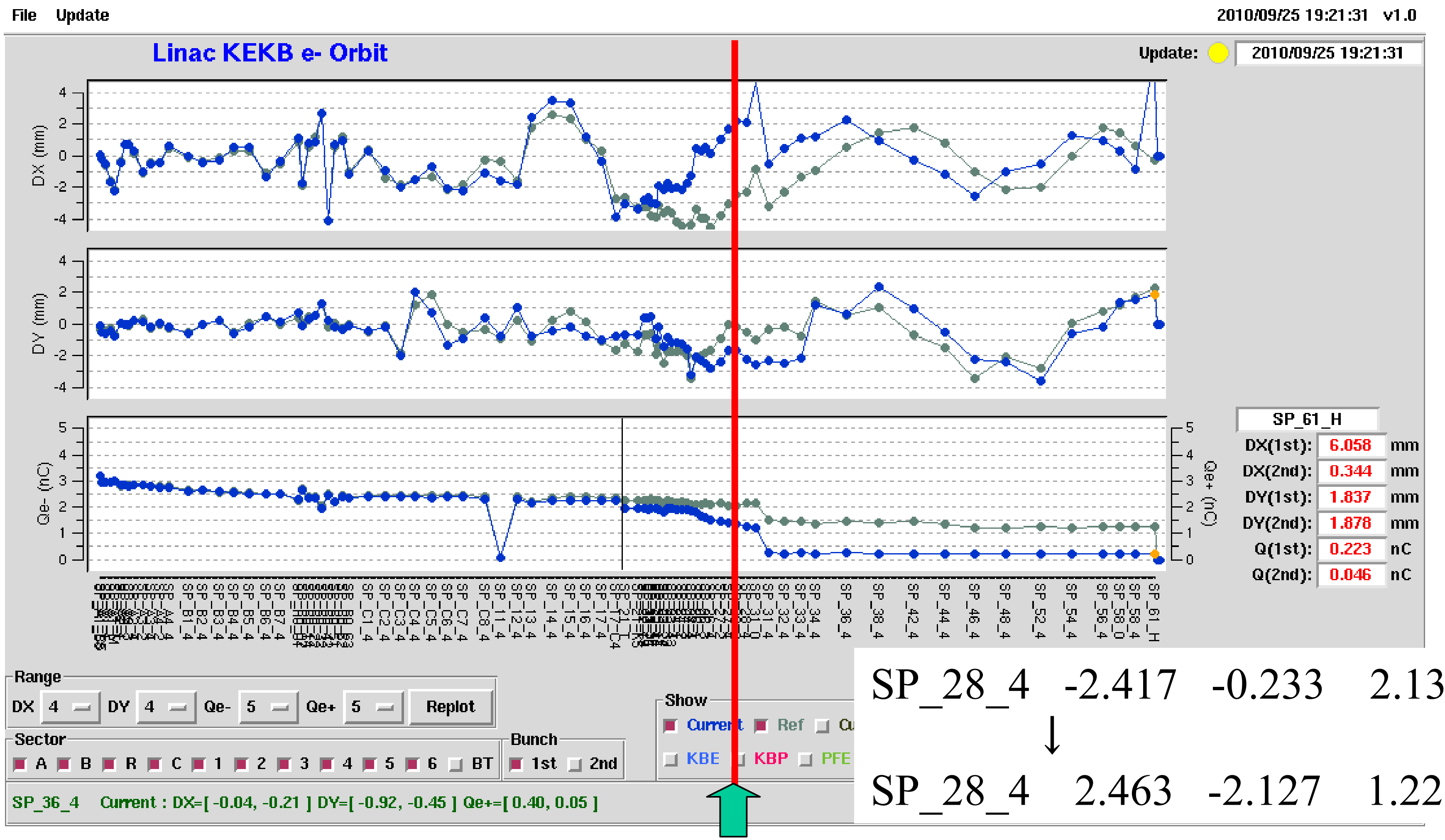
Show: ☒ Current ☒ Ref ☐ Current-Ref ☐ Average5 ☐ Average10

☐ KBE ☐ KBP ☐ PFE ☐ QFE ☐ ARE ☐ JBE ☐ JBP ☐ RFE ☐ SFE ☐ ZRE

SP_11_4 Current : DX=[0.88, 1.93] DY=[-1.27, 2.38] Qe-=[0.06, 0.08]

$$\delta = 0.1\%\ (8\text{ps}),\quad \eta = 210\text{ mm} \quad \Rightarrow \frac{\gamma\eta(s)^2\,\delta(s)^2}{2\langle\beta\rangle} \sim 30\, mm \cdot mrad$$

C-1 Standby での Dispersion



SP_61_H

DX(1st):	6.058	mm
DX(2nd):	0.344	mm
DY(1st):	1.837	mm
DY(2nd):	1.878	mm
Q(1st):	0.223	nC
Q(2nd):	0.046	nC

SP_36_4 Current : DX=[-0.04, -0.21] DY=[-0.92, -0.45] Qe+=[0.40, 0.05]

SP_28_4	-2.417	-0.233	2.139
	↓		
SP_28_4	2.463	-2.127	1.220

R_{16} = 5mm / (160MeV/1.6GeV) = 50 mm @ 2-8

R_{36} = 2mm / (160MeV/1.6GeV) = 20 mm @ 2-8

Same as r0_kbe → J-ARC dispersion is not large.

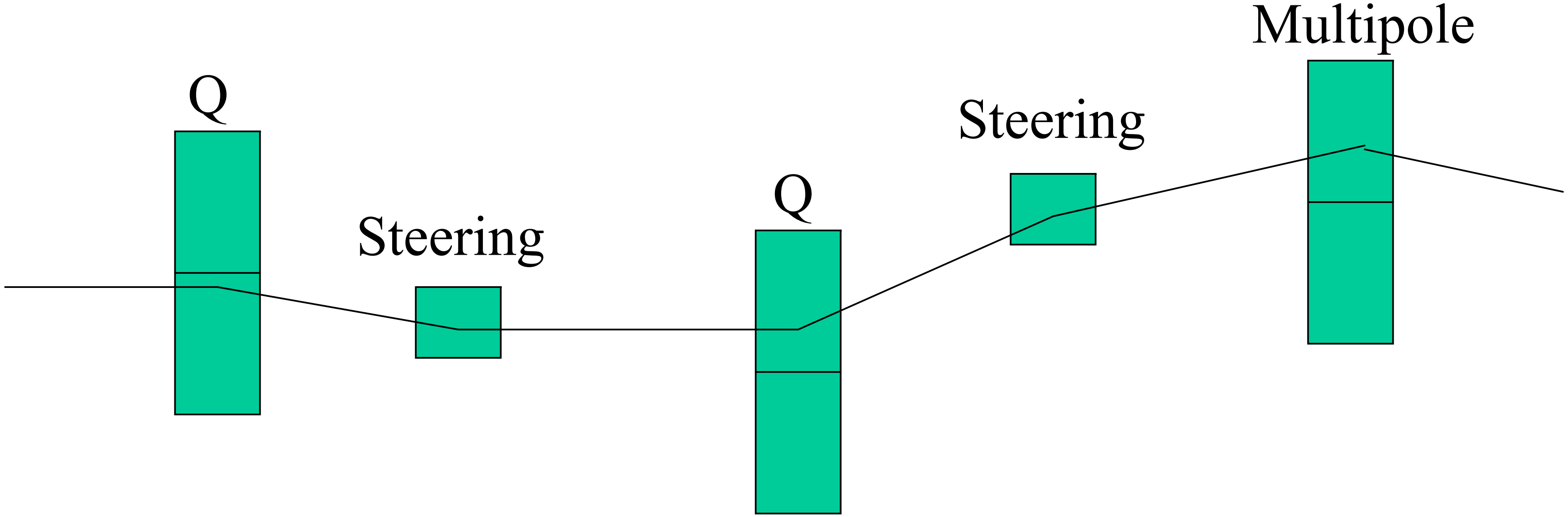
Injector control software for SuperKEKB

- Multi-line / Multi-bunch : orbit & dispersion compensation
- Continuous measurement using study mode

⬇

- Response measurement for all magnets.
  → Paraxial & reference orbit measurement
    → Beam based alignment / Dispersion

Paraxial and reference orbit



Transfer matrix

$$\begin{pmatrix} X \\ X' \\ \vdots \end{pmatrix} = M \begin{pmatrix} X \\ X' \\ \vdots \end{pmatrix} + \begin{pmatrix} O_0 \\ O'_0 \\ \vdots \end{pmatrix},$$

$$x = X - X_0,\ x' = X' - X'_0$$

$$\begin{pmatrix} x \\ x' \\ \vdots \end{pmatrix} = \underline{M_{paraxial}} \begin{pmatrix} x \\ x' \\ \vdots \end{pmatrix}$$

Paraxial

Reference matrix

$$\begin{pmatrix} X_0 \\ X'_0 \\ \vdots \end{pmatrix} = \underline{M_{ref}} \begin{pmatrix} X_0 \\ X'_0 \\ \vdots \end{pmatrix} + \underline{\begin{pmatrix} x_0 \\ x'_0 \\ \vdots \end{pmatrix}}$$

↓ calculation

$$\begin{pmatrix} X \\ X' \\ \vdots \end{pmatrix} = M_{paraxial} \begin{pmatrix} x \\ x' \\ \vdots \end{pmatrix} + M_{ref} \begin{pmatrix} X_0 \\ X'_0 \\ \vdots \end{pmatrix} + \begin{pmatrix} x_0 \\ x'_0 \\ \vdots \end{pmatrix}$$

$$= M_{paraxial} \begin{pmatrix} X \\ X' \\ \vdots \end{pmatrix} + \left(M_{ref} - M_{paraxial} \right) \begin{pmatrix} X_0 \\ X'_0 \\ \vdots \end{pmatrix} + \begin{pmatrix} x_0 \\ x'_0 \\ \vdots \end{pmatrix}$$

Emittance measurement

⇩ Recent modification of fitting program for the wire scanner