Design of 200MeV KEK-ERL Test facility by using SAD

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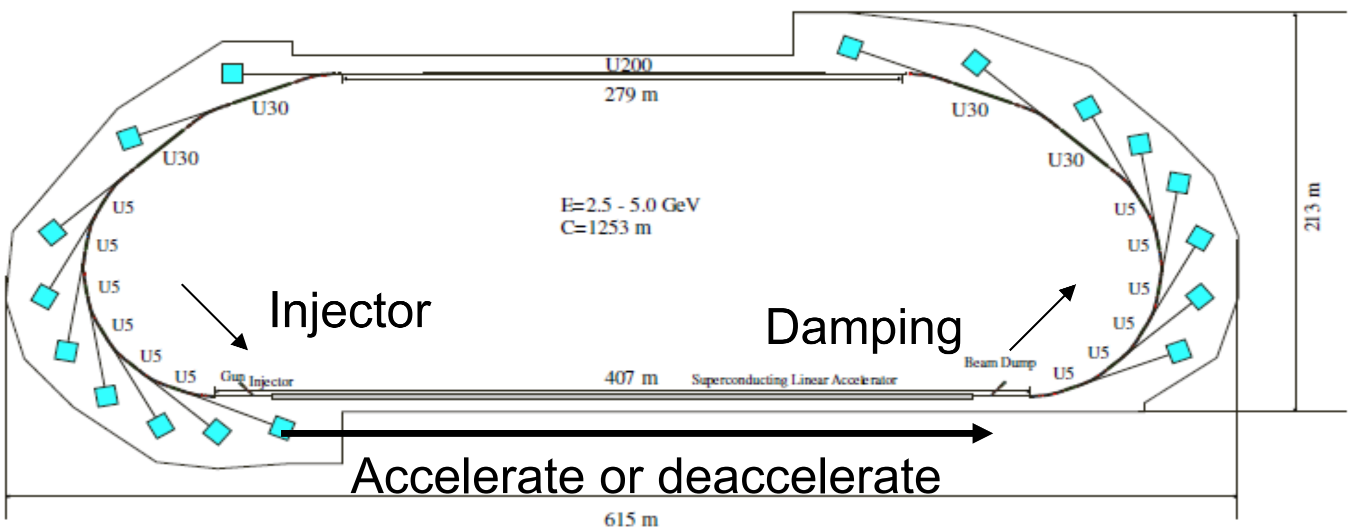
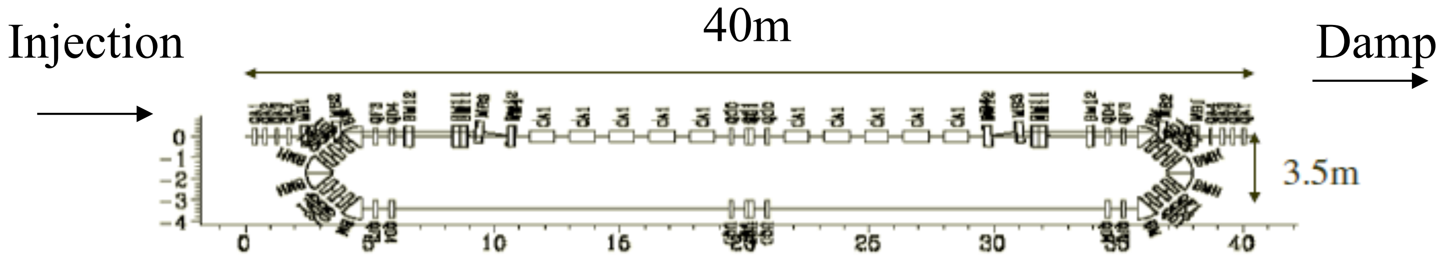
Energy Recovery Linac (ERL)

- Beam energy were recovered and putted into the following bunch
  - High coherency, low emittance and short bunch beam

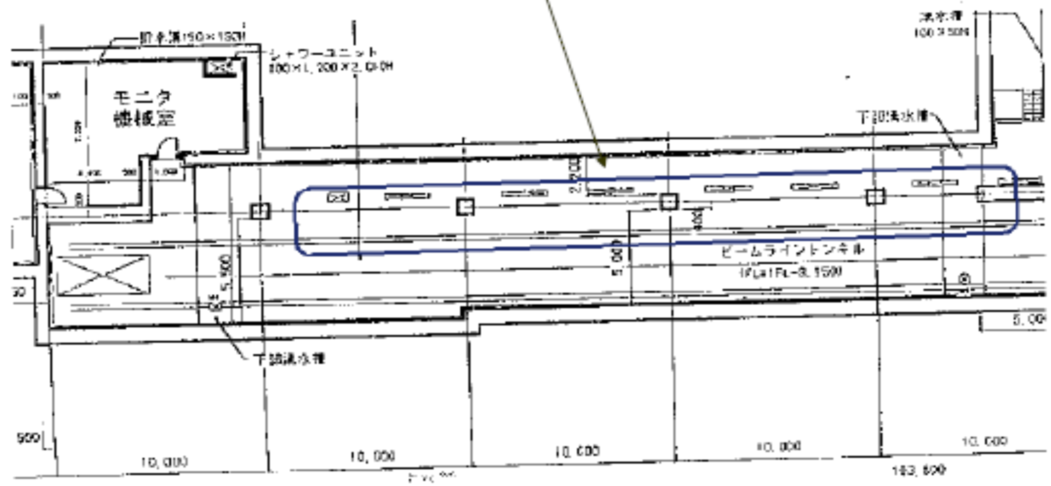


5GeV ERL planned by KEK

Plan of 200MeV KEK-ERL Test Facility
(～2005 year)

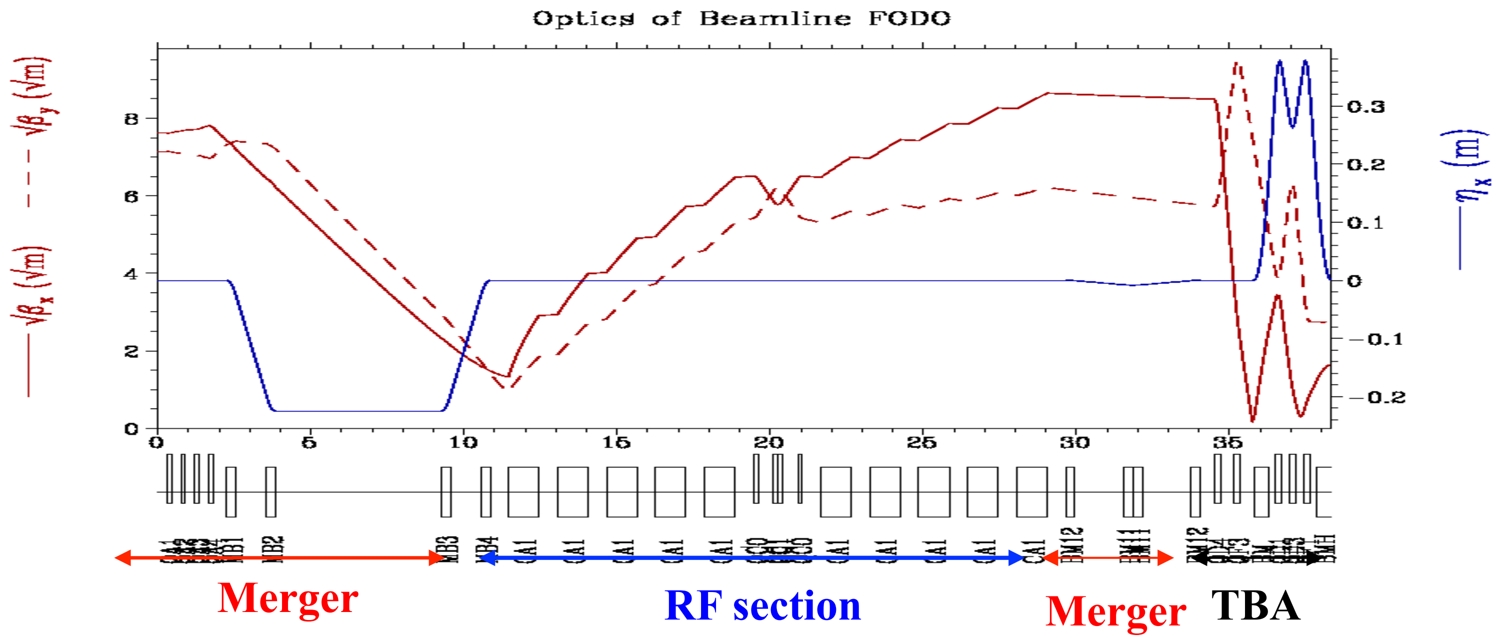


設計条件:陽子加速器棟に収納可能なこと

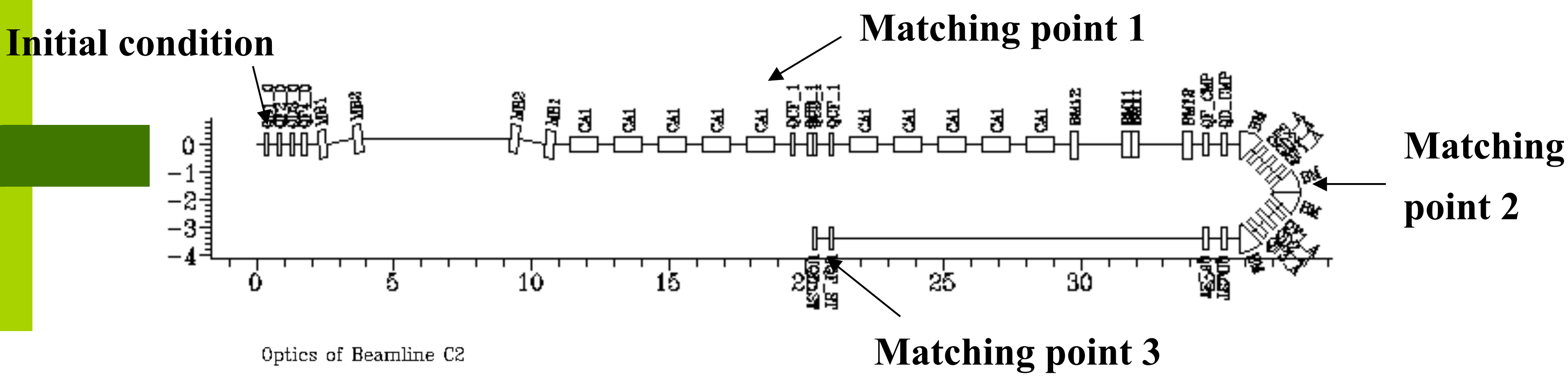


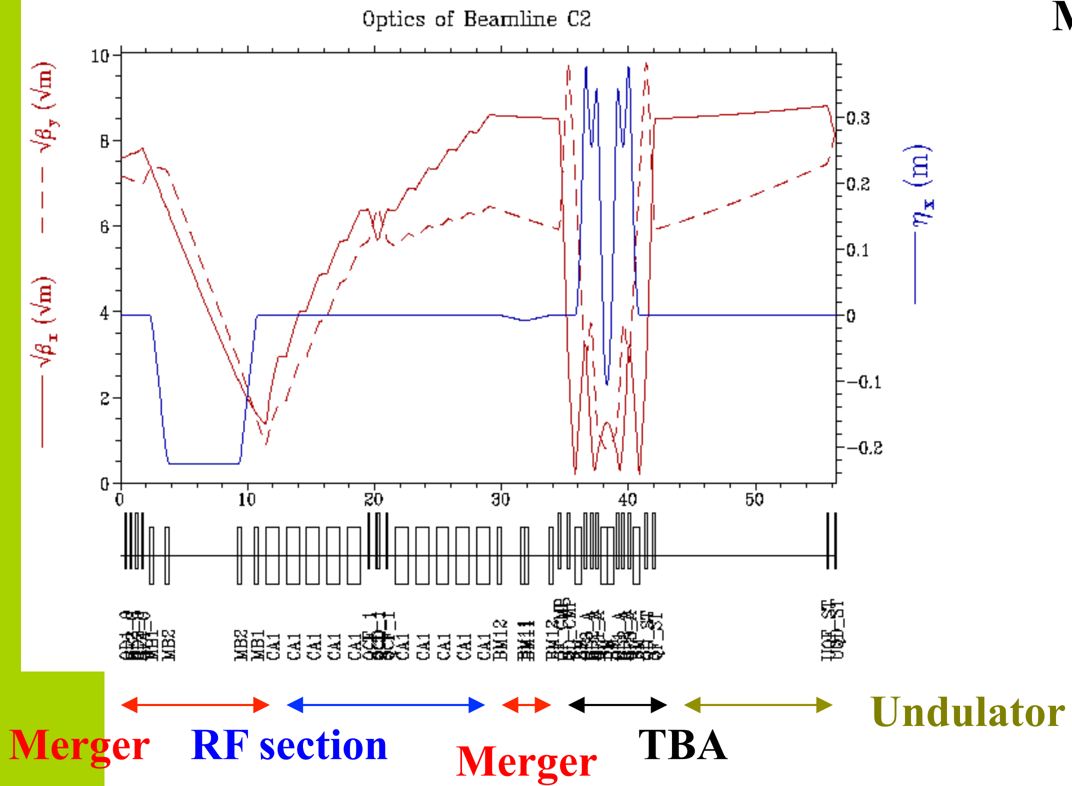
Merging optics

- The merging optics comprise
  - 4 quadrupoles — for matching the injector lattice functions into the linac
  - 4 dipoles — chicane for merging the injector to main linac.



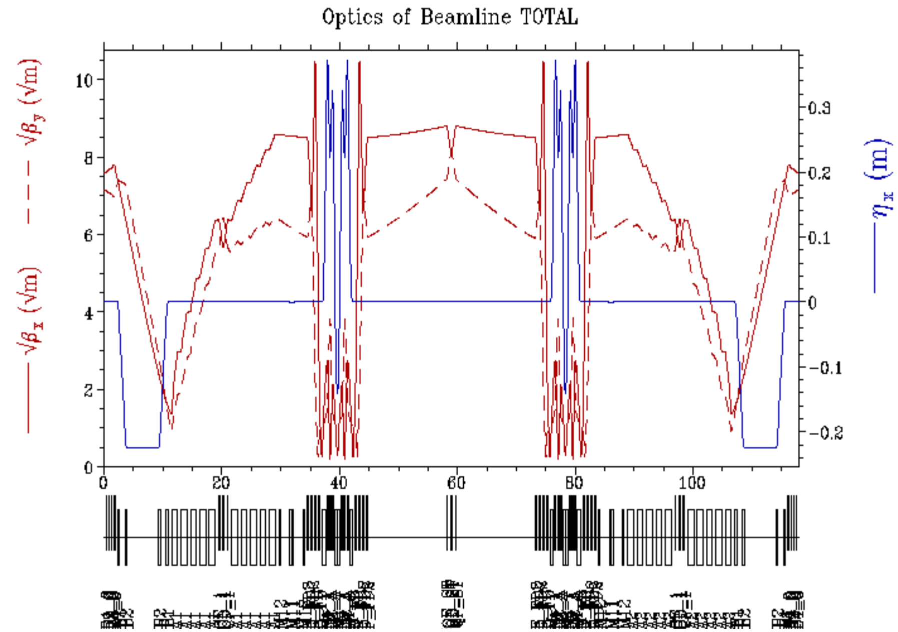
Optics up to the insertion devices

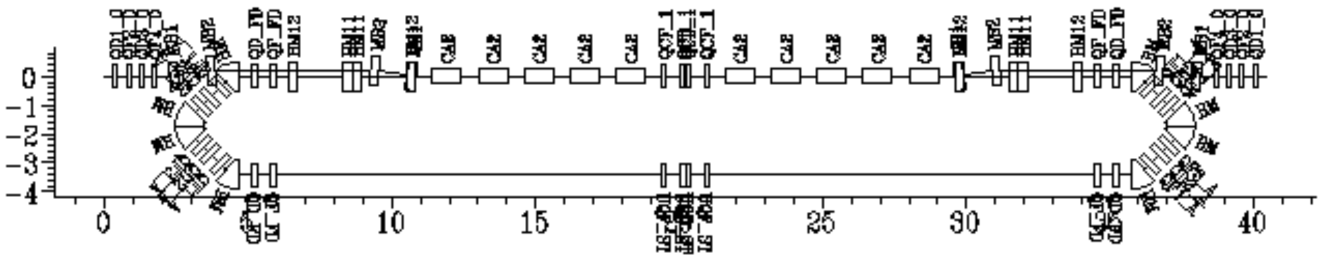




- Initial condition
  b_x=58m, b_y =51m,
  a_x=a_y =0, h_x=h_y=h'_x=h'_y=0
- Matching point 1, 3
  a_x=a_y =0, h_x=h_y=h'_x=h'_y=0
- Matching point 2
  a_x=a_y =0, h_x=h_y=h'_x=h'_y=0

Lattice of 200MeV KEK-ERL Test Facility





Parameters of ERL Test Facility

• Max. beam energy :	205 MeV
• Max. average beam current :	100 mA
• Max. bunch charge :	77 pC
• Operating frequency :	1.3 GHz
• Normalized transverse emittance (x/y) :	100 nm rad
• Rms bunch length :	1 ps $\rightarrow$ 0.1ps
• Rms energy spread :	5×10^{-5}
• RF cavity gradient :	20 MV /m
• Injection beam energy :	5 MeV
• R_{56} in one TBA :	-0.7 ~ 0.0

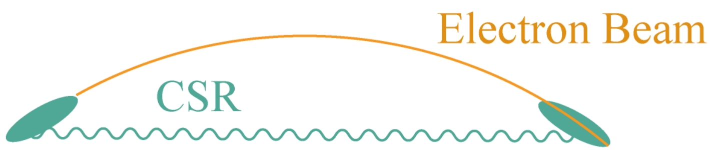
Required beam quality

- Small normalized emittance $e_{pnx} <$ 100nm rad
- Short bunch $s_z \sim$ 0.1 psec
- High current $\sim$ 100mA
- High efficiency energy recovery

etc

- Simulation
  1. Emittance growth due to Coherent Synchrotron Radiation (CSR) at the chicane with low energy (Kim *et al*)
  2. Emittance growth due to HOMs in multi-bunch (Kim *et al*)
  3. Emittance growth in the arc section for bunh compression
  4. Efficiency of beam energy recover after bunch compression

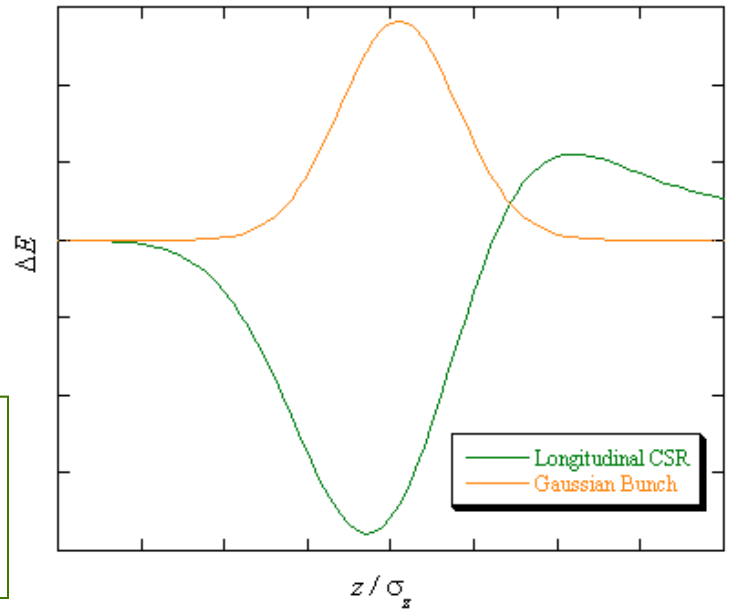
Emittance growth due to CSR wake



$$\frac{dE(z)}{dz} = -\frac{1}{\sqrt{2\pi}} \frac{2q}{(3\rho^2\sigma_z^4)^{1/3}} F(z/\sigma_z),$$

$$F(x) = \int_{-\infty}^{\xi} \frac{d\xi}{(x-\xi)^{1/3}} \frac{\partial}{\partial \xi} e^{\xi^2/2},$$

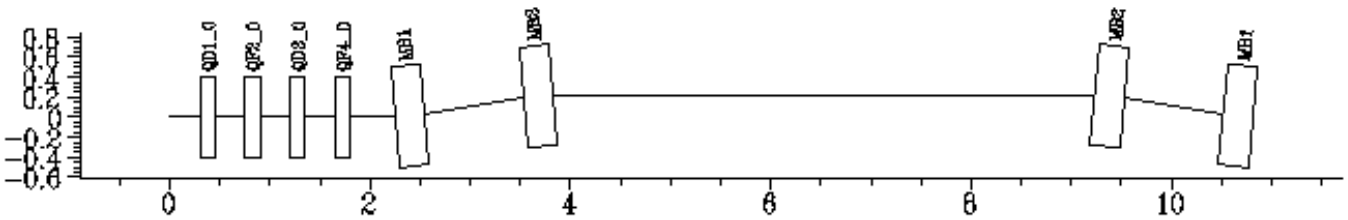
r : bending radius
s_z : rms bunch length
q : charge per bunch



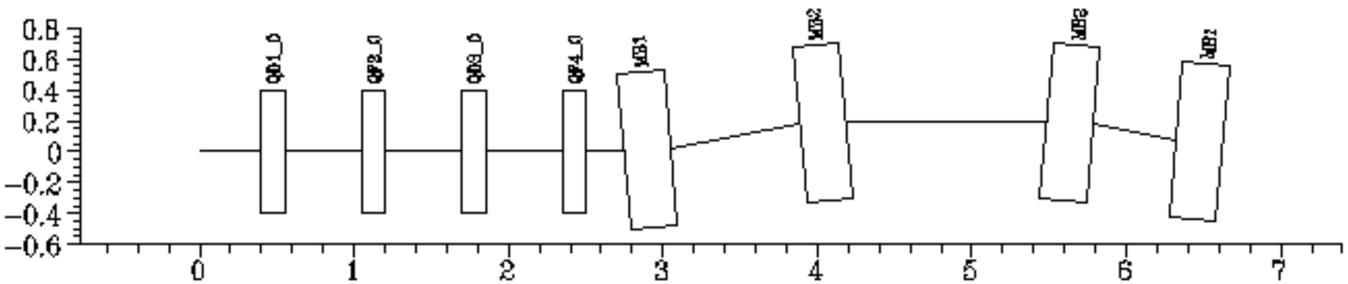
- Emittance growth caused by the aberration from the nominal orbit by the energy change due to coherent synchrotron radiation (CSR).

1. Optimization of the optics of the merger (Kim *et al*)

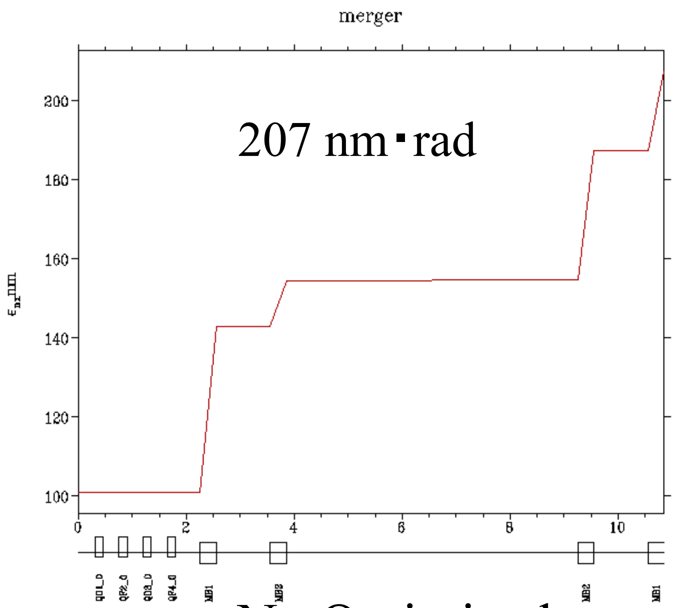
Bending angle in merging dipoles should be as small as possible to minimize the influence of CSR on the beam emittance.



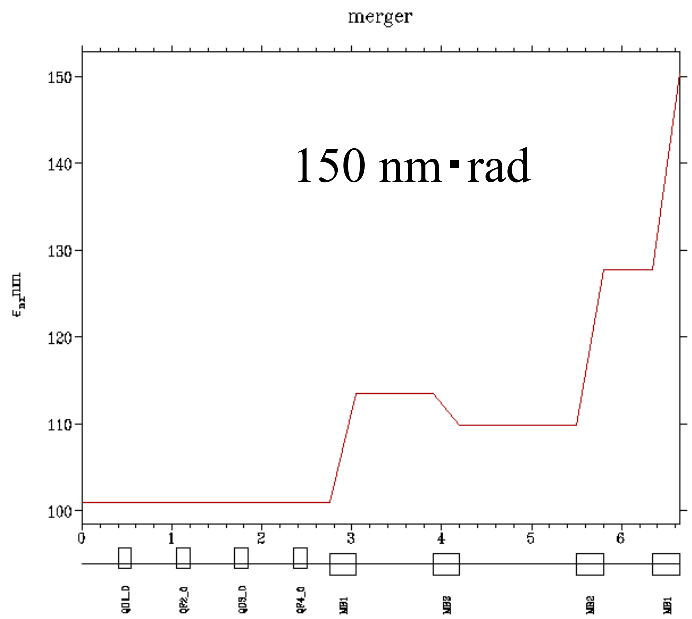
Minimization of Emittance growth



Optimization of the merger section for minimization of the emittance growth due to CSR



No Optimized



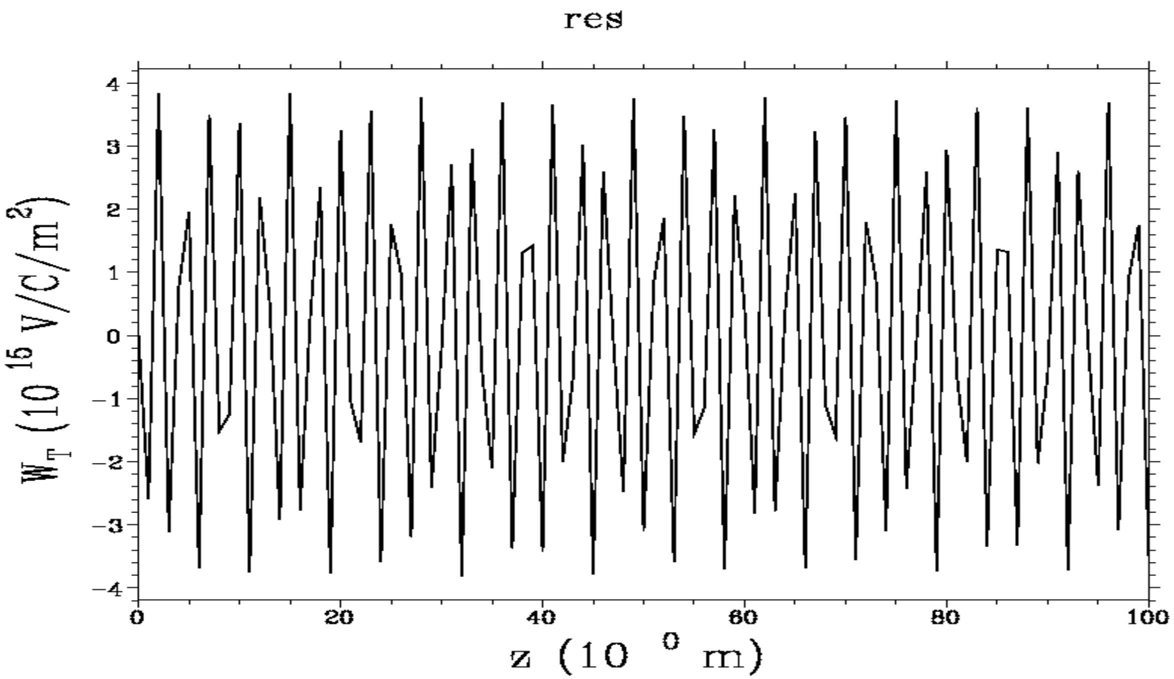
Optimized

- Optimization of the length of the drifts and b_x, b_y at the injection
- q = 37 pC, s_z = 1 psec, e_{nx} = 100 nm▪rad

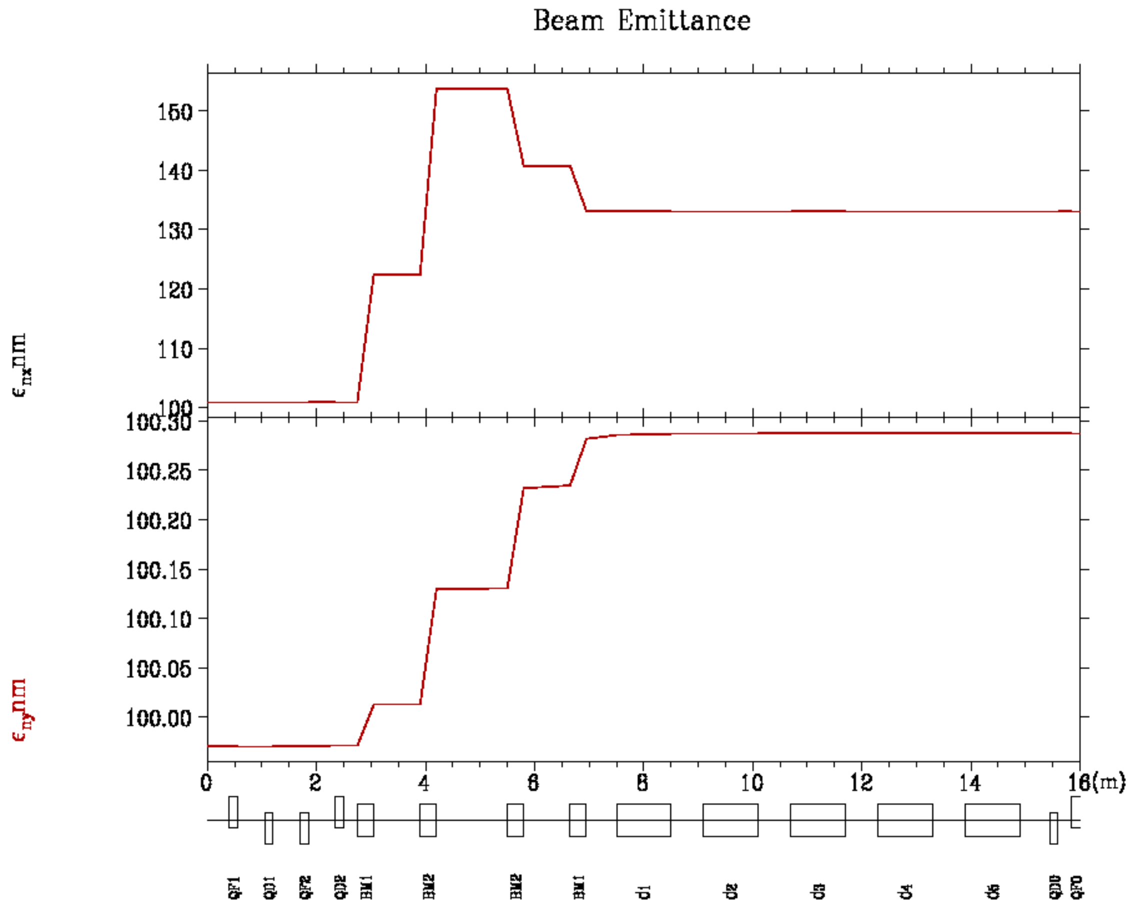
2. Emittance growth due to HOM in Multi-bunch (Kim *et al*)

A resonator wake by RF HOM

- R/Q = 23.8 x10^4 [Ohm/m^2] : Tesla type

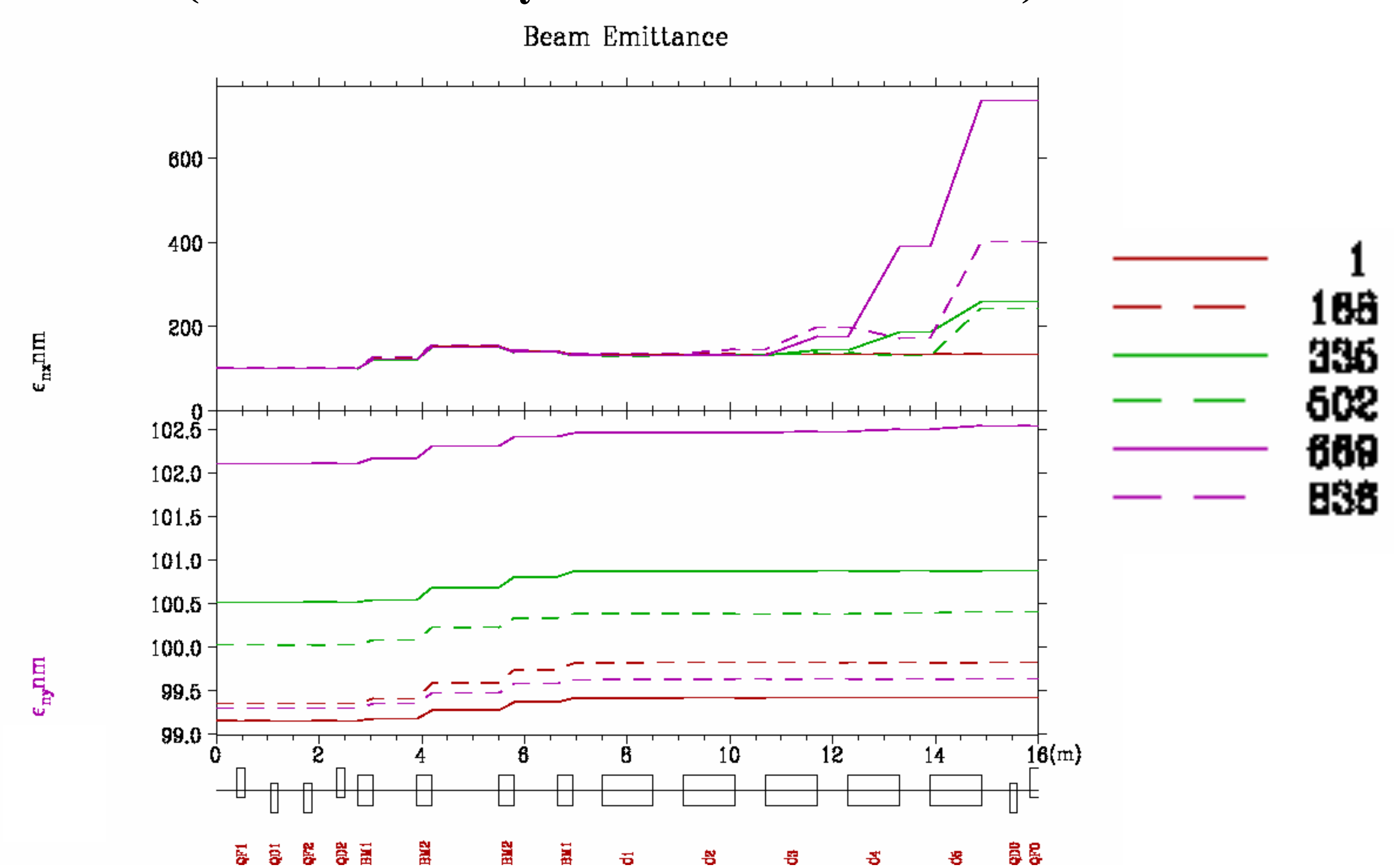


Emittance in Single bunch tracking



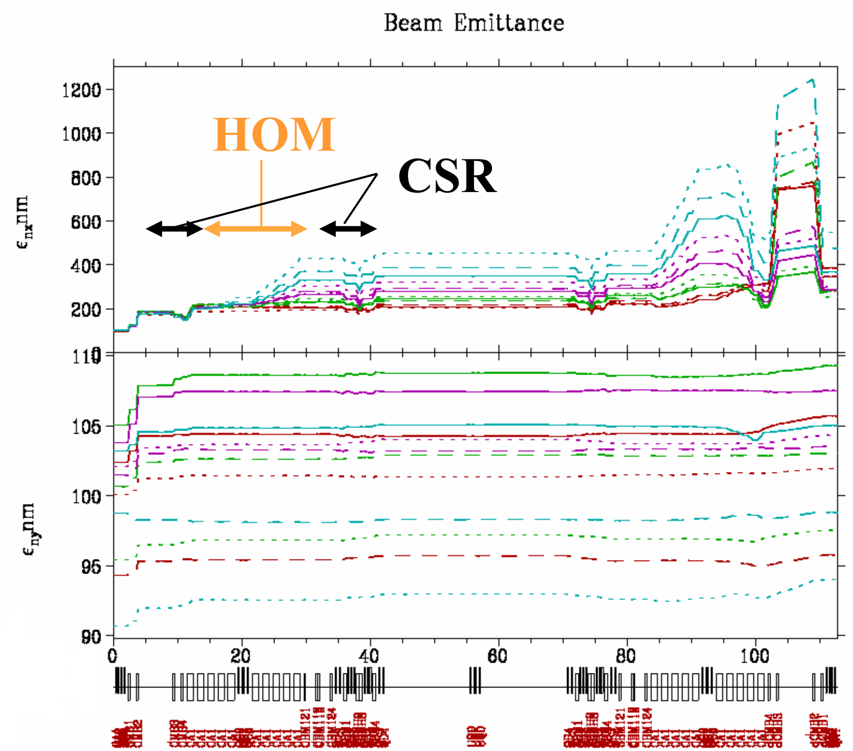
Emittance by continuous 1000 bunches passage

(Offset in x and y directions = 10 micron)



Multi-bunch instability due to RF HOMs and CSR effect

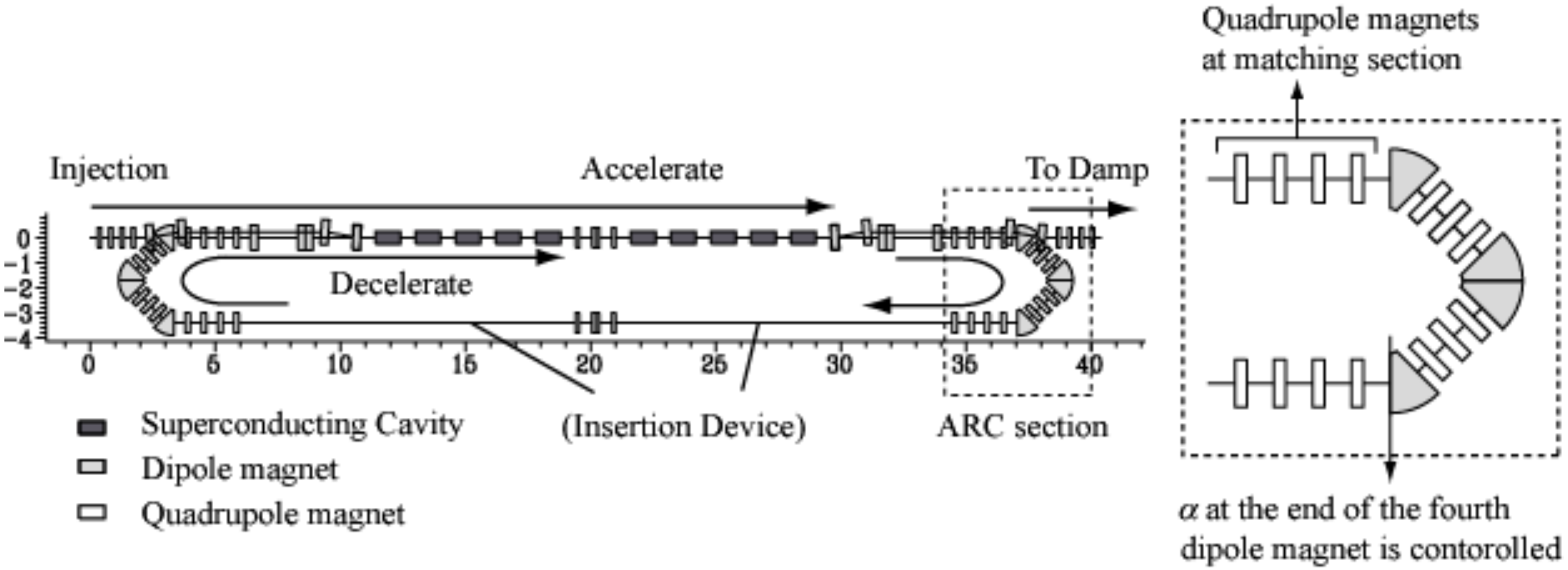
320 bunches, q = 37 pC, s_z = 1 psec, e_{nx} = 100 mm·mrad



- R/Q= 23.8D4, fh=2.5752D9, Q=5D4
- R/Q=8.69D4, fh=1.8722D9, Q=7D4
- R/Q=6.54D4, fh=1.8642D9, Q=5D4

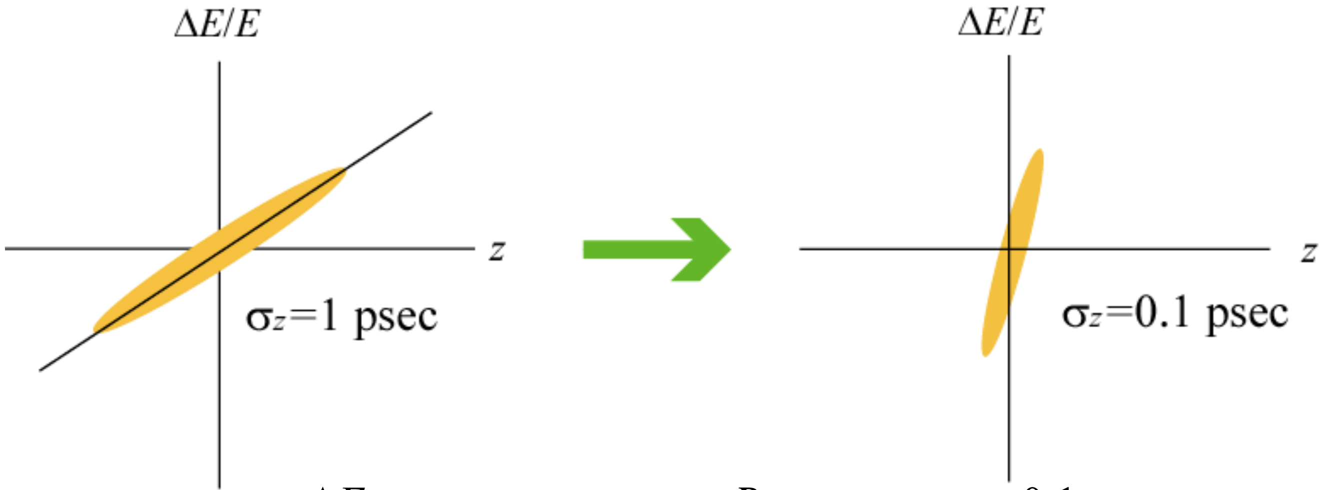
If s_z = 1 psec, the emittance growth is caused by HOM rather than CSR.

Bunch compression and emittance growth due to CSR



- Bunch compression is performed at the arc section

Bunch compression at the arc

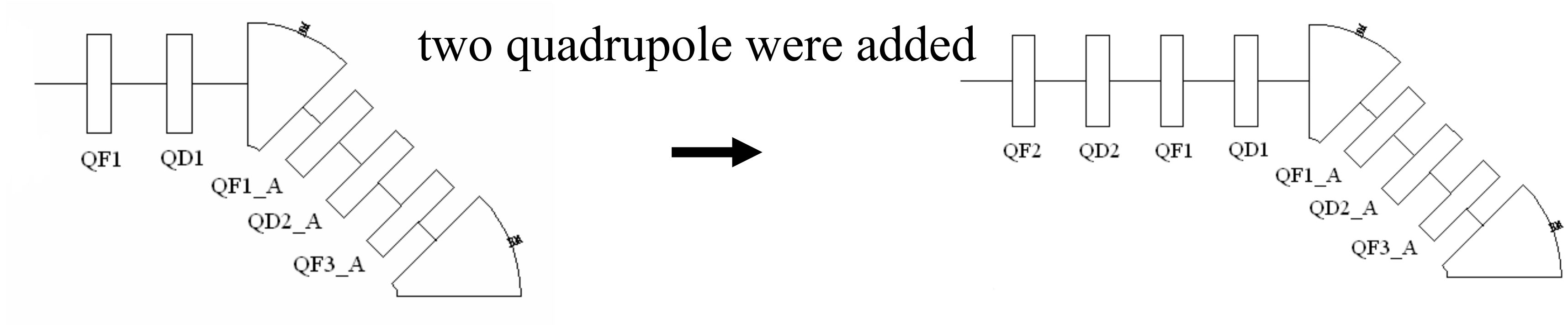


$$\Delta z = R_{56}\frac{\Delta E}{E_0} \qquad \tan\phi_{RF} = -\frac{cR_\sigma}{2\pi f_{RF}R_{56}} \qquad R_\sigma = \frac{0.1 p\sec}{1 p\sec}$$

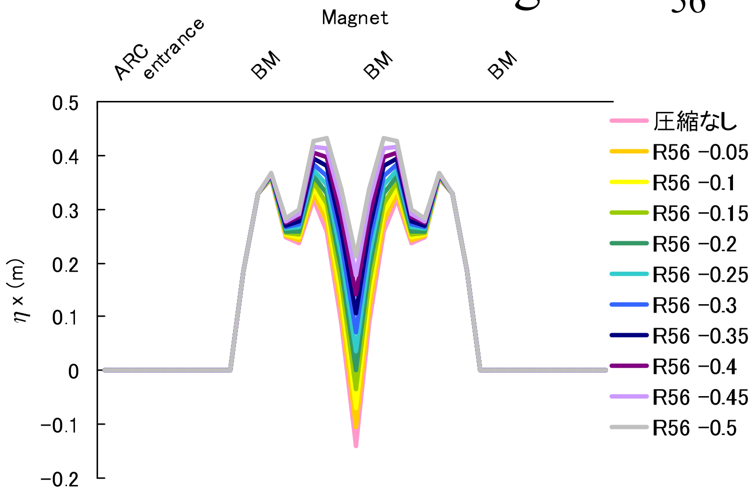
How to optimize the bunch compression?

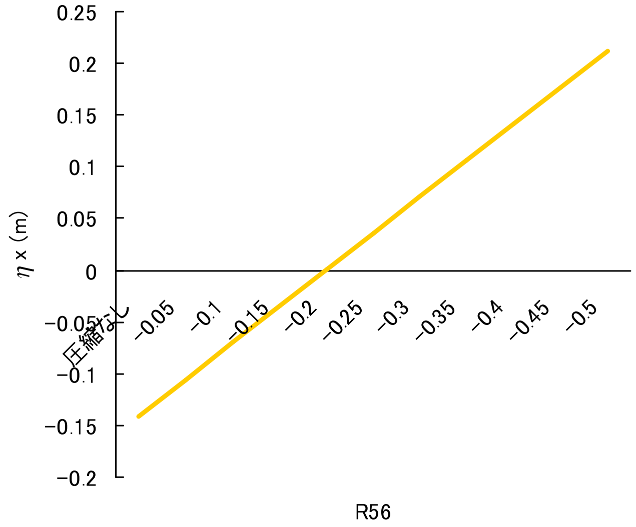
1. R_{56} of ARC section was varied from 0 to -0.7 m.
2. RF phase shift, f_{RF}, was controlled.
3. Broaden the energy spread, s_E.

Additional two quadrupole magnets

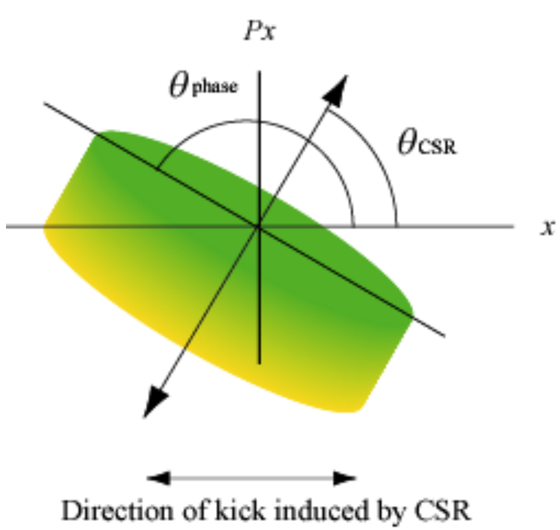


- Controllable range in R_{56} is widen from **-0.3~0** to **-0.7~0**

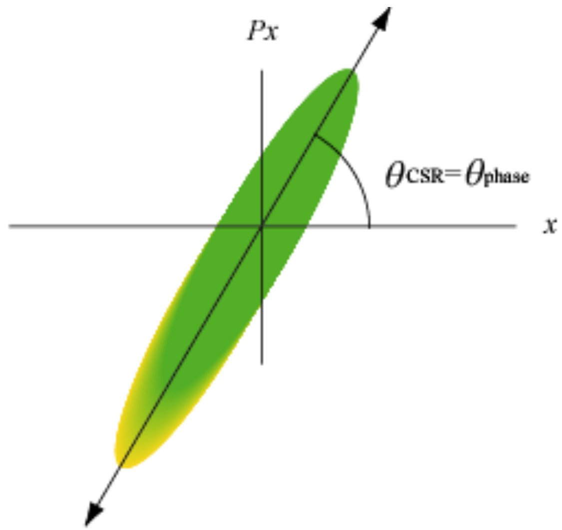




Matching q_{CSR} and q_{Phase} at the end of the fourth bending magnet



Emittance growth is large



Minimized emittance growth

When the direction of the transverse phase space, q_{Phase}, is parallel to the direction of the CSR kick, q_{CSR}, the emittance growth can be minimized.

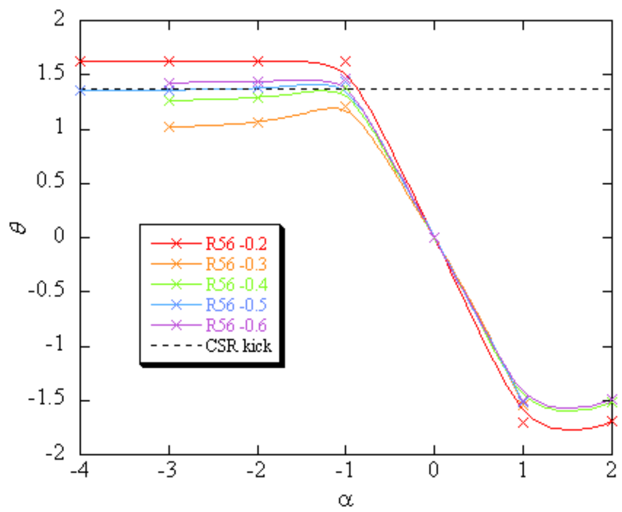
$$\tan 2\theta_{Phase} = \alpha/(\gamma - \beta)$$

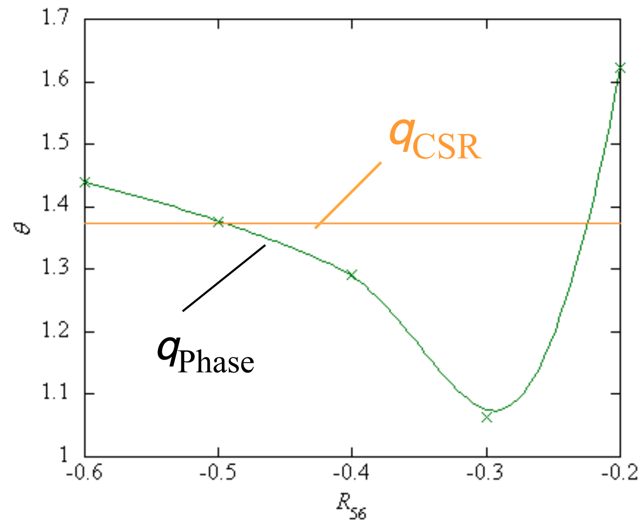
a, b, g : Twiss parameter

$$\theta_{CSR} = \sin\phi / \rho(1-\cos\phi)$$

f, r : Bending angle and radius

q_{Phase} vs. R_{56}

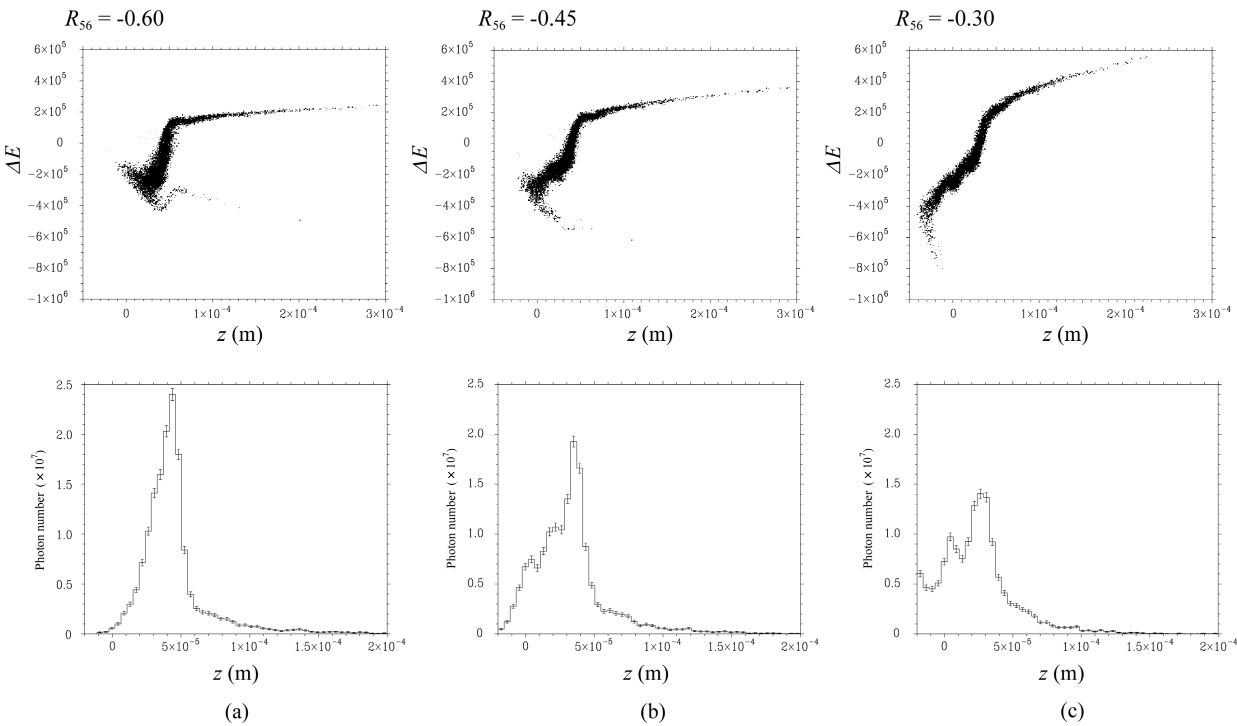




q_{CSR} and q_{Phase} at a=-3

- q_{Phase} was controlled by changing twiss parameter a at the end of the fourth bending magnet
- Controllable range in q_{Phase} is depend on R_{56}
- According to the left graph, q_{CSR} agree well with q_{Phase} at R_{56} = -0.5 m. The emittance growth can be minimized around it.

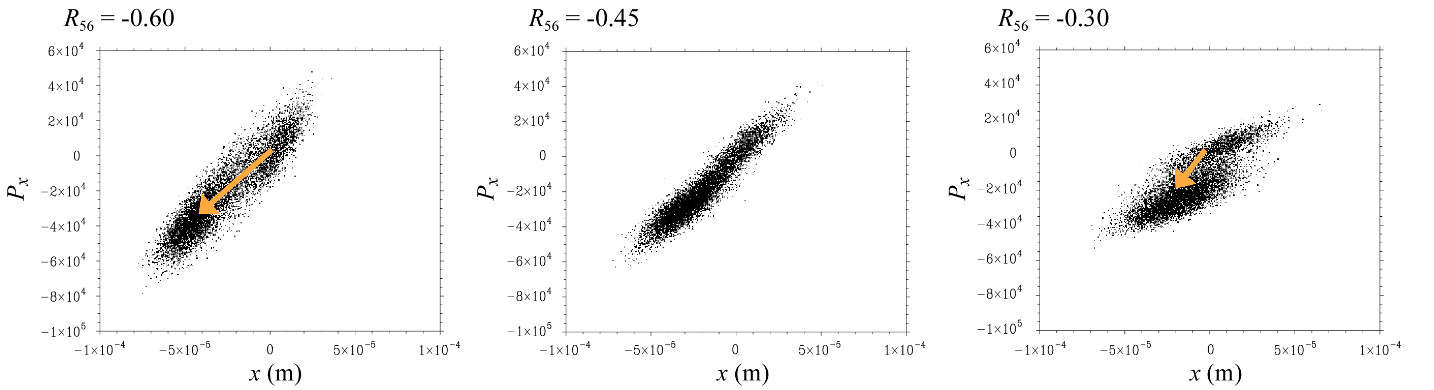
Longitudinal Phase space



Sharp peak → Large CSR

Smooth shape → Small CSR

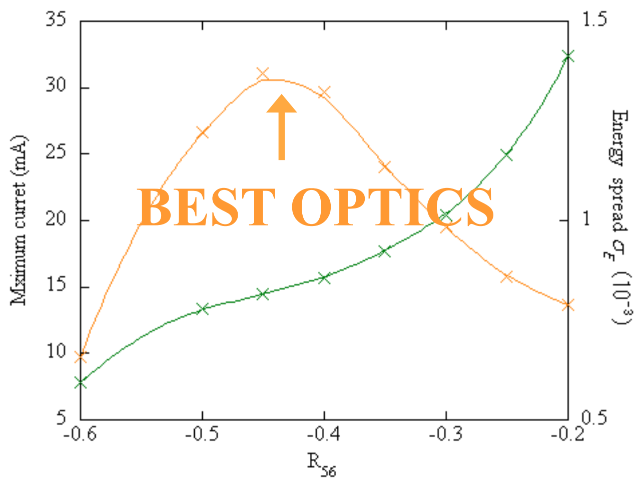
Transverse Phase Space



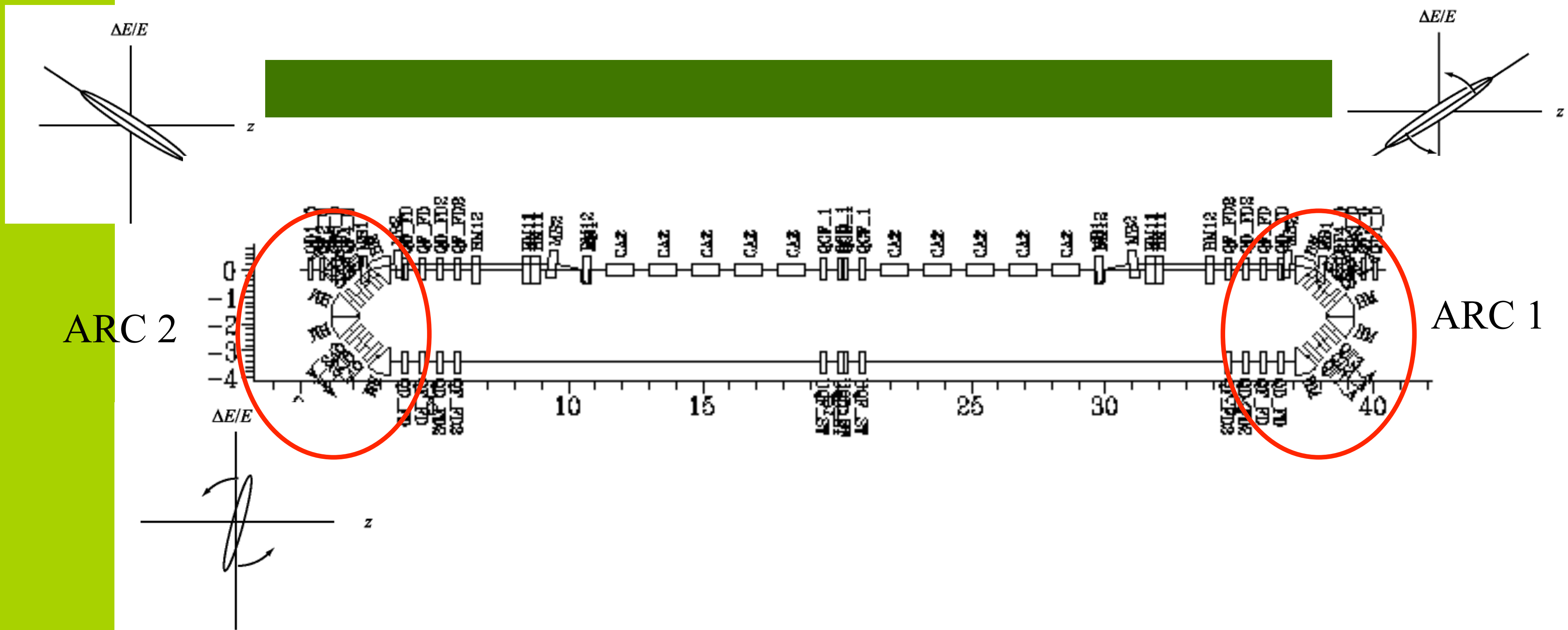
(a) (b) (c)

Large CSR

Mismatch
q_{Phase} and q_{CSR}

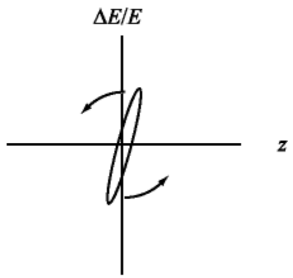


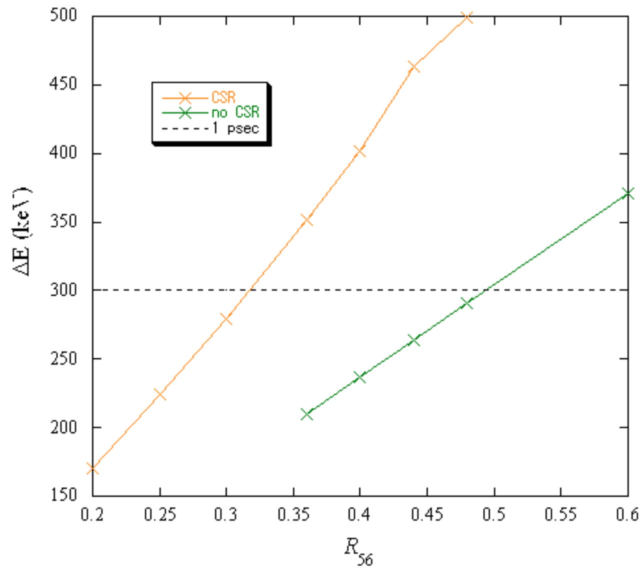
4. Energy recovery after bunching

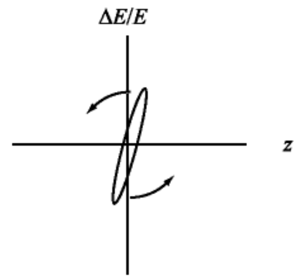


- The optics of ARC 1 and ARC 2 are not symmetry because the longitudianal phase space is not accurately upright at the insertion device.
- R_{56} of ARC 2 was controlled under the condition that R_{56} of ARC 1 is -0.4, q is 19.4 C, in which e_x~200nm･rad at the insertion devices.

Relationship s_z beginning of the cavity for energy recovery and R_{56} of ARC 2



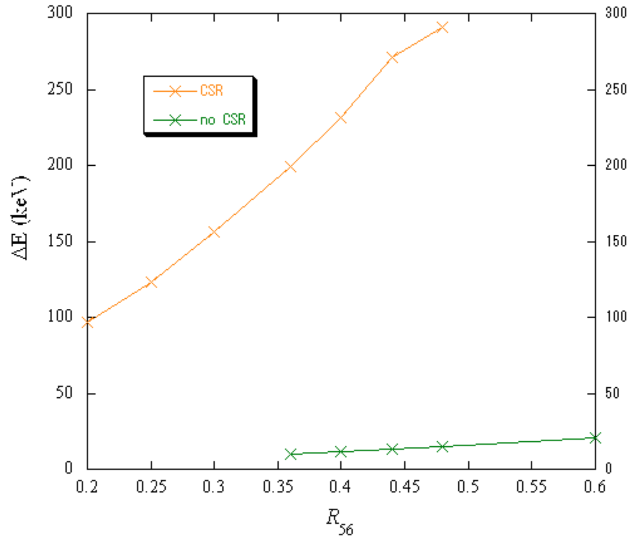




Small Rotation ⟷ **Large Rotation**

- In no CSR case, the optimum optics to recover the bunch length, 1 psec, is R_{56} = -0.5 m.
- In CSR case, small R_{56} is enough to recover the bunch length, which is extended by CSR.

Residual energy after the energy recovery and R_{56} of ARC section for return

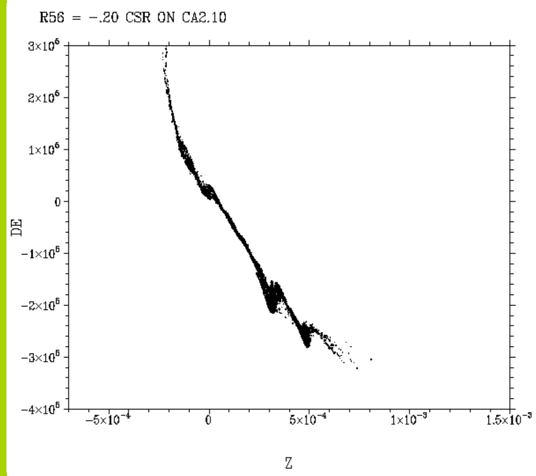


Short bunch at the deaccelerate cavity

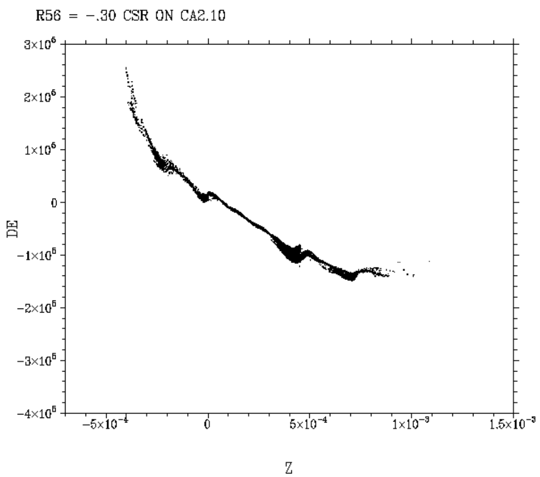
Long bunch at the deaccelerate cavity

- The figure shows the change in the energy before and after the cavity for energy recovery.
- Efficiency of energy recovery is high for a short bunch.

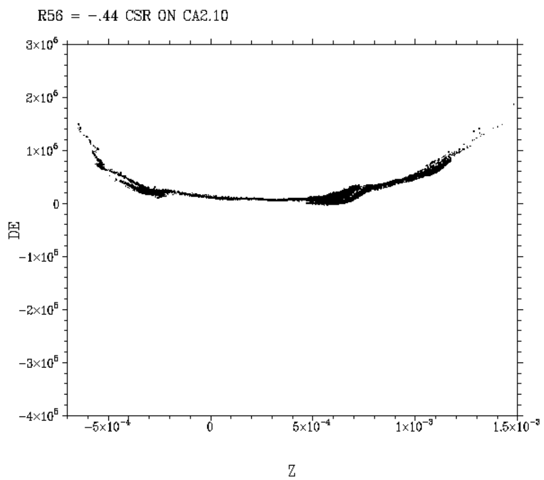
Energy distribution after the cavity for energy recovery (energy recovery＋energy loss due to CSR)



R_{56} = -0.2 m



R_{56} = -0.3 m



R_{56} = -0.44 m

- **Short bunch**
- **High efficiency**
- **Inhomogeneous**

- **Long bunch**
- **Low efficiency**
- **Homogeneous**

Summary

- In the case of 1 psec electron bunch, HOM is more critical issue for the emittance growth than CSR.

- By optimization of arc section, 30mA is achieved with keeping the condition that e_{pnx}>200nm rad and s_z< 0.1psec (30*m*m) at the insertion device.

- For high efficiency energy recovery, the bunch length should not be recovered but remain to be short.

- In some simulation, we employed ERL Track developed by K. Yokoya, which is similar to SAD and work on Windows platform.