Merger Design session

Emittance control & multiple modes of operation

Merger design exercise

R. Hajima

Design Issues

- merging energy
  - high energy = smaller emittance
  - low energy = better economics
- configuration
  - 3-dipole, zigzag, multi-loop
  - pros & cons
- multiple merger
  - how many ? configuration ?
- simulation tools
  - space charge, CSR in a curved path
  - comparison : simulation / real machine

Merging Energy

- Energy balance

$$E_{inj} + \left(E_{acc} - E_{dec}\right) = E_{loss} + E_{dump}$$

RF for the injector

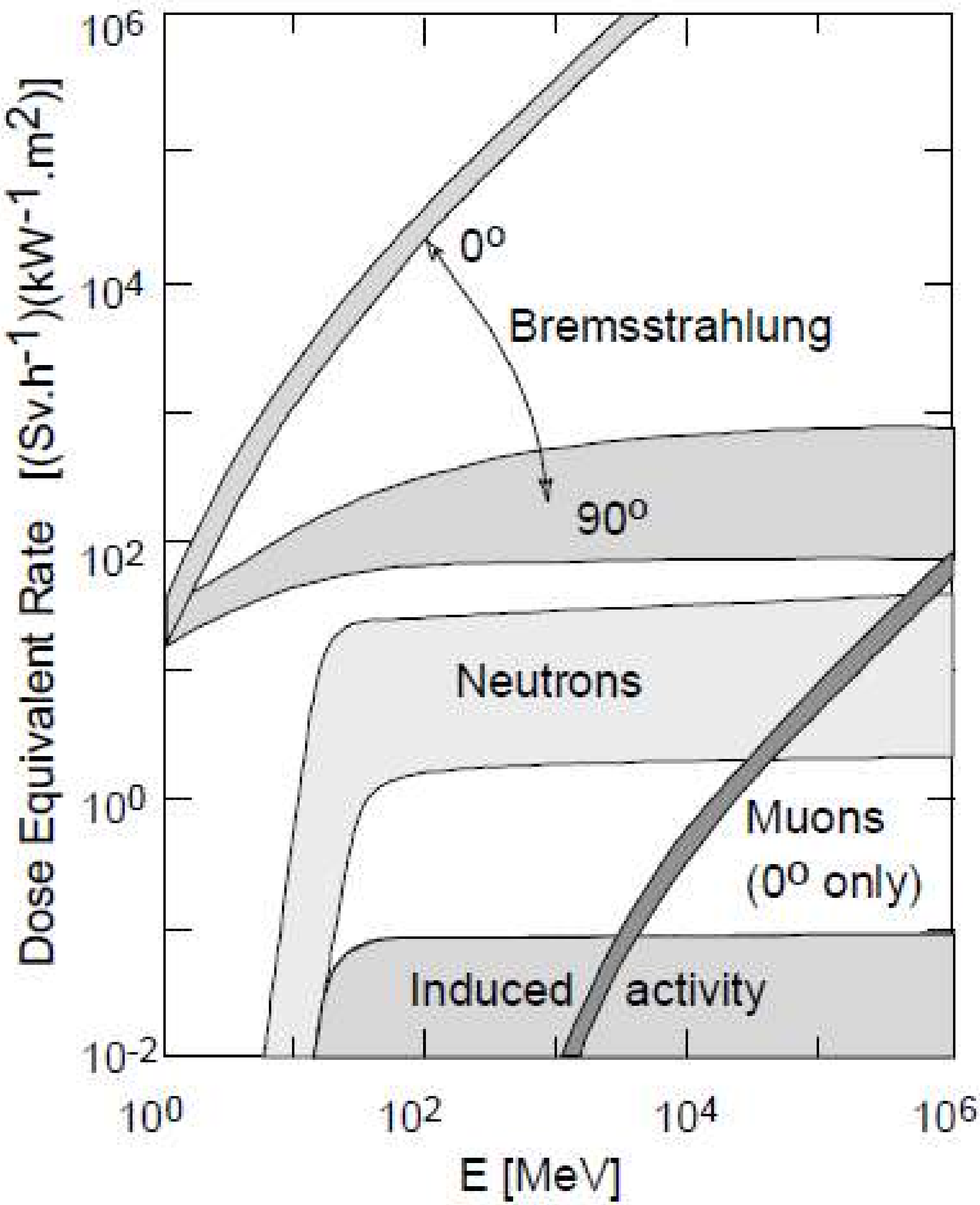
RF for the main linac

- dump energy < 10 MeV to avoid neutron generation, but must have some amount of kinetic energy for easy handling.

dump current is important information in the operation.

- large RF sources for the main linac = large investment (source, circulator, coupler ...)

dose per unit beam power



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Merging Energy (cont.)

- injected by small energy causes "phase slip" but rapid acceleration eliminates it.

for 5-GeV light source (0.1% energy loss at most)

$$E_{inj} + (E_{acc} - E_{dec}) = E_{loss} + E_{dump}$$

$$5\,\text{MeV} + 5\,\text{MeV} = 5\,\text{MeV} + 5\,\text{MeV}$$

↓

for 100mA, additional 5 kW per 20 MV acceleration

$$10\,\text{MeV} + 0\,\text{MeV} = 5\,\text{MeV} + 5\,\text{MeV}$$

↓

need off-crest acc. for energy compression

Merging Energy (cont.)

for 50-MeV FEL (1% energy loss, 10% energy spread)

$$E_{inj} + (E_{acc} - E_{dec}) = E_{loss} + E_{dump}$$

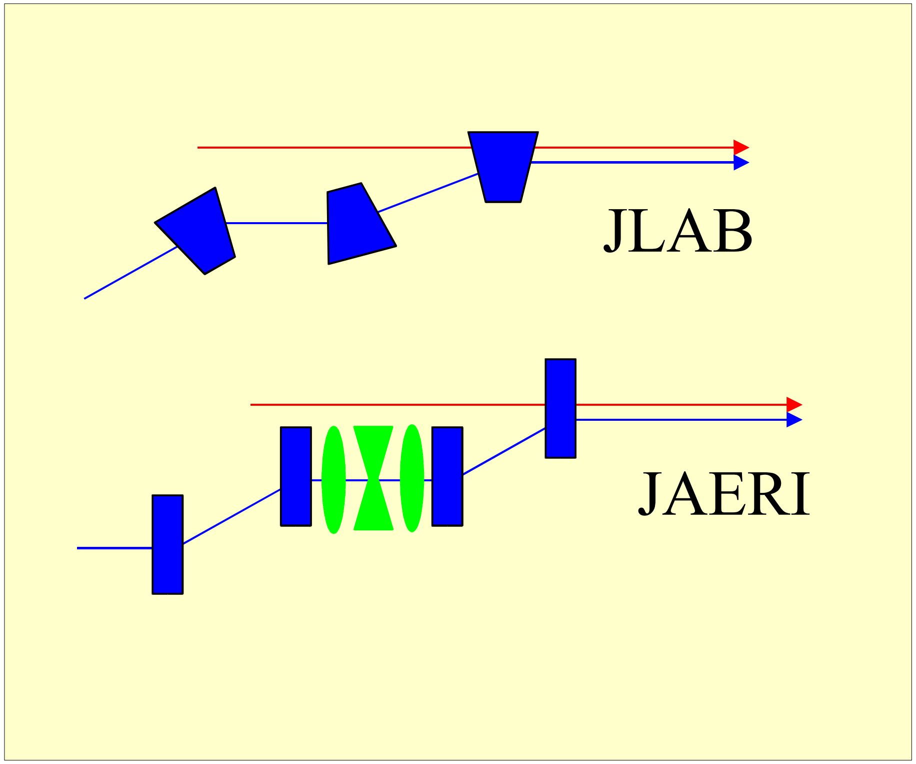
$$5\,\mathrm{MeV} + 0.5\,\mathrm{MeV} = 0.5\,\mathrm{MeV} + 5\,\mathrm{MeV}$$

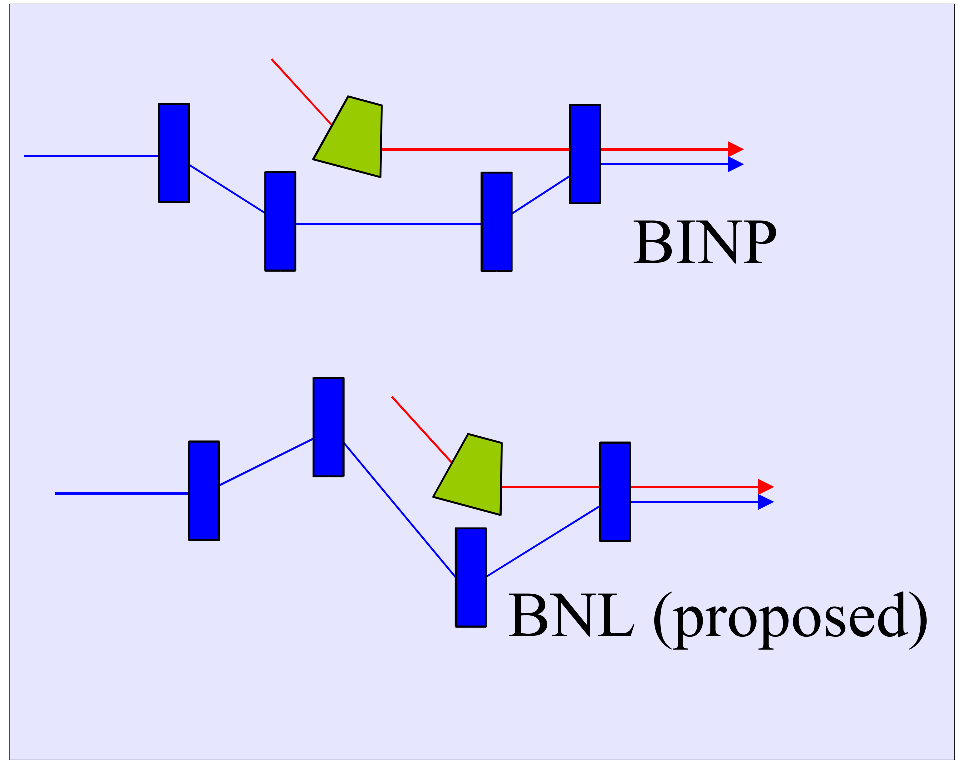
for 100 mA, additional 10 kW per 10 MV acceleration,
energy compression is possible, but maybe insufficient.
10 kW / 1 MW = 1% RF power budget.

$$5\,\mathrm{MeV} + 0\,\mathrm{MeV} = 0.5\,\mathrm{MeV} + 4.5\,\mathrm{MeV}$$

need off-crest acc. for energy compression

Merger Configuration





"slide injection"

injection / recirculation are tilted or shifted.

flexible BT for the high-E beam.

“in-line injection"

injection / recirculation are in line.

suitable for small E_{high}.

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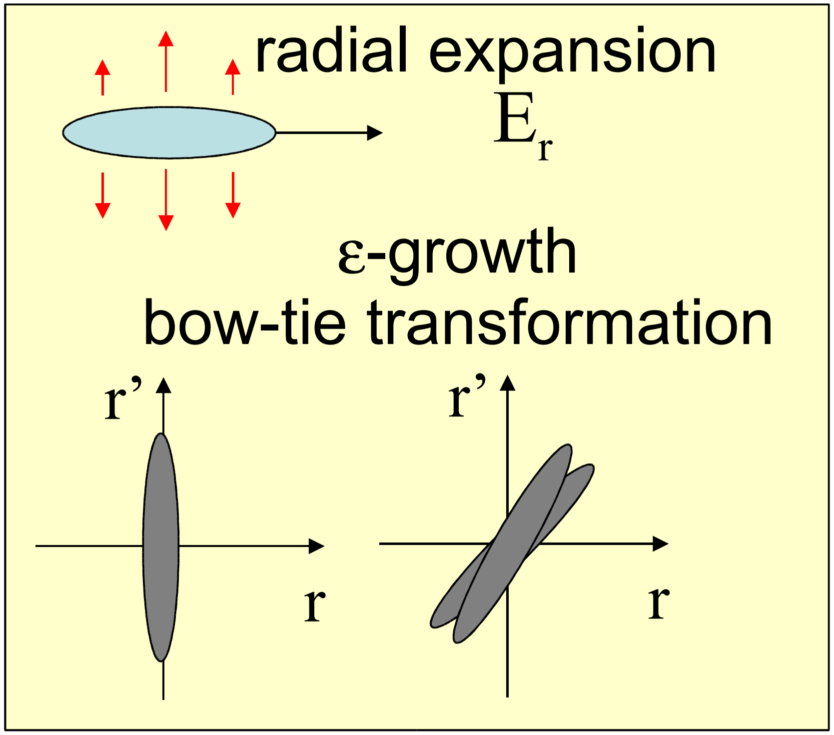
Transverse emittance growth by Ex, Ey

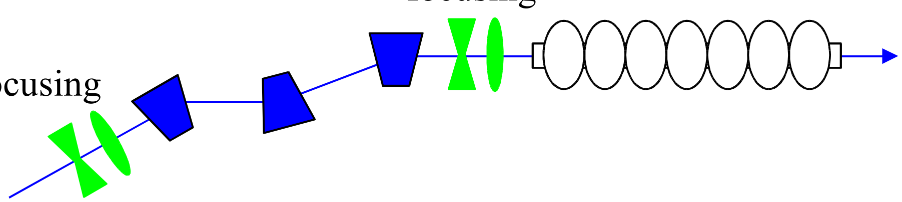


$$\sigma'' - \frac{(I/2I_0)}{\sigma \beta^3 \gamma^3} - \frac{\varepsilon_n^2}{\sigma^3 \beta^2 \gamma^2} = 0$$

in the limit of zero slice emittance

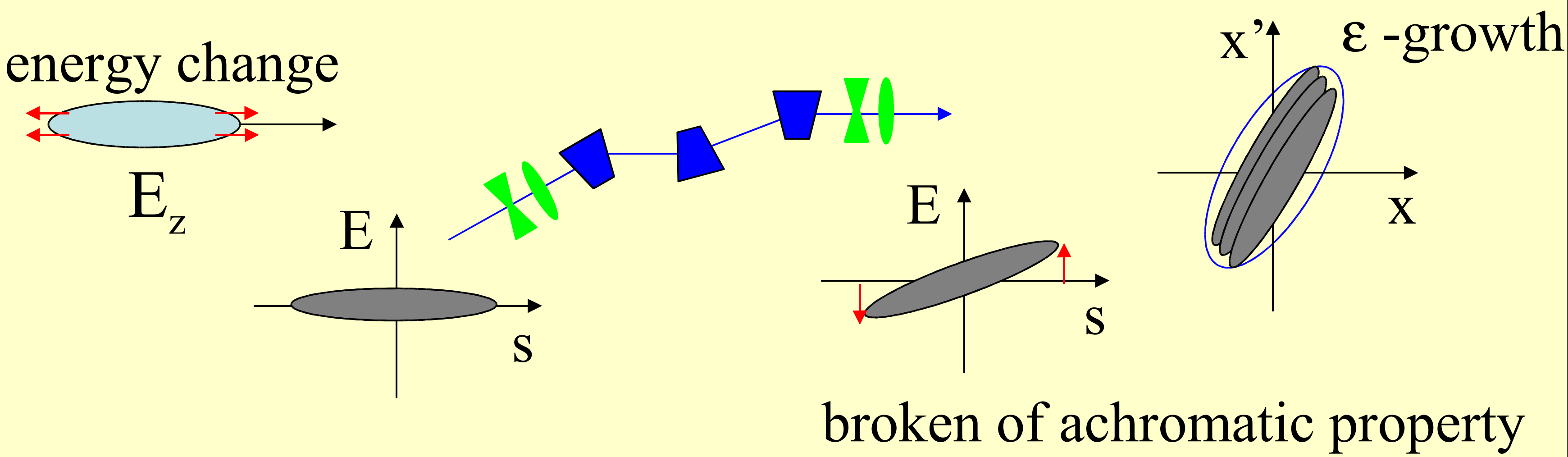
$\varepsilon_n \sim 0$

$$\Delta \varepsilon_n \sim \delta \sigma' \sigma \gamma \propto \gamma^{-2}$$



emittance compensation
by appropriate focusing

Transverse emittance growth by Ez



see for example, B.E. Carlsten et al., IEEE QE **27**, 2580 (1991).

assuming steady-state Ez $\Delta E/E=\delta=\delta_0+\kappa(s-s_0)$

We can track bunch slice motion by linear matrix.

$$\varepsilon^2=(\varepsilon_0\beta_x+D^2)(\varepsilon_0\gamma_x+D'^2)-(-\varepsilon_0\alpha_x+DD')^2$$

$$(D,D')=\Delta\kappa_{rms}(\zeta_x,\zeta_x')$$

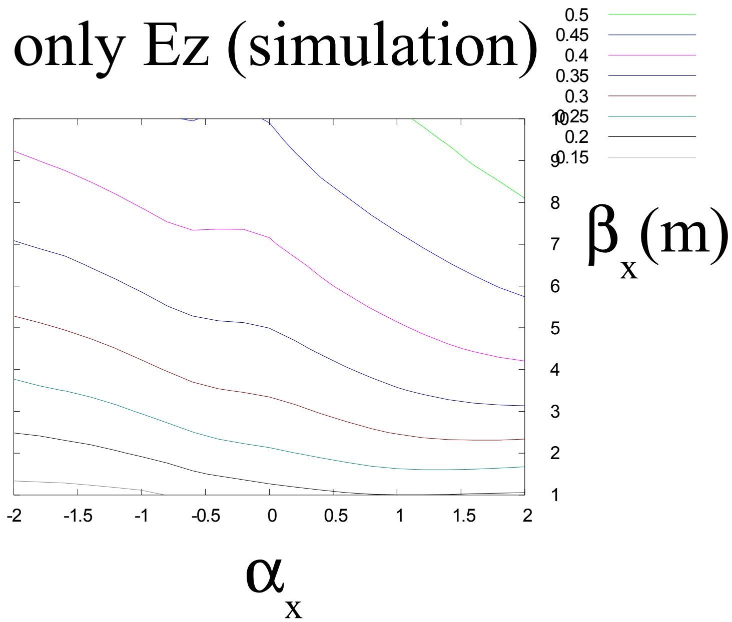
similar to the CSR case

$$E_z\propto\gamma^{-1}\qquad \Delta E/E\propto\gamma^{-2}\qquad \Delta\varepsilon_n\propto\gamma^{-3/2}$$

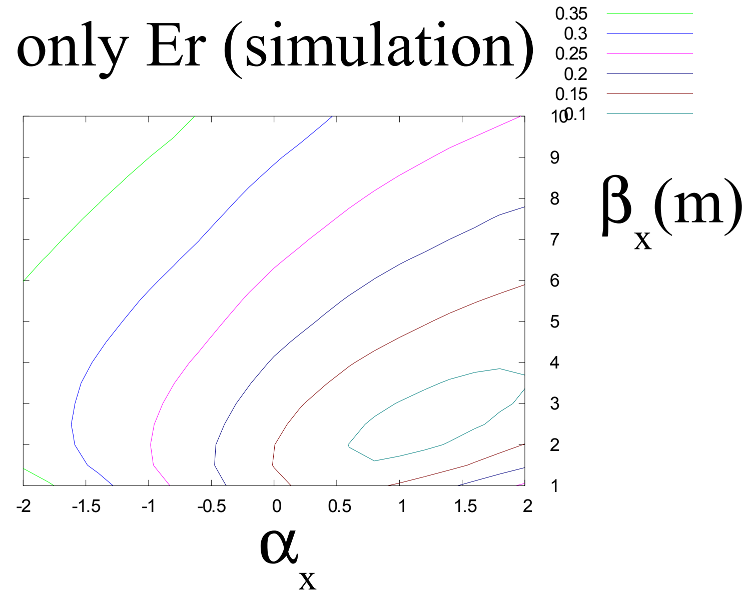
Optimum injection to a 3-dipole merger

calculate emittance growth with varying injection parameters (α_x, β_x)

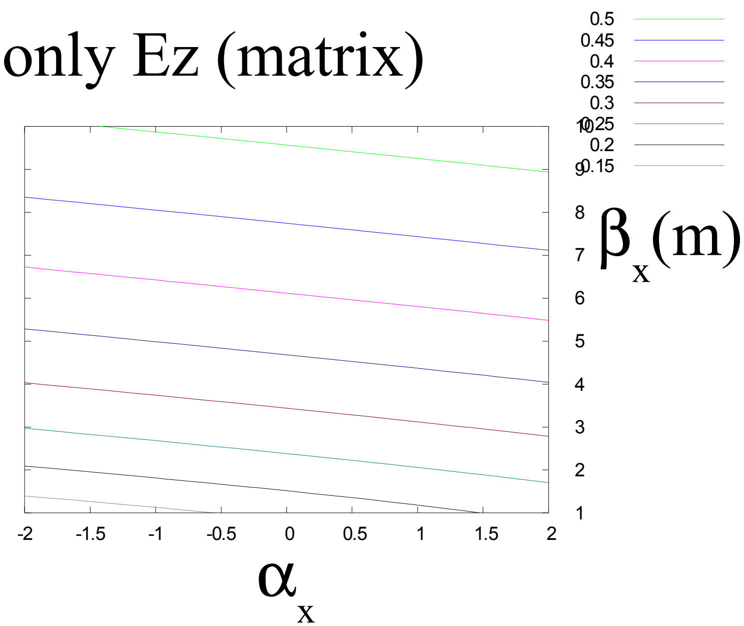
only Ez (simulation)



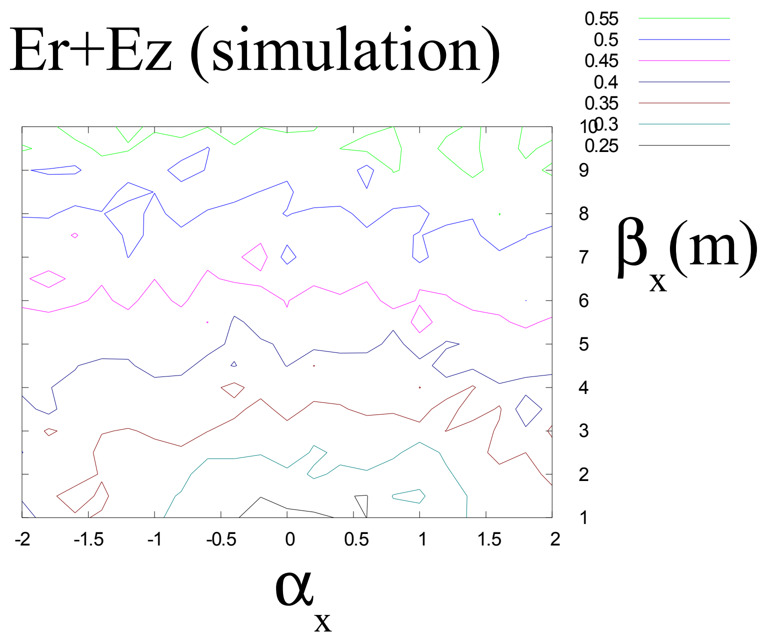
only Er (simulation)



only Ez (matrix)



Er+Ez (simulation)



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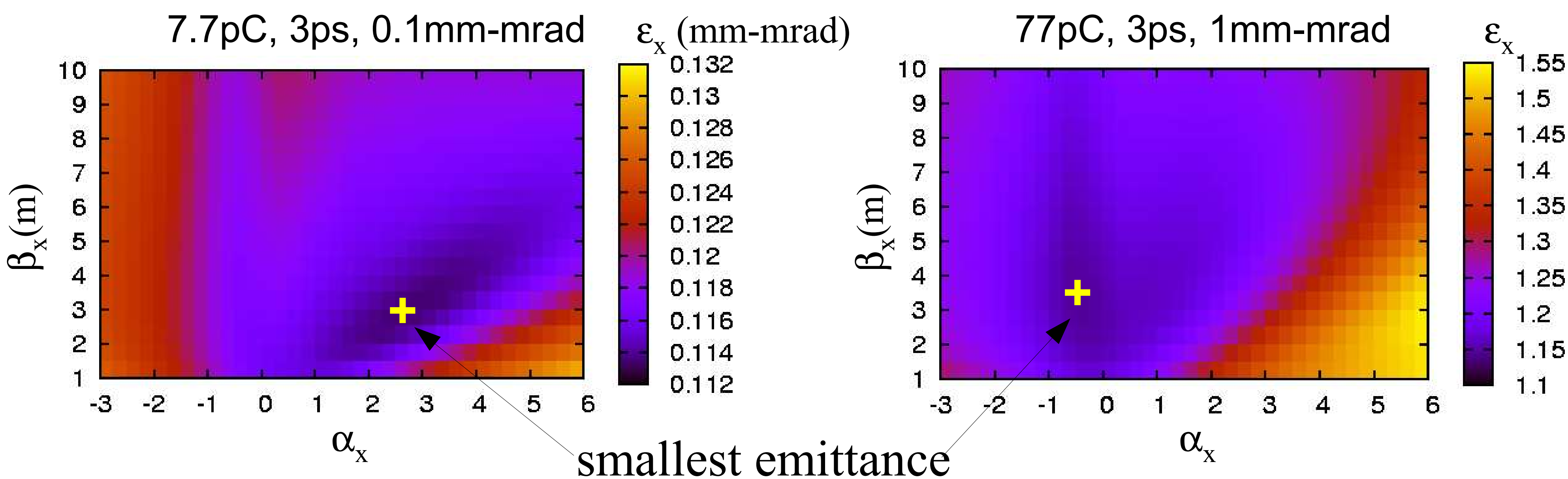
Optimum injection to a 3-dipole merger

optimum envelope is a function of bunch parameters.

PARMELA runs for the merger (3 dipoles only) with varying α_x, β_x at the merger entrance.



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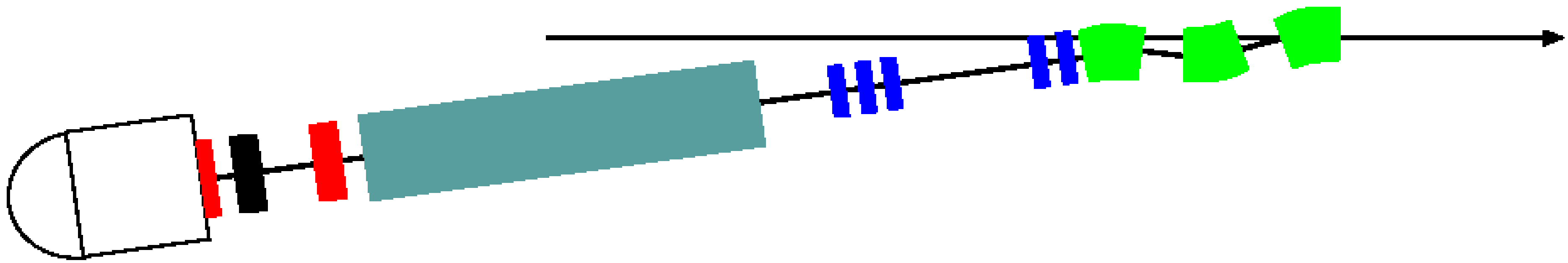
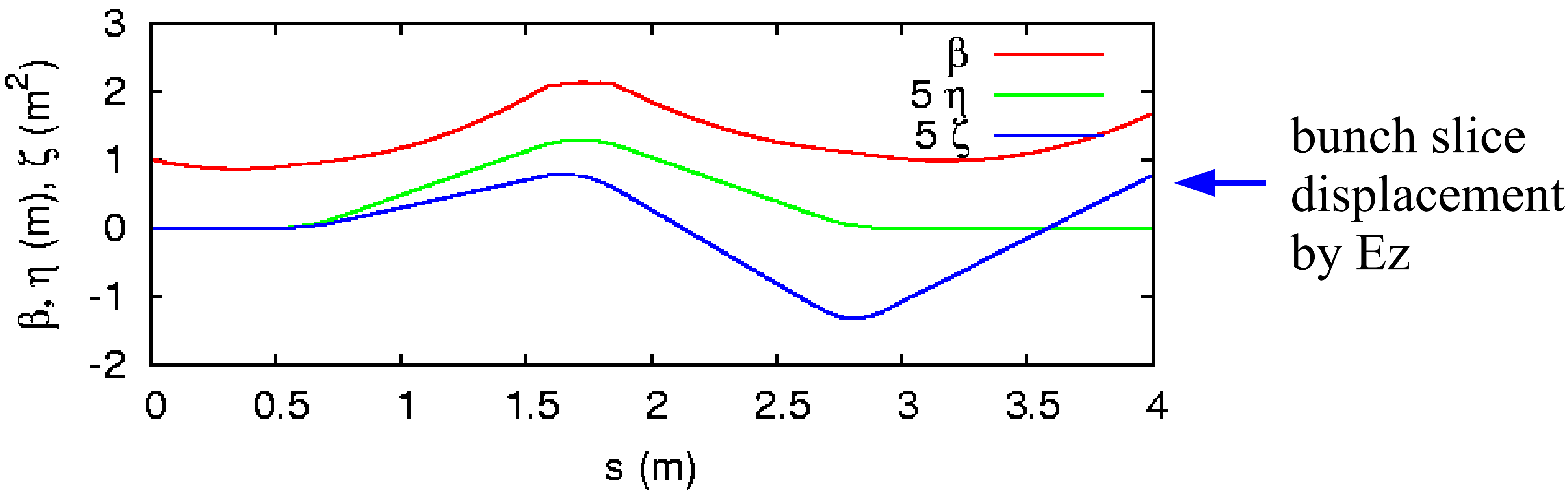
3-dipole merger

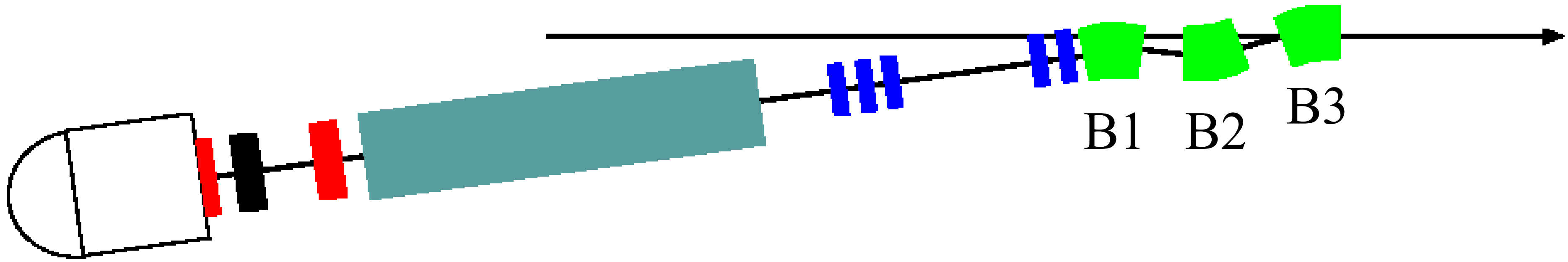


longitudinal space charge dispersion



the bending angle should be small,
and the total length should be short

3-dipole merger



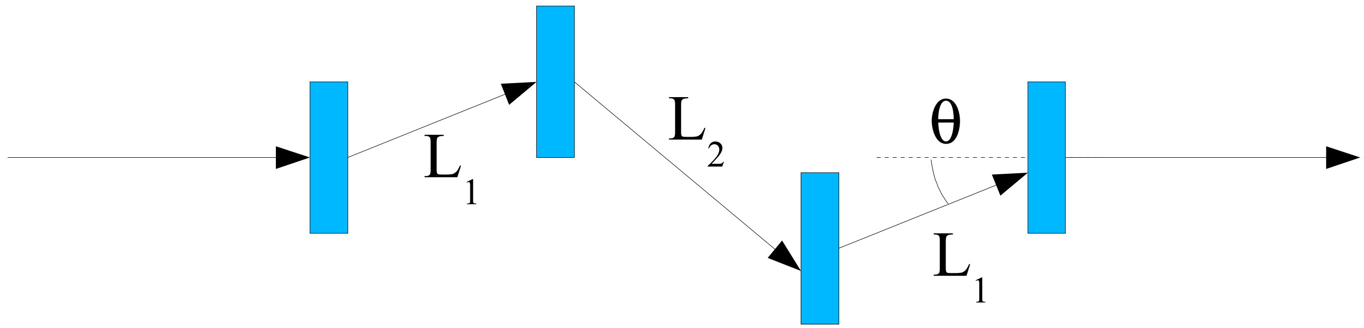
for example,

	B1 / B3	B2
bending radius	1m	1m
bending angle	15 deg.	22 deg.
edge angle	0	-20 deg.

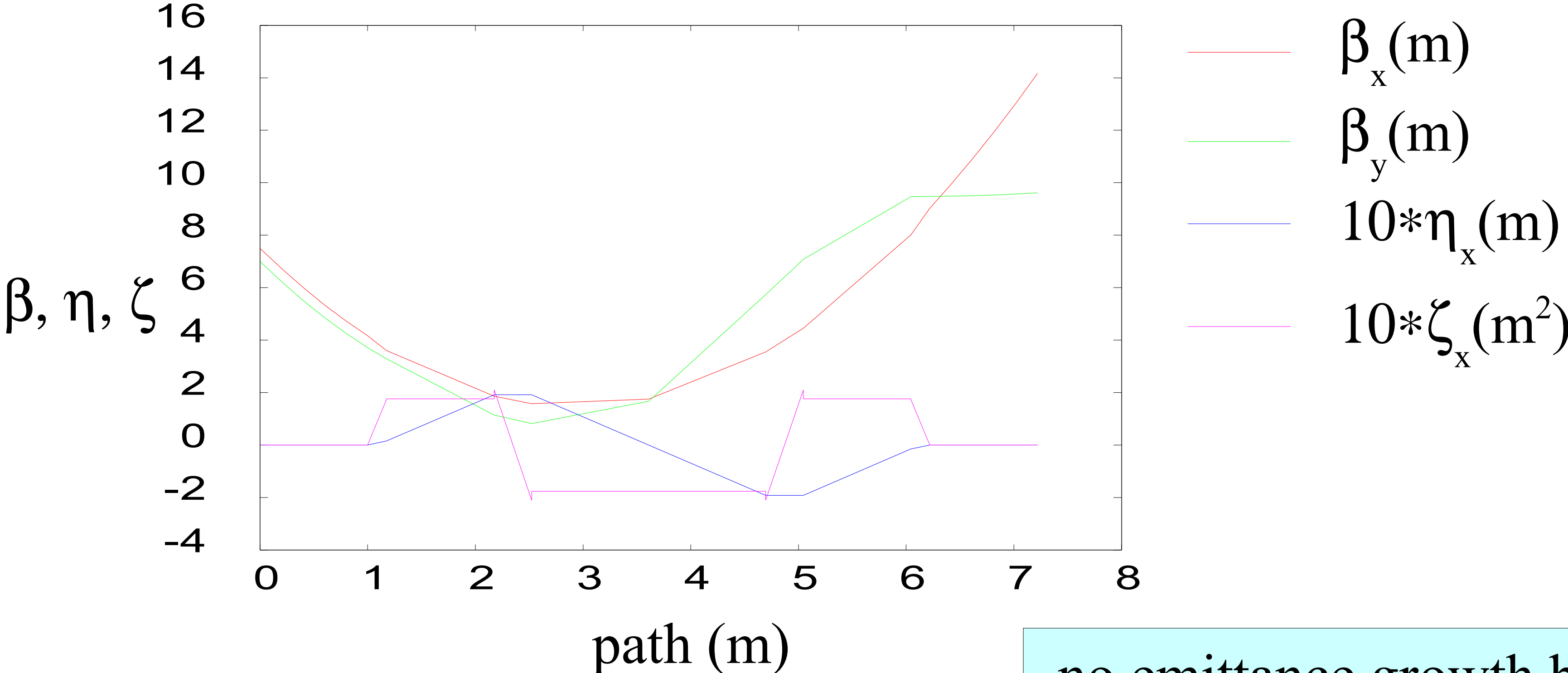
drift between bends = 0.316m
total path length = 1.54m
total deflection angle = 8 deg.

total deflection angle is determined so that we can keep space for the cryomodule (D=670mm).

zigzag merger

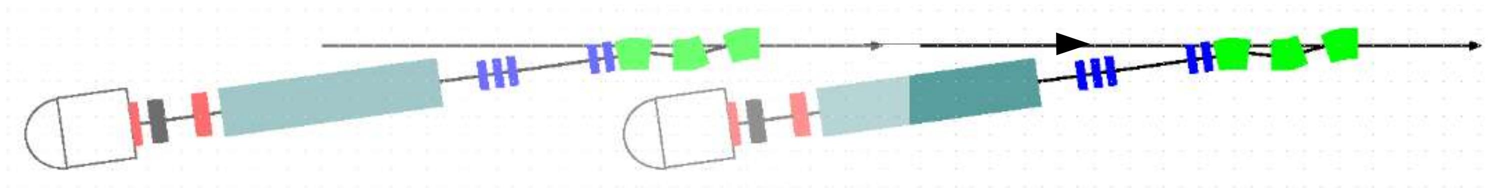


ρ=1m, θ=10deg., L_1=1m, L_2=2.17m

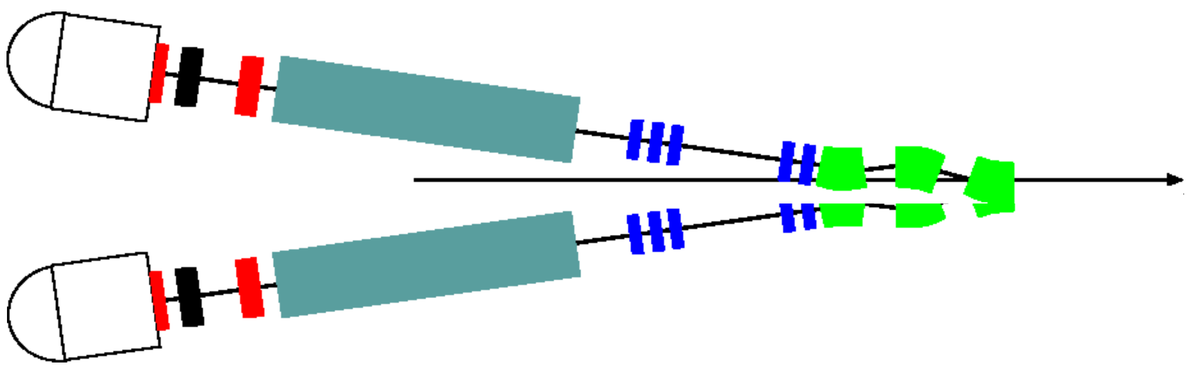


no emittance growth by Ez !

multi-merger for multi-injector



tandem configuration



symmetric configuration

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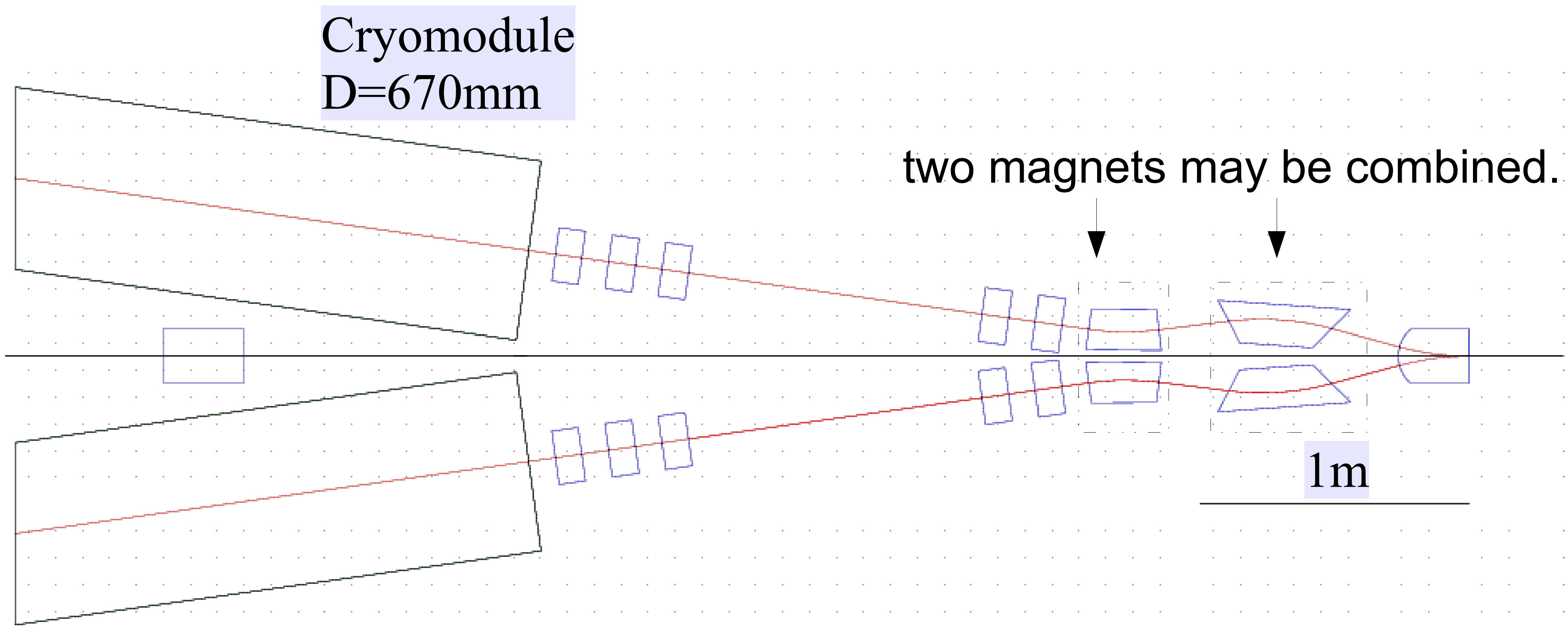
Multi-merger example



5x5 R-Matrix for the CSR Analysis

electron's motion in the bending plane is expressed by a vector

$$\vec{x}(s)=(x, x', \delta_0, \kappa L_b, \kappa)^T \qquad \delta_{CSR}(s)=\kappa L_b(s)$$

$L_b(s)$: sum of bending path length in the upstream

before the bend

$$\vec{x}(s_0)=(x, x', \delta_0, \kappa L_b, \kappa)^T$$

after the bend

$$\vec{x}(s_1)=(x, x', \delta_0, \kappa L_b, \kappa)^T$$

transfer matrix of the bend

$$\vec{x}(s_1)=R_{bend}\,\vec{x}(s_0)$$

5x5 R-matrix for a sector bending magnet

$$R_{bend}=\begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) & \rho(1-\cos\theta) & \rho^2(\theta-\sin\theta) \\ -\rho^{-1}\sin\theta & \cos\theta & \sin\theta & \sin\theta & \rho(1-\cos\theta) \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & \rho\theta \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

extension of the conventional 3x3 R-matrix

R. Hajima, JJAP 42, L974 (2003).

CSR-wake dispersion function

Following the momentum dispersion function "η",
we define the CSR wake dispersion function "ζ"

momentum dispersion function

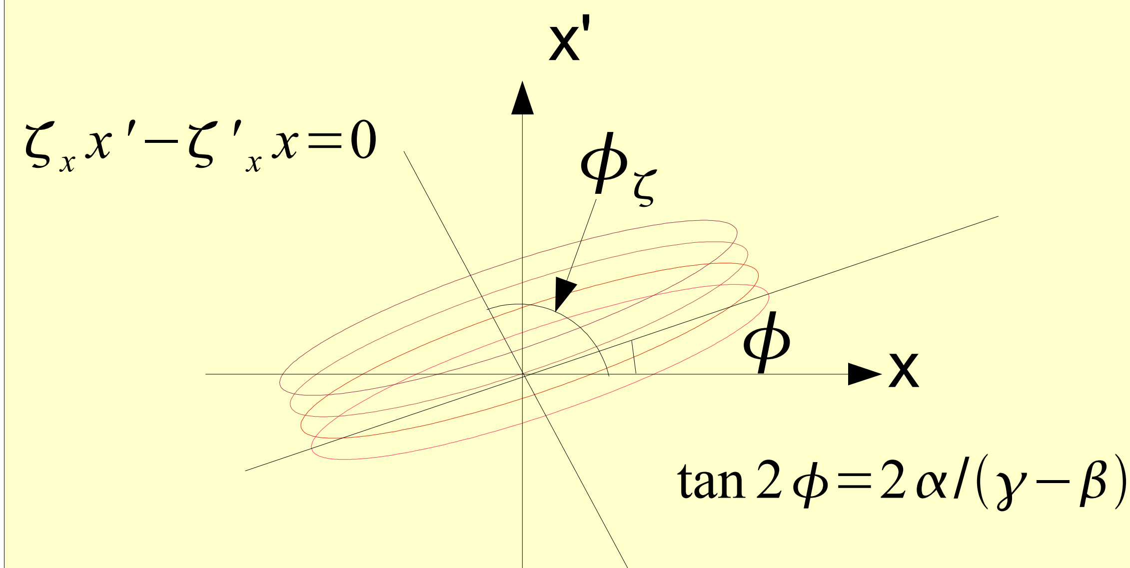
$$(\eta, \eta')$$

$$\begin{pmatrix} \eta_x(s_1) \\ \eta'_x(s_1) \\ 1 \\ 0 \\ 0 \end{pmatrix} = R_{0\to 1} \begin{pmatrix} \eta_x(s_0) \\ \eta'_x(s_0) \\ 1 \\ 0 \\ 0 \end{pmatrix}$$

CSR wake dispersion function

$$(\zeta, \zeta')$$

$$\begin{pmatrix} \zeta_x(s_1) \\ \zeta'_x(s_1) \\ 0 \\ L_b(s_1) \\ 1 \end{pmatrix} = R_{0\to 1} \begin{pmatrix} \zeta_x(s_0) \\ \zeta'_x(s_0) \\ 0 \\ L_b(s_0) \\ 1 \end{pmatrix}$$



bunch slices align on a line :

$$\zeta_x x' - \zeta'_x x = 0$$

We can track the motion of bunch slices.

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Emittance Growth by CSR, and its Compensation

coincidence between the CSR kick and the phase ellipse orientation.

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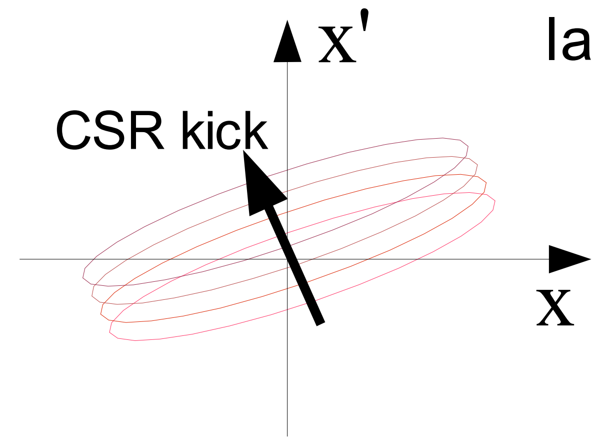
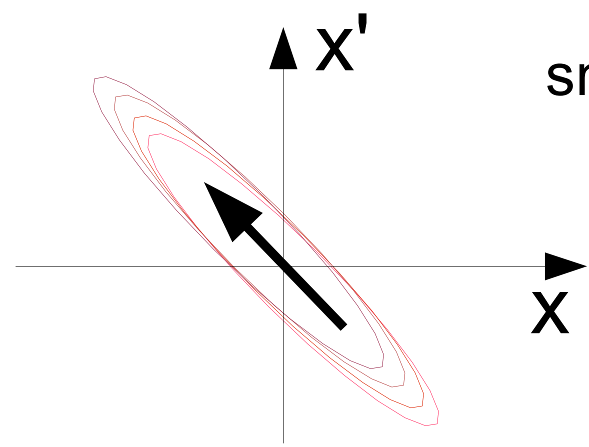
minimum emittance growth





projection emittance is evaluated by

$$\varepsilon^2 = (\varepsilon_0 \beta_x + D^2)(\varepsilon_0 \gamma_x + D'^2) - (-\varepsilon_0 \alpha_x + D D')^2$$

$$(D, D') = \Delta \kappa_{rms} (\zeta_x, \zeta_x')$$

$$\Delta \kappa_{rms} = \frac{\Delta E_{rms}}{E_0 L_b}$$

$$\varepsilon^2 - \varepsilon_0^2 = \varepsilon_0 (\Delta \kappa_{rms})^2 (\beta_x \zeta'^2 + \gamma_x \zeta^2 - 2 \alpha_x \zeta \zeta')$$

bunch parameter ($(\Delta \kappa_{rms})^2$) — beam transport ($\beta_x \zeta'^2 + \gamma_x \zeta^2 - 2 \alpha_x \zeta \zeta'$)