USPAS Accelerator Physics 2021
(Virtually) Texas A&M University

Lattice Examples II
Dispersion Suppressors and Achromats
(or More Stupid Lattice Tricks)

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Today: 1D+ and 2-3D+

- Bending Transverse Lattices (FODO)
  - Review: FODO cell, with dipoles
  - FODO cell dispersion suppressors
- Achromats
  - Doglegs and achromatic doglegs
  - Chicanes and bunch compressors
  - Double bend achromat
  - Triple bend achromat
  - (Multi-bend achromat (HMBA))
- 4D/6D manipulation
  - Transverse/longitudinal emittance exchange
  - (Flat to round/round to flat transforms)

(Review: Matrices of Magnetic Elements)

- For our purposes yet again:
  - All motion is linearized
$$\begin{pmatrix} x \\ x' \end{pmatrix}_2 = M \begin{pmatrix} x \\ x' \end{pmatrix}_1 \qquad x' \equiv \frac{p_x}{p_0}$$
  - Linear transport matrices:
$$M_{\text{drift}} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$
Book A.1.1
$$M_{\text{quad}} \approx \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$
Book A.1.6
for thin quads
  - (Sector) dipole includes constant fractional momentum offset
$$\begin{pmatrix} x \\ x' \\ \delta \end{pmatrix}_2 = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho(1-\cos\theta) \\ \frac{1}{\rho}\sin\theta & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ x' \\ \delta \end{pmatrix}_1 \qquad \delta \equiv \frac{\Delta p}{p_0}$$
Book A.1.2
for subset of phase
space

(Review: Dispersion)

- Add explicit momentum dependence to (linearized) equation of motion

$$x'' + K(s)x = \frac{\delta}{\rho(s)}$$

Perturb our zero-dispersion solution to find

$$x(s) = C(s)x_0 + S(s)x_0' + D(s)\delta_0$$
$$x'(s) = C'(s)x_0 + S'(s)x_0' + D'(s)\delta_0$$

$$\begin{pmatrix} x(s) \\ x'(s) \\ \delta(s) \end{pmatrix} = \begin{pmatrix} C(s) & S(s) & D(s) \\ C'(s) & S'(s) & D'(s) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x_0' \\ \delta_0 \end{pmatrix}$$

The trajectory has two parts:

linear

$$x(s) = \text{betatron} + \eta_x(s)\delta \qquad \eta_x(s) \equiv \frac{dx}{d\delta}$$

(Review: Dispersion)

- Substituting and noting dispersion is periodic, $\eta_x(s+C) = \eta_x(s)$

$$\begin{pmatrix} \eta_x(s) \\ \eta'_x(s) \\ \delta(s) \end{pmatrix} = \begin{pmatrix} C(s) & S(s) & D(s) \\ C'(s) & S'(s) & D'(s) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \eta_x(s) \\ \eta'_x(s) \\ \delta_0 \end{pmatrix} \qquad \text{achromat} : D = D' = 0$$

  - If we take $\delta_0 = 1$ we can solve this in a clever way

$$\begin{pmatrix} \eta_x(s) \\ \eta'_x(s) \end{pmatrix} = \begin{pmatrix} C(s) & S(s) \\ C'(s) & S'(S) \end{pmatrix} \begin{pmatrix} \eta_x(s) \\ \eta'_x(s) \end{pmatrix} + \begin{pmatrix} D(s) \\ D'(s) \end{pmatrix} = M \begin{pmatrix} \eta_x(s) \\ \eta'_x(s) \end{pmatrix} + \begin{pmatrix} D(s) \\ D'(s) \end{pmatrix}$$

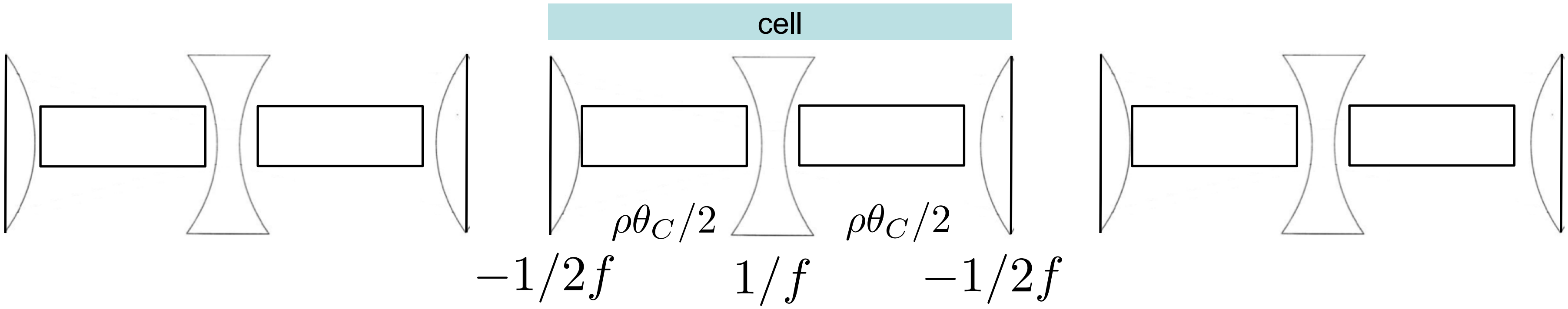
$$(I - M) \begin{pmatrix} \eta_x(s) \\ \eta'_x(s) \end{pmatrix} = \begin{pmatrix} D(s) \\ D'(s) \end{pmatrix} \quad \Rightarrow \quad \boxed{\begin{pmatrix} \eta_x(s) \\ \eta'_x(s) \end{pmatrix} = (I - M)^{-1} \begin{pmatrix} D(s) \\ D'(s) \end{pmatrix}}$$

  - Solving gives

$$\eta(s) = \frac{[1 - S'(s)]D(s) + S(s)D'(s)}{2(1 - \cos\mu)}$$

$$\eta'(s) = \frac{[1 - C(s)]D'(s) + C'(s)D(s)}{2(1 - \cos\mu)}$$

Review: FODO with dipoles



- A periodic lattice without dipoles has no **intrinsic** dispersion
- Consider FODO with long dipoles and thin quadrupoles
  - Each dipole has total length $\rho\theta_C/2$ so each cell is of length $L = \rho\theta_C$
  - Assume a large accelerator with many FODO cells so $\theta_C \ll 1$

$$M_{-2f} = \begin{pmatrix} 1 & 0 & 0 \\ -\frac{1}{2f} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad M_{\text{dipole}} = \begin{pmatrix} 1 & \frac{L}{2} & \frac{L\theta_C}{8} \\ 0 & 1 & \frac{\theta_C}{2} \\ 0 & 0 & 1 \end{pmatrix} \qquad M_f = \begin{pmatrix} 1 & 0 & 0 \\ \frac{1}{f} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$M_{\text{FODO}} = M_{-2f} M_{\text{dipole}} M_f M_{\text{dipole}} M_{-2f}$$

$$M_{\text{FODO}} = \begin{pmatrix} 1 - \frac{L^2}{8f^2} & L\left(1 + \frac{L}{4f}\right) & \frac{L}{2}\left(1 + \frac{L}{8f}\right)\theta_C \\ -\frac{L}{4f^2}\left(1 - \frac{L}{4f}\right) & 1 - \frac{L^2}{8f^2} & \left(1 - \frac{L}{8f} - \frac{L^2}{32f^2}\right)\theta_C \\ 0 & 0 & 1 \end{pmatrix}$$

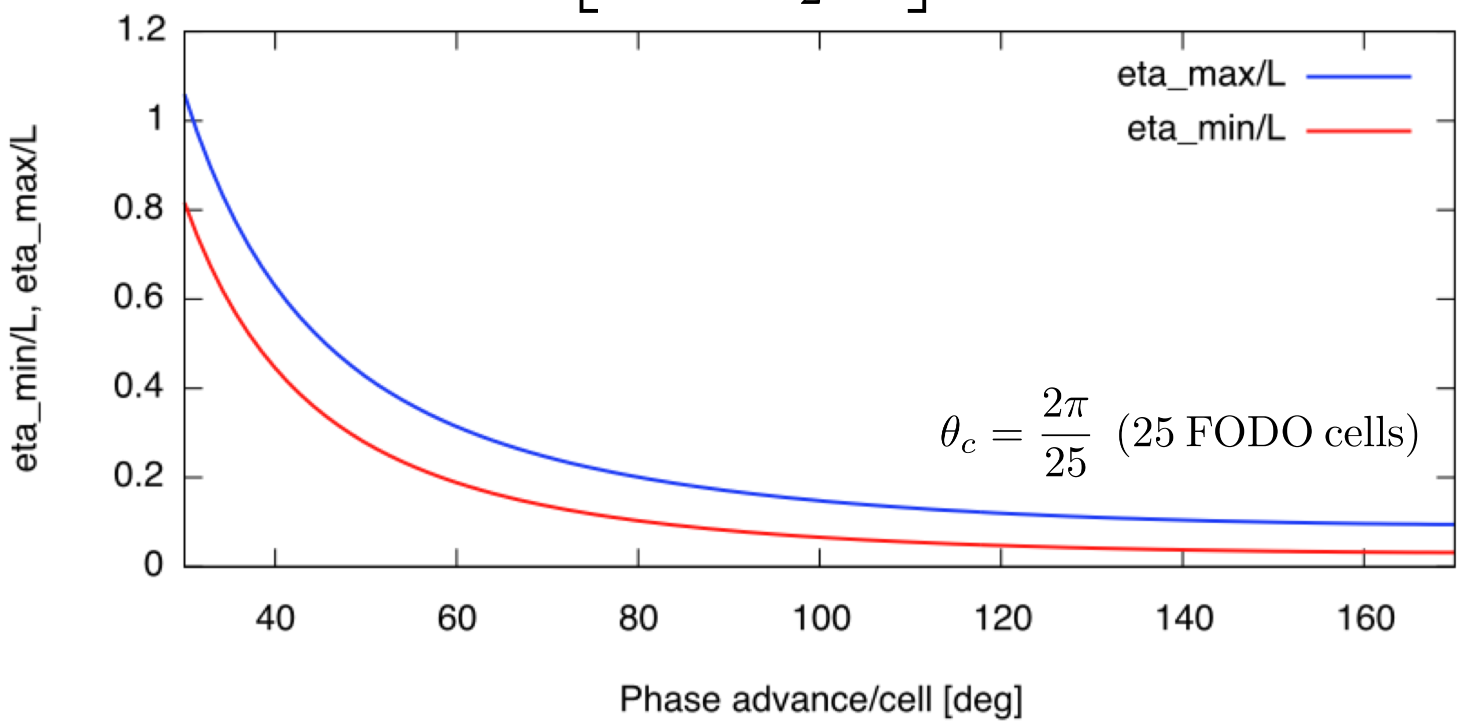
Review: FODO with dipoles

- Like $\hat{\beta}$ before, this choice of periodicity gives us $\hat{\eta}_x$

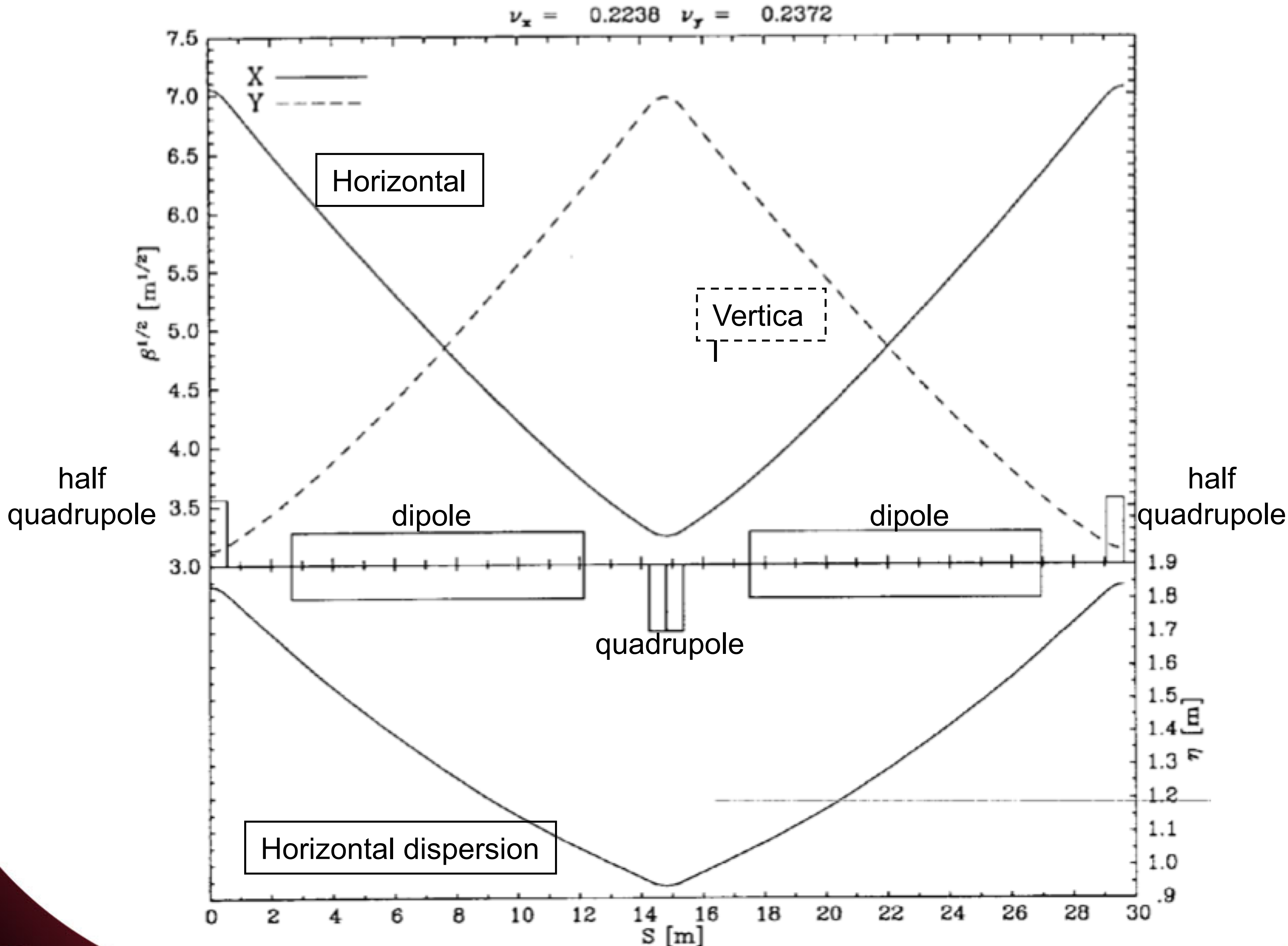
$$\hat{\eta}_x = \frac{L\theta_C}{4}\left[\frac{1+\frac{1}{2}\sin\frac{\mu}{2}}{\sin^2\frac{\mu}{2}}\right] \qquad \eta'_x = 0 \text{ at max}$$

- Changing periodicity to defocusing quad centers gives $\check{\eta}_x$

$$\check{\eta}_x = \frac{L\theta_C}{4}\left[\frac{1-\frac{1}{2}\sin\frac{\mu}{2}}{\sin^2\frac{\mu}{2}}\right] \qquad \eta'_x = 0 \text{ at min}$$

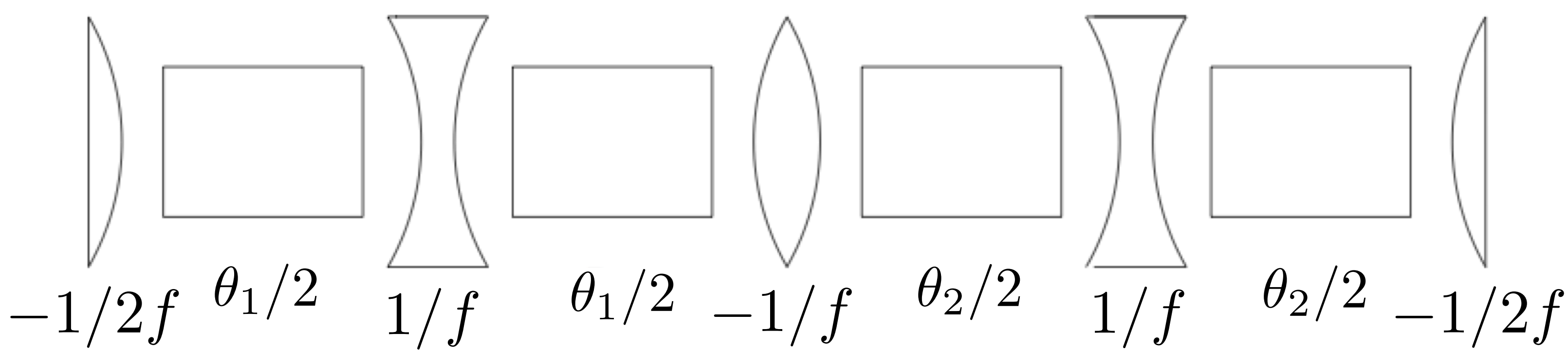


Review: RHIC FODO Cell



Dispersion suppressors

- The FODO dispersion solution is non-zero everywhere
  - But in straight sections we often want $\eta_x = \eta'_x = 0$
    - e.g. to keep beam small in wigglers/undulators in a light source
  - We can "match" between these two conditions with with a **dispersion suppressor**, a **non-periodic** set of magnets that transforms FODO (η_x, η'_x) to zero.



- Consider two FODO cells with different total bend angles θ_1, θ_2
  - Same quadrupole focusing to not disturb $\beta_x,\ \mu_x$ much
  - We want this to match $(\eta_x, \eta'_x) = (\hat{\eta}_x, 0)$ to $(\eta_x, \eta'_x) = (0, 0)$
  - $\alpha_x = 0$ at ends to simplify periodic matrix

Dispersion suppressors

Zero dispersion area

slope η' =0

$$\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = \begin{pmatrix} \cos 2\mu_x & \beta_x \sin 2\mu_x & D(s) \\ -\frac{\sin 2\mu_x}{\beta_x} & \cos 2\mu_x & D'(s) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \hat{\eta}_x \\ 0 \\ 1 \end{pmatrix}$$

FODO peak dispersion,

slope η' =0

multiply matrices $\Rightarrow$

$$D(s) = \frac{L}{2}\left(1 + \frac{L}{8f}\right)\left[\left(3 - \frac{L^2}{4f^2}\right)\theta_1 + \theta_2\right]$$

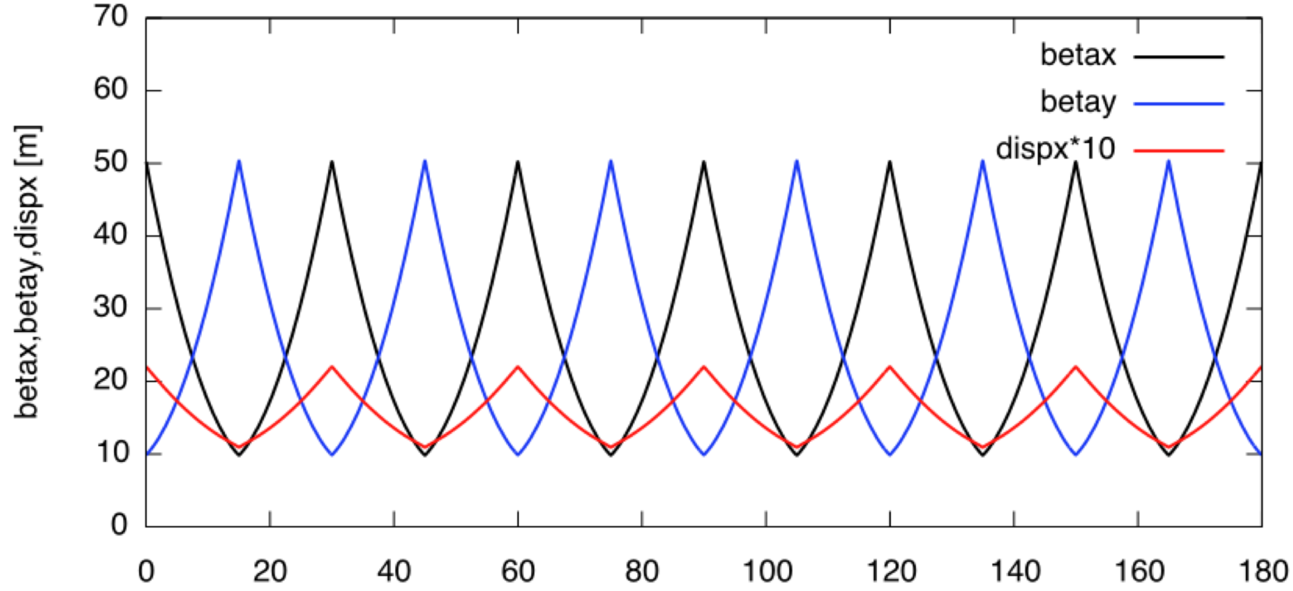
$$D'(s) = \left(1 - \frac{L}{8f} - \frac{L^2}{32f^2}\right)\left[\left(1 - \frac{L^2}{4f^2}\right)\theta_1 + \theta_2\right]$$

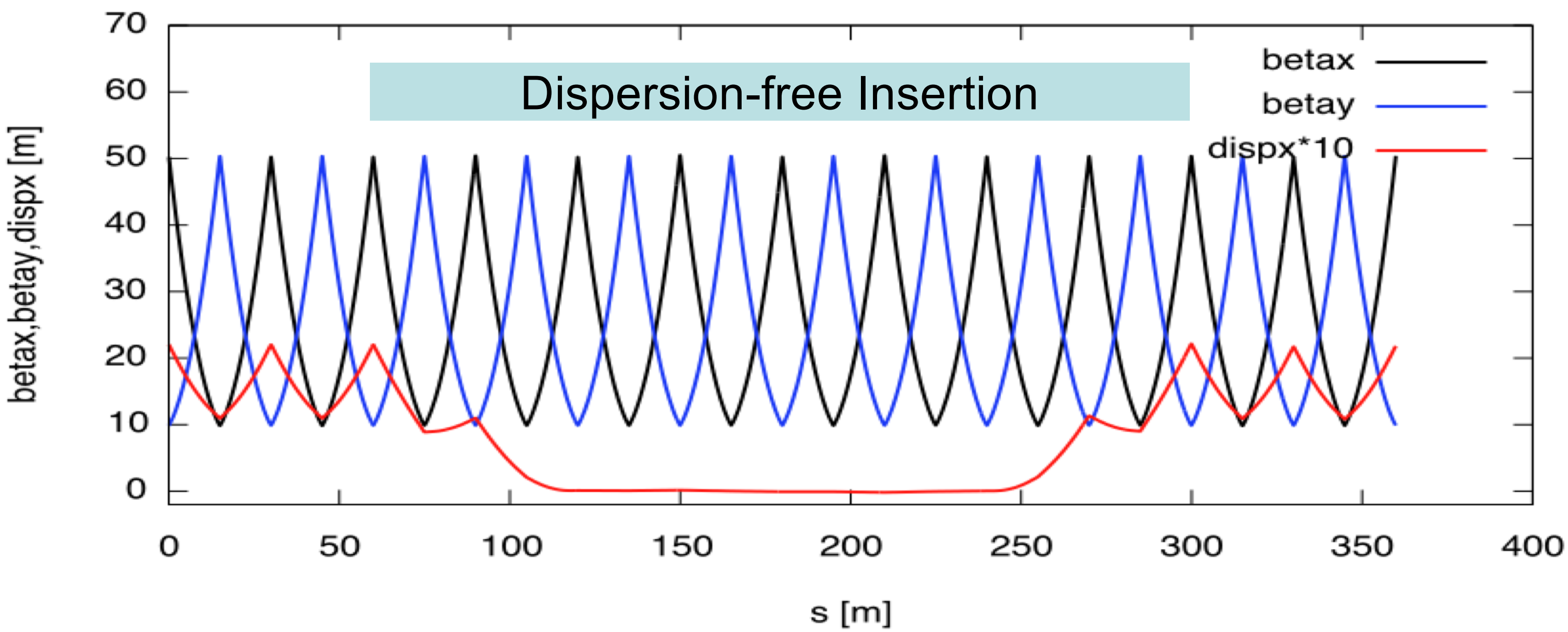
$$\hat{\eta}_x = \frac{4f^2}{L}\left(1 + \frac{L}{8f}\right)(\theta_1 + \theta_2)$$

$$\theta_1 = \left(1 - \frac{1}{4\sin^2\frac{\mu}{2}}\right)\theta \qquad \theta_2 = \left(\frac{1}{4\sin^2\frac{\mu}{2}}\right)\theta$$

$\theta = \theta_1 + \theta_2$ two cells, one FODO bend angle $\rightarrow$ reduced bending

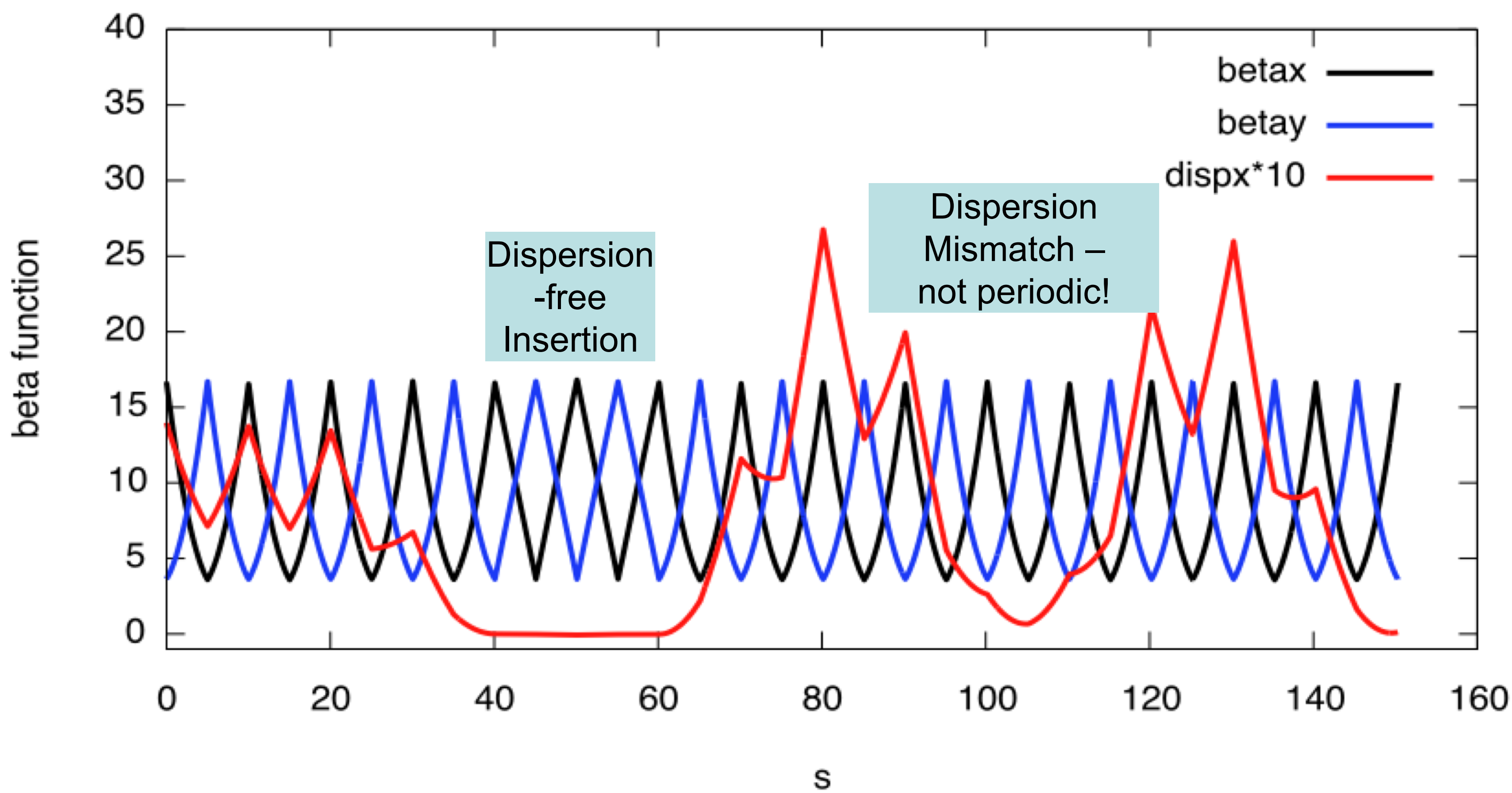
FODO Cell Dispersion and Suppressor



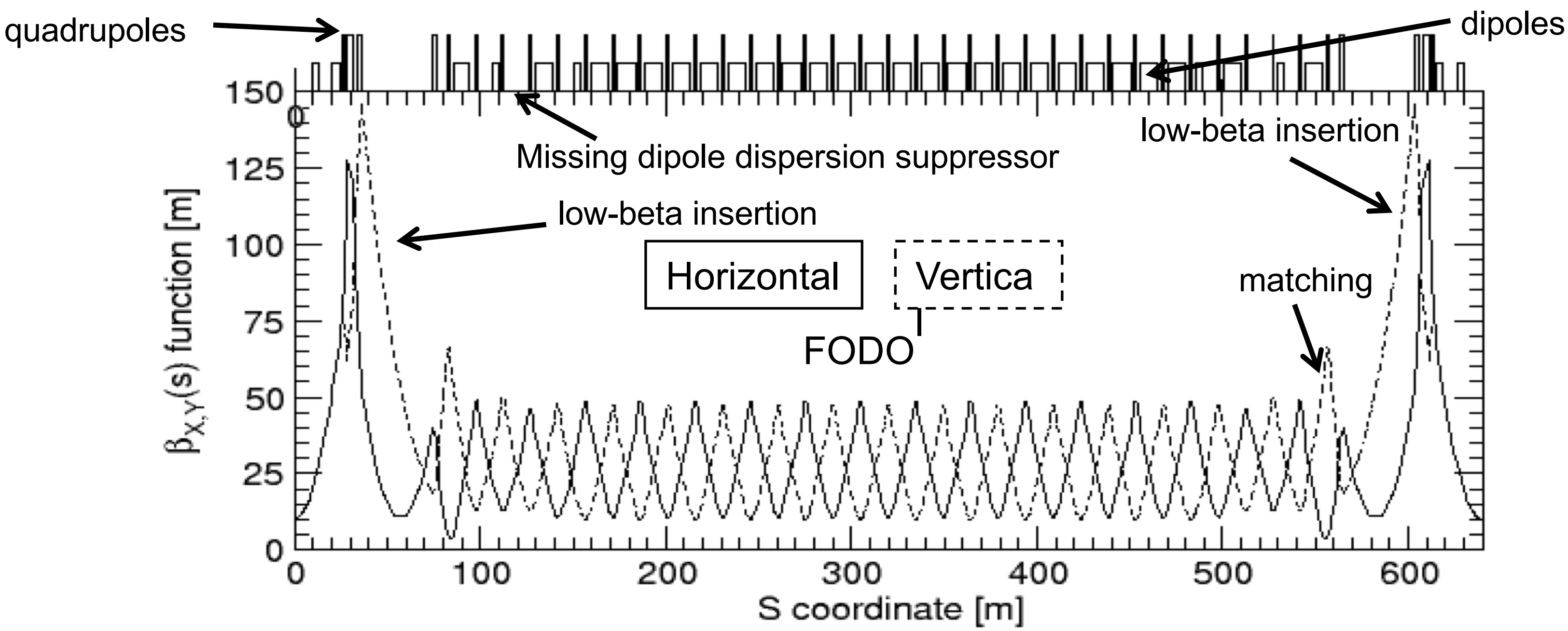


Mismatched Dispersion

- What does mismatched dispersion look like?
  - For example, this is what happens when the second dispersion suppressor is eliminated and the dipole-free FODO cells run right up against the FODO cells with dipoles

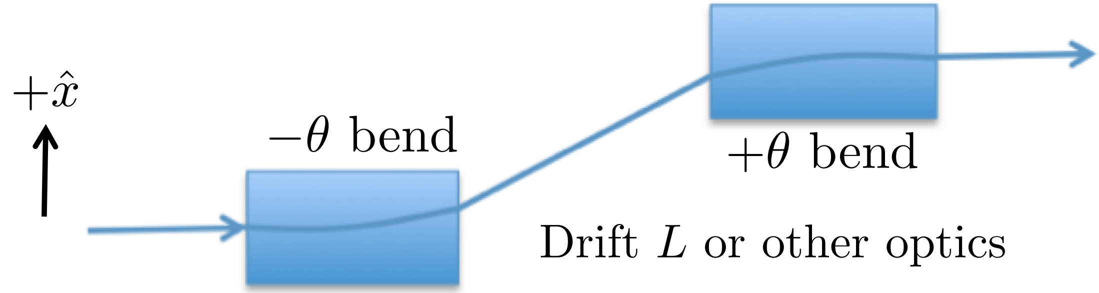


RHIC Lattice Revisited



- Note modular design, including low-beta insertions
  - Used for experimental collisions
  - Minimum beam size σ (with zero dispersion)
    - **maximize luminosity**
  - Large σ, beam size in "low beta quadrupoles"
  - Other facilities also have longitudinal bunch compressors (this afternoon)

Doglegs (Corrected Feb 9 2021)



- Displaces beam transversely without changing direction
- What is effect on 6D optics?

small $\theta \Rightarrow \rho\theta^2/2$

$$\mathbf{M}_{\text{dipole}}(\rho,\theta) = \begin{pmatrix} \cos\theta & \rho\sin\theta & 0 & 0 & 0 & \rho(1-\cos\theta) \\ -\frac{1}{\rho}\sin\theta & \cos\theta & 0 & 0 & 0 & \sin\theta \\ 0 & 0 & 1 & \rho\theta & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -\sin\theta & -\rho(1-\cos\theta) & 0 & 0 & 1 & \boxed{\frac{\rho\theta}{(\gamma\beta)^2}} - \rho(\theta-\sin\theta) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

- Be careful about the coordinate system and signs!!
- If $\rho,\theta>0$, positive displacement points **out** from dipole curvature
- Be careful about order of matrix multiplication!

Reverse Bend Dipole Transport

- What is the correct 6x6 transport matrix of a reverse bend dipole?
- It turns out to be achieved by reversing **both** ρ **and** θ
  - ρθ=L (which stays positive) so both must change sign

small $\theta \Rightarrow -\rho\theta^2/2$

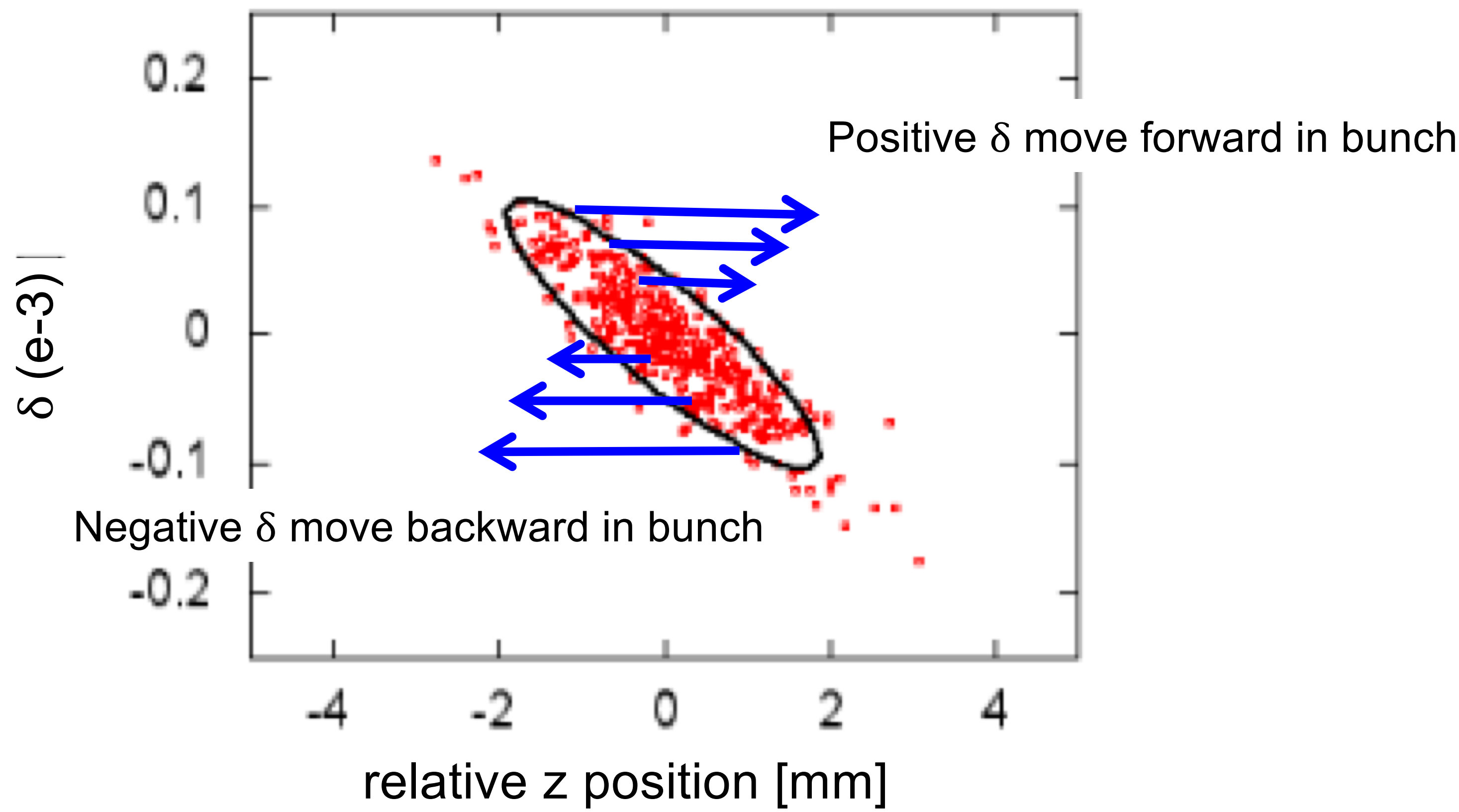
$$\mathbf{M}_{\text{dipole}}(-\rho,-\theta) = \begin{pmatrix} \cos\theta & \rho\sin\theta & 0 & 0 & 0 & -\rho(1-\cos\theta) \\ -\frac{1}{\rho}\sin\theta & \cos\theta & 0 & 0 & 0 & -\sin\theta \\ 0 & 0 & 1 & \rho\theta & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ \sin\theta & \rho(1-\cos\theta) & 0 & 0 & 1 & \frac{\rho\theta}{(\gamma\beta)^2} - \rho(\theta+\sin\theta) \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{M}_{\text{drift}} = \begin{pmatrix} 1 & L & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & L & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \frac{\rho\theta}{(\gamma\beta)^2} \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

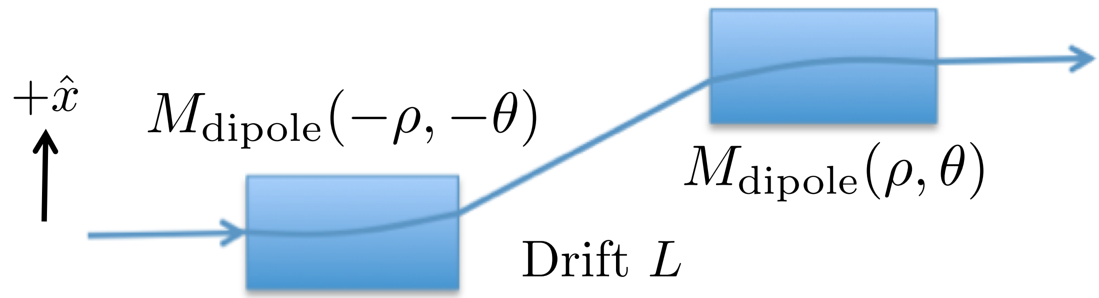
Ballistic drift term:
Easy to ignore in ultrarelativistic approximation.

Aside: Longitudinal Phase Space Drift

- Wait, what was that M_{56} term with the relativistic effects?
  - Recall longitudinal coordinates are (z, δ)
  - This extra term is called "ballistic drift": not in all codes!
    - Important at low to modest energies and for bunch compression
    - Relativistic terms enter converting momentum p to velocity v



Weak Dogleg (Corrected Feb 9 2021)



$$\begin{pmatrix} 1 & rt & -r\times\frac{t^2}{2} \\ 0 & 1 & t \\ 0 & 0 & 1 \end{pmatrix} . \begin{pmatrix} 1 & L & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} . \begin{pmatrix} 1 & rt & r\times\frac{t^2}{2} \\ 0 & 1 & -t \\ 0 & 0 & 1 \end{pmatrix}$$

Result:

$$\begin{pmatrix} 1 & L+2rt & -t(L+rt) \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Wolfram Alpha

$$\mathbf{M}_{\rm dogleg} = \mathbf{M}_{\rm dipole}(-\rho, -\theta)\mathbf{M}_{\rm drift}\mathbf{M}_{\rm dipole}(\rho, \theta)$$

$$\mathbf{M}_{\text{weak dogleg}} = \begin{pmatrix} 1 & \rho\theta & -\frac{\rho\theta^2}{2} \\ 0 & 1 & \theta \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & L & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & \rho\theta & \boxed{\frac{\rho\theta^2}{2}} \\ 0 & 1 & \boxed{-\theta} \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} 1 & L+2\rho\theta & \boxed{-L\theta - r\theta^2} \\ 0 & 1 & \boxed{0} \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{array}{l} (\eta, \eta')_{\rm in} = 0 \\ (\eta, \eta')_{\rm out} = (-L\theta - \rho\theta^2, 0) \end{array}$$

"Strong" dogleg (θ not small) can also be derived:

$$D = \cos\theta[2\rho(\cos\theta - 1) - L\sin\theta]$$
$$D' = \sin\theta[(L/\rho)\sin\theta - 2\cos\theta + 2]$$

Wolfram Alpha

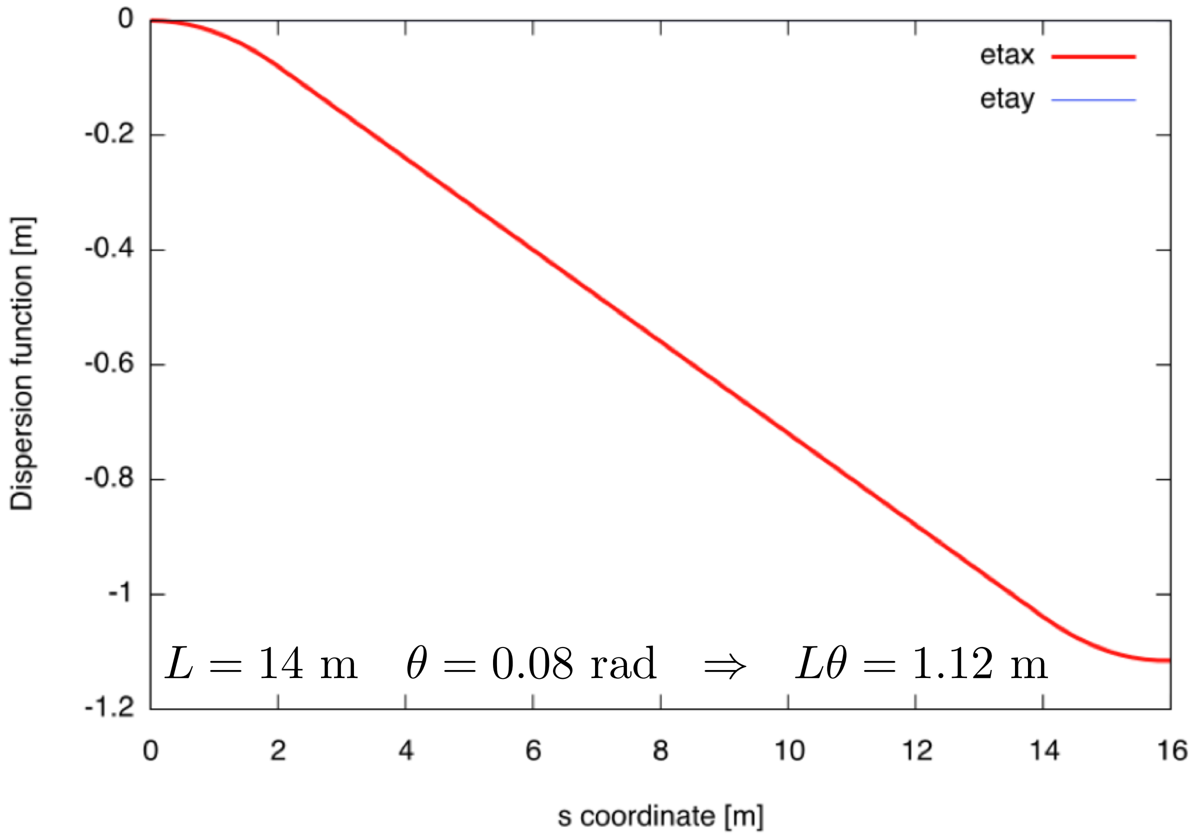
simplify | expand

$$\begin{pmatrix} \cos(t) & r\sin(t) & r(1-\cos(t)) \\ -\frac{\sin(t)}{r} & \cos(t) & \sin(t) \\ 0 & 0 & 1 \end{pmatrix} . \begin{pmatrix} 1 & L & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} . \begin{pmatrix} \cos(t) & r\sin(t) & -r(1-\cos(t)) \\ -\frac{\sin(t)}{r} & \cos(t) & -\sin(t) \\ 0 & 0 & 1 \end{pmatrix}$$

Results: Enlarge

$$\begin{pmatrix} \cos(2t) - \frac{L\sin(t)\cos(t)}{r} & \cos(t)(L\cos(t) + 2r\sin(t)) & \cos(t)(2r(\cos(t)-1) - L\sin(t)) \\ \frac{\sin(t)(L\sin(t) - 2r\cos(t))}{r^2} & \cos(2t) - \frac{L\sin(t)\cos(t)}{r} & \frac{\sin(t)(L\sin(t) - 2r\cos(t) + 2r)}{r} \\ 0 & 0 & 1 \end{pmatrix}$$

Dogleg Dispersion



For weak dogleg

$$(\eta, \eta')_{\text{in}} = 0$$

$$(\eta, \eta')_{\text{out}} = (-L\theta - \rho\theta^2, 0)$$

Does this make sense?

$$\Delta x'(\delta) = \frac{BL}{(B\rho)} = \frac{q}{p(1+\delta)}[BL] \approx \frac{q}{p}[BL](1-\delta) = (1-\delta)\Delta x'(\delta = 0)$$

Caution: Here (Brho) is rigidity and L is length of **dipole**

Achromatic Dogleg

- How can we make an achromatic dogleg?

$$(\eta, \eta')_{\text{in}} = (0\ \text{m}, 0) \quad \Rightarrow \quad (\eta, \eta')_{\text{out}} = (0\ \text{m}, 0)$$

- Use an I insertion (e.g. four consecutive π/2 insertions)

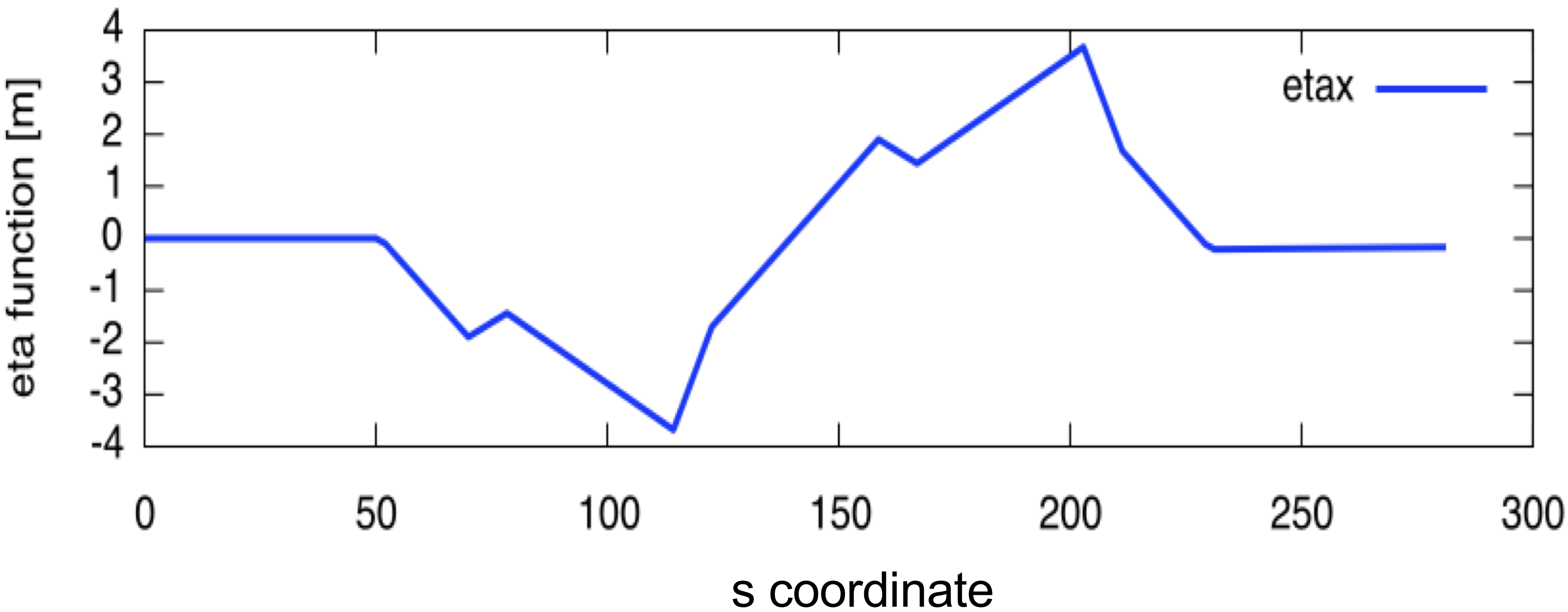
$$\mathbf{M}_{\pi/2} = \begin{pmatrix} \alpha & \beta \\ -\gamma & -\alpha \end{pmatrix} = \mathbf{J} \qquad (\text{Recall } \mathbf{J}^4 = \mathbf{I})$$

$$\mathbf{M}_{\text{achromatic dogleg}} = \begin{pmatrix} \cos(2\theta) & \rho \sin(2\theta) & 0 \\ -\frac{\sin(2\theta)}{\rho} & \cos(2\theta) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

achromatic!

- **Any** transport with net phase advance of 2nπ will be achromatic (nπ if all dipoles bend in same direction)
  - common trick for matching dispersive bending arcs to non-dispersive straight sections.

Achromatic Dogleg



Achromatic Dogleg: Steffen CERN School Notes

<u>Example of nondispersive translating system</u>

Φ = sector magnet bend. angle

$\varphi = \ell\sqrt{k}$ = quadrupole magnet phase angle

d, λ = drift space lengths.

The system is nondispersive if the sinelike trajectory (with respect to the central symmetry point) goes through the mid-point of the bending magnets, i.e. if

$$\rho \tan\frac{\Phi}{2} + \lambda = \frac{1}{\sqrt{k}} \, \frac{d\sqrt{k}\cos\varphi + 2\sin\varphi}{d\sqrt{k}\sin\varphi - 2\cos\varphi} \, .$$

Focusing also in the other plane may be obtained by adding a third quadrupole of opposite polarity at the symmetry point.

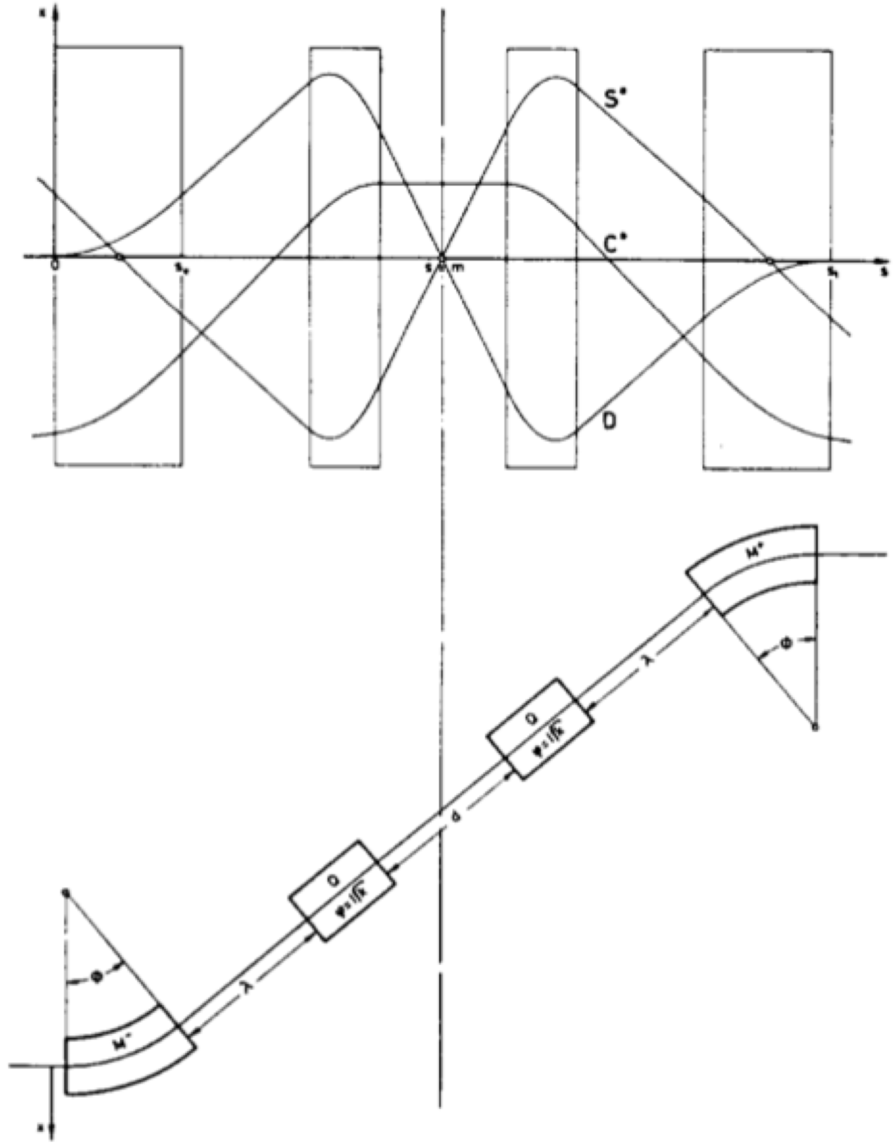


Fig. 15: Nondispersive translating system.

K. Steffen, CERN-85-19-V-1, 1985, p. 55

First-Order Achromat Theorem

- A lattice of n repetitive cells is achromatic (to first order, or in the linear approximation) iff $\mathbf{M}^n = I$ or each cell is achromatic
- Proof:

$$\text{Consider } \mathbf{R} \equiv \begin{pmatrix} \mathbf{M} & \bar{d} \\ 0 & 1 \end{pmatrix} \quad \text{where} \quad \begin{pmatrix} x \\ x' \\ \delta \end{pmatrix}_2 = \mathbf{R} \begin{pmatrix} x \\ x' \\ \delta \end{pmatrix}_1 \qquad \bar{d} = \begin{pmatrix} M_{16} \\ M_{26} \end{pmatrix}$$

$$\textbf{For } n \text{ cells}: \quad \mathbf{R}^n = \begin{pmatrix} \mathbf{M}^n & (\mathbf{M}^{n-1} + \mathbf{M}^{n-2} + \ldots + \mathbf{I})\bar{d} \\ 0 & 1 \end{pmatrix}$$

$$\text{but} \quad (\mathbf{M}^{n-1} + \mathbf{M}^{n-2} + \ldots + \mathbf{I}) = (\mathbf{M}^n - I)(\mathbf{M} - I)^{-1}$$

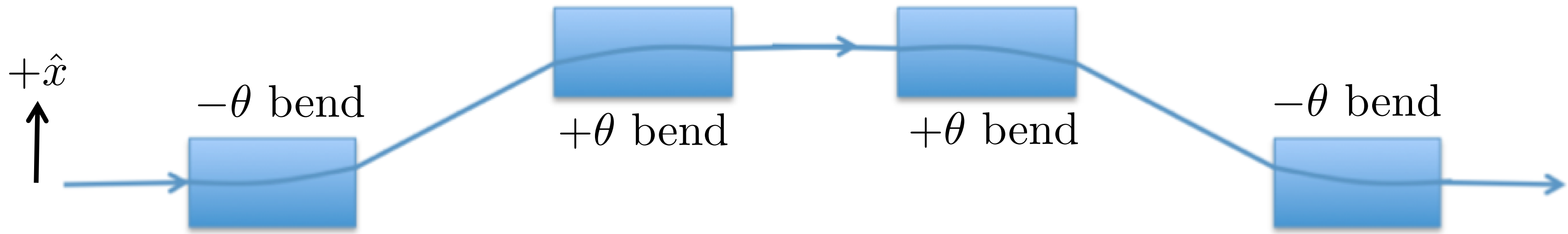
$$\text{So for } n \text{ cells}: \quad \mathbf{R}^n = \begin{pmatrix} \mathbf{M}^n & (\mathbf{M}^n - \mathbf{I})(\mathbf{M} - \mathbf{I})^{-1}\bar{d} \\ 0 & 1 \end{pmatrix}$$

- So the lattice is achromatic only if $\bar{d} = 0$ or $\mathbf{M}^n = \mathbf{I}$

$$\mathbf{M}^n = \mathbf{I}\cos\mu_{\text{tot}} + \mathbf{J}\sin\mu_{\text{tot}} \quad \Rightarrow \quad \mu_{\text{tot}} = 2\pi k$$

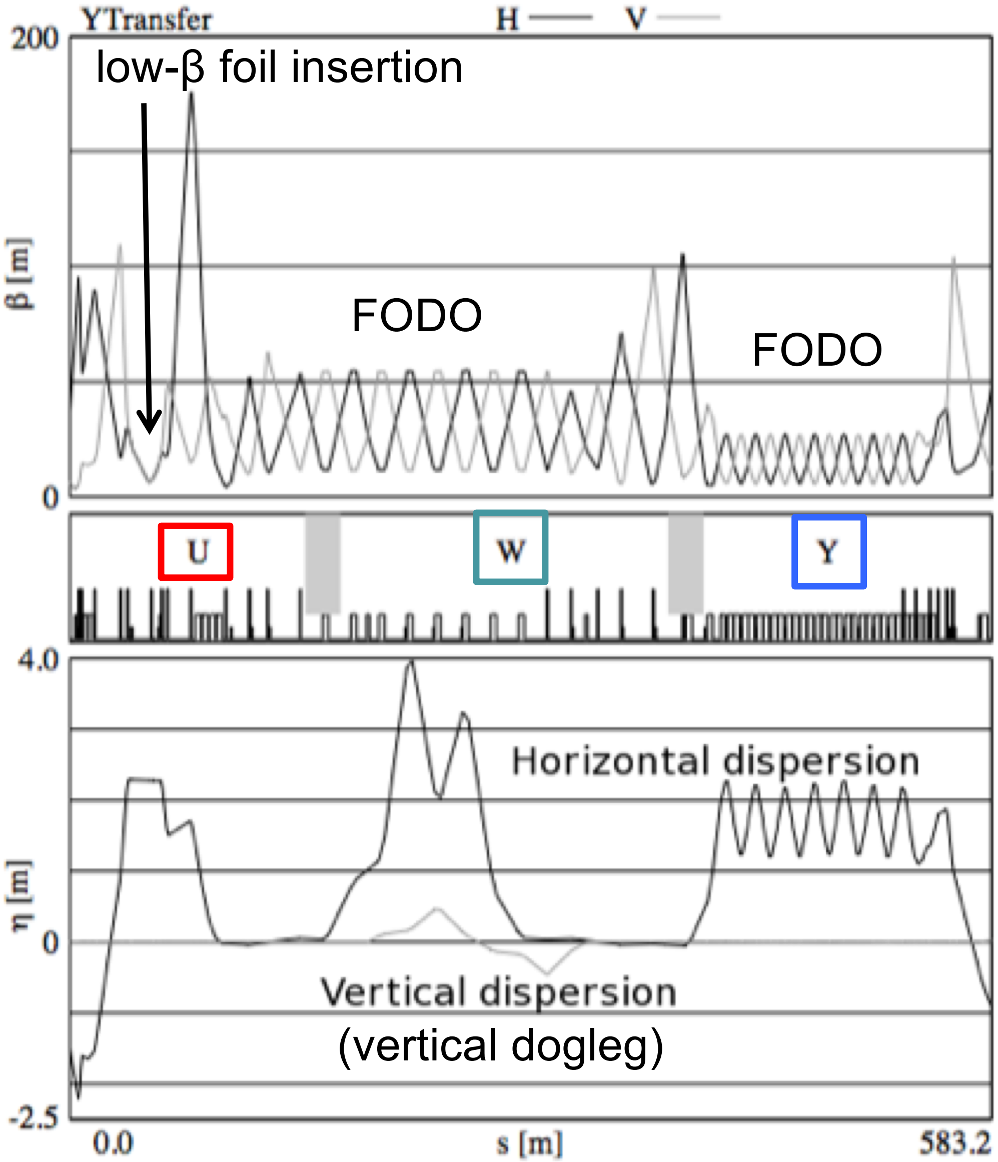
S.Y. Lee, "Accelerator Physics"

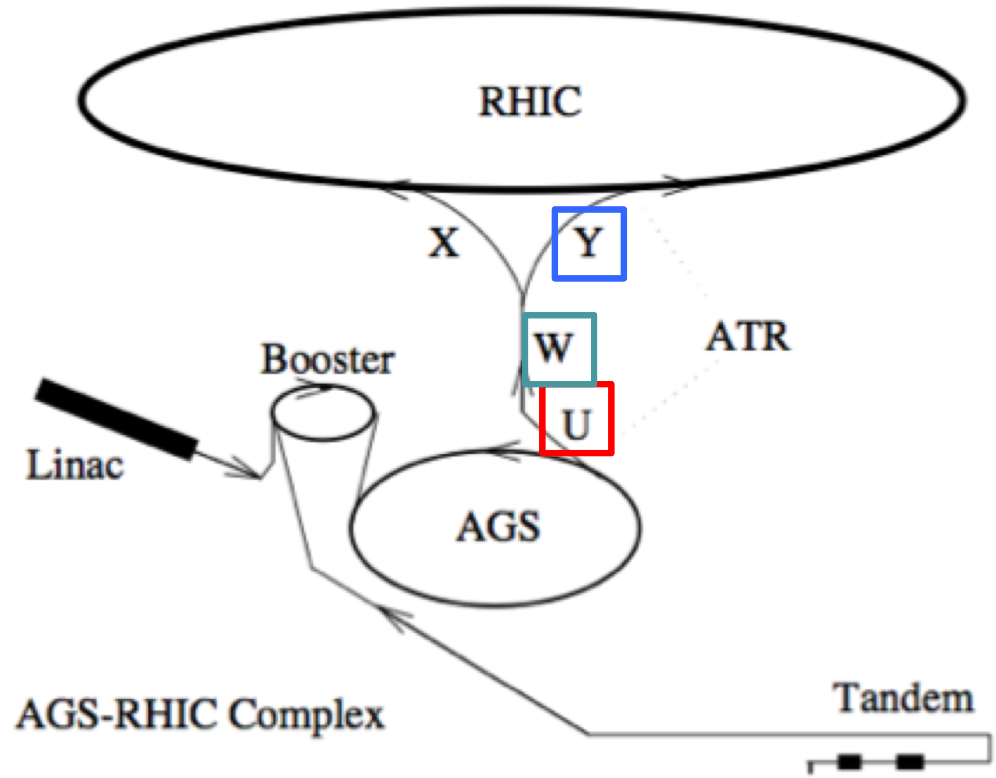
Chicane



- Divert beam around an obstruction
  - e.g. vertical bypass chicane in Fermilab Main Ring
  - e.g. horizontal injection chicane in CEBAF recirculating linac
  - Essentially a design orbit “4-bump” (4 dipoles)
- Usually need some focusing, optics between dipoles
- Usually design optics to be achromatic
  - Operationally null orbit motion at end of chicane vs changes in input beam energy
- Naively expect $M_{56}<0$ (bunch lengthening or decompression)
  - Higher energy particles ($+\delta$) have shorter path lengths
  - But can compress bunches with introduction of longitudinal correlation

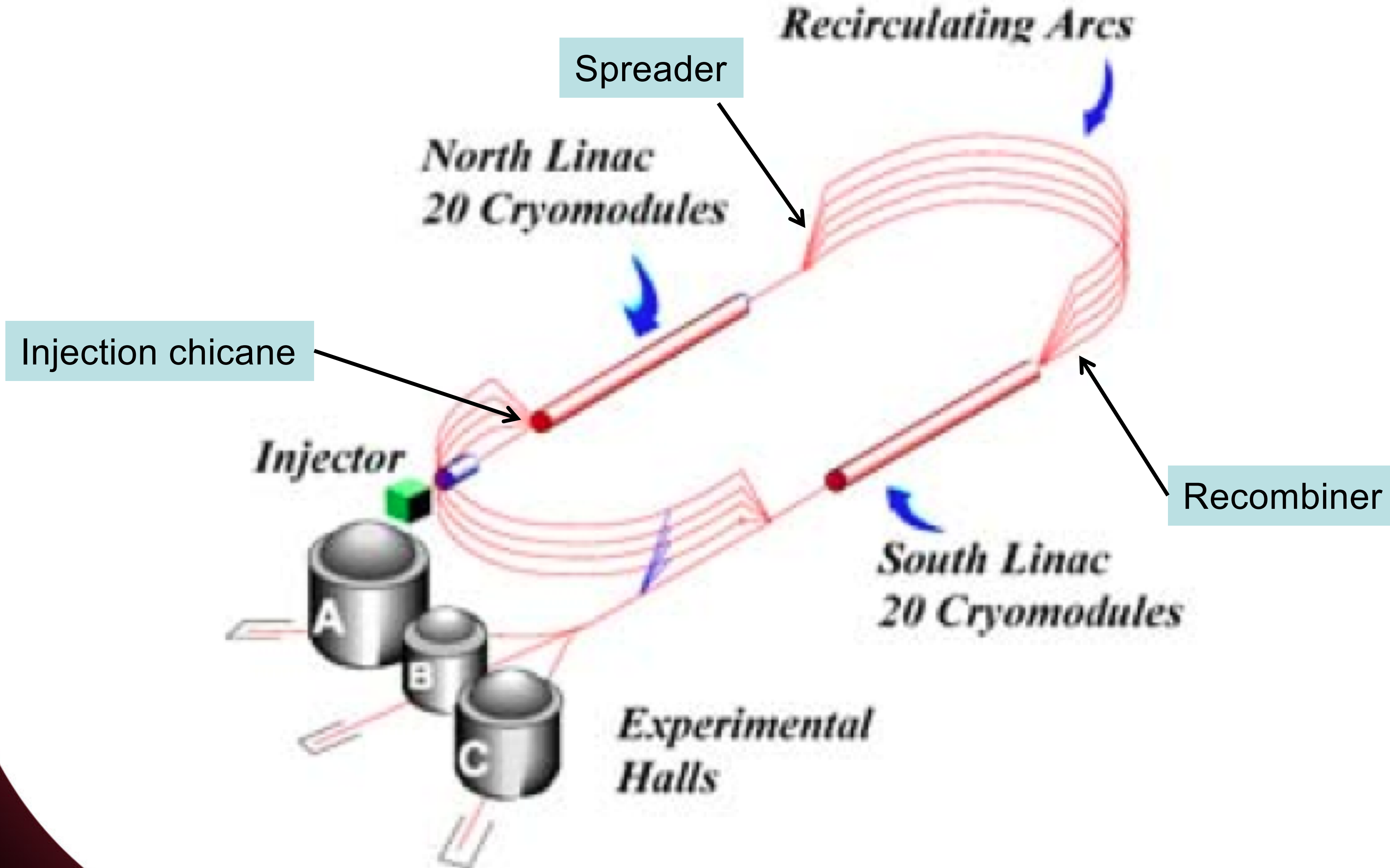
AGS to RHIC (ATR) Transfer Line





The ATR vertical dogleg is not strictly a dogleg since the planes of the AGS and RHIC accelerators are not parallel

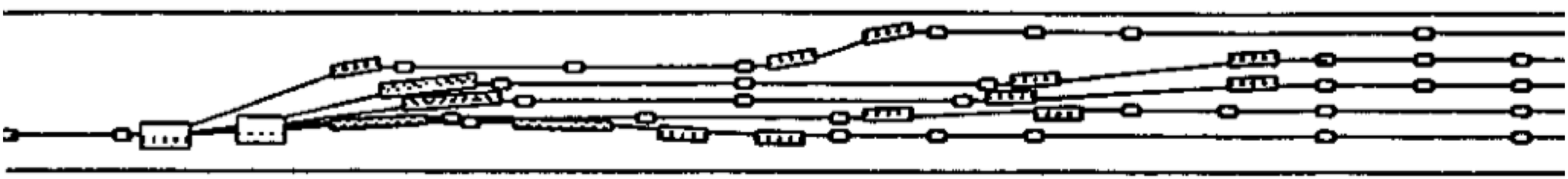
CEBAF



Recirculating Arcs
Spreader
North Linac
20 Cryomodules
Injection chicane
Injector
Recombiner
South Linac
20 Cryomodules
A
B
C
Experimental
Halls

CEBAF Spreaders/Recombiners

- Problem: Separate different energy beams for transport into arcs of CEBAF, and recombine before next linac
  - Achromats: arcs are FODO-like, linacs are dispersion-free
  - “I” insertion: 1 betatron wavelength between dipoles
  - Single dogleg: unacceptably high beta functions
  - Two consecutive “staircase” doglegs with same total phase advance was solution

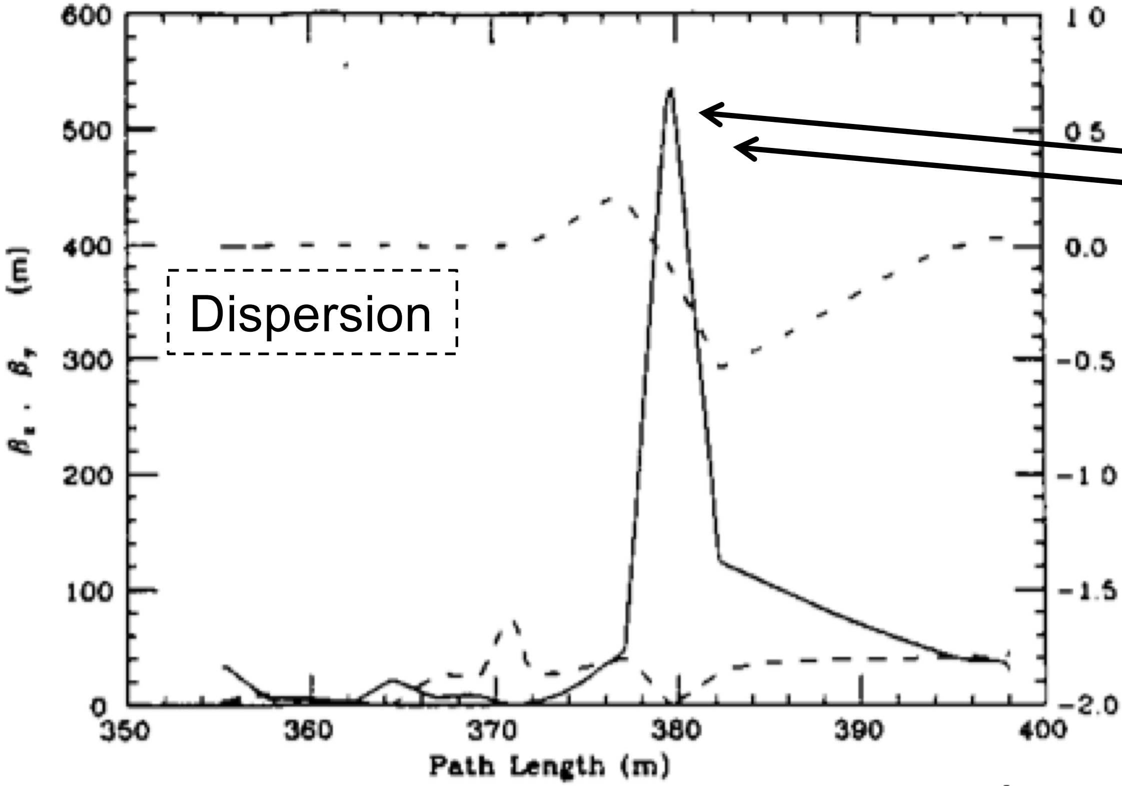


EAST ARC ELEVATION

  - Still quite a challenge in physical layout of real magnets!

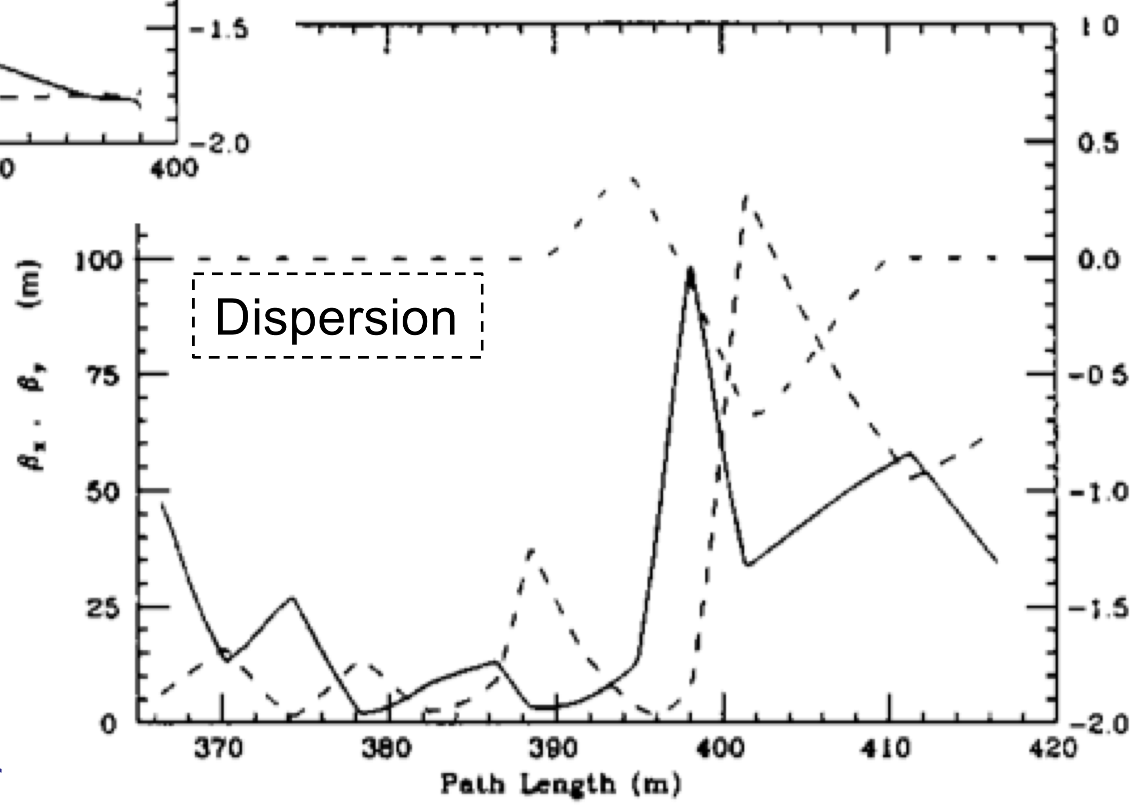
D. Douglas, R.C. York, J. Kewisch, “Optical Design of the CEBAF Beam Transport System”, 1989

CEBAF Spreaders/Recombiners

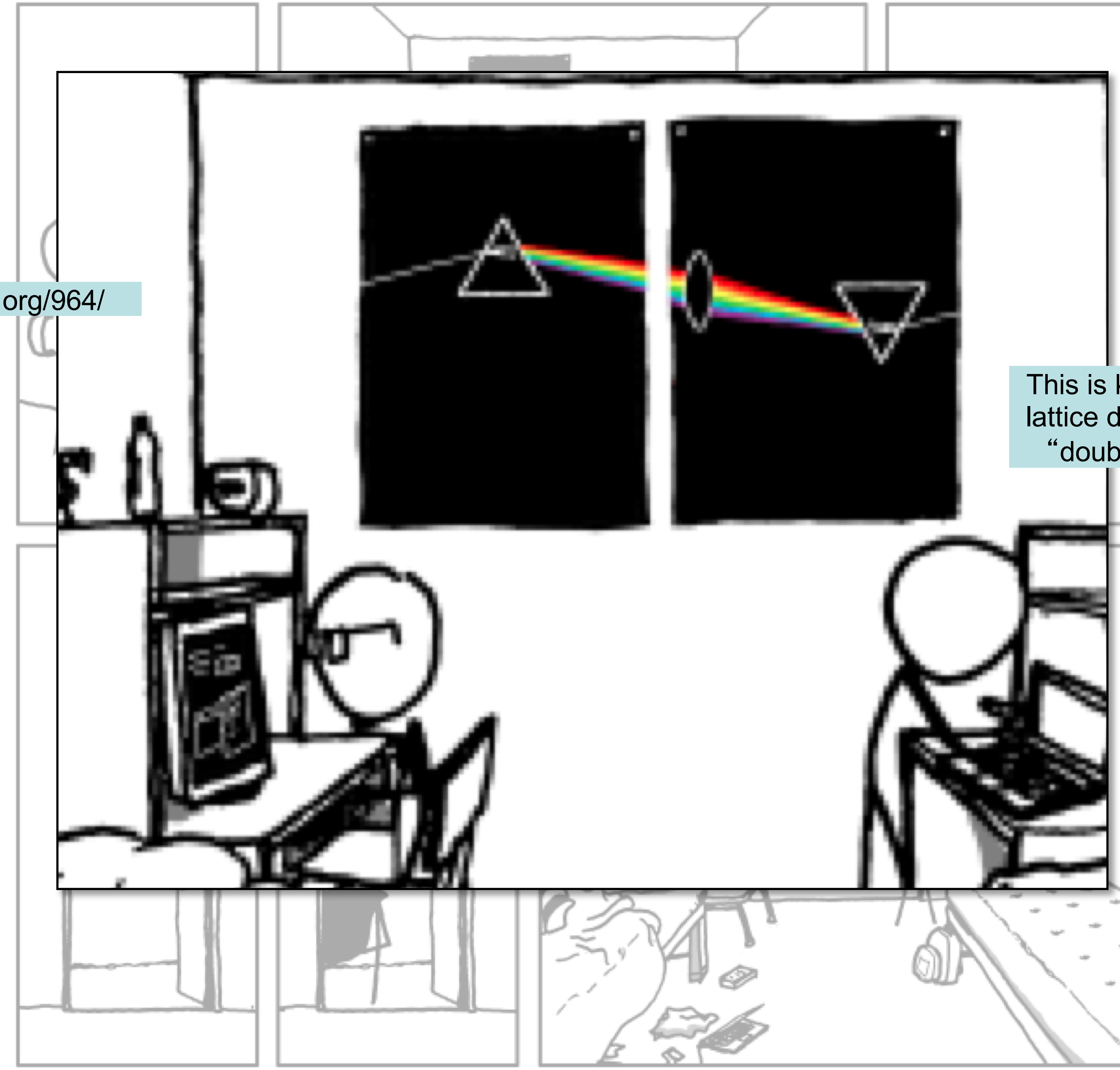


"One step" recombiner
Unacceptably large vertical beta function/beam size (550 m)

"Staircase" two-step recombiner
Acceptable beta functions and beam sizes in both planes (100 m)



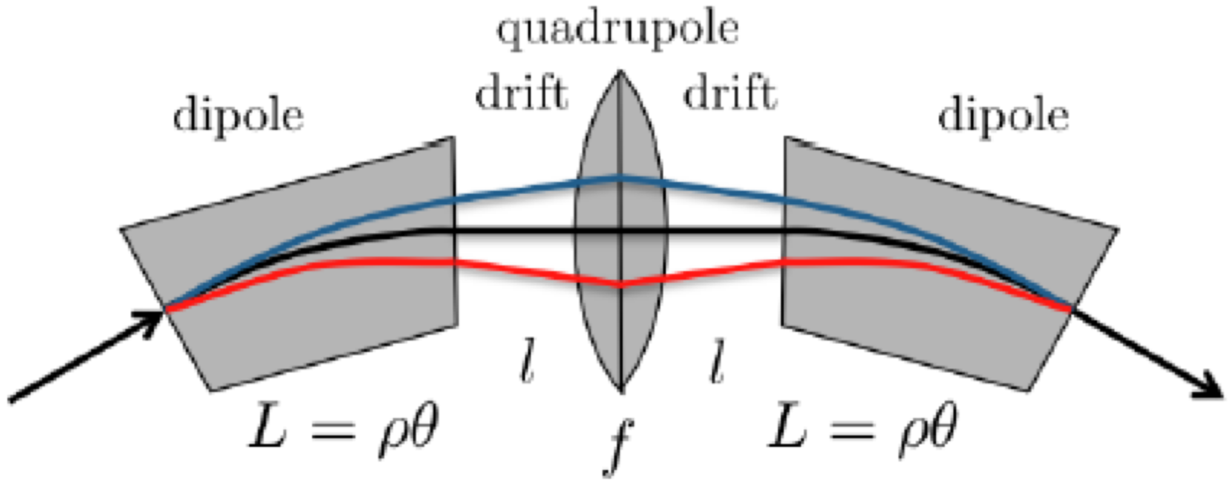
(xkcd interlude)



http://www.xkcd.org/964/

This is known in accelerator lattice design language as a "double bend achromat"

Double Bend Achromat (approximate)



- Let's calculate constraints for the double bend achromat

$$M_{\text{dipole}} = \begin{pmatrix} \cos\theta & \rho\sin\theta & \rho[1-\cos\theta] \\ -\frac{1}{\rho}\sin\theta & \cos\theta & \sin\theta \\ 0 & 0 & 1 \end{pmatrix}$$

Keep lowest-order terms in θ, including θ^2 in upper right term since $\rho\theta=L$

$$M_{\text{dipole}} = \begin{pmatrix} 1 & L & L\theta/2 \\ 0 & 1 & \theta \\ 0 & 0 & 1 \end{pmatrix}$$

Double Bend Achromat (approximate)

$$\mathbf{M}_{\mathrm{DBA}} = \begin{pmatrix} 1 & L & L\theta/2 \\ 0 & 1 & \theta \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & l & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ -\frac{1}{f} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & l & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & L & L\theta/2 \\ 0 & 1 & \theta \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mathbf{M}_{\mathrm{DBA}} = \begin{pmatrix} C & S & D \\ C' & S' & D' \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{aligned} C &= 1 - \frac{(L+l)}{f} \\ S &= \frac{(L+l)(2f-L-l)}{f} \\ D &= \theta\frac{(L+l)(4f-L-2l)}{2f} \\ C' &= -\frac{1}{f} \\ S' &= 1 - \frac{(L+l)}{f} = C \\ D' &= \theta\frac{(4f-L-2l)}{2f} = \frac{D}{L+l} \end{aligned}$$

Double Bend Achromat (approximate)

- The periodic solutions for dispersion for the general M matrix were shown in class earlier today

$$\eta(\text{periodic}) = \frac{[1-S']D + SD'}{2(1-\cos\mu)} = 0$$

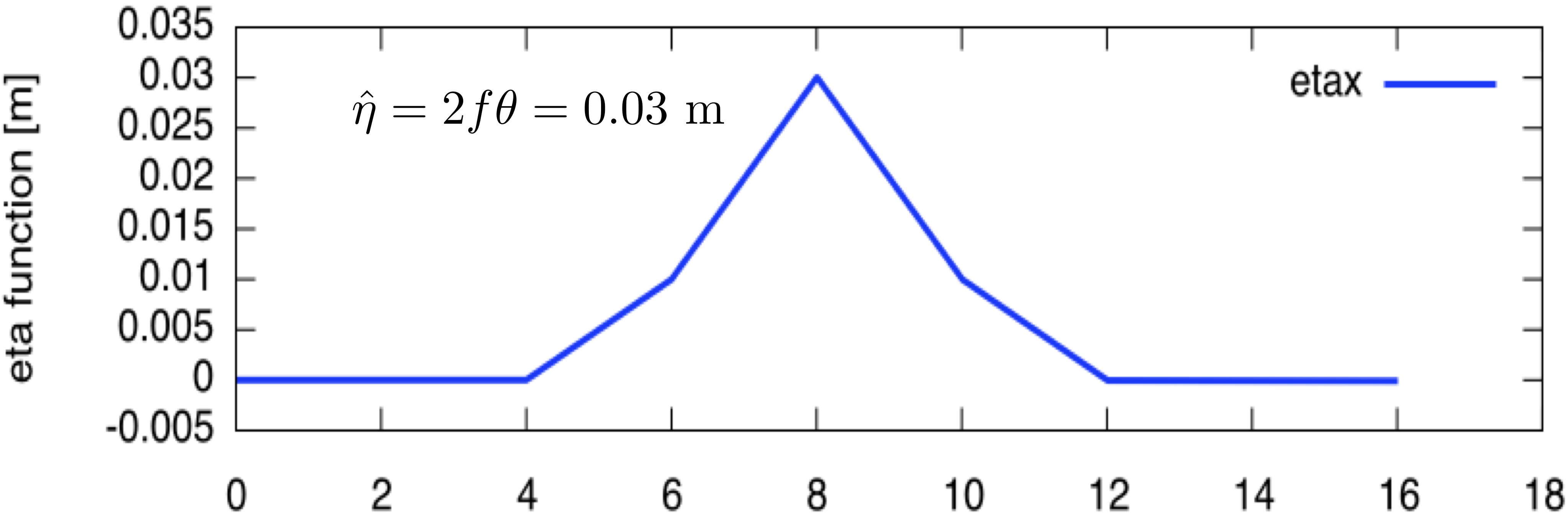
$$\eta'(\text{periodic}) = \frac{[1-C]D' + C'D}{2(1-\cos\mu)} = 0$$

- It turns out that the η' equation is satisfied automatically!
  - This is a consequence of the mirror symmetry of the system
- The η equation is satisfied if D=0:

$$D = \theta\frac{(L+l)(4f-L-2l)}{2f} = 0$$

$$\Rightarrow 4f - L - 2l = 0 \qquad \Rightarrow \qquad f = \frac{L+2l}{4} \qquad \hat{\eta} = \frac{(L+2l)\theta}{2} = 2f\theta$$

Double Bend Achromat



$$L = l = 2\ \mathrm{m} \quad \theta = 0.01\ \mathrm{rad} \quad f = \frac{L+2l}{4} = 1.5\ \mathrm{m} \quad (KL_{\mathrm{quad}}) = 0.667\ \mathrm{m}^{-1}$$

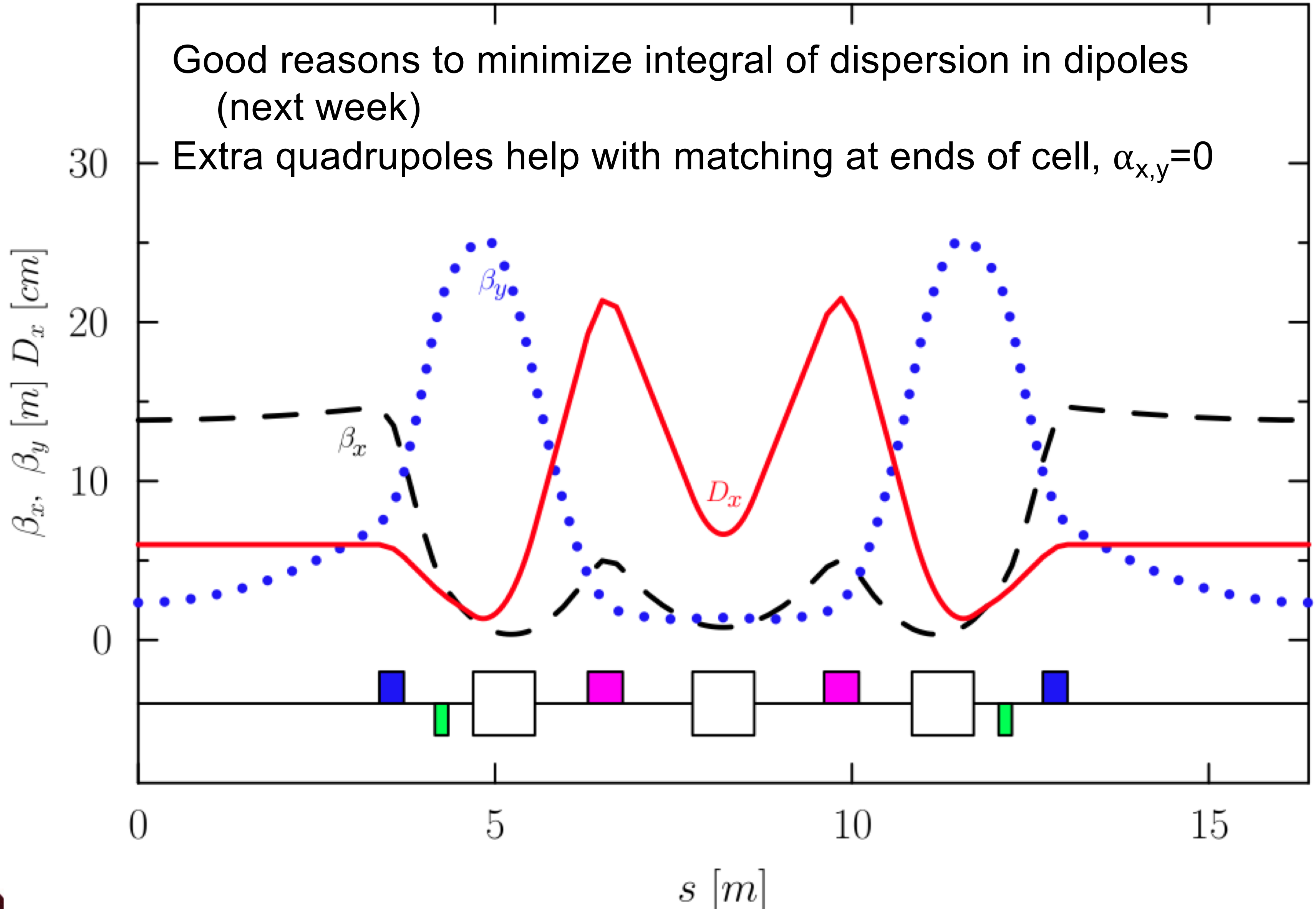
$$\text{Exact DBA}: \quad f = \frac{l}{2} + \frac{\rho}{2}\tan(\theta/2) \qquad \hat{\eta} = \rho(1-\cos\theta) + l\sin\theta$$

- DBA is also known as a Chasman-Green lattice
  - Used in early third-generation light sources (e.g. NSLS at BNL)
  - More after we discuss synchrotron radiation, $\mathcal{H}$ functions

Triple Bend Achromat Cell (ALS at LBL)

Good reasons to minimize integral of dispersion in dipoles (next week)

Extra quadrupoles help with matching at ends of cell, $\alpha_{x,y}=0$



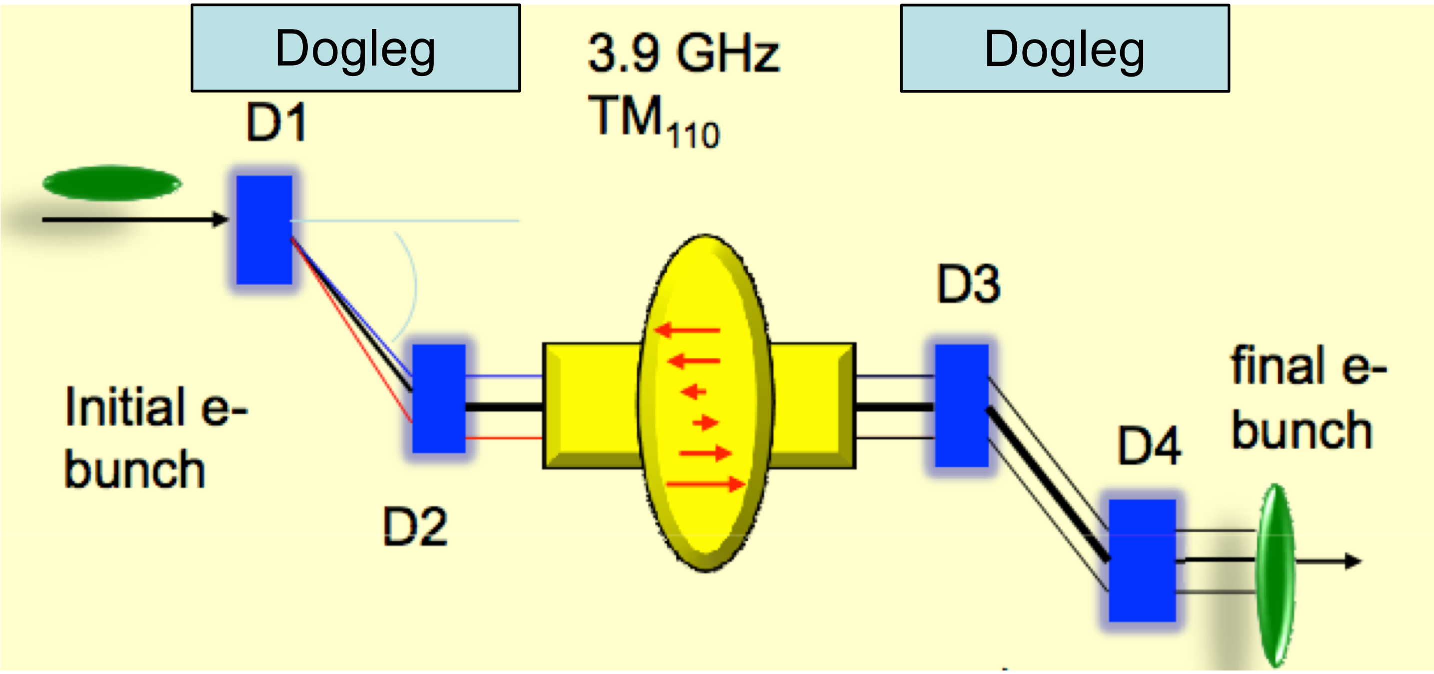
L. Yang et al, Global Optimization of an Accelerator Lattice Using Multiobjective Genetic Algorithms, 2009

Transverse/Longitudinal Emittance Exchange

- X-ray FELs demand ultra-low transverse emittance beam*
- State-of-the art photo-injectors can generate low 6-D emittance. Typically asymmetric emittances. Emittance exchange can swap transverse with the longitudinal emittance.
- Allows one to convert transverse modulations to longitudinal modulations : Beam shaping application
- Can also be used to suppress microbunching instability**

J.C.T. Thangaraj, Experimental Studies on an Emittance Exchange Beamline at the A0 Photoinjector, 2012

Fermilab A0 Emittance Exchanger



θ : Bending angle
η : dogleg dispersion
L : dogleg length
L_c : RF cell length

$$\mathbf{M} = \begin{pmatrix} 1 & \frac{L_c}{4} & -\frac{(4L+L_c)}{4\eta} & \eta - \frac{\theta(4L+L_c)}{4} \\ 0 & 1 & -\frac{1}{\eta} & -\theta \\ -\theta & \eta - \frac{\theta(4L+L_c)}{4} & 1 + \frac{\theta L_c}{4\eta} & \frac{\theta^2 L_c}{4} \\ -\frac{1}{\eta} & -\frac{4L+L_c}{4\eta} & \frac{\theta L_c}{4\eta^2} & 1 + \frac{\theta L_c}{4\eta} \end{pmatrix} \begin{pmatrix} x \\ x' \\ z \\ \delta \end{pmatrix}$$

J.C.T. Thangaraj, Experimental Studies on an Emittance Exchange Beamline at the A0 Photoinjector, 2012

TM110 RF Cavity Mode

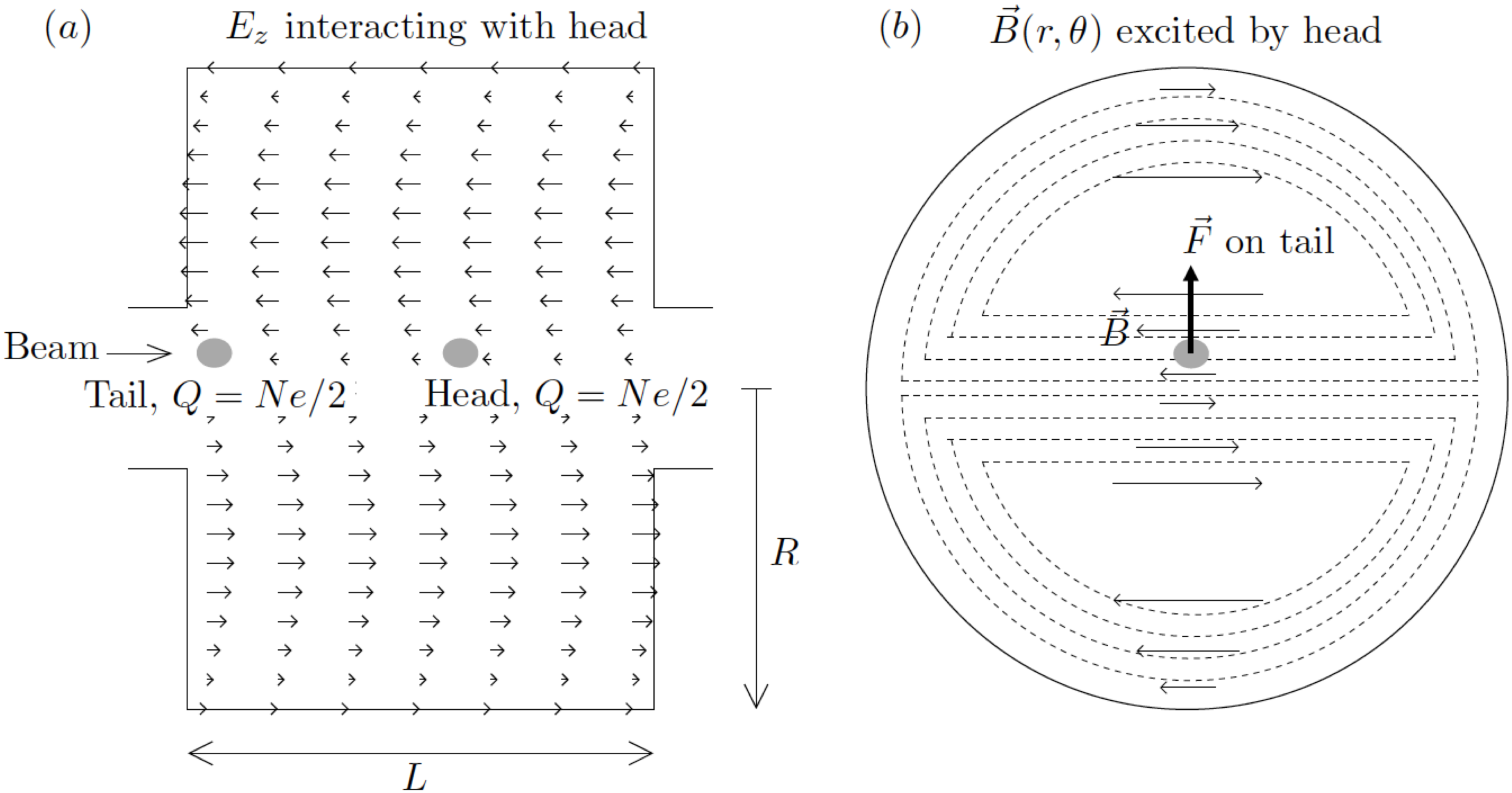


Figure 14.6 in textbook

Chicane Style Emittance Exchange

DAO XIANG *et al.* Phys. Rev. ST Accel. Beams **14,** 114001 (2011)

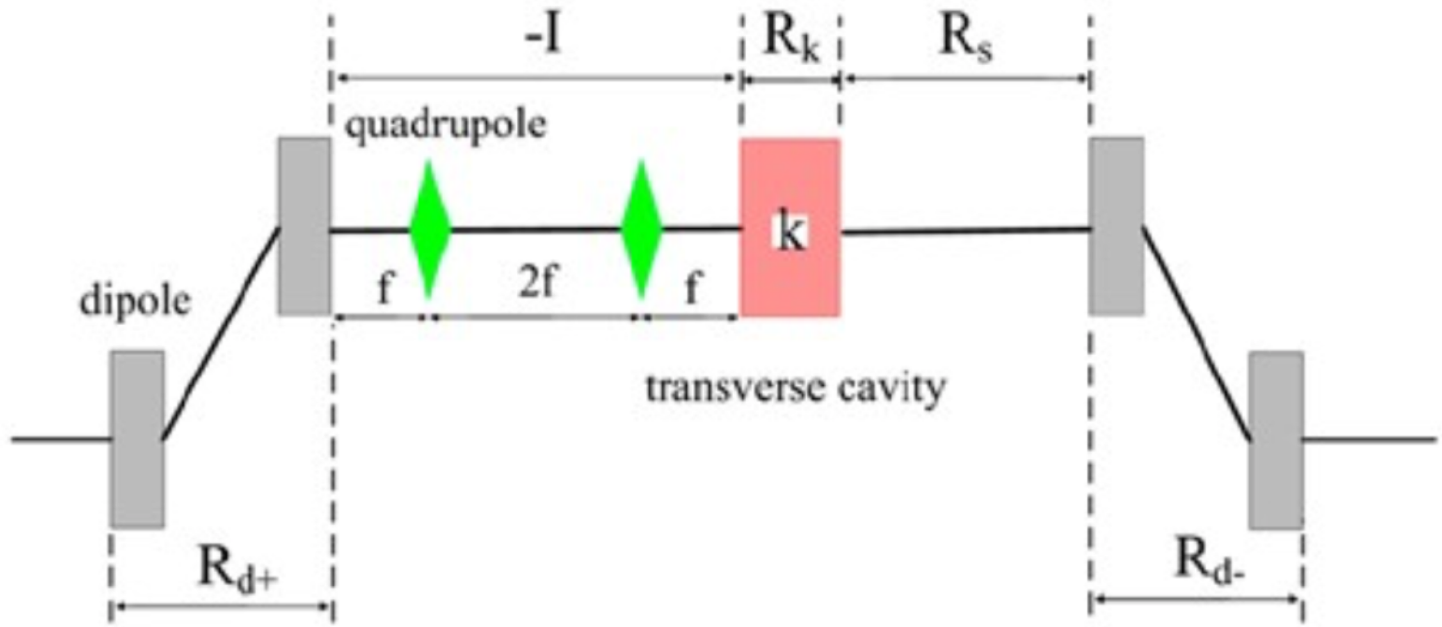


FIG. 2. A chicane-type exact EEX beam line. Two quadrupoles (green diamonds) are put upstream of the transverse cavity to reverse the dispersion.

- Reversing dispersion before the TM cavity allows you to flip the second dogleg to make a chicane
  - More transversely compact emittance exchange