Transverse Centroid and Envelope Descriptions of Beam Evolution

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Transverse Centroid and Envelope Model: Outline

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References

Comments:

- Some of this material related to J.J. Barnard lectures:
  - Transport limit discussions (Introduction)
  - Transverse envelope modes (Continuous Focusing Envelope Modes and Halo)
  - Longitudinal envelope evolution (Longitudinal Beam Physics III)
  - 3D Envelope Modes in a Bunched Beam (Cont. Focusing Envelope Modes and Halo)
- Specific transverse topics will be covered in more detail here for s-varying focusing
- Extensive Review paper covers envelope mode topics presented in more detail:
Transverse Centroid and Envelope Model: Detailed Outline

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Contact Information
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Acknowledgments
S1: Overview

Analyze **transverse centroid and envelope** properties of an unbunched \((\partial / \partial z = 0)\) beam

**Centroid:**

\[
X = \langle x \rangle_\perp \quad \text{and} \quad Y = \langle y \rangle_\perp
\]

**Envelope:** (edge measure)

\[
x\text{- and } y\text{-principal axis radii of an elliptical beam envelope}
\]

\[
r_x = 2 \sqrt{\langle (x - X)^2 \rangle_\perp}
\]

\[
r_y = 2 \sqrt{\langle (y - Y)^2 \rangle_\perp}
\]

Apply to general \(f_\perp\) but base on uniform density \(f_\perp\)

Factor of 2 results from dimensionality (diff 1D and 3D)

Transverse averages:

\[
\langle \cdots \rangle_\perp \equiv \frac{\int d^2 x_\perp \int d^2 x'_\perp \cdots f_\perp}{\int d^2 x_\perp \int d^2 x'_\perp f_\perp}
\]
Oscillations in the statistical beam centroid and envelope radii are the \textit{lowest-order} collective responses of the beam.

\textbf{Centroid Oscillations}: Associated with errors and are suppressed to the extent possible:

- \textbf{Error Sources}:
  - Beam distribution asymmetries (even emerging from injector)
  - Dipole bending terms from applied field optics (due to field error or mech misalignment)
  - Imperfect mechanical alignment
- Exception: When the beam is kicked (insertion or extraction) into or out of a transport channel as is often done in rings

\textbf{Envelope Oscillations}: Can have two components in periodic focusing lattices

1) \textbf{Matched Envelope}: Periodic “flutter” synchronized to period of focusing lattice to yield net focusing
   - Properly tuned flutter essential in Alternating Gradient quadrupole lattices

2) \textbf{Mismatched Envelope}: Excursions deviate from matched flutter motion and are seeded/driven by errors

   Limiting maximum beam-edge excursions is desired for economical transport
   - Reduces cost by Limiting material volume needed to transport an intense beam
Mismatched beams have larger envelope excursions and have more collective stability and beam halo problems since mismatch adds another source of free energy that can drive statistical increases in particle amplitudes (see: J.J. Barnard lectures on Envelopes and Halo)

Example: FODO Quadrupole Transport Channel

Larger machine aperture is needed to confine a mismatched beam
Centroid and Envelope oscillations are the *most important collective modes* of an intense beam

- Force balances based on matched beam envelope equation predict scaling of transportable beam parameters
  - Used to design transport lattices
- Instabilities in beam centroid and/or envelope oscillations can prevent reliable transport
  - Parameter locations of instability regions should be understood and avoided in machine design/operation

Although it is *necessary* to avoid envelope and centroid instabilities in designs, it is not alone *sufficient* for effective machine operation

- Higher-order kinetic and fluid instabilities not expressed in the low-order envelope models can degrade beam quality and control and must also be evaluated
  - To be covered (see: S.M. Lund, lectures on Kinetic Stability)
S2: Derivation of Transverse Centroid and Envelope Equations of Motion

Analyze centroid and envelope properties of an unbunched \((\partial / \partial z = 0)\) beam

**Transverse Statistical Averages:**

Let \(N\) be the number of particles in a thin axial slice of the beam at axial coordinate \(s\).

Averages can be equivalently defined in terms of the discreet particles making up the beam or the continuous model transverse Vlasov distribution function:

\[
\langle \cdots \rangle_{\perp} \equiv \frac{1}{N} \sum_{i=1}^{N} \left|_{\text{slice}} \cdots \right.
\]

\[
\langle \cdots \rangle_{\perp} \equiv \frac{\int d^2 x_{\perp} \int d^2 x_{\perp}' \cdots f_{\perp}}{\int d^2 x_{\perp} \int d^2 x_{\perp}' f_{\perp}}
\]

*Averages can be generalized to include axial momentum spread*
Transverse Particle Equations of Motion

Consistent with earlier analysis [lectures on Transverse Particle Dynamics], take:

\[ \begin{align*}
    x'' &+ \frac{\left(\gamma_b \beta_b\right)'}{\left(\gamma_b \beta_b\right)} x' + \kappa_x x = - \frac{q}{m\gamma_b^3 \beta_b^2 c^2} \frac{\partial \phi}{\partial x} \\
y'' &+ \frac{\left(\gamma_b \beta_b\right)'}{\left(\gamma_b \beta_b\right)} y' + \kappa_y y = - \frac{q}{m\gamma_b^3 \beta_b^2 c^2} \frac{\partial \phi}{\partial y}
\end{align*} \]

\[ \nabla_\perp^2 \phi = \left( \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \phi = -\frac{\rho}{\epsilon_0} \]

\[ \rho = q \int d^2 x'_\perp f_\perp \quad \phi|_{\text{aperture}} = 0 \]

Assume:
- Unbunched beam
- No axial momentum spread
- Linear applied focusing fields described by \( \kappa_x, \kappa_y \)
- Possible acceleration, \( \gamma_b \beta_b \)
  need not be constant

Various apertures are possible influence solution for \( \phi \). Some simple examples:

- **Round Pipe**

  \[ \rho = q \int d^2 x'_\perp f_\perp \quad \phi|_{\text{aperture}} = 0 \]

  Linac magnetic quadrupoles, acceleration cells, ....

- **Elliptical Pipe**

  In rings with dispersion: in drifts, magnetic optics, ....

- **Hyperbolic Sections**

  Electric quadrupoles
Review: Focusing lattices we will take in examples: Continuous and piecewise constant periodic solenoid and quadrupole doublet

Lattice Period $L_p$

Occupancy $\eta$

$\eta \in [0, 1]$

Solenoid description carried out implicitly in Larmor frame
[see: S.M. Lund lectures on Transverse Particle Dynamics]

Syncopation Factor $\alpha$

$\alpha \in [0, \frac{1}{2}]$

$\alpha = \frac{1}{2} \implies FODO$

$\kappa_x(s)$

a) Continuous

$\kappa_x = \kappa_y = k_{\beta_0}^2 = \text{const}$

$b) \text{Periodic Solenoid}$

$\kappa_x = \kappa_y$

$c) \text{Periodic Quadrupole Doublet}$

$\kappa_x = -\kappa_y$

$\eta L_p$
**Distribution Assumptions**

To lowest order, linearly focused intense beams are expected to be nearly uniform in density within the core of the beam out to an edge where the density falls rapidly to zero.

![Diagram of beam distribution](image.png)

Charge conservation requires:

\[ \lambda = \text{const} \]

Uniform density in beam:

\[ \rho = \frac{\lambda}{\pi r_x r_y} \]

\[
\rho(x, y) = q \int d^2 x'_{\perp} \ f_{\perp} \approx \begin{cases} 
\frac{\lambda}{\pi r_x r_y}, & (x - X)^2 / r_x^2 + (y - Y)^2 / r_y^2 < 1 \\
0, & (x - X)^2 / r_x^2 + (y - Y)^2 / r_y^2 > 1 
\end{cases}
\]

\[ \lambda = q \int d^2 x_{\perp} \int d^2 x'_{\perp} \ f_{\perp} = \int d^2 x \ \rho = \text{const} \]
Comments:

- Nearly uniform density out to a sharp beam edge expected for near equilibrium structure beam with strong space-charge due to Debye screening
  - see: S.M. Lund, lectures on Transverse Equilibrium Distributions
- Simulations support that uniform density model is a good approximation for stable non-equilibrium beams when space-charge is high
- Assumption of a fixed form of distribution essentially closes the infinite hierarchy of moments that are needed to describe a general beam distribution
  - Need only describe shape/edge and center for uniform density beam to fully specify the distribution!
  - Analogous to closures of fluid theories using assumed equations of state etc.
Self-Field Calculation

Temporarily, we will consider an arbitrary beam charge distribution within an arbitrary aperture to formulate the problem.

Electrostatic field of a line charge in free-space

\[ E_{\perp} = \frac{\lambda_0}{2\pi \varepsilon_0} \frac{(x_{\perp} - \tilde{x})}{|x_{\perp} - \tilde{x}|^2} \]

\( \lambda_0 = \) line charge  
\( x_{\perp} = \tilde{x} = \) coordinate of charge

Resolve the field of the beam into direct (free space) and image terms:

\[ E_{\perp}^s = -\frac{\partial \phi}{\partial x_{\perp}} = E_{\perp}^d + E_{\perp}^i \]

and superimpose free-space solutions for direct and image contributions

Direct Field

\[ E_{\perp}^d(x_{\perp}) = \frac{1}{2\pi \varepsilon_0} \int d^2 \tilde{x}_{\perp} \frac{\rho(\tilde{x}_{\perp})(x_{\perp} - \tilde{x}_{\perp})}{|x_{\perp} - \tilde{x}_{\perp}|^2} \]

\( \rho(x) = \) beam charge density

Image Field

\[ E_{\perp}^i(x_{\perp}) = \frac{1}{2\pi \varepsilon_0} \int d^2 \tilde{x}_{\perp} \frac{\rho^i(\tilde{x}_{\perp})(x_{\perp} - \tilde{x}_{\perp})}{|x_{\perp} - \tilde{x}_{\perp}|^2} \]

\( \rho^i(x) = \) beam image charge density induced on aperture
Direct Field:

The direct field solution for a uniform density beam in free-space was calculated for the KV equilibrium distribution - see: S.M. Lund, lectures on Transverse Equilibrium Distributions

Uniform density in beam:

$$\rho = \frac{\lambda}{\pi r_x r_y} = \text{const}$$

Expressions are valid only within the elliptical density beam -- where they will be applied in taking averages

$$E^d_x = \frac{\lambda}{\pi \varepsilon_0 (r_x + r_y) r_x} \frac{x - X}{(r_x + r_y) r_x}$$
$$E^d_y = \frac{\lambda}{\pi \varepsilon_0 (r_x + r_y) r_y} \frac{y - Y}{(r_x + r_y) r_y}$$
Image Field:
Image structure depends on the aperture. Assume a round pipe (most common case) for simplicity.

\[ \lambda_I = -\lambda_0 \quad \text{image charge} \]
\[ x_I = \frac{r_p^2}{|x_0|^2} x_0 \quad \text{image location} \]

Will be derived in the problem sets.

\[ \phi(r = r_p) = \text{const} \]

superimpose all images of beam:

\[ \mathbf{E}_\perp^i(x_\perp) = -\frac{1}{2\pi\epsilon_0} \int_{\text{pipe}} d^2\tilde{x}_\perp \rho(\tilde{x}_\perp) \frac{(x_\perp - r_p^2\tilde{x}_\perp / |\tilde{x}_\perp|^2)}{|x_\perp - r_p^2\tilde{x}_\perp / |\tilde{x}_\perp|^2|^2} \]

Difficult to calculate even for \( \rho \) corresponding to a uniform density beam
Examine limits of the image field to build intuition on the range of properties:

1) Line charge along $x$-axis:

\[ \rho(x_\perp) = \lambda \delta(x_\perp - X \hat{x}) \]

Choose coordinates to make true

Plug this density in the image charge expression for a round-pipe aperture:
- Need only evaluate at $x_\perp = X \hat{x}$ since beam is at that location

\[ E_\perp(x_\perp = X \hat{x}) = \frac{\lambda}{2\pi \varepsilon_0 (r_p^2 / X - X)} \hat{x} \]

- Generates **nonlinear field** at position of direct charge
- Field creates **attractive force** between direct and image charge
2) Centered, uniform density elliptical beam:

\[ \rho(x_\perp) = \frac{\lambda}{\pi r_x r_y} \begin{cases} \frac{\lambda}{r_x r_y}, & x^2/r_x^2 + y^2/r_y^2 < 1 \\ 0, & x^2/r_x^2 + y^2/r_y^2 > 1 \end{cases} \]

Expand using complex coordinates starting from the general image expression:

- Image field is in vacuum aperture so complex methods help calculation

\[ E^{i*} = E_x^i - iE_y^i = \sum_{n=2,4,\ldots}^{\infty} c_n z^{n-1} \]

\[ z = x + iy \]

\[ i = \sqrt{-1} \]

The linear (\( n = 2 \)) components of this expansion give:

\[ E_x^i = \frac{\lambda}{8\pi \epsilon_0} \frac{r_x^2 - r_y^2}{r_p^4} x, \quad E_y^i = -\frac{\lambda}{8\pi \epsilon_0} \frac{r_x^2 - r_y^2}{r_p^4} y \]

- Rapidly vanish (higher order terms more rapid) as beam becomes more round
- Case will be analyzed further in the problem sets
3) Uniform density elliptical beam with a small displacement along the $x$-axis:

\[ Y = 0 \quad |X|/r_p \ll 1 \]

Expand using complex coordinates starting from the general image expression:

- Use complex coordinates to simplify calculation
  
  E.P. Lee, E. Close, and L. Smith, Nuclear Instruments and Methods, 1126 (1987)

- Expressions become even more complicated with simultaneous $x$- and $y$-displacements and more complicated aperture geometries
Leading order terms expanded in $|X|/r_p$ without assuming small ellipticity obtain:

$$E^i_x = \frac{\lambda}{2\pi\varepsilon_0 r_p^2} [f \cdot (x - X) + g \cdot X] + \Theta \left( \frac{X}{r_p} \right)^3$$

$$E^i_y = -\frac{\lambda}{2\pi\varepsilon_0 r_p^2} f \cdot y + \Theta \left( \frac{X}{r_p} \right)^3$$

Where $f$ and $g$ are focusing and bending coefficients that can be calculated in terms of $X$, $Y$, $r_x$, $r_y$ (which all may vary in $s$) as:

**Focusing Term:**

$$f = \frac{r_x^2 - r_y^2}{4r_p^2} + \frac{X^2}{r_p^2} \left[ 1 + \frac{3}{2} \left( \frac{r_x^2 - r_y^2}{r_p^2} \right) + \frac{3}{8} \left( \frac{r_x^2 - r_y^2}{r_p^2} \right)^2 \right]$$

**Bending Term:**

$$g = 1 + \frac{r_x^2 - r_y^2}{4r_p^2} + \frac{X^2}{r_p^2} \left[ 1 + \frac{3}{4} \left( \frac{r_x^2 - r_y^2}{r_p^2} \right) + \frac{1}{8} \left( \frac{r_x^2 - r_y^2}{r_p^2} \right)^2 \right]$$

- Expressions become even more complicated with simultaneous $x$- and $y$-displacements and more complicated aperture geometries
Comments on images:

- Sign is generally such that it will **tend to increase beam displacements**
  - Also (usually) weak linear focusing corrections for an elliptical beam
- **Can be very difficult to calculate explicitly**
  - Even for simple case of circular pipe
  - Special cases of simple geometry formulas can give idea on scaling
  - Generally suppress just by making the beam small relative to characteristic aperture dimensions and keeping the beam steered near-axis
  - Simulations typically applied
- **Depend strongly on the aperture geometry**
  - Generally varies as a function of $s$ in the machine aperture due to changes in accelerator lattice elements and/or as beam symmetries evolve

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**Round Pipe**

![Round Pipe Diagram](image1.png)

**Elliptical Pipe**

![Elliptical Pipe Diagram](image2.png)

**Hyperbolic Sections**

![Hyperbolic Sections Diagram](image3.png)
Coupled centroid and envelope equations of motion

Consistent with the assumed structure of the distribution (uniform density elliptical beam), denote:

**Beam Centroid:**

\[
X \equiv \langle x \rangle_\perp \quad X' = \langle x' \rangle_\perp \\
Y \equiv \langle y \rangle_\perp \quad Y' = \langle y' \rangle_\perp
\]

**Coordinates with respect to centroid:**

\[
\tilde{x} \equiv x - X \quad \tilde{x}' = x' - X' \\
\tilde{y} \equiv y - Y \quad \tilde{y}' = y' - Y'
\]

**Envelope Edge Radii:**

\[
r_x \equiv 2 \sqrt{\langle \tilde{x}^2 \rangle_\perp} \quad r'_x = 2 \langle \tilde{x} \tilde{x}' \rangle_\perp / \langle \tilde{x}^2 \rangle_\perp \\
r_y \equiv 2 \sqrt{\langle \tilde{y}^2 \rangle_\perp} \quad r'_y = 2 \langle \tilde{y} \tilde{y}' \rangle_\perp / \langle \tilde{y}^2 \rangle_\perp
\]

With the assumed uniform elliptical beam, all moments can be calculated in terms of: \(X, \ Y, \ r_x, \ r_y\)

- Such truncations follow whenever the form of the distribution is “frozen”
Derive centroid equations: First use the self-field resolution for a uniform density beam, then the equations of motion for a particle within the beam are:

\[
x'' + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} x' + \kappa_x x = -\frac{2Q}{(r_x + r_y) r_x} (x - X) = \frac{q}{m \gamma_b^3 \beta_b^2 c^2} E_x^i
\]

\[
y'' + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} y' + \kappa_y y = -\frac{2Q}{(r_x + r_y) r_y} (y - Y) = \frac{q}{m \gamma_b^3 \beta_b^2 c^2} E_y^i
\]

Direct Terms  Image Terms

Perveance:

\[
Q \equiv \frac{q \lambda}{2\pi\varepsilon_0 m \gamma_b^3 \beta_b^2 c^2}
\]

(not necessarily constant if beam accelerates)

average equations using:  \( \langle x' \rangle_\perp = \langle x \rangle_\perp' = X' \) etc., to obtain:

Centroid Equations:

\[
X'' + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} X' + \kappa_x X = Q \left[ \frac{2\pi\varepsilon_0}{\lambda} \langle E_x^i \rangle_\perp \right]
\]

\[
Y'' + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} Y' + \kappa_y Y = Q \left[ \frac{2\pi\varepsilon_0}{\lambda} \langle E_y^i \rangle_\perp \right]
\]

Note: the electric image field will cancel the coefficient \( 2\pi\varepsilon_0/\lambda \)

\( \langle E_x^i \rangle_\perp \) will generally depend on: \( X, Y \) and \( r_x, r_y \)
To derive equations of motion for the envelope radii, first subtract the centroid equations from the particle equations of motion \( \tilde{x} = x - X \) to obtain:

\[
\tilde{x}'' + \frac{(\gamma_b \beta_b)'}{\left(\gamma_b \beta_b\right)} \tilde{x}' + \kappa_x \tilde{x} - \frac{2Q \tilde{x}}{(r_x + r_y)r_x} = \frac{q}{m\gamma_b^3 \beta_b^2 c^2} \left[ E_x^i - \langle E_x^i \rangle_\perp \right]
\]

\[
\tilde{y}'' + \frac{(\gamma_b \beta_b)'}{\left(\gamma_b \beta_b\right)} \tilde{y}' + \kappa_y \tilde{y} - \frac{2Q \tilde{y}}{(r_x + r_y)r_x} = \frac{q}{m\gamma_b^3 \beta_b^2 c^2} \left[ E_y^i - \langle E_y^i \rangle_\perp \right]
\]

Differentiate the equation for the envelope radius (\(y\)-equations analogous):

\[
r_x = 2\langle \tilde{x}^2 \rangle_\perp^{1/2} \quad \implies \quad r_x' = \frac{2\langle \tilde{x} \tilde{x}' \rangle_\perp}{\langle \tilde{x}^2 \rangle_\perp^{1/2}} = \frac{4\langle \tilde{x} \tilde{x}' \rangle_\perp}{r_x}
\]

Define (motivated the KV equilibrium results) a statistical rms edge emittance:

\[
\varepsilon_x \equiv 4\varepsilon_{x,rms} \equiv 4 \left[ \langle \tilde{x}^2 \rangle_\perp \langle \tilde{x}'^2 \rangle_\perp - \langle \tilde{x} \tilde{x}' \rangle_\perp^2 \right]^{1/2}
\]

Differentiate the equation for \( r_x' \) again and use the emittance definition:

\[
r_x'' = 4\frac{\langle \tilde{x} \tilde{x}'' \rangle_\perp}{r_x} + \frac{16[\langle \tilde{x}^2 \rangle_\perp \langle \tilde{x}'^2 \rangle_\perp - \langle \tilde{x} \tilde{x}' \rangle_\perp^2]}{r_x^3}
\]

\[
= 4\frac{\langle \tilde{x} \tilde{x}'' \rangle_\perp}{r_x} + \frac{\varepsilon_x^2}{r_x^3}
\]

and then employ the equations of motion to eliminate \( \tilde{x}'' \) in \( \langle \tilde{x} \tilde{x}'' \rangle_\perp \) to obtain:
Envelope Equations:

\[ r''_x + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} r'_x + \kappa_x r_x - \frac{2Q}{r_x + r_y} - \frac{\varepsilon_x^2}{r_x^3} = 8Q \left[ \frac{\pi \varepsilon_0}{\lambda} \langle \tilde{x} E_x^i \rangle_\perp \right] \]

\[ r''_y + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} r'_y + \kappa_y r_y - \frac{2Q}{r_x + r_y} - \frac{\varepsilon_y^2}{r_y^3} = 8Q \left[ \frac{\pi \varepsilon_0}{\lambda} \langle \tilde{y} E_y^i \rangle_\perp \right] \]

\( \langle \tilde{x} E_x^i \rangle_\perp \) will generally depend on: \( X, \ Y \) and \( r_x, \ r_y \)

Comments on Centroid/Envelope equations:

- Centroid and envelope equations are coupled and must be solved simultaneously when image terms on the RHS cannot be neglected
- Image terms contain nonlinear terms that can be difficult to evaluate explicitly
  - Aperture geometry changes image correction
- The formulation is not self-consistent because a frozen form (uniform density) charge profile is assumed
  - Uniform density choice motivated by KV results and Debye screening
    see: S.M. Lund, lectures on Transverse Equilibrium Distributions
  - The assumed distribution form not evolving represents a fluid model closure
  - Generally find with simulations that uniform density frozen form distribution models can provide reasonably accurate approximate models for centroid and envelope evolution
Comments on Centroid/Envelope equations (Continued):

- Constant (normalized when accelerating) emittances are generally assumed
  - For strong space charge emittance terms small and limited emittance evolution does not strongly influence evolution outside of final focus
  - See: S.M. Lund, lectures on Transverse Particle Dynamics and Transverse Kinetic Theory to motivate when this works well

\[ \beta_b, \gamma_b, \lambda \quad \text{s-variation set by acceleration schedule} \]

\[ \varepsilon_{nx} = \gamma_b \beta_b \varepsilon_x = \text{const} \]

\[ \varepsilon_{ny} = \gamma_b \beta_b \varepsilon_y = \text{const} \quad \longrightarrow \quad \text{used to calculate } \varepsilon_x, \varepsilon_y \]

\[ Q = \frac{q \lambda}{2\pi m \varepsilon_0 \gamma_b^3 \beta_b^2 c^2} \]
Neglect image charge terms, then the centroid equation of motion becomes:

\[
X'' + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} X' + \kappa_x X = 0 \\
Y'' + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} Y' + \kappa_y Y = 0
\]

- Usual Hill's equation with acceleration term
- Single particle form. Apply results from S.M. Lund lectures on Transverse Particle Dynamics: phase amplitude methods, Courant-Snyder invariants, and stability bounds, ...

Assume that applied lattice focusing is tuned for constant phase advances with normalized coordinates and/or that acceleration is weak and can be neglected with

Then single particle stability results give immediately:

\[
\frac{1}{2} |\text{Tr} \mathbf{M}_x (s_i + L_p |s_i)| \leq 1 \\
\frac{1}{2} |\text{Tr} \mathbf{M}_y (s_i + L_p |s_i)| \leq 1
\]

\[\sigma_{0x} < 180^\circ \quad \text{centrodit stability} \quad \sigma_{0y} < 180^\circ \]

1\text{st stability condition}
/// Example: FODO channel centroid evolution

Mid-drift launch:

\[ X(0) = 1 \text{ mm} \]
\[ X'(0) = 1 \text{ mrad} \]

Centroid exhibits expected characteristic stable betatron oscillations

Motion in \( y \)-plane analogous

lattice/beam parameters:

\[ \beta_b = \text{const} \]
\[ \sigma_{0x} = 80^\circ \]
\[ L_p = 0.5 \text{ m} \]
\[ \eta = 0.5 \]
Effect of Driving Errors

The reference orbit is ideally tuned for zero centroid excursions. But there will always be driving errors that can cause the centroid oscillations to accumulate with beam propagation distance:

\[
X'' + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} X' + \sum_n \frac{G_n}{G_0} \kappa_n(s) X = \sum_n \frac{G_n}{G_0} \kappa_n(s) \Delta x_n
\]

\[\kappa_q(s) = \sum \kappa_n(s) \quad \kappa_n(s) \text{ nominal gradient function, } n\text{th quadrupole}\]

\[\frac{G_n}{G_0} = n\text{th quadrupole gradient error (unity for no error; } s\text{-varying)}\]

\[\Delta_{xn} = n\text{th quadrupole transverse displacement error (} s\text{-varying)}\]

/// Example: FODO channel centroid with quadrupole displacement errors

\[\frac{G_n}{G_0} = 1\]

\[\Delta_{xn} = [-0.5, 0.5] \text{ mm (uniform dist)}\]

solid — with errors
dashed — no errors

same lattice as previous
Errors will result in a characteristic random walk increase in oscillation amplitude due to the (generally random) driving terms.

Control by:
- Synthesize small applied dipole fields to regularly steer the centroid back on-axis to the reference trajectory: \(X = 0 = Y, \quad X' = 0 = Y'\)
- Fabricate and align focusing elements with higher precision
- Employ a sufficiently large aperture to contain the oscillations and limit detrimental nonlinear image charge effects

Economics dictates the optimal strategy
- Usually sufficient control achieved by a combination of methods
Effects of Image Charges

Model the beam as a displaced line-charge in a circular aperture. Then using the previously derived image charge field, the equations of motion reduce to:

\[ X'' + \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} X' + \kappa_x X = \frac{QX}{r_p^2 - X^2} \]

Examine oscillation along x-axis

\[
\frac{QX}{r_p^2 - X^2} \approx \frac{Q}{r_p^2} X + \frac{Q}{r_p^4} X^3
\]

Linear correction

Nonlinear correction (smaller)

Example: FODO channel centroid with image charge corrections

For a specific example:

- \( r_p = 30 \text{ mm} \)
- \( Q = 2 \times 10^{-4} \)

Same lattice as previous

Solid – with images

Dashed – no images
Main effect of images is generally an accumulated phase error of the centroid orbit since, generally the centroid error oscillations are not “matched” orbits and errors are not regularly “undone”

- This will complicate extrapolations of errors over many lattice periods

**Control by:**

- Keeping centroid displacements X, Y small by correcting
- Make aperture (pipe radius) larger

**General Comments:**

- Images contributions to centroid excursions generally less problematic than misalignment errors in focusing elements
- More detailed analysis show that the coupling of the envelope radii $r_x$, $r_y$ to the centroid evolution in X, Y is often weak
- Fringe fields are more important for accurate calculation of centroid orbits since orbits are not part of a matched lattice
  - Non-ideal orbits are poorly tuned to lattice and become more sensitive to the precise phase of impulses
- Over long path lengths many nonlinear terms can influence results
- Lattice errors are not often known so one must often analyze characteristic error distributions to see if centroids measured are consistent with expectations
S4: Envelope Equations of Motion

Overview: Reduce equations of motion for $r_x$, $r_y$

- Generally found that couplings to centroid coordinates $X$, $Y$ are weak
  - Centroid ideally zero in a well tuned system
- Envelope eqns are most important in designing transverse focusing systems
  - Expresses average radial force balance (see following discussion)
  - Can be difficult to analyze analytically for scaling properties
  - “Systems” codes generally written using envelope equations, stability criteria, and practical engineering constraints
- Instabilities of the envelope equations in periodic focusing lattices must be avoided in machine operation
  - Instabilities are strong and real: not washed out with realistic distributions without frozen form
  - Represent lowest order “KV” modes of a full kinetic theory
- Previous derivation of envelope equations relied on Courant-Snyder invariants in linear applied and self-fields. Analysis shows that the same force balances result for a uniform elliptical beam with no image couplings.
  - Debye screening arguments suggest assumed uniform density model taken should be a good approximation for intense space-charge
The envelope equation reflects low-order force balances:

\[ \begin{align*}
  r''_x &+ \left( \frac{\gamma b \beta_b'}{(\gamma b \beta_b)} \right) r'_x + \kappa_x r_x - \frac{2Q}{r_x + r_y} = 0 \\
  r''_y &+ \left( \frac{\gamma b \beta_b'}{(\gamma b \beta_b)} \right) r'_y + \kappa_y r_y - \frac{2Q}{r_x + r_y} = 0
\end{align*} \]

Terms: Applied Acceleration, Applied Focusing Lattice, Space-Charge Defocusing, Thermal Defocusing Emittance

The "acceleration schedule" specifies both \( \gamma_b \beta_b \) and \( \lambda \) and then the equations are integrated with:

\[ \begin{align*}
  \gamma_b \beta_b \varepsilon_x &= \text{const} \\
  \gamma_b \beta_b \varepsilon_y &= \text{const}
\end{align*} \]

normalized emittance conservation

\[ Q = \frac{q\lambda}{2\pi \epsilon_0 m \gamma^3 b \beta_b^2 c^2} \]

specified perveance
Reminder: It was shown for a coasting beam that the envelope equations remain valid for elliptic charge densities suggesting more general validity [Sacherer, IEEE Trans. Nucl. Sci. 18, 1101 (1971), J.J. Barnard, Intro. Lectures]

For any beam with elliptic symmetry charge density in each transverse slice:

\[ \rho = \rho \left( \frac{x^2}{r_x^2} + \frac{y^2}{r_y^2} \right) \]

the KV envelope equations

\[
\begin{align*}
\frac{r''_x(s)}{r_x(s) + r_y(s)} - \frac{2Q}{r_x(s)} - \frac{\varepsilon_x^2(s)}{r_x^3(s)} &= 0 \\
\frac{r''_y(s)}{r_x(s) + r_y(s)} - \frac{2Q}{r_y(s)} - \frac{\varepsilon_y^2(s)}{r_y^3(s)} &= 0
\end{align*}
\]

remain valid when (averages taken with the full distribution):

\[ Q = \frac{q\lambda}{2\pi\epsilon_0 m_0^3 \beta_b^6 \gamma_b^2 c^2} = \text{const} \]

\[ \lambda = q \int d^2x \rho = \text{const} \]

\[ r_x = 2 \langle x^2 \rangle_{\perp}^{1/2} \]

\[ r_y = 2 \langle y^2 \rangle_{\perp}^{1/2} \]

\[ \varepsilon_x = 4 \left[ \langle x^2 \rangle_{\perp} \langle x'^2 \rangle_{\perp} - \langle xx' \rangle_{\perp}^2 \right]^{1/2} \]

\[ \varepsilon_y = 4 \left[ \langle y^2 \rangle_{\perp} \langle y'^2 \rangle_{\perp} - \langle yy' \rangle_{\perp}^2 \right]^{1/2} \]

*Evolution changes often small in \( \varepsilon_x, \varepsilon_y \)*
Properties of Envelope Equation Terms:

**Applied Focusing:** $\kappa_x r_x$, $\kappa_y r_y$  

**and Acceleration:** \[
\frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} r_x', \quad \frac{(\gamma_b \beta_b)'}{(\gamma_b \beta_b)} r_y'.
\]

- Analogous to single particle orbit terms
- Contributions to beam envelope essentially the same as in single particle case
- Have strong $s$ dependence, *can be both focusing and defocusing*
  - Act only in focusing elements and acceleration gaps

**Perveance:** \[
\frac{2Q}{r_x + r_y}
\]

- Acts continuously in $s$, *always defocusing*
- Becomes stronger (relatively to other terms) when the beam expands in cross-sectional area

**Emittance:** \[
\frac{\varepsilon_x^2}{r^3_x}
\]

- Acts continuously in $s$, *always defocusing*
- Becomes stronger (relatively to other terms) when the beam becomes small in cross-sectional area
- Scaling makes clear why it is necessary to inhibit emittance growth for applications where small spots are desired on target
As the beam expands, perveance term will eventually dominate emittance term:
[see: Lund and Bukh, PRSTAB 7, 024801 (2004)]

Free expansion \((\kappa_x = \kappa_y = 0)\)

**Initial conditions:**

\[
\begin{align*}
& r_x(s_i) = r_y(s_i) \\
& r'_x(s_i) = r'_y(s_i) = 0
\end{align*}
\]

\[
\frac{Q}{r_x(s_i)} = \frac{\varepsilon_x^2}{r_x^3(s_i)}
\]

\[
Q = \frac{\varepsilon_x^2}{r_x^2(s_i)} = 10^{-3}
\]

**Cases:**

- Space-Charge Dominated: \(\varepsilon_x = 0\)
- Emittance Dominated: \(Q = 0\)

See next page: solution is analytical in bounding limits shown

Parameters are chosen such that initial defocusing forces in two limits are equal to compare case
For an emittance dominated beam in free-space, the envelope equation becomes:

\[
\frac{Q}{r_x + r_y} \ll \frac{\varepsilon_{x,y}^2}{r_{x,y}^3} \implies r''_j - \frac{\varepsilon_j^2}{r_j^3} = 0 \quad j = x, y
\]

The envelope Hamiltonian gives:

\[
\frac{1}{2} r''_j + \frac{\varepsilon_j^2}{2r_j^2} = \text{const}
\]

which can be integrated from the initial envelope at \( s = s_i \) to show that:

**Emittance Dominated Free-Expansion** \( (Q = 0) \)

\[
r_j(s) = r_j(s_i) \sqrt{1 + \frac{2r'_j(s_i)}{r_j(s_i)}(s - s_i) + \left[1 + \frac{r_{j}^2(s_i)r''_{j}(s_i)}{\varepsilon_j^2} \right] \frac{\varepsilon_j^2}{r_{j}^4(s_i)(s - s_i)^2}}
\]

\( j = x, y \)

Conversely, for a space-charge dominated beam in free-space, the envelope equation becomes:

\[
\frac{Q}{r_x + r_y} \gg \frac{\varepsilon_{x,y}^2}{r_{x,y}^3} \implies r''_+ - \frac{Q}{r_+} = 0 \quad r_+ \equiv \frac{1}{2}(r_x \pm r_y)
\]

\[
r''_- = 0
\]
The equations of motion

\[
\begin{align*}
    r''_+ - \frac{Q}{r_+} &= 0 \\
    r''_- &= 0
\end{align*}
\]

can be integrated from the initial envelope at \( s = s_i \) to show that:

- \( r_- \) equation solution trivial
- \( r_+ \) equation solution exploits Hamiltonian

\[
\frac{1}{2} r'_+ r'^2_+ - Q \ln r_+ = \text{const}
\]

**Space-Charge Dominated Free-Expansion** (\( \varepsilon_x = \varepsilon_y = 0 \))

\[
\begin{align*}
    r_+(s) &= r_+(s_i) \exp \left( -\frac{r'^2_+(s_i)}{2Q} + \left[ \text{erfi}^{-1} \left\{ \text{erfi} \left[ \frac{r'_+(s_i)}{\sqrt{2Q}} \right] + \sqrt{\frac{2Q}{\pi}} e^{\frac{r'^2_+(s_i)}{2Q}} \frac{(s - s_i)}{r_+(s_i)} \right\} \right]^2 \right) \\
    r_-(s) &= r_-(s_i) + r'_-(s_i)(s - s_i) \\
    r_{\pm} &= \frac{1}{2} (r_x \pm r_y)
\end{align*}
\]

**Imaginary Error Function**

\[
\text{erfi}(z) \equiv \frac{\text{erf}(iz)}{i} \equiv \frac{2}{\sqrt{\pi}} \int_0^z dt \exp(t^2)
\]

The free-space expansion solutions for emittance and space-charge dominated beams will be explored more in the problems
Neglect acceleration \((\gamma_b \beta_b = \text{const})\) or use transformed variables:

\[
\begin{align*}
    r''_x(s) + \kappa_x(s) r_x(s) - \frac{2Q}{r_x(s) + r_y(s)} - \frac{\varepsilon_x^2}{r^3_x(s)} &= 0 \\
    r''_y(s) + \kappa_y(s) r_y(s) - \frac{2Q}{r_x(s) + r_y(s)} - \frac{\varepsilon_y^2}{r^3_y(s)} &= 0
\end{align*}
\]

Matching involves finding specific initial conditions for the envelope to have the periodicity of the lattice:

Find Values of:

\[
\begin{align*}
    r_x(s_i), r'_x(s_i) \\
    r_y(s_i), r'_y(s_i)
\end{align*}
\]

Such That: (periodic)

\[
\begin{align*}
    r_x(s_i + L_p) &= r_x(s_i) & r'_x(s_i + L_p) &= r'_x(s_i) \\
    r_y(s_i + L_p) &= r_y(s_i) & r'_y(s_i + L_p) &= r'_y(s_i)
\end{align*}
\]

- Typically constructed with numerical root finding from estimated/guessed values
- Can be surprisingly difficult for complicated lattices and/or strong space-charge
- Iterative technique developed to numerically calculate without root finding
  \[\text{[Lund, Chilton and Lee, PRSTAB 9, 064201 (2006)]}\]

Method exploits Courant-Snyder invariants of depressed orbits within the beam.
Typical **Matched** vs **Mismatched** solution for FODO channel:

**Matched**

The matched beam is the most radially compact solution to the envelope equations rendering it highly important for beam transport.

- Matching tends to exploit optics most efficiently to maintain confinement.
The matched solution to the KV envelope equations reflects the symmetry of the focusing lattice and must in general be calculated numerically.

\[
\begin{align*}
  r_x(s + L_p) &= r_x(s) \\
  r_y(s + L_p) &= r_y(s) \\
  \varepsilon_x &= \varepsilon_y
\end{align*}
\]

**Parameters**

- \( L_p = 0.5 \text{ m} \), \( \sigma_0 = 80^\circ \), \( \eta = 0.5 \)
- \( \varepsilon_x = 50 \text{ mm-mrad} \)
- \( \sigma/\sigma_0 = 0.2 \)

Perveance \( Q \) iterated to obtain matched solution with this tune depression.

**Solenoidal Focusing**

\( (Q = 6.6986 \times 10^{-4}) \)

**FODO Quadrupole Focusing**

\( (Q = 6.5614 \times 10^{-4}) \)
Symmetries of a matched beam are interpreted in terms of a local rms equivalent KV beam and moments/projections of the KV distribution

[see: S.M. Lund, lectures on Transverse Equilibrium Distributions]

**Projection**

$x-y$
area: $\pi r_x r_y \neq \text{const}$

$x-x'$
area: $\pi \varepsilon_x = \text{const}$
(CS Invariant)

$y-y'$
area: $\pi \varepsilon_y = \text{const}$
(CS Invariant)
**S6: Envelope Perturbations:**

In the envelope equations take:

\[
\begin{align*}
\hat{r}_x(s) &= r_{xm}(s) + \delta r_x(s) \\
\hat{r}_y(s) &= r_{ym}(s) + \delta r_y(s)
\end{align*}
\]

*Matched Envelope Perturbations*:

- \(r_{xm}(s + L_p) = r_{xm}(s)\quad r_{xm}(s) > 0\)
- \(r_{ym}(s + L_p) = r_{ym}(s)\quad r_{ym}(s) > 0\)

Perturbations in envelope radii are small relative to matched solution and driving terms are consistently ordered:

\[r_{xm}(s) \gg |\delta r_x(s)|\]
\[r_{ym}(s) \gg |\delta r_y(s)|\]

Amplitudes defined in terms of producing small envelope perturbations

- Driving perturbations and distribution errors generate/pump envelope perturbations
- Arise from many sources: focusing errors, lost particles, emittance growth, .....
The matched solution satisfies:

- Add subscript $m$ to denote matched envelope solution and distinguish from other evolutions

\[
\begin{align*}
\tau_x & \rightarrow \tau_{xm} & \text{For matched beam envelope} \\
\tau_y & \rightarrow \tau_{ym} & \text{with periodicity of lattice}
\end{align*}
\]

\[
\begin{align*}
\tau''_{xm}(s) + \kappa_x(s)\tau_{xm}(s) - \frac{2Q}{\tau_{xm}(s) + \tau_{ym}(s)} - \frac{\varepsilon_x^2}{r_{xm}^3(s)} & = 0 \\
\tau''_{ym}(s) + \kappa_y(s)\tau_{ym}(s) - \frac{2Q}{\tau_{xm}(s) + \tau_{ym}(s)} - \frac{\varepsilon_y^2}{r_{ym}^3(s)} & = 0
\end{align*}
\]

\[
\begin{align*}
\tau_{xm}(s + L_p) & = \tau_{xm}(s) & \tau_{xm}(s) > 0 \\
\tau_{ym}(s + L_p) & = \tau_{ym}(s) & \tau_{ym}(s) > 0
\end{align*}
\]

Matching is usually cast in terms of finding 4 “initial” envelope phase-space values where the envelope solution satisfies the periodicity constraint for specified focusing, perveance, and emittances:

\[
\begin{align*}
\tau_{xm}(s_i) & \quad \tau'_{xm}(s_i) \\
\tau_{ym}(s_i) & \quad \tau'_{ym}(s_i)
\end{align*}
\]
Linearized Perturbed Envelope Equations:

- Neglect all terms of order $\delta^2$ and higher: $(\delta r_x)^2$, $\delta r_x \delta r_y$, $\delta Q \delta r_x$, \ldots

\[
\begin{align*}
\delta r'''_x + \kappa_x \delta r_x &+ \frac{2Q}{(r_{xm} + r_{ym})^2} (\delta r_x + \delta r_y) + \frac{3\varepsilon_x^2}{r_{xm}^4} \delta r_x \\
&= -r_{xm} \delta \kappa_x + \frac{2}{r_{xm} + r_{ym}} \delta Q + \frac{2\varepsilon_x}{r_{xm}^3} \delta \varepsilon_x \\
\delta r'''_y + \kappa_y \delta r_y &+ \frac{2Q}{(r_{xm} + r_{ym})^2} (\delta r_x + \delta r_y) + \frac{3\varepsilon_y^2}{r_{ym}^4} \delta r_y \\
&= -r_{ym} \delta \kappa_y + \frac{2}{r_{xm} + r_{ym}} \delta Q + \frac{2\varepsilon_y}{r_{ym}^3} \delta \varepsilon_y
\end{align*}
\]

Homogeneous Equations:

- Linearized envelope equations with driving terms set to zero

\[
\begin{align*}
\delta r'''_x + \kappa_x \delta r_x &+ \frac{2Q}{(r_{xm} + r_{ym})^2} (\delta r_x + \delta r_y) + \frac{3\varepsilon_x^2}{r_{xm}^4} \delta r_x = 0 \\
\delta r'''_y + \kappa_y \delta r_y &+ \frac{2Q}{(r_{xm} + r_{ym})^2} (\delta r_x + \delta r_y) + \frac{3\varepsilon_y^2}{r_{ym}^4} \delta r_y = 0
\end{align*}
\]
Martix Form of the Linearized Perturbed Envelope Equations:

\[
\frac{d}{ds} \delta \mathbf{R} + \mathbf{K} \cdot \delta \mathbf{R} = \delta \mathbf{P}
\]

\[\delta \mathbf{R} \equiv \begin{pmatrix}
\delta r_x \\
\delta r'_x \\
\delta r_y \\
\delta r'_y
\end{pmatrix} \text{ Coordinate vector}
\]

\[\mathbf{K} \equiv \begin{pmatrix}
0 & -1 & 0 & 0 \\
k_{xm} & 0 & k_{0m} & 0 \\
0 & 0 & 0 & -1 \\
k_{0m} & 0 & k_{ym} & 0
\end{pmatrix} \text{ Coefficient matrix}
\]

\[\delta \mathbf{P} \equiv \begin{pmatrix}
0 \\
-\delta \kappa_x r_{xm} + 2 \frac{\delta Q}{r_{xm} + r_{ym}} + 2 \frac{\varepsilon_x \delta \varepsilon_x}{r_{xm}^3} \\
0 \\
-\delta \kappa_y r_{ym} + 2 \frac{\delta Q}{r_{xm} + r_{ym}} + 2 \frac{\varepsilon_y \delta \varepsilon_y}{r_{ym}^3}
\end{pmatrix} \text{ Driving perturbation vector}
\]

Has periodicity of the lattice period

\[k_{0m} = \frac{2Q}{(r_{xm} + r_{ym})^2}
\]

\[k_{jm} = \kappa_j + 3 \frac{\varepsilon_j^2}{r_{jm}^4} + k_{0m} \quad j = x, y
\]

Expand solution into \textit{homogeneous} and \textit{particular} parts:

\[\delta \mathbf{R} = \delta \mathbf{R}_h + \delta \mathbf{R}_p
\]

\[\delta \mathbf{R}_h = \text{ homogeneous solution}
\]

\[\delta \mathbf{R}_p = \text{ particular solution}
\]

\[\frac{d}{ds} \delta \mathbf{R}_h + \mathbf{K} \cdot \delta \mathbf{R}_h = 0
\]

\[\frac{d}{ds} \delta \mathbf{R}_p + \mathbf{K} \cdot \delta \mathbf{R}_p = \delta \mathbf{P}
\]
Homogeneous Solution: Normal Modes
- Describes normal mode oscillations
- Original analysis by Struckmeier and Reiser [Part. Accel. 14, 227 (1984)]

Particular Solution: Driven Modes
- Describes action of driving terms
- Characterize in terms of projections on homogeneous response (on normal modes)

Homogeneous solution expressible as a map:
\[
\delta \mathbf{R}(s) = \mathbf{M}_e(s|s_i) \cdot \delta \mathbf{R}(s_i)
\]
\[
\delta \mathbf{R}(s) = (\delta r_x, \delta r'_x, \delta r_y, \delta r'_y)
\]
\[
\mathbf{M}_e(s|s_i) = 4 \times 4 \text{ transfer map}
\]

Eigenvalues and eigenvectors of map through one period characterize normal modes and stability properties:
\[
\mathbf{M}_e(s_i + L_p|s_i) \cdot \mathbf{E}_n(s_i) = \lambda_n \mathbf{E}_n(s_i)
\]

Stability
\[
\lambda_n = \gamma_n e^{i \sigma_n} \quad \sigma_n \rightarrow \text{mode phase advance (real)}
\]
\[
\gamma_n \rightarrow \text{mode growth/damp factor (real)}
\]

Mode Expansion/Launching
\[
\delta \mathbf{R}(s_i) = \sum_{n=1}^{4} \alpha_n \mathbf{E}_n(s_i)
\]
\[
\alpha_n = \text{const (complex)}
\]
Eigenvalue/Eigenvector Symmetry Classes:

Symmetry classes of eigenvalues/eigenvectors:

- Determine normal mode symmetries
- Hamiltonian dynamics allow only 4 distinct classes of eigenvalue symmetries
  - See A. Dragt, Lectures on Nonlinear Orbit Dynamics,
- Envelope mode symmetries discussed fully in PRSTAB review
- Caution: Textbook by Reiser makes errors in quadrupole mode symmetries and
  mislabels/identifies dispersion characteristics and branch choices

SM Lund, USPAS, June 2011
### Pure mode launching conditions:

Launching conditions for distinct normal modes corresponding to the eigenvalue classes illustrated:

- $A_\ell = $ mode amplitude (real)
- $\psi_\ell = $ mode launch phase (real)
- $\ell = $ mode index
- $C.C. = $ complex conjugate

<table>
<thead>
<tr>
<th>Case</th>
<th>Mode</th>
<th>Launching Condition</th>
<th>Lattice Period Advance</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Stable</td>
<td>1 - Stable Osc.</td>
<td>$\delta R_1 = A_1 e^{i\psi_1} E_1 + C.C.$</td>
<td>$M_e \delta R_1(\psi_1) = \delta R_1(\psi_1 + \sigma_1)$</td>
</tr>
<tr>
<td></td>
<td>2 - Stable Osc.</td>
<td>$\delta R_2 = A_2 e^{i\psi_2} E_2 + C.C.$</td>
<td>$M_e \delta R_2(\psi_2) = \delta R_2(\psi_2 + \sigma_2)$</td>
</tr>
<tr>
<td>(b) Unstable</td>
<td>1 - Exp. Growth</td>
<td>$\delta R_1 = A_1 e^{i\psi_1} E_1 + C.C.$</td>
<td>$M_e \delta R_1(\psi_1) = \gamma_1 \delta R_1(\psi_1 + \sigma_1)$</td>
</tr>
<tr>
<td>Confluent Res.</td>
<td>2 - Exp. Damping</td>
<td>$\delta R_2 = A_2 e^{i\psi_2} E_2 + C.C.$</td>
<td>$M_e \delta R_2(\psi_2) = (1/\gamma_1) \delta R_2(\psi_2 + \sigma_1)$</td>
</tr>
<tr>
<td>(c) Unstable</td>
<td>1 - Stable Osc.</td>
<td>$\delta R_1 = A_1 e^{i\psi_1} E_1 + C.C.$</td>
<td>$M_e \delta R_1(\psi_1) = \delta R_1(\psi_1 + \sigma_1)$</td>
</tr>
<tr>
<td>Lattice Res.</td>
<td>2 - Exp. Growth</td>
<td>$\delta R_2 = A_2 E_2$</td>
<td>$M_e \delta R_2 = -\gamma_2 \delta R_2$</td>
</tr>
<tr>
<td></td>
<td>3 - Exp. Damping</td>
<td>$\delta R_3 = A_3 E_4$</td>
<td>$M_e \delta R_3 = -(1/\gamma_2) \delta R_3$</td>
</tr>
<tr>
<td>(d) Unstable</td>
<td>1 - Exp. Growth</td>
<td>$\delta R_1 = A_1 E_1$</td>
<td>$M_e \delta R_1 = -\gamma_1 \delta R_1$</td>
</tr>
<tr>
<td>Double Lattice</td>
<td>2 - Exp. Growth</td>
<td>$\delta R_2 = A_2 E_2$</td>
<td>$M_e \delta R_2 = -\gamma_2 \delta R_2$</td>
</tr>
<tr>
<td>Resonance</td>
<td>3 - Exp. Damping</td>
<td>$\delta R_3 = A_3 E_3$</td>
<td>$M_e \delta R_3 = -(1/\gamma_1) \delta R_3$</td>
</tr>
<tr>
<td></td>
<td>4 - Exp. Damping</td>
<td>$\delta R_4 = A_4 E_4$</td>
<td>$M_e \delta R_4 = -(1/\gamma_2) \delta R_4$</td>
</tr>
</tbody>
</table>

\[
\delta R_\ell \equiv \delta R_\ell (s_i) \quad E_\ell \equiv E_\ell (s_i) \quad M_e \equiv M_e (s_i + L_p | s_i)
\]

\[
\delta R(s) = \begin{cases} 
A_1 [E_1(s) e^{i\psi_1(s)} + E_1^*(s) e^{-i\psi_1(s)}] + A_2 [E_2(s) e^{i\psi_2(s)} + E_2^*(s) e^{-i\psi_2(s)}], & \text{cases (a) and (b)} \\
A_1 [E_1(s) e^{i\psi_1(s)} + E_1^*(s) e^{-i\psi_1(s)}] + A_2 E_2(s) + A_3 E_4(s), & \text{case (c)} \\
A_1 E_1(s) + A_2 E_2(s) + A_3 E_3(s) + A_4 E_4(s), & \text{case (d)} 
\end{cases}
\]
Decoupled Modes

In a continuous or periodic solenoidal focusing channel
\[ \kappa_x(s) = \kappa_y(s) = \kappa(s) \]

with a round matched-beam solution
\[ \varepsilon_x = \varepsilon_y \equiv \varepsilon = \text{const} \]
\[ r_{xm}(s) = r_{ym}(s) \equiv r_m(s) \]
envelope perturbations are simply decoupled with:

**Breathing Mode:**
\[ \delta r_+ \equiv \frac{\delta r_x + \delta r_y}{2} \]

**Quadrupole Mode:**
\[ \tilde{\delta} r_- \equiv \frac{\delta r_x - \delta r_y}{2} \]

The resulting decoupled envelope equations are:

**Breathing Mode:**
\[ \delta r''_+ + \kappa \delta r_+ + \frac{Q}{r_m^2} \delta r_+ + \frac{3\varepsilon^2}{r_m^4} \delta r_+ = -r_m \left( \frac{\delta \kappa_x + \delta \kappa_y}{2} \right) + \frac{1}{r_m} \delta Q + \frac{2\varepsilon}{r_m^3} \left( \frac{\delta \varepsilon_x + \delta \varepsilon_y}{2} \right) \]

**Quadrupole Mode:**
\[ \delta r''_- + \kappa \delta r_- + \frac{3\varepsilon^2}{r_m^4} \delta r_- = -r_m \left( \frac{\delta \kappa_x - \delta \kappa_y}{2} \right) + \frac{2\varepsilon}{r_m^3} \left( \frac{\delta \varepsilon_x - \delta \varepsilon_y}{2} \right) \]
Graphical interpretation of mode symmetries:

**Breathing Mode:**

\[ \delta r_+ = \frac{\delta r_x + \delta r_y}{2} \]

**Quadrupole Mode:**

\[ \delta r_- = \frac{\delta r_x - \delta r_y}{2} \]
Decoupled Mode Properties:

Space charge terms $\sim Q$ only directly expressed in equation for $\delta r_+(s)$
- Indirectly present in both equations from matched envelope $r_m(s)$

Homogeneous Solution:
- Restoring term for $\delta r_+(s)$ larger than for $\delta r_-(s)$
  - Breathing mode should oscillate faster than the quadrupole mode

Particular Solution:
- Misbalances in focusing and emittance driving terms can project onto either mode
  - Nonzero perturbed $\kappa_x(s) + \kappa_y(s)$ and $\varepsilon_x(s) + \varepsilon_y(s)$ project onto breathing mode
  - Nonzero perturbed $\kappa_x(s) - \kappa_y(s)$ and $\varepsilon_x(s) - \varepsilon_y(s)$ project onto quadrupole mode
- Perveance driving perturbations project only on breathing mode
Previous symmetry classes greatly reduce for decoupled modes:

Previous homogeneous 4x4 solution map:

\[
\delta \mathbf{R}(s) = \mathbf{M}_e(s|s_i) \cdot \delta \mathbf{R}(s_i)
\]
\[
\delta \mathbf{R}(s) = (\delta r_x, \delta r'_x, \delta r_y, \delta r'_y)
\]
\[
\mathbf{M}_e(s|s_i) = 4 \times 4 \text{ transfer map}
\]

reduces to two independent 2x2 maps with greatly simplified symmetries:

\[
\delta \mathbf{R} \equiv (\delta r_+, \delta r'_+, \delta r_-, \delta r'_-)
\]
\[
\mathbf{M}_e(s_i + L_p|s_i) = \begin{bmatrix}
\mathbf{M}_+(s_i + L_p|s_i) & 0 \\
0 & \mathbf{M}_-(s_i + L_p|s_i)
\end{bmatrix}
\]

with corresponding eigenvalue problems:

\[
\mathbf{M}_\pm(s_i + L_p|s_i) \cdot \mathbf{E}_n(s_i) = \lambda_\pm \mathbf{E}_n(s_i)
\]

Many familiar results from analysis of Hills equation (see: S.M. Lund lectures on Transverse Particle Dynamics) can be immediately applied to the decoupled case, for example:

\[
\frac{1}{2} |\text{Tr} \mathbf{M}_\pm(s_i + L_p|s_i)| \leq 1 \quad \iff \quad \text{mode stability}
\]
Eigenvalue symmetries and launching conditions simplify for decoupled modes.

**Eigenvalue Symmetry 1:**

**Stable**

\[ \lambda_\pm = e^{i \sigma_\pm} \]

\[ \lambda_\pm \ast = 1/\lambda_\pm = e^{-i \sigma_\pm} \]

**Launching Condition / Projections**

**Eigenvalue Symmetry 2:**

**Unstable, Lattice Resonance**

\[ \lambda_\pm = \gamma_\pm e^{-i \pi} \]

\[ 1/\lambda_\pm = (1/\gamma_\pm)e^{-i \pi} \]
General Mode Limits

Using phase-amplitude analysis can show for any linear focusing lattice:

1) Phase advance of any normal mode satisfies the zero space-charge limit:

\[
\lim_{Q \to 0} \sigma_\ell = 2\sigma_0
\]

2) Pure normal modes (not driven) evolve with a quadratic phase-space (Courant-Snyder) invariant in the normal coordinates of the mode

Simply expressed for decoupled modes with \( \kappa_x = \kappa_y, \ \varepsilon_x = \varepsilon_y \)

\[
\left[ \frac{\delta r_{\pm}(s)}{w_{\pm}(s)} \right]^2 + [w'_{\pm}(s)\delta r_{\pm}(s) - w_{\pm}(s)\delta r'_{\pm}(s)]^2 = \text{const}
\]

where

\[
\begin{align*}
&w''_+ + \kappa w_+ + \frac{Q}{r_m^2} w_+ + \frac{3\varepsilon^2}{r_m^4} w_+ - \frac{1}{w_+^3} = 0 \\
&w''_- + \kappa w_- + \frac{3\varepsilon^2}{r_m^4} w_- - \frac{1}{w_-^3} = 0 \\
&w_{\pm}(s + L_p) = w_{\pm}(s)
\end{align*}
\]

Analogous results for coupled modes [See Edwards and Teng, IEEE Trans Nuc. Sci. 20, 885 (1973)]

- More complex expression due to coupling
Focusing:
\[ \kappa_x(s) = \kappa_y(s) = k_{\beta_0}^2 = \left( \frac{\sigma_0}{L_p} \right)^2 = \text{const} \]

Matched beam:
symmetric beam:
\[ \varepsilon_x = \varepsilon_y = \varepsilon = \text{const} \]
\[ r_{xm}(s) = r_{ym}(s) = r_m = \text{const} \]
matched envelope:
\[ k_{\beta_0}^2 r_m - \frac{Q}{r_m} - \frac{\varepsilon^2}{r_m^3} = 0 \]
depressed phase advance:
\[ \sigma = \sqrt{\sigma_0^2 - \frac{Q}{(r_m/L_p)^2}} = \frac{\varepsilon L_p}{r_m^2} \]

one parameter needed for scaled solution:

Decoupled Modes:
\[ \frac{k_{\beta_0}^2 \varepsilon^2}{Q^2} = \frac{\sigma_0^2 \varepsilon^2}{Q^2 L_p^2} = \frac{(\sigma/\sigma_0)^2}{[1 - (\sigma/\sigma_0)^2]^2} \]

\[ \delta r_{\pm}(s) = \frac{\delta r_x(s) \pm \delta r_y(s)}{2} \]
Envelope equations of motion become:

\[
L_p^2 \frac{d^2}{ds^2} \left( \frac{\delta r_+}{r_m} \right) + \sigma_+^2 \left( \frac{\delta r_+}{r_m} \right) = -\frac{\sigma_0^2}{2} \left( \frac{\delta \kappa_x}{k_{\beta 0}^2} + \frac{\delta \kappa_y}{k_{\beta 0}^2} \right) + \left( \sigma_0^2 - \sigma^2 \right) \frac{\delta Q}{Q} + \sigma^2 \left( \frac{\delta \varepsilon_x}{\varepsilon} + \frac{\delta \varepsilon_y}{\varepsilon} \right)
\]

\[
L_p^2 \frac{d^2}{ds^2} \left( \frac{\delta r_-}{r_m} \right) + \sigma_-^2 \left( \frac{\delta r_-}{r_m} \right) = -\frac{\sigma_0^2}{2} \left( \frac{\delta \kappa_x}{k_{\beta 0}^2} - \frac{\delta \kappa_y}{k_{\beta 0}^2} \right) + \sigma^2 \left( \frac{\delta \varepsilon_x}{\varepsilon} - \frac{\delta \varepsilon_y}{\varepsilon} \right)
\]

\[
\sigma_+ \equiv \sqrt{2\sigma_0^2 + 2\sigma^2} \quad \text{“breathing” mode phase advance}
\]

\[
\sigma_- \equiv \sqrt{\sigma_0^2 + 3\sigma^2} \quad \text{“quadrupole” mode phase advance}
\]

Homogeneous equations for normal modes:

\[
\frac{d^2}{ds^2} \delta r_\pm + \left( \frac{\sigma_\pm}{L_p} \right)^2 \delta r_\pm = 0
\]

See also lectures by J.J. Barnard, Envelope Modes and Halo

- Simple harmonic oscillator equation

Homogeneous Solution (normal modes):

\[
\delta r_\pm(s) = \delta r_\pm(s_i) \cos \left( \frac{\sigma_\pm s - s_i}{L_p} \right) + \frac{\delta r'_\pm(s_i)}{\sigma_\pm/L_p} \sin \left( \frac{\sigma_\pm s - s_i}{L_p} \right)
\]

\[
\delta r_\pm(s_i), \quad \delta r'_\pm(s_i) \quad \text{mode initial conditions}
\]
Properties of continuous focusing homogeneous solution: Normal Modes

**Mode Phase Advances**

Breathing Mode:

\[
\sigma_+ \equiv \sqrt{2\sigma_0^2 + 2\sigma^2}
\]

Quadrupole Mode:

\[
\sigma_- \equiv \sqrt{\sigma_0^2 + 3\sigma^2}
\]

**Mode Projections**

Breathing Mode:

\[
\delta r_+ \equiv \frac{\delta r_x + \delta r_y}{2}
\]

Quadrupole Mode:

\[
\delta r_- \equiv \frac{\delta r_x - \delta r_y}{2}
\]
Particular Solution (driving perturbations):
Green's function form of solution derived using projections onto normal modes

- See proof that this is a valid solution is given in Appendix A

\[
\frac{\delta r_{\pm}(s)}{r_m} = \frac{1}{L_p^2} \int_{s_i}^{s} d\tilde{s} \ G_{\pm}(s, \tilde{s}) \delta p_{\pm}(\tilde{s})
\]

\[
\delta p_{+}(s) = -\frac{\sigma_0^2}{2} \left[ \frac{\delta \kappa_x(s)}{k_{\beta_0}^2} + \frac{\delta \kappa_y(s)}{k_{\beta_0}^2} \right] + (\sigma_0^2 - \sigma^2) \frac{\delta Q(s)}{Q} + \sigma^2 \left[ \frac{\delta \varepsilon_x(s)}{\varepsilon} + \frac{\delta \varepsilon_y(s)}{\varepsilon} \right]
\]

\[
\delta p_{-}(s) = -\frac{\sigma_0^2}{2} \left[ \frac{\delta \kappa_x(s)}{k_{\beta_0}^2} - \frac{\delta \kappa_y(s)}{k_{\beta_0}^2} \right] + \sigma^2 \left[ \frac{\delta \varepsilon_x(s)}{\varepsilon} - \frac{\delta \varepsilon_y(s)}{\varepsilon} \right]
\]

\[
G_{\pm}(s, \tilde{s}) = \frac{1}{\sigma_{\pm}/L_p} \sin \left( \sigma_{\pm} \frac{s - \tilde{s}}{L_p} \right)
\]

Green's function solution is *fully general*. Insight gained from simplified solutions for specific classes of driving perturbations:

- Adiabatic covered in these lectures
- Sudden
- Ramped covered in PRSTAB Review article
- Harmonic
Continuous Focusing – adiabatic particular solution

For driving perturbations $\delta p_+(s)$ and $\delta p_-(s)$ slow on quadrupole mode (slower mode) wavelength $\sim 2\pi L_p/\sigma_-$ the Green function solution reduces to:

\[
\frac{\delta r_+(s)}{r_m} = \frac{\delta p_+(s)}{\sigma_+^2} = -\left[\frac{1}{2} \frac{1}{1 + (\sigma/\sigma_0)^2}\right] \frac{1}{2} \left( \frac{\delta \kappa_x(s)}{k_{\beta_0}^2} + \frac{\delta \kappa_y(s)}{k_{\beta_0}^2} \right) + \left[\frac{1}{2} \frac{1}{1 + (\sigma/\sigma_0)^2}\right] \frac{\delta Q(s)}{Q} \\
+ \left[\frac{(\sigma/\sigma_0)^2}{1 + (\sigma/\sigma_0)^2}\right] \frac{1}{2} \left( \frac{\delta \varepsilon_x(s)}{\varepsilon} + \frac{\delta \varepsilon_y(s)}{\varepsilon} \right),
\]

\[
\frac{\delta r_-(s)}{r_m} = \frac{\delta p_-(s)}{\sigma_-^2} = -\left[\frac{1}{1 + 3(\sigma/\sigma_0)^2}\right] \frac{1}{2} \left( \frac{\delta \kappa_x(s)}{k_{\beta_0}^2} - \frac{\delta \kappa_y(s)}{k_{\beta_0}^2} \right) \\
+ \left[\frac{2(\sigma/\sigma_0)^2}{1 + 3(\sigma/\sigma_0)^2}\right] \frac{1}{2} \left( \frac{\delta \varepsilon_x(s)}{\varepsilon} - \frac{\delta \varepsilon_y(s)}{\varepsilon} \right).
\]
Derivation of Adiabatic Solution:

- Several ways to derive, show more “mechanical” procedure here ....

Use:

\[
\frac{\delta r_\pm(s)}{r_m} = \frac{1}{L_p^2} \int_{s_i}^{s} d\tilde{s} \ G_\pm(s, \tilde{s}) \delta p_\pm(\tilde{s})
\]

\[
G_\pm(s, \tilde{s}) = \frac{1}{\sigma_\pm/L_p} \sin \left( \sigma_\pm \frac{s - \tilde{s}}{L_p} \right) = \frac{1}{(\sigma_\pm/L_p)^2} \frac{d}{d\tilde{s}} \cos \left( \sigma_\pm \frac{s - \tilde{s}}{L_p} \right)
\]

Gives:

\[
\frac{\delta r_\pm(s)}{r_m} = \int_{s_i}^{s} d\tilde{s} \left[ \frac{d}{d\tilde{s}} \cos \left( \sigma_\pm \frac{s - \tilde{s}}{L_p} \right) \right] \frac{\delta p_\pm(\tilde{s})}{\sigma_\pm} = \int_{s_i}^{s} d\tilde{s} \left[ \cos \left( \sigma_\pm \frac{s - \tilde{s}}{L_p} \right) \frac{\delta p_\pm(\tilde{s})}{\sigma_\pm} \right] - \int_{s_i}^{s} d\tilde{s} \cos \left( \sigma_\pm \frac{s - \tilde{s}}{L_p} \right) \frac{d}{d\tilde{s}} \frac{\delta p_\pm(\tilde{s})}{\sigma_\pm}
\]

\[
= \cos \left( \sigma_\pm \frac{s - \tilde{s}}{L_p} \right) \frac{\delta p_\pm(\tilde{s})}{\sigma_\pm} \bigg|_{\tilde{s} = s_i} = \frac{\delta p_\pm(s)}{\sigma_\pm} - \cos \left( \sigma_\pm \frac{s - s_i}{L_p} \right) \frac{\delta p_\pm(s_i)}{\sigma_\pm}
\]

Adiabatic \( \Rightarrow 0 \)

No Initial Perturbation \( \Rightarrow 0 \)
Comments on **Adiabatic Solution**:

- Adiabatic response is essentially a slow adaptation in the matched envelope to perturbations (solution does not oscillate due to slow changes)
- Slow envelope frequency $\sigma_-$ sets the scale for slow variations required

**Replacements in adiabatically adapted match:**

\[
\begin{align*}
    r_x &= r_m \rightarrow r_m + \delta r_+ + \delta r_- \\
    r_y &= r_m \rightarrow r_m + \delta r_- - \delta r_+
\end{align*}
\]

**Parameter replacements in rematched beam** (no longer axisymmetric):

\[
\begin{align*}
    \kappa_x &= k_{\beta_0}^2 \rightarrow k_{\beta_0}^2 + \delta \kappa_x(s) \\
    \kappa_y &= k_{\beta_0}^2 \rightarrow k_{\beta_0}^2 + \delta \kappa_y(s) \\
    Q &= Q + \delta Q(s) \\
    \varepsilon_x &= \varepsilon \rightarrow \varepsilon + \delta \varepsilon_x(s) \\
    \varepsilon_y &= \varepsilon \rightarrow \varepsilon + \delta \varepsilon_y(s)
\end{align*}
\]
Continuous Focusing – adiabatic solution coefficients

a) $\delta r_+ = (\delta r_x + \delta r_y)/2$  Breathing Mode Projection

Relative strength of:
- Space-Charge (Perveance)
- Applied Focusing
- Emittance

Terms vary with space-charge depression $(\sigma/\sigma_0)$ for both breathing and quadrupole mode projections.

Plots allow one to read off the relative importance of various contributions to beam mismatch as a function of space-charge strength.

b) $\delta r_- = (\delta r_x - \delta r_y)/2$  Quadrupole Mode Projection
Continuous Focusing – sudden particular solution

For sudden, step function driving perturbations of form:

\[ \hat{\delta p}_\pm (s) = \hat{\delta p}_\pm \Theta (s - s_p) \]

\( s = s_p \) = axial coordinate perturbation applied

Hat quantities are constant amplitudes

with amplitudes:

\[ \hat{\delta p}_+ = -\frac{\sigma_0^2}{2} \left[ \frac{\hat{\delta k}_x}{k_\beta^2} + \frac{\hat{\delta k}_y}{k_\beta^2} \right] + (\sigma_0^2 - \sigma^2) \frac{\hat{\delta Q}}{Q} + \sigma^2 \left[ \frac{\hat{\delta \varepsilon}_x}{\varepsilon} + \frac{\hat{\delta \varepsilon}_y}{\varepsilon} \right] = \text{const} \]

\[ \hat{\delta p}_- = -\frac{\sigma_0^2}{2} \left[ \frac{\hat{\delta k}_x}{k_\beta^2} - \frac{\hat{\delta k}_y}{k_\beta^2} \right] + \sigma^2 \left[ \frac{\hat{\delta \varepsilon}_x}{\varepsilon} - \frac{\hat{\delta \varepsilon}_y}{\varepsilon} \right] = \text{const} \]

The solution is given by the substitution in the expression for the adiabatic solution:

- Manipulate Green's function solution to show (similar to Adiabatic case steps)

\[ \delta p_\pm (s) \to \hat{\delta p}_\pm \left[ 1 - \cos \left( \sigma_\pm \frac{s - s_p}{L_p} \right) \right] \Theta (s - s_p) \]
**Sudden perturbation solution**, substitute in previous adiabatic expressions:

\[
\delta p_{\pm}(s) \rightarrow \widehat{\delta p}_{\pm} \left[ 1 - \cos \left( \sigma_{\pm} \frac{s - s_p}{L_p} \right) \right] \Theta(s - s_p)
\]

Illustration of solution properties for a sudden \( \delta p_+(s) \) perturbation term

For the same amplitude of total driving perturbations, **sudden perturbations result in 2x the envelope excursion** that adiabatic perturbations produce.
Continuous Focusing – Driven perturbations on a continuously focused matched equilibrium (summary)

Adiabatic Perturbations:
- Essentially a rematch of equilibrium beam if the change is slow relative to quadrupole envelope mode oscillations

Sudden Perturbations:
- Projects onto breathing and quadrupole envelope modes with 2x adiabatic amplitude oscillating from zero to max amplitude

Ramped Perturbations: (see PRSTAB article; based on Green's function)
- Can be viewed as a superposition between the adiabatic and sudden form perturbations

Harmonic Perturbations: (see PRSTAB article; based on Green's function)
- Can build very general cases of driven perturbations by linear superposition
- Results may be less “intuitive” (expressed in complex form)

Cases covered in class illustrate a range of common behavior and help build intuition on what can drive envelope oscillations and the relative importance of various terms as a function of space-charge strength
Appendix A: Particular Solution for Driven Envelope Modes
Lund and Bukh, PRSTAB 7, 024801 (2004)

Following Wiedemann (Particle Accelerator Physics, 1993, pp 106) first, consider more general *Driven Hill's Equation*

\[ x'' + \kappa(s)x = p(s) \]

The corresponding homogeneous equation:

\[ x'' + \kappa(s)x = 0 \]

has principal solutions

\[ x(s) = C_1 \mathcal{C}(s) + C_2 \mathcal{S}(s) \quad C_1, C_2 = \text{constants} \]

where

- **Cosine-Like Solution**
  \[ \mathcal{C}'' + \kappa(s)\mathcal{C} = 0 \]
  \[ \mathcal{C}(s = s_i) = 1 \]
  \[ \mathcal{C}'(s = s_i) = 0 \]

- **Sine-Like Solution**
  \[ \mathcal{S}'' + \kappa(s)\mathcal{S} = 0 \]
  \[ \mathcal{S}(s = s_i) = 0 \]
  \[ \mathcal{S}'(s = s_i) = 1 \]

Recall that the homogeneous solutions have the Wronskian symmetry:

- See S.M. Lund lectures on Transverse Dynamics, S5C

\[ W(s) = \mathcal{C}(s)\mathcal{S}'(s) - \mathcal{C}'(s)\mathcal{S}(s) = 1 \]
A particular solution to the *Driven Hill's Equation* can be constructed using a Greens' function method:

\[
x(s) = \int_{s_i}^{s} d\tilde{s} \ G(s, \tilde{s})p(\tilde{s})
\]

\[
G(s, \tilde{s}) = S(s)C(\tilde{s}) - C(s)S(\tilde{s})
\]

Demonstrate this works by first taking derivatives:

\[
x = S(s) \int_{s_i}^{s} d\tilde{s} \ C(\tilde{s})p(\tilde{s}) - C(s) \int_{s_i}^{s} d\tilde{s} \ S(\tilde{s})p(\tilde{s})
\]

\[
x' = S'(s) \int_{s_i}^{s} d\tilde{s} \ C(\tilde{s})p(\tilde{s}) - C'(s) \int_{s_i}^{s} d\tilde{s} \ S(\tilde{s})p(\tilde{s})
\]

\[
+ p(s) [S(s)C(s) - S(s)C(s)]
\]

\[
= S'(s) \int_{s_i}^{s} d\tilde{s} \ C(\tilde{s})p(\tilde{s}) - C'(s) \int_{s_i}^{s} d\tilde{s} \ S(\tilde{s})p(\tilde{s})
\]

\[
x'' = S''(s) \int_{s_i}^{s} d\tilde{s} \ C(\tilde{s})p(\tilde{s}) - C''(s) \int_{s_i}^{s} d\tilde{s} \ S(\tilde{s})p(\tilde{s})
\]

\[
\text{Wronskian Symmetry}
\]

\[
= p(s) + S''(s) \int_{s_i}^{s} d\tilde{s} \ C(\tilde{s})p(\tilde{s}) - C''(s) \int_{s_i}^{s} d\tilde{s} \ S(\tilde{s})p(\tilde{s})
\]
Apply these results in the *Driven Hill's Equation*:

\[
x'' + \kappa(s)x = p(s) + \left[ S'' + \kappa S \right] \int_{s_i}^{s} d\tilde{s} \ C(\tilde{s}) p(\tilde{s}) - \left[ C'' + \kappa C \right] \int_{s_i}^{s} d\tilde{s} \ S(\tilde{s}) p(\tilde{s}) = p(s)
\]

Thereby proving we have a valid particular solution. The general solution to the *Driven Hill's Equation* is then:

- Choose constants \( C_1, C_2 \) consistent with particle initial conditions at \( s = s_i \)

\[
x(s) = x(s_i) C(s) + x'(s_i) S(s) + \int_{s_i}^{s} d\tilde{s} \ G(s, \tilde{s}) p(\tilde{s})
\]

\[
G(s, \tilde{s}) = S(s) C(\tilde{s}) - C(s) S(\tilde{s})
\]

Apply these results to the driven perturbed envelope equation:

\[
\frac{d^2}{ds^2} \delta r_{\pm} + \frac{\sigma_{\pm}^2}{L_p^2} \delta r_{\pm} = \frac{r_m}{L_p^2} \delta p_{\pm}
\]
The homogeneous equations can be solved exactly for continuous focusing:

\[ C(s) = \cos \left( \sigma_\pm \frac{s - s_i}{L_p} \right) \]
\[ S(s) = \frac{L_p}{\sigma_\pm} \sin \left( \sigma_\pm \frac{s - s_i}{L_p} \right) \]

and the Green's function can be simplified as:

\[ G(s, \tilde{s}) = S(s)C(\tilde{s}) - C(s)S(\tilde{s}) \]
\[ = \frac{L_p}{\sigma_\pm} \left\{ \sin \left( \sigma_\pm \frac{s - s_i}{L_p} \right) \cos \left( \sigma_\pm \frac{\tilde{s} - s_i}{L_p} \right) - \cos \left( \sigma_\pm \frac{s - s_i}{L_p} \right) \sin \left( \sigma_\pm \frac{\tilde{s} - s_i}{L_p} \right) \right\} \]
\[ = \frac{L_p}{\sigma_\pm} \sin \left( \sigma_\pm \frac{s - \tilde{s}}{L_p} \right) \]

Using these results the particular solution for the driven perturbed envelope equation can be expressed as:

\[ \frac{\delta r_{\pm}(s)}{r_m} = \frac{1}{L_p^2} \int_{s_i}^{s} d\tilde{s} \ G_{\pm}(s, \tilde{s}) \delta p_{\pm}(\tilde{s}) \]

\[ G_{\pm}(s, \tilde{s}) = \frac{1}{\sigma_\pm / L_p} \sin \left( \sigma_\pm \frac{s - \tilde{s}}{L_p} \right) \]
Overview

- Much more complicated than continuous focusing results
  - Lattice can couple to oscillations and destabilize the system
  - Broad parametric instability bands can result
- Instability bands calculated will exclude wide ranges of parameter space from machine operation
  - Exclusion region depends on focusing type
  - Will find that alternating gradient quadrupole focusing tends to have more instability than high occupancy solenoidal focusing due to larger envelope flutter driving stronger, broader instability
- Results in this section are calculated numerically and summarized parametrically to illustrate the full range of normal mode characteristics
  - Driven modes not considered but should be mostly analogous to CF case
  - Results presented in terms of phase advances and normalized space-charge strength to allow broad applicability
  - Coupled 4x4 eigenvalue problem and mode symmetries identified in S6 are solved numerically and analytical limits are verified
  - Carried out for piecewise constant lattices for simplicity (fringe changes little)
- More information on results presented can be found in the PRSTAB review
Solenoidal Focusing – Matched Envelope Solution

Focusing:
\[ \kappa_x(s) = \kappa_y(s) = \kappa(s) \]
\[ \kappa(s + L_p) = \kappa(s) \]

Matched Beam:
\[ \varepsilon_x = \varepsilon_y = \varepsilon = \text{const} \]
\[ r_{xm}(s) = r_{ym}(s) = r_m(s) \]
\[ r_m(s + L_p) = r_m(s) \]

Comments:
- Envelope flutter a strong function of occupancy \( \eta \)
- Space-charge expands envelope but does not strongly modify periodic flutter
Envelope Flutter Scaling of Matched Envelope Solution

Add material explaining scaling better in future editions
Using a transfer matrix approach on undepressed single-particle orbits set the strength of the focusing function for specified undepressed particle phase advance by solving:

- See: S.M. Lund, lectures on Transverse Particle Dynamics
- Particle phase-advance is measured in the rotating Larmor frame

**Solenoidal Focusing** - piecewise constant focusing lattice

\[
\cos \sigma_0 = \cos(2\Theta) - \frac{1 - \eta}{\eta} \Theta \sin(2\Theta)
\]

\[
\Theta \equiv \frac{\sqrt{\kappa} L_p}{2}
\]

\[
\begin{align*}
\kappa_x(s) & \quad (\kappa_x = \kappa_y) \\
\hat{\kappa} & \\
\ell & \\
d/2 & \\
d/2 & \\
L_p & \text{Lattice Period}
\end{align*}
\]

\[
\begin{align*}
d &= (1 - \eta)L_p \\
\ell &= \eta L_p \\
\eta &\in (0, 1] = \text{Occupancy}
\end{align*}
\]
Solenoidal Focusing – parametric plots of breathing and quadrupole envelope mode phase advances two values of undepressed phase advance

\[ \eta = 0.25, \sigma_0 = 80^\circ \]

\[ \eta = 0.25, \sigma_0 = 115^\circ \]

Phase Adv. (deg/period) vs. \( \sigma / \sigma_0 \)

Growth Factor vs. \( \sigma / \sigma_0 \)
Solenoidal Focusing – mode instability bands become wider and stronger for smaller occupancy

\[
\eta = \begin{cases} 
0.75 \text{ (Blue)} \\
0.25 \text{ (Green)} \\
0.10 \text{ (Red)} 
\end{cases} \quad \sigma_0 = 115°
\]

Comments:
- Mode phase advance in instability band 180 degrees per lattice period
- Significant deviations from continuous model even outside the band of instability when space-charge is strong
- Instability band becomes stronger/broader for low occupancy and weaker/narrower for high occupancy
- Disappears at full occupancy (continuous limit)
Solenoidal Focusing – broad ranges of parametric instability are found for the breathing and quadrupole bands that must be avoided in machine operation.

\[ \eta = 0.75 \]

\[ \eta = 0.25 \]
Solenoidal Focusing – parametric mode properties of band oscillations

a) $\eta = 0.75$

Breathing Mode Phase Advance, $\sigma_+$

b) $\eta = 0.25$

Quadrupole Mode Phase Advance, $\sigma_-$
Parametric scaling of the boundary of the region of instability

Solenoid instability bands identified as a Lattice Resonance Instability corresponding to a 1/2-integer parametric resonance between the mode oscillation frequency and the lattice

Estimate normal mode frequencies for weak focusing from continuous focusing theory:

\[ \sigma_+ \approx \sqrt{2\sigma_0^2 + 2\sigma^2} \]

\[ \sigma_- \approx \sqrt{\sigma_0^2 + 3\sigma^2} \]

This gives (measure phase advance in degrees):

**Breathing Band:**

\[ \sigma_+ = 180^\circ \]

\[ \sqrt{2\sigma_0^2 + 2\sigma^2} = 180^\circ \]

**Quadrupole Band:**

\[ \sigma_- = 180^\circ \]

\[ \sqrt{\sigma_0^2 + 3\sigma^2} = 180^\circ \]

- Predictions poor due to inaccurate mode frequency estimates
  - Predictions nearer to left edge of band rather than center (expect resonance strongest at center)
- Simple resonance condition cannot predict width of band
  - Important to characterize width to avoid instability in machine designs
  - Width of band should vary strongly with solenoid occupancy \( \eta \)
To provide a practical guide on the location/width of the breathing and quadrupole envelope bands, many parametric runs were made and the instability band boundaries were quantified through curve fitting:

**Breathing Band Boundaries:**

\[ \sigma^2 + f\sigma_0^2 = (90^\circ)^2 (1 + f) \]

\[ f = f(\sigma_0, \eta) = \begin{cases} 1.113 - 0.413\eta + 0.00348\sigma_0, & \text{left-edge} \\ 1.046 + 0.318\eta - 0.00410\sigma_0, & \text{right-edge} \end{cases} \]

- Breathing band: maximum errors ~5/~2 degrees on left/right boundaries

**Quadrupole Band Boundaries:**

Left:

\[ \frac{\sigma}{\sigma_0} + g\frac{\sigma_0}{90^\circ} = 1 + g \]

Right:

\[ \sigma + g\sigma_0 = 90^\circ (1 + g) \]

\[ g = g(\eta) = \begin{cases} 1, & \text{left-edge} \\ 0.227 - 0.173\eta, & \text{right-edge} \end{cases} \]

- Quadrupole band: maximum errors ~8/~3 degrees on left/right boundaries
Pure eigenmode launching conditions are simple for the ideal solenoid case and correspond to the breathing (+) and quadrupole (-) mode symmetries covered for decoupled modes in S6

Breathing Mode:

\[ \delta r_+ = \frac{\delta r_x + \delta r_y}{2} \]

Quadrupole Mode:

\[ \delta r_- = \frac{\delta r_x - \delta r_y}{2} \]

Caution:

Recall we are describing problem implicitly in the rotating (Larmor) frame and to express launch conditions in the lab frame quadrupole mode conditions must be projected back with the correct overall rotation through magnet fringe fields.
Quadrupole Doublet Focusing – Matched Envelope Solution

**FODO and Syncopated Lattices**

<table>
<thead>
<tr>
<th>Description</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FODO</strong></td>
<td>$\sigma_0 = 80^\circ, \eta = 0.6949, \text{ and } \alpha = 1/2$</td>
</tr>
<tr>
<td></td>
<td>$\kappa_x(s) = -\kappa_y(s) = \kappa(s)$</td>
</tr>
<tr>
<td></td>
<td>$\kappa(s + L_p) = \kappa(s)$</td>
</tr>
<tr>
<td><strong>Syncopated</strong></td>
<td>$\sigma_0 = 80^\circ, \eta = 0.6949, \text{ and } \alpha = 0.1$</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_x = \varepsilon_y = \varepsilon = \text{const}$</td>
</tr>
<tr>
<td></td>
<td>$r_{xm}(s + L_p) = r_{xm}(s)$</td>
</tr>
<tr>
<td></td>
<td>$r_{ym}(s + L_p) = r_{ym}(s)$</td>
</tr>
</tbody>
</table>

**Comments:**
- Envelope flutter a *weak* function of occupancy $\eta$
- Syncopation factors $\alpha \neq 1/2$ reduce envelope symmetry and can drive more instabilities
- Space-charge expands envelope
Envelope Flutter Scaling of Matched Envelope Solution

For FODO quadrupole transport, plot relative matched beam envelope excursions for a fixed form focusing lattice and fixed beam perveance as the strength of applied focusing strength increases as measured by $\sigma_0$

**FODO Quadrupole**

$$\bar{r}_x = \int_0^{L_p} \frac{ds}{L_p} r_x(s)$$

$\eta = 0.5 \quad L_p = 0.5 \text{ m} \quad Q = 5 \times 10^{-4}$

$\varepsilon_x = \varepsilon_y = 50 \text{ mm-mrad}$

<table>
<thead>
<tr>
<th>$\sigma_0$</th>
<th>$\sigma / \sigma_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45°</td>
<td>0.20</td>
</tr>
<tr>
<td>80°</td>
<td>0.26</td>
</tr>
<tr>
<td>110°</td>
<td>0.32</td>
</tr>
</tbody>
</table>

- Larger matched envelope “flutter” corresponds to larger $\sigma_0$
- More flutter results in higher prospects for instability due to transfer of energy from applied focusing
- Little dependence of flutter on quadrupole occupancy

SM Lund, USPAS, June 2011
Using a transfer matrix approach on undepressed single-particle orbits set the strength of the focusing function for specified undepressed particle phase advance by solving:

\[ \cos \sigma_0 = \cos \theta \cosh \theta + \frac{1 - \eta}{\eta} \theta (\cos \theta \sinh \theta - \sin \theta \cosh \theta) - 2\alpha (1 - \alpha) \frac{(1 - \eta)^2}{\eta^2} \Theta^2 \sin \theta \sinh \theta \]

\[ \Theta \equiv \frac{\sqrt{|\kappa|} L_p}{2} \]

Quadrupole Doublet Focusing - piecewise constant focusing lattice

\[ \kappa_x(s) \quad (\kappa_x = -\kappa_y) \]

\[ F \text{ Quad} \quad \eta L_p/2 \quad D \text{ Quad} \quad \eta L_p/2 \]

\[ L_p \quad \text{Lattice Period} \]

\[ d_1 = \alpha (1 - \eta) L_p \quad d_2 = (1 - \alpha)(1 - \eta) L_p \]

\[ \eta \in (0, 1] \quad \text{Occupancy} \]

\[ \alpha \in [0, 1/2] \quad \text{Syncopation Factor} \]

\[ \alpha = 1/2 \rightarrow \text{FODO} \]
Quadrupole Focusing – parametric plots of breathing and quadrupole envelope mode phase advances two values of undepressed phase advance

a) $\eta = 0.6949, \alpha = 0.1, \sigma_0 = 80^0$

b) $\eta = 0.6949, \alpha = 0.1, \sigma_0 = 115^0$ Syncopated

FODO

SM Lund, USPAS, June 2011

Transverse Centroid and Envelope Descriptions of Beam Evolution
**Important point:**

For quadrupole focusing the normal mode coordinates are NOT

\[ \delta r_{\pm} = \frac{\delta r_x \pm \delta r_y}{2} \]

\[ \delta r_+ \quad \Longleftrightarrow \quad \text{Breathing Mode} \]

\[ \delta r_- \quad \Longleftrightarrow \quad \text{Quadrupole Mode} \]

- Only works for axisymmetric focusing \((\kappa_x = \kappa_y = \kappa)\)
  
  with an axisymmetric matched beam \((\varepsilon_x = \varepsilon_y = \varepsilon)\)

However, for low \(\sigma_0\) we will find that the two stable modes correspond closely in frequency with continuous focusing model breathing and quadrupole modes even though they have different symmetry properties in terms of normal mode coordinates. Due to this, we denote:

- Subscript B \(\Longleftrightarrow\) Breathing Mode
- Subscript Q \(\Longleftrightarrow\) Quadrupole Mode

- Label branches breathing and quadrupole in terms of low \(\sigma_0\) branch frequencies corresponding to breathing and quadrupole frequencies from continuous theory
- Continue label to larger values of \(\sigma_0\) where frequency correspondence with continuous modes breaks down
Quadrupole Focusing – mode instability bands vary little/strongly with occupancy for FODO/syncopated lattices

a) $\alpha = 1/2$ (FODO), $\sigma_0 = 115^\circ$

FODO

\[ \eta = \begin{cases} 
0.90 & \text{(Blue)} \\
0.6949 & \text{(Black)} \\
0.25 & \text{(Green)} \\
0.10 & \text{(Red)} 
\end{cases} \]

b) $\alpha = 0.1$, $\sigma_0 = 115^\circ$

Syncopated
Quadrupole Focusing – broad ranges of parametric instability are found for the breathing and quadrupole bands that must be avoided in machine operation.

FODO Lattice

\[ \eta = 0.6949, \quad \alpha = 1/2 \]

Syncopated Lattice

\[ \eta = 0.6949, \quad \alpha = 0.1 \]
Quadrupole Focusing – parametric mode properties of band oscillations

a) \( \eta = 0.6949, \alpha = 1/2 \) FODO

b) \( \eta = 0.6949, \alpha = 0.1 \) Syncopated

Breathing Mode Phase Advance, \( \sigma_B \)

Quadrupole Mode Phase Advance, \( \sigma_Q \)
Parametric scaling of the boundary of the region of instability

Quadrupole instability bands identified:

- **Confluent Band**: 1/2-integer parametric resonance between both breathing and quadrupole modes and the lattice
- **Lattice Resonance Band** (Syncopated lattice only): 1/2-integer parametric resonance between one envelope mode and the lattice

Estimate mode frequencies for weak focusing from continuous focusing theory:

\[
\sigma_B = \sigma_+ = \sqrt{2\sigma_0^2 + 2\sigma^2}
\]

\[
\sigma_Q = \sigma_- = \sqrt{\sigma_0^2 + 3\sigma^2}
\]

This gives (measure phase advance in degrees):

- **Confluent Band**:
  \[
  \frac{\sigma_+ + \sigma_-}{2} = 180^\circ
  \]
  \[
  \sqrt{2\sigma_0^2 + 2\sigma^2} + \sqrt{\sigma_0^2 + 3\sigma^2} = 360^\circ
  \]

- **Lattice Resonance Band**:
  \[
  \sigma_+ = 180^\circ
  \]
  \[
  \sqrt{2\sigma_0^2 + 2\sigma^2} = 180^\circ
  \]

- Predictions poor due to inaccurate mode frequency estimates from continuous model
  - Predictions nearer to edge of band rather than center (expect resonance strongest at center)
- Cannot predict width of band
  - Important to characterize to avoid instability
To provide a rough guide on the location/width of the important FODO confluent instability band, many parametric runs were made and the instability region boundary was quantified through curve fitting:

![Diagram showing Left and Right Edge Boundaries](env_band_quad_lab.png)

**Left Edge Boundary:**

\[
\sigma^2 + f(\eta)\sigma_0^2 = (90^\circ)^2[1 + f(\eta)]
\]

\[
f(\eta) = \frac{4}{3}
\]

- Negligible variation in quadrupole occupancy \( \eta \) is observed
- Formulas have a maximum error \( \sim 5 \) and \( \sim 2 \) degrees on left and right boundaries

**Right Edge Boundary:**

\[
\sigma + g(\eta)\sigma_0 = 90^\circ[1 + g(\eta)]
\]

\[
g(\eta) = \frac{1}{9}
\]
Pure mode launching conditions for quadrupole focusing

Launching a pure breathing (B) or quadrupole (Q) mode in alternating gradient quadrupole focusing requires specific projections that generally require an eigenvalue/eigenvector analysis of symmetries to carry out.

- See eigenvalue symmetries given in S6

Show example launch conditions for:

FODO Lattice

\[ \eta = 0.6949 \]

\[ \sigma_0 = 80^\circ \]

\[ \sigma/\sigma_0 = 0.2 \]
Quadrupole Focusing – projections of perturbations on pure modes varies strongly with mode phase and the location in the lattice (FODO example)

Breathing Mode, Mid–Quadrupole

Quadrupole Mode, Mid–Quadrupole

\[ \delta r_x, \delta r_y \]

\[ \psi_B / \pi \]

\[ \psi_Q / \pi \]

\[ \delta r_x' \]

\[ \delta r_y' \]

\[ \psi_B / \pi \]

\[ \psi_Q / \pi \]

\[ \delta r_x \neq \delta r_y \]

generally not exact breathing symmetry

\[ \delta r_x \neq -\delta r_y \]

generally not exact quadrupole symmetry
Transverse Centroid and Envelope Descriptions of Beam Evolution

Breathing Mode, Mid-Drift

Quadrupole Mode, Mid-Drift

\[ \delta r_x' \neq \delta r_y' \]

generally not exact
breathing symmetry

\[ \delta r_x \neq -\delta r_y \]

generally not exact
quadrupole symmetry
As a further guide in pure mode launching, summarize FODO results for:

- Mid-axial $x$-focusing quadrupole with the additional choice $\delta r'_j = 0$
- Specify ratio of $\delta r_x / \delta r_y$ to launch pure mode
- Plot as function of $\sigma_0$ for $\sigma_0 < 90^\circ$

- Results vary little with occupancy $\eta$ or $\sigma / \sigma_0$

$$\eta = \begin{cases} 
0.90 & \text{(Blue)} \\
0.6949 & \text{(Black)} \\
0.25 & \text{(Green)} \\
0.10 & \text{(Red)} 
\end{cases}$$
Comments:

- For quadrupole transport using the axisymmetric equilibrium projections on the breathing (+) mode and quadrupole (-) mode will \textit{NOT} generally result in nearly pure mode projections:

\[
\delta r_+ \equiv \frac{\delta r_x + \delta r_y}{2} \neq \text{Breathing Mode Projection} \\
\delta r_- \equiv \frac{\delta r_x - \delta r_y}{2} \neq \text{Quadrupole Mode Projection}
\]

- Mistake can be commonly found in research papers and can confuse analysis of supposidly pure classes of envelope oscillations which are not.

- Recall: reason denoted generalization of breathing mode with a subscript B and quadrupole mode with a subscript Q was an attempt to avoid confusion by overgeneralization

- Must solve for eigenvectors of 4x4 envelope transfer matrix through one lattice period calculated from the launch location in the lattice and analyze symmetries to determine proper projections (see S6)

- Normal mode coordinates can be found for the quadrupole and breathing modes in AG quadrupole focusing lattices through analysis of the eigenvectors but the expressions are typically complicated

- Modes have underlying Courant-Snyder invariant but it will be a complicated
Summary: Envelope band instabilities and growth rates for periodic solenoidal and quadrupole doublet focusing lattices

Envelope Mode Instability Growth Rates

Solenoid (\(\eta_0 = 0.25\))

Quadrupole FODO (\(\eta_0 = 0.70\))
S9: Transport Limit Scaling Based on Envelope Models

See Handwritten Notes from 2008 USPAS
- Will convert to slides in future versions of the class
S10: Centroid and Envelope Descriptions via 1st Order Coupled Moment Equations

When constructing centroid and moment models, it can be efficient to simply write moments, differentiate them, and then apply the equation of motion. Generally, this results in lower order moments coupling to higher order ones and an infinite chain of equations. But the hierarchy can be truncated by:
- Assuming a fixed functional form of the distribution in terms of moments
- Neglecting coupling to higher order terms

Resulting first order moment equations can be expressed in terms of a closed set of moments and advanced in $s$ or $t$ using simple (ODE based) numerical codes. This approach can prove simpler to include effects where invariants are not easily extracted to reduce the form of the equations (as when solving the KV envelope equations in the usual form).

Examples of effects that might be more readily analyzed:
- Skew coupling in quadrupoles
- Chromatic effects in final focus
- Dispersion in bends

See: references at end of notes

J.J. Barnard, lecture on Heavy-Ion Fusion and Final Focusing
Resulting 1\textsuperscript{st} order form of coupled moment equations:

\[ \frac{d}{ds} M = F(M) \]

\( M \) = vector of moments, and their \( s \) derivatives, generally infinite

\( F \) = vector function of \( M \), generally nonlinear

\* System advanced from a specified initial condition (initial value of \( M \))

Transverse moment definition:

\[
\langle \cdots \rangle_\perp \equiv \frac{\int d^2 x_\perp \int d^2 x'_\perp \cdots f_\perp}{\int d^2 x_\perp \int d^2 x'_\perp f_\perp}
\]

Can be generalized if other variables such as off momentum are included in \( f \)

Differentiate moments and apply equations of motion:

\[
\frac{d}{ds} \langle \cdots \rangle_\perp \equiv \frac{\int d^2 x_\perp \int d^2 x'_\perp \left[ \frac{d}{ds} \cdots \right] f_\perp}{\int d^2 x_\perp \int d^2 x'_\perp f_\perp}
\]

+ apply equations of motion to simplify \( \frac{d}{ds} \cdots \)
When simplifying the results, if the distribution form is frozen in terms of moments (Example: assume uniform density elliptical beam) then we use constructs like:

\[ n = \int d^2 x'_{\perp} f_{\perp} = n(M) \]

to simplify the resulting equations and express the RHS in terms of elements of \( M \).

**1\textsuperscript{st} order moments:**

\[
\begin{align*}
X_{\perp} &= \langle x_{\perp} \rangle_{\perp} & \text{Centroid coordinate} \\
X'_{\perp} &= \langle x'_{\perp} \rangle_{\perp} & \text{Centroid angle}
\end{align*}
\]

+ possible others if more variables. Example

\[
\Delta = \left\langle \frac{\delta p_s}{p_s} \right\rangle = \langle \delta \rangle & \quad \text{Centroid off-momentum} \\
\vdots & \\
\vdots &
\]
2\textsuperscript{nd} order moments:
It is typically convenient to subtract centroid from higher-order moments

\[\tilde{x} \equiv x - X \quad \tilde{x}' \equiv x' - X'\]
\[\tilde{y} \equiv y - Y \quad \tilde{y}' \equiv y' - Y'\]
\[\tilde{\delta} \equiv \delta - \Delta\]

\[\langle \tilde{x}^2 \rangle_{\perp} \quad \langle \tilde{y}^2 \rangle_{\perp} \quad \langle \tilde{x}\tilde{y} \rangle_{\perp} \quad \langle \tilde{x}\tilde{\delta} \rangle, \quad \langle \tilde{y}\tilde{\delta} \rangle\]
\[\langle \tilde{x}\tilde{x}' \rangle_{\perp} \quad \langle \tilde{y}\tilde{y}' \rangle_{\perp} \quad \langle \tilde{x}'\tilde{y} \rangle_{\perp}, \quad \langle \tilde{x}\tilde{y}' \rangle_{\perp}\]
\[\langle \tilde{x}'^2 \rangle_{\perp} \quad \langle \tilde{y}'^2 \rangle_{\perp} \quad \langle \tilde{x}'\tilde{y}' \rangle_{\perp}\]
\[\langle \tilde{\delta}^2 \rangle\]

3\textsuperscript{rd} order moments: Analogous to 2\textsuperscript{nd} order case, but more for each order

\[\langle \tilde{x}^3 \rangle_{\perp}, \quad \langle \tilde{x}^2\tilde{y} \rangle_{\perp}, \quad \cdots\]
Many quantities of physical interest are expressed in transport can then be expressed in terms of moments calculated when the equations are numerically advanced in $s$ and their evolutions plotted to understand behavior.

Many quantities of physical interest are expressible in terms of $1^{\text{st}}$ and $2^{\text{nd}}$ order moments.

Example moments often projected:

**Statistical beam size:**
(rms edge measure)

$$r_x = 2\langle \hat{x}^2 \rangle^{1/2}_{\perp}$$

$$r_y = 2\langle \hat{y}^2 \rangle^{1/2}_{\perp}$$

**Statistical emittances:**
(rms edge measure)

$$\varepsilon_x = 4 \left[ \langle \hat{x}^2 \rangle_{\perp} \langle \hat{x}'^2 \rangle_{\perp} - \langle \hat{x}\hat{x}' \rangle_{\perp}^2 \right]^{1/2}$$

$$\varepsilon_y = 4 \left[ \langle \hat{y}^2 \rangle_{\perp} \langle \hat{y}'^2 \rangle_{\perp} - \langle \hat{y}\hat{y}' \rangle_{\perp}^2 \right]^{1/2}$$

**Kinetic longitudinal temperature:**
(rms measure)

$$T_s = \text{const} \times \langle \tilde{\delta}^2 \rangle$$
Illustrate approach with the familiar KV model

Truncation assumption: unbunched uniform density elliptical beam in free space

- $\delta = 0$, no axial velocity spread
- All cross moments zero, i.e. $\langle \tilde{x}\tilde{y} \rangle \perp = 0$

\[
\frac{d}{ds} \langle x \rangle \perp = \langle x' \rangle \perp \\
\frac{d}{ds} \langle x' \rangle \perp = \langle x'' \rangle \perp \\
\vdots \\
\frac{d}{ds} \langle x^{2} \rangle \perp = 2\langle xx' \rangle \perp \\
\frac{d}{ds} \langle x'^{2} \rangle \perp = 2\langle x'x'' \rangle \perp \\
\vdots
\]

Use particle equations of motion within beam, neglect images, and simplify

- Apply equations in $S2$ with $E^{i}_{\perp} = 0$

\[
x'' + \left(\frac{\gamma b \beta b}{\gamma b \beta b} \right)' x' + \kappa x x - \frac{2Q}{(r_{x} + r_{y})r_{x}} (x - \langle x \rangle \perp) = 0
\]
\[
y'' + \left(\frac{\gamma b \beta b}{\gamma b \beta b} \right)' y' + \kappa y y - \frac{2Q}{(r_{x} + r_{y})r_{y}} (y - \langle y \rangle \perp) = 0
\]
Resulting system of 1st and 2nd order moments

1st order moments:

\[ \frac{d}{ds} \begin{bmatrix} \langle x \rangle_\perp \\ \langle x' \rangle_\perp \\ \langle y \rangle_\perp \\ \langle y' \rangle_\perp \end{bmatrix} = \begin{bmatrix} \langle x' \rangle_\perp \\ -\kappa_x(s)\langle x \rangle_\perp \\ \langle y' \rangle_\perp \\ -\kappa_y(s)\langle y \rangle_\perp \end{bmatrix} \]

2nd order moments:

\[ \frac{d}{ds} \begin{bmatrix} \langle \tilde{x}^2 \rangle_\perp \\ \langle \tilde{x}\tilde{x}' \rangle_\perp \\ \langle \tilde{x}'^2 \rangle_\perp \\ \langle \tilde{y} \rangle_\perp \\ \langle \tilde{y} \tilde{y}' \rangle_\perp \\ \langle \tilde{y}'^2 \rangle_\perp \end{bmatrix} = \begin{bmatrix} 2\langle \tilde{x}\tilde{x}' \rangle_\perp \\ \langle \tilde{x}'^2 \rangle_\perp - \kappa_x(s)\langle \tilde{x}^2 \rangle_\perp + \frac{Q\langle \tilde{x}^2 \rangle_\perp^{1/2}}{2[\langle \tilde{x}^2 \rangle_\perp^{1/2} + \langle \tilde{y}^2 \rangle_\perp^{1/2}]} \end{bmatrix} \]

Express 1st and 2nd order moments separately in this case since uncoupled

Form truncates due to frozen distribution form: all moments on LHS on RHS

Integrate from initial moments values of s and project out desired quantities
Using 2\textsuperscript{nd} order moment equations we can show that

\[ \frac{d}{ds} \varepsilon_x^2 = 0 = \frac{d}{ds} \varepsilon_y^2 \]

\[ \varepsilon_x^2 = 16 \left[ \langle x'^2 \rangle_\perp - \langle xx' \rangle_\perp^2 \right] = \text{const} \]

\[ \varepsilon_y^2 = 16 \left[ \langle y'^2 \rangle_\perp - \langle yy' \rangle_\perp^2 \right] = \text{const} \]

Using this, the 2\textsuperscript{nd} order moment equations can be equivalently expressed in the standard KV envelope form:

\[ \frac{dr_x}{ds} = r_x' ; \quad \frac{d}{ds} r_x' + \kappa_x r_x - \frac{2Q}{r_x + r_y} - \frac{\varepsilon_x^2}{r_x^3} = 0 \]

\[ \frac{dr_y}{ds} = r_y' ; \quad \frac{d}{ds} r_y' + \kappa_y r_y - \frac{2Q}{r_x + r_y} - \frac{\varepsilon_y^2}{r_y^3} = 0 \]

- Moment form fully consistent with usual KV model .... as it must be
- Moment form generally easier to put in additional effects that would violate the usual emittance invariants
Relative advantages of the use of coupled matrix form versus reduced equations can depend on the problem/situation

**Coupled Matrix Equations**

\[ \frac{d}{ds} \mathbf{M} = \mathbf{F}(\mathbf{M}) \]

\( \mathbf{M} = \) Moment Vector
\( \mathbf{F} = \) Force Vector

- Easy to formulate
  - Straightforward to incorporate additional effects
- Natural fit to numerical routine
  - Easy to numerically code/solve

**Reduced Equations**

\[ \ddot{X} + \kappa_x X = 0 \]

\[ \ddot{r}_x + \kappa_x r_x - \frac{2Q}{r_x + r_y} - \frac{\varepsilon_x^2}{r_x^3} = 0 \]

etc.

Reduction based on identifying invariants such as

\[ \varepsilon_x^2 = 16 \left[ \langle \tilde{x}^2 \rangle_{\perp} \langle \tilde{x}'^2 \rangle_{\perp} - \langle \tilde{x}\tilde{x}' \rangle_{\perp}^2 \right] \]

helps understand solutions

- Compact expressions can help analytical understanding
These notes will be corrected and expanded for reference and future editions of US Particle Accelerator School and University of California at Berkeley courses:

“Beam Physics with Intense Space Charge”
“Interaction of Intense Charged Particle Beams with Electric and Magnetic Fields”
by J.J. Barnard and S.M. Lund

Corrections and suggestions for improvements are welcome. Contact:

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Please do not remove author credits in any redistributions of class material.
References: For more information see:

Image charge couplings:


Seminal work on envelope modes:


Extensive review on envelope instabilities:


Efficient, Fail-Safe Generation of Matched Envelope Solutions:

KV distribution:


Symmetries and phase-amplitude methods:


Analytical analysis of matched envelope solutions and transport scaling:


Coupled Moment Formulations of Centroid and Envelope Evolution:


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