Compensation of insertion device induced emittance variations in ultralow emittance storage rings

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Content

• Problem definition.

• Possible compensation schemes:
  • Use a variable gap wiggler to generate emittance.
  • Use of a “dispersion bump” inside a wiggler with gap at a fixed position.
  • Compensation by small variation of the beam momentum.
  • Using intra-beam scattering (IBS).

• Final Considerations.
The MBA Lattice Revolution

Tens of pm emittances, orders of magnitude brightness increase, approaching fully photon coherence in the transverse plane!
Ultra-Low Emittance MBA Lattices
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Example: ALS-U 9BA Lattice v18_127 (obsolete)

- 1.15 nC/bunch - 2 GeV - L = 196.5 m - h = 328
- Dipole: $\rho = 8.6$ m ; $k_1 = -7$ m$^{-2}$; $\theta = 3.33$ deg
- $\varepsilon_0 = 109$ pm (no IBS) – 12 super-periods
- Full coupling:
  - $\varepsilon_x = \varepsilon_y = 81.32$ pm (with IBS and harm. cav.)
  - $\sigma_z = 14.56$ mm (with IBS and harm. cavities)
  - $\delta_0 = 0.0828\%$ - $U_0 = 181.9$ keV (no IDs)
  - $\alpha_c = 2.68 \times 10^{-4}$ - $j_x = 1.865$
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In such lattices, the typically large bending radius decreases the energy radiated in the bends making it comparable to that radiated in insertion devices (IDs).

In this situation, the IDs’ contribution significantly contributes to radiation damping and hence in defining the ring natural emittance.
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How large are ID induced energy losses in a real ring?
Example of ID Induced Energy Losses in a Ring
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ALS Insertion Devices

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<thead>
<tr>
<th>Name</th>
<th>Alias</th>
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Example of ID Induced Energy Losses in a Ring

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Random ID gaps variation generates random beam radiated power variations.
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\[ \langle U_0 \rangle = 18.5 \text{ keV}, \sigma_{U0} = 5.6 \text{ keV} \]

\[ \frac{\Delta \varepsilon}{\varepsilon} \sim 7 \% \quad (4 \text{ sigma}) \]
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$<U_0> = 18.5$ keV, $\sigma_{U_0} = 5.6$ keV

$\Delta \varepsilon / \varepsilon \sim 7\%$ (4 sigma)

How important such an emittance variation to experiments?
X-ray microscopy/spectroscopy technique very sensitive to beam size and hence to emittance variations.

Compensation by Variable Gap Wiggler
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\[ U_0 = \frac{C_Y}{2\pi} E^4 I_2 \quad C_Y = 8.846 \times 10^{-5} \; m/GeV^3 \]

\[ I_2 = \int \frac{ds}{\rho^2} = \frac{B^2 L_w}{2 (B\rho)^2} \quad \text{(wiggler)} \]

\[ B = 2\pi \frac{mc}{e} \frac{K_w}{\lambda_w} \quad \text{(wiggler)} \]

\[ U_0 = \pi C_Y \left( \frac{mc^2}{e} \right)^4 \gamma^2 \left( \frac{K_w}{\lambda_w} \right)^2 L_w \]
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- Allow operating at an emittance value smaller than the one obtainable from the bare lattice without IDs.
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- Requires a dedicated wiggler
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**ALS Wiggler example:** \( \lambda_w = 0.114 \text{ m}; \) \( N_{\text{Periods}} = 29; \) \( L_w = 3.3 \text{ m}; \) \( K_w = 20.6; \) \( B_w = 1.94 \text{ T}; \)

\[ U_0 = 28.3 \text{ keV @ 1.9 GeV} \text{ or } 31.4 \text{ keV @ 2 GeV} \]
Compensation by Local Dispersion Bump in Fixed Gap Wiggler

\[ \varepsilon_0 = C_q \frac{\gamma^2 I_5}{J_x I_2} \]
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\[
J_x = 1 - \frac{I_4}{I_2}
\]

\[
I_2 = \int \frac{ds}{\rho^2}
\]

\[
I_4 = \int \frac{\eta_x}{\rho} \left( \frac{1}{\rho^2} + 2k_1 \right) ds
\]

\[
I_5 = \int \frac{\mathcal{H}}{|\rho^3|} ds
\]

\[
\mathcal{H} = \gamma x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x \eta'_x^2
\]

\[
C_q = \frac{55}{32\sqrt{3}} \frac{h}{2\pi mc} \approx 3.832 \times 10^{-13} m
\]

\[
k_1 = \frac{e}{p} \frac{\partial B_y}{\partial x}
\]
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Assuming a horizontal dispersion bump Inside the wiggler with \( \eta_x \) constant and \( \eta'_x = 0 \)

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\[ k_1 = \frac{e}{p} \frac{\partial B_y}{\partial x} \]

\[ I_5 = \int \frac{\mathcal{H}}{|\rho|^3} ds \]

\[ \mathcal{H} = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta_x' + \beta_x \eta_x'^2 \]

Assuming a horizontal dispersion bump inside the wiggler with \( \eta_x \) constant and \( \eta_x' = 0 \)

\[ \Delta I_{5W} \sim \frac{4}{3\pi} \frac{B_W^3}{(B\rho)^3} L_w \langle \gamma_x \rangle \eta_x^2, \quad \Delta I_{2W} = 0, \quad \Delta I_{4W} \sim 0 \]
Compensation by Local Dispersion Bump in Fixed Gap Wiggler

\[ \varepsilon_0 = C_q \frac{\gamma^2 I_5}{J_x I_2} \]

\[ I_2 = \int \frac{ds}{\rho^2} \quad C_q = \frac{55}{32\sqrt{3}} \frac{h}{2\pi mc} \approx 3.832 \times 10^{-13} m \]

\[ J_x = 1 - \frac{I_4}{I_2} \quad I_4 = \int \frac{\eta_x}{\rho} \left( \frac{1}{\rho^2} + 2k_1 \right) ds \quad k_1 = \frac{e}{p} \frac{\partial B_y}{\partial x} \]

\[ I_5 = \int \frac{\mathcal{H}}{|\rho^3|} ds \quad \mathcal{H} = \gamma_x \eta_x^2 + 2\alpha_x \eta_x \eta'_x + \beta_x \eta'_x^2 \]

Assuming a horizontal dispersion bump inside the wiggler with \( \eta_x \) constant and \( \eta'_x = 0 \)

\[ \Delta I_{5W} \sim \frac{4}{3\pi (B\rho)^3} L \langle \gamma_x \rangle \eta_x^2, \quad \Delta I_{2W} = 0, \quad \Delta I_{4W} \sim 0 \]

\[ \frac{\Delta \varepsilon}{\varepsilon} \sim \frac{\Delta I_{5W}}{I_5} \]
Compensation by Local Dispersion Bump in Fixed Gap Wiggler

\[ \varepsilon_0 = C_q \frac{\gamma^2 I_5}{J_x I_2} \]

\[ I_2 = \int \frac{ds}{\rho^2} \]

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Using the ALS wiggler and \( \langle \gamma_x \rangle = 1/2.5 \text{ m}^{-1} \) (ALS-U 18.127) and \( \eta_x = 1 \text{ cm} \) \( \Rightarrow \Delta \varepsilon / \varepsilon \sim 5\% \)
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Pros:
- Potentially compatible with user operation of the wiggler at fixed gap
  (if wiggler users can accept horizontal beam size variations)

Cons:
- Requires extra knobs to perform the local dispersion bump.
- Bump size significant. Possible effects on beam dynamics should be evaluated.
Compensation by Small Beam Momentum Variations
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The beam momentum can be modified by varying the RF frequency

\[ \delta p = \frac{dp}{p_0} = -\frac{1}{\alpha_c} \frac{df_{RF}}{f_{RF}} \]
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And due to the dependence of the emittance terms on energy, we can change the emittance:

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The scheme it is not practical because it moves source points in dipoles, change the energy of the radiated photons, and can challenge the ring dynamic aperture.
Using Intra-beam Scattering (IBS) to Compensate Emittance
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\[
\frac{1}{T_x} \approx 2\pi^{3/2} A \sqrt{\frac{\mathcal{H}_x \sigma_H^2}{\varepsilon_x}} \left( \frac{1}{a} g \left( \frac{b}{a} \right) + \frac{1}{b} g \left( \frac{a}{b} \right) \right) - a g \left( \frac{b}{a} \right) \quad \text{(log)}
\]

\[
A = \frac{r_e^2 c N_0}{64\pi^2\gamma^4 \varepsilon_x \varepsilon_y \sigma_z \sigma_\delta}
\]

Bjorken-Mtingwa

\[
\varepsilon'_{x_0} = \frac{1}{1 - \frac{T_x}{\tau_x}} \varepsilon_{x_0}
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The last expression shows that bunch length can be used for generating emittance variations and hence to compensate for ID induced emittance variations.
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Harmonic cavities, when present, can be used for that purpose.
Using Intra-beam Scattering (IBS) to Compensate Emittance

IDs losses simulated with ELEGANT by adding 12 wigglers to the ALS-U v18.127 lattice:

\[ \lambda_W = 7.63 \text{cm}, \ L_W = 4.196 \text{ m}, \ N_p = 55, \ \text{variable} \ \mathbf{K}_W \]
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- ALS-U v18.127 with 17.8 keV wigglers
- 1.15 nC - 2 GeV
- 109.02 pm nat. emi.
- 81.32 pm operation emittance
- 14.56 mm operation bunch length

Fit: $Y = Y_0 + A X^{\text{pow}}$

$Y_0 = 0.77627 \pm 0.00336$

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ALS-U v18.127
1.15 nC - 2 GeV - 109.02 pm nat. emi.
81.32 pm operation emittance at full coupling

ID induced losses:
- 8.8 keV
- 17.8 keV
- 35.6 keV
- 51.7 keV
- 71.2 keV

Bunch shortening compensation factor

Fit: \( Y = Y_0 + A e^{(-b X)} \)
\[
Y_0 = 0.25924 \pm 0.0147
A = 0.73631 \pm 0.0139
b = 0.03302 \pm 0.00166 \text{ keV}^{-1}
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**Example**: Wigglers tuned for ~18 keV losses. Emittance decreases to ~95% of the no ID value if the bunch length is not changed. To reestablish the emittance to the original value the bunch must be shortened to ~66% of the no ID value (using the harmonic cavities). Lifetime will be also reduced by the same factor!
Final Considerations

• In presently proposed/built low emittance MBA lattices, insertion device and bend magnet radiation losses are now comparable.
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  - Small electron beam momentum variations could be used but they move dipole source points, shift photon energy and potentially challenges the ring dynamic aperture.
  - Control by IBS requires significant bunch length shortening using harmonic cavities, affecting lifetime and stressing cavity tuning control.