Low Emittance Storage Ring for Light Source

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PHY 554 Fall 2016
Content

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• Radiative effect and emittance
• Theory
  • Theoretical Minimum Emittance (TME) cell
  • Double-bend achromat (DBA)
• Multi-bend achromat (MBA)
  • MAX IV (7BA)
• Upgrading of Synchrotron Storage Rings
Brightness and emittance

• All beamline experiments require high brightness of the light

\[ B_{\Delta \omega/\omega} = \frac{\Delta P}{\Delta A \Delta \Omega \Delta \omega/\omega}, \]

which depends on emittance

• Example: Undulator

\[ \sigma = \sqrt{\varepsilon \beta} \quad \text{and} \quad \sigma' = \sqrt{\varepsilon / \beta} \]
Radiative Effects

- Balance between Beam damping and Quantum fluctuation
- Emittance can be determined by

\[
\varepsilon_x = C_q \gamma^2 \frac{I_5}{I_2 - I_4} = C_q \gamma^2 \frac{\langle H(s)/\rho^3 \rangle}{J_x \langle 1/\rho^2 \rangle},
\]

where

\[
H(s) = \gamma D^2 + 2\alpha DD' + \beta D'^2,
\]

which can be adjusted by vary magnetic strength

Damping term \(\alpha_x = \frac{U_0}{2T_0E} (1 - \bar{D}) = \frac{U_0}{2T_0E} J_x\)
Radiative Effects

• Most Storage rings use identical bending radius
• Strongly focusing machines generally have $J_x \approx 1$
• The emittance becomes

$$\varepsilon_x = C_q \gamma^2 \frac{\langle H(s)/\rho^3 \rangle}{J_x \langle 1/\rho^2 \rangle},$$

where $l$ is length of bending magnets
• Optimize $H(s)$ to reduce the emittance

Klaus Wille, “The Physics of Particle Accelerators: An Introduction”, Oxford University press
Chaseman-Green Lattice DBA

- Designed by Renate Chaseman and George K. Green of BNL in mid-1970s
- Aka “double bend achromat”
- Dispersion, $D = 0, D' = 0$ in straight section for IDs
- Optimize Betatron function

Klaus Wille, “The Physics of Particle Accelerators: An Introduction”, Oxford University press
Evolution of optical parameters in Bending

• Find evolution of $D(s), D'(s), \beta(s), \alpha(s)$ for

$$H(s) = \gamma D^2 + 2\alpha DD' + \beta D'^2$$

• For dispersion

$$\begin{pmatrix} D(s) \\ D'(s) \end{pmatrix} = \begin{pmatrix} \cos(s/\rho) & \rho \sin(s/\rho) & \rho (1 - \cos(s/\rho)) \\ -\sin(s/\rho)/\rho & \cos(s/\rho) & \sin(s/\rho) \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} D_0 \\ D'_0 \\ 1 \end{pmatrix}$$

and $D_0 = 0, D'_0 = 0$ gives

$$D(s) = \rho (1 - \cos(s/\rho)) \approx \frac{s^2}{2\rho}$$

$$D'(s) = \sin(s/\rho) \approx \frac{s}{\rho}$$

Klaus Wille, “The Physics of Particle Accelerators: An Introduction”, Oxford University press
Evolution of optical parameters in Bending

For Betatron function (transformation Matrix for drift space)

\[
\begin{pmatrix}
\beta(s) & -\alpha(s) \\
-\alpha(s) & \gamma(s)
\end{pmatrix}
= \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix}
\begin{pmatrix}
\beta_0 & -\alpha_0 \\
-\alpha_0 & \gamma_0
\end{pmatrix}
\begin{pmatrix} 1 & 0 \\ s & 1 \end{pmatrix}
\]

gives

\[
\begin{align*}
\beta(s) &= \beta_0 - 2\alpha_0 s + \gamma_0 s^2 \\
\alpha(s) &= \alpha_0 + \gamma_0 s \\
\gamma(s) &= \gamma_0
\end{align*}
\]

Klaus Wille, “The Physics of Particle Accelerators: An Introduction”, Oxford University press
Emittance

Hence

\[ H(s) = \frac{1}{\rho^2} \left( \frac{\gamma_0}{4} s^4 - \alpha_0 s^3 + \beta_0 s^2 \right) \]

\[ \varepsilon_x = C_q \frac{\gamma^2}{\rho l} \int_0^l H(s) \, ds \]

Finally,

\[ \varepsilon_x = C_q \gamma^2 \Theta^3 \left( \frac{\gamma_0 l}{20} - \frac{\alpha_0}{4} + \frac{\beta_0}{3l} \right) \]

where \( \Theta = \frac{l}{\rho} \)

Klaus Wille, “The Physics of Particle Accelerators: An Introduction”, Oxford University press
Minimum Emittance

Differentiate respects to initial condition

\[
\frac{\partial \varepsilon_x}{\partial \beta_0} = 0 \text{ and } \frac{\partial \varepsilon_x}{\partial \alpha_0} = 0
\]

give

\[- \frac{1 + \alpha_0^2}{\beta_0^2} \frac{l^2}{20} + \frac{1}{3} = 0 \text{ and } \frac{\alpha_0}{\beta_0} \frac{l}{10} - \frac{1}{4} = 0\]

So

\[
\beta_0 = \sqrt{\frac{12}{5}} l, \quad \alpha_0 = \sqrt{15}
\]

Klaus Wille, “The Physics of Particle Accelerators: An Introduction”, Oxford University press
Minimum Emittance

For Chasman-Green lattice (double bend achromat)

$$\varepsilon_x \,[\text{nm} - \text{rad}] = 94.7 \, \Theta^3 \, E^2 \,[\text{GeV}]$$

Note that if it’s not Achromat lattice
when $D \neq 0$ and $D' \neq 0$

$$\varepsilon_x \,[\text{nm} - \text{rad}] = \frac{31.65}{f_x} \, \Theta^3 \, E^2 \,[\text{GeV}]$$

This is the theoretical minimum emittance (TME)

Multi Bend Achromat (MBA)

- D. Einfeld et al. proposed the use of MBA in 1993.
- From
  \[ \varepsilon_x = C_q \frac{\gamma^2}{J_x} \Theta^3 F, \]
where \( F \) is factor depends on Betatron function
- \( \Theta = \frac{2\pi}{N} \), \( N \) is number of bending
- Hence
  \[ \varepsilon_x \propto \frac{E^2}{N^3} \]
- Increase \( N \) -> reduce \( \Theta \) -> reduce \( \varepsilon_x \)

Thapakron Pulampong, “Ultra-low Emittance Lattice Design for Advanced Synchrotron Light Sources”, thesis submitted at the University of Oxford
MBA

- Stronger focusing
- High Chromaticity (negative)

Require (expensive) strong Sextupole strength -> reduce Dynamics Aperture -> difficult to inject

MBA

• More bending -> reduce space for IDs
• Require combine magnet -> increase $J_x$ which reduce $\varepsilon_x$

\[
\alpha_E = \frac{U_0}{2T_0E} (2 + \bar{D}) = \frac{U_0}{2T_0E} J_E
\]

\[
\alpha_x = \frac{U_0}{2T_0E} (1 - \bar{D}) = \frac{U_0}{2T_0E} J_x
\]

Hence $J_x + J_E = 3$ constant

• Increase $J_x$ will reduce $J_E$ -> increase energy spread
MAX IV

The world’s first MBA storage ring, Lund, Sweden

528 m circumference
MAX IV

Consists of

• 3 GeV LINAC (300 m)
  • 10 Hz for full energy injection
  • XFEL
• 1.5 GeV 96 m circumference
  • Soft x-ray and UV users
• 3 GeV: 528 m circumference
  • Hard x-ray users
Comparison between
• NSLS-II
• MAX IV

<table>
<thead>
<tr>
<th>Parameters</th>
<th>NSLS-II</th>
<th>MAX IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>792</td>
<td>528</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>No. of Straight Section</td>
<td>15 (9.3 m) / 15 (6.6 m)</td>
<td>20</td>
</tr>
<tr>
<td>Horizontal Emittance (nm rad)</td>
<td>0.55</td>
<td>~0.2 - 0.33</td>
</tr>
<tr>
<td>Vertical Emittance (pm)</td>
<td>8</td>
<td>2 - 8</td>
</tr>
</tbody>
</table>
MAX IV: Magnets

• In order to reach low emittance with small circumference
  • Compact magnet
  • Reduce magnets gap -> Strong magnetic field
  • Shorter

• Integrated units
  • BM, QM pole are machined out of a pair of iron blocks
  • Each unit holding all the magnets of a complete cell

Top and bottom parts of multiple function magnet of MAX IV
Credit: Danfysik
Magnets

Separated function magnets (NSLS-II)  Two complete 7-bend achromats at MAX IV
MAX IV: Chamber

• Compact magnet design lead to narrow low-conductance vacuum chambers
  • Distributed pumping and heat load
• Heat load problem
  • Use copper as a chamber
  • Water cooling
• Pumping problem
  • Provide by non-evaporable getter (NEG) coating at the inner surface
  • Reduce number of pumps and absorbers
Advance Photon Source (APS) upgrading

Stuart Henderson, “APS Upgrade Overview and Status”, APS Users Organization/Partner User Council Joint Meeting July 9, 2014
Advance Photon Source (APS) upgrading

• 1104 m circumference
• Upgrade
  • APS-U MBA
  • 67 pm-rad
• 100 fold increase in brightness and coherent flux

<table>
<thead>
<tr>
<th>Radiation-integral-related quantities</th>
<th>DBA</th>
<th>MBA</th>
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</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>7 GeV</td>
<td>6 GeV</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>2527.5 pm</td>
<td>66.9 pm</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.095 %</td>
<td>0.096 %</td>
</tr>
</tbody>
</table>
Survey of low emittance lattices

Summary

• Theoretical Minimum Emittance (TME) consider only on emittance
  • Difficult to reach

• In reality, other parameters need to be considered
  • Non-linear term e.g. dynamics aperture
  • Space for IDs
  • Costs e.g. high-tech magnets

• MBA can reduce emittance because reduce the bending angle

• Many Synchrotrons around the world plan to upgrade to MBA
Reference

• PHY 554 CASE course, Stony Brook University, Fall 2016
• Klaus Wille, “The Physics of Particle Accelerators: An Introduction”, Oxford University press
• Pedro F. Tavares, “The MAX IV storage ring project”, Journal of Synchrotron Radiation ISSN, 1600-5775
• Thapakron Pulampong, “Ultra-low Emittance Lattice Design for Advanced Synchrotron Light Sources”, thesis submitted at the University of Oxford
• Stuart Henderson, “APS Upgrade Overview and Status”, APS Users Organization/Partner User Council Joint Meeting July 9, 2014
Extra Slide: Chromaticity

- Chromaticity leads to tune shifted
  \[ \xi \equiv \frac{\Delta Q}{\Delta p/p} = \int k(s)\beta(s)ds \]

- Sextupole magnets
  - Compensate the Chromaticity
  \[ k_{\text{Sext}} = m D \frac{\Delta p}{p} \]
  Where \( m \) is sextupole strength
Extra Slide: NEG coating

• **Non evaporable getters** (NEG), based on the principle of metallic surface sorption of gas molecules, are mostly porous alloys or powder mixtures of Al, Zr, Ti, V and Fe. They help to establish and maintain vacuums by soaking up or bonding to gas molecules that remain within a partial vacuum.

• They are important tools for improving the performance of many vacuum systems.

• the NEG coating can be applied even to spaces that are narrow and hard to pump out, which makes it very popular in particle accelerators where this is an issue.

• The NEG acts as a getter or getter pump that is able to reduce the pressure to less than $10^{-7}$ Pa.