Outline: “Engineering-Science”

Predictable Results:
  • First Principles: Global Optimization.
  • Systematic Approaches.
  • Robust Design and Control.

Application to: Chasman-Green Lattices and Damping Wigglers.

Conclusions.
1. Horizontal emittance (natural): damping ↔ diffusion (fundamental limit is IBS).

2. Optimize (for Insertion Devices, (EPAC 2008):

\[ \varepsilon_x \sim \frac{1}{R^2 \cdot P}, \]

\( R \) bend radius

Optics guidelines:
- max chromaticity per cell,
- min peak dispersion,
- max values for the beta functions.
Systematic Approaches

“Closed-Loop” Control:
- lattice design,
- control of DA,
- guidelines for engineering tolerances, ring magnets, and insertion devices,
- correction algorithms,
- aka TQM in industry.

“Use Case” approach:
- model based control.
Challenge: re-use the design model for model based (on-line) control.
Chasman-Green Lattices and Damping Wigglers


Already 1985 Teng noted that (p. 18):

“This theoretical minimum should be at least a factor 2 smaller than the desired emittance because when one gets to the later steps, it is unlikely that one can attain and then maintain optimum values for all the parameters.”

i.e., a system approach.
Ring-Based Syncr. Light Sources: Basics

The dynamic equilibrium for the horizontal emittance and momentum spread are

\[ \varepsilon_x = \tau_x \langle \mathcal{H}_x \cdot D_\delta \rangle, \quad \sigma_\delta^2 = \tau_E \langle D_\delta \rangle, \quad \tau_E = \frac{2T_0 E_0}{J_E U_{\text{tot}}}, \quad \tau_x = \frac{2}{J_x} \tau_E. \]

where (linear dispersion action)

\[ \mathcal{H}_x \equiv \tilde{\eta}^T \tilde{\eta}, \quad \tilde{\eta} \equiv \begin{bmatrix} \eta_x \\ \eta'_x \end{bmatrix}, \quad \tilde{\eta} \equiv A^{-1} \tilde{\eta}, \quad A^{-1} = \begin{bmatrix} 1/\sqrt{\beta_x} & 0 \\ \alpha_x/\sqrt{\beta_x} & \sqrt{\beta_x} \end{bmatrix} \]

The partition numbers are governed by ("sum rule", Robinson, 1958)

\[ J_x + J_y + J_E = 4 \]

No dipole gradients \( \Rightarrow J_x \approx 1, J_E \approx 2. \)
The dynamic quantities can be expressed in terms of the global linear optics properties for the lattice (Sands, 1970)

\[ \varepsilon_x = \tau_x \langle \mathcal{H}_x \cdot D_\delta \rangle = \frac{C_q \gamma^2 \langle \mathcal{H}_x / |\rho|^3 \rangle_0}{J_x \langle 1 / \rho^2 \rangle_0}, \quad \sigma^2_\delta = \frac{C_q \gamma^2 \langle 1 / |\rho|^3 \rangle_0}{J_E \langle 1 / \rho^2 \rangle_0}, \quad C_q = \frac{55}{32 \sqrt{3}} \frac{m_e c_0}{\hbar} \]

i.e., convenient for linear optics design.

For an isomagnetic lattice

\[ \varepsilon_x [\text{nm} \cdot \text{rad}] = 7.84 \times 10^3 \cdot \frac{(E [\text{GeV}])^2 F}{J_x N_d^3} \]

where \( N_d \) is the number of dipoles and \( F \geq 1 \).

The equilibrium can be shifted by introducing Damping Wigglers (DWs)

\[
\frac{\varepsilon_{xw}}{\varepsilon_{x0}} = \frac{1 + \langle \mathcal{H}_x / |\rho|^3 \rangle_w / \langle \mathcal{H}_x / |\rho|^3 \rangle_0}{1 + \langle 1 / \rho^2 \rangle_w / \langle 1 / \rho^2 \rangle_0} \approx \frac{U_0}{U_0 + U_w}, \quad \frac{\sigma_{\delta w}}{\sigma_{\delta 0}} = \sqrt{\frac{1 + \frac{8}{3\pi} \frac{B_w U_w}{B_0 U_0}}{1 + \frac{U_w}{U_0}}}. \]
For a fixed number of dipoles, it follows that

\[
\varepsilon_x \sim \frac{\langle |y^3|/|p|^3 \rangle}{\langle 1/\rho^2 \rangle} \frac{U_0}{U_0 + U_w} \sim \frac{1}{\rho^2 U_{\text{tot}}}
\]

where \( P \) is the total radiated power.

Hence, apart from IBS (Intra Beam Scattering), there is no “show stopper” for a diffraction limited ring-based synchrotron light source.

Clearly, PETRA III, NSLS-II, and MAX-IV (R&D by MAX-III) have “paved the way”; i.e., how to avoid the “chromaticity wall”. An artifact originating from the TME (“Theoretical” Minimum Emittance) cell; reductionism vs. “engineering-science”.

The circumference for a few existing facilities are:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Circ. [km]</th>
<th>E [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESRF</td>
<td>0.84</td>
<td>6</td>
</tr>
<tr>
<td>APS</td>
<td>1.1</td>
<td>7</td>
</tr>
<tr>
<td>SPRING-8</td>
<td>1.4</td>
<td>8</td>
</tr>
<tr>
<td>PEP X</td>
<td>2.2</td>
<td>4.5</td>
</tr>
<tr>
<td>PETRA III</td>
<td>2.3</td>
<td>6</td>
</tr>
</tbody>
</table>
Emittance of Electron Storage Rings

- Quantum excitation causes emittance growth in any bending system
  \[
  \left( \frac{d}{dt} \langle \epsilon \rangle \right)_q \approx \frac{\langle N_{ph} \langle u_{\gamma}^2 \rangle \mathcal{H}(s) \rangle_s}{2E_0^2} \approx E_0^5 \]
  \[
  \mathcal{H} = \beta_x \eta_x^2 + 2\alpha_x \eta_x \eta_x^\prime + \frac{1+\alpha_x^2}{\beta_x} \eta_x^2
  \]

- Fortunately, in electron rings there is also damping
  \[
  \left( \frac{d}{dt} \langle \epsilon \rangle \right)_d \approx -\frac{\langle P_{\gamma} \rangle}{E_0} \epsilon \approx E_0^3
  \]

- Giving the equilibrium emittance
  \[
  \epsilon \approx E_0^2 \frac{\langle \mathcal{H} / \rho^3 \rangle}{\langle 1 / \rho^2 \rangle}
  \]

- A common mistake
  \[
  \epsilon \propto \frac{E_0^2}{R} \quad \text{Wrong!}
  \]

1H. Wiedemann, Particle Accelerator Physics.
A Perspective (ESRF, LEL 2015)

**LOW EMITTANCE RINGS TREND**

- **Based on 1980 KnowHow**
- **Based on state of the art technologies**

Existing machines
In Construction
Advanced Projects
Concept stage

Several facilities will implement Low Horizontal Emittance Lattices by the next decade
3.6.5 The Chromatic Control Problem: A Measure for Stiffness

It is known that (fixed $\rho_b$) [36]

$$
\varepsilon_x [\text{nm-rad}] = 1470 \cdot \frac{(E [\text{GeV}])^2 \langle H_x \rangle^{\text{min}}}{\rho_b J_x} = 1470 \cdot \frac{(E [\text{GeV}])^2 (2\pi)^3 F}{12 \sqrt{15} J_x N_b^3}
$$

(2)

where $N_b$ is the total number of dipoles and [37]

$$
F_{CB} = 1, \quad F_{EB} = 3, \quad F_{N-BA} = \left( \frac{N}{2 + (N - 2) \cdot 3^{1/3}} \right)^3 F_{EB}
$$

(3)

for a “center bend”, “end bend”, and $N$-BA, respectively.

As a measure for the stiffness of the chromatic control problem, we introduce

$$
S \equiv \frac{\left| \varepsilon_x \right|}{V_x \sqrt{\langle H_x \rangle}} \sim \frac{1}{\text{DA}}
$$

(4)

Note that the DA has a minimum for the $\langle H_x \rangle^{\text{min}}$-cell. A survey of $F_{\text{rel}}$ ($= 1$ for $\langle H_x \rangle^{\text{min}}$) vs. $S$ is summarized in Tab. 1. For the operating facilities we find: $S = 49 \pm 23$. 

12 of 46
Table 1: Survey of $F_{\text{rel}}$ vs. Stiffness $S$ for some Storage-Ring Light Sources.

<table>
<thead>
<tr>
<th>Lattice</th>
<th>Type</th>
<th>$E$ [GeV]</th>
<th>$\xi_x$ [nm·rad]</th>
<th>$\xi_x^{*}$ [nm·rad]</th>
<th>$J_1$</th>
<th>$&lt;\sqrt{g}&gt;$ [×10^{-3}]</th>
<th>$F_{\text{rel}}$</th>
<th>$\xi_x/v_x$</th>
<th>$S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPring-8</td>
<td>DB-4</td>
<td>11</td>
<td>8</td>
<td>3.4</td>
<td>3.7</td>
<td>1.0</td>
<td>1.42</td>
<td>4.6</td>
<td>2.2</td>
</tr>
<tr>
<td>ESRF</td>
<td>DB-32</td>
<td>6</td>
<td>6.3</td>
<td>3.8</td>
<td>3.1</td>
<td>1.0</td>
<td>1.68</td>
<td>3.5</td>
<td>3.6</td>
</tr>
<tr>
<td>APS</td>
<td>DB-40</td>
<td>7</td>
<td>2.5</td>
<td>2.5</td>
<td>3.1</td>
<td>1.0</td>
<td>1.35</td>
<td>3.3</td>
<td>2.5</td>
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<tr>
<td>PETRA III</td>
<td>Mod. FODO</td>
<td>6</td>
<td>6</td>
<td>1</td>
<td>1.0</td>
<td>3.62</td>
<td>39.8</td>
<td>1.2</td>
<td>20</td>
</tr>
<tr>
<td>SPEAR3</td>
<td>DB-18</td>
<td>3</td>
<td>11.2</td>
<td>6.4</td>
<td>6.4</td>
<td>1.0</td>
<td>4.99</td>
<td>10.4</td>
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<td>ALS</td>
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<td>6.3</td>
<td>6.4</td>
<td>6.4</td>
<td>1.0</td>
<td>4.83</td>
<td>2.9</td>
<td>2.8</td>
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<td>BESSY II</td>
<td>TBA-10</td>
<td>1.9</td>
<td>6.1</td>
<td>6.1</td>
<td>6.1</td>
<td>1.0</td>
<td>4.38</td>
<td>2.6</td>
<td>2.6</td>
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<tr>
<td>SLS</td>
<td>TBA-12</td>
<td>2.4</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>1.0</td>
<td>3.38</td>
<td>2.6</td>
<td>2.6</td>
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<td>DIAMOND</td>
<td>DB-24</td>
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<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>1.0</td>
<td>1.46</td>
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<td>ASP</td>
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<td>7</td>
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<td>4.3</td>
<td>4.3</td>
<td>1.3</td>
<td>2.96</td>
<td>2.6</td>
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<td>SOLEIL</td>
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<td>3.7</td>
<td>3.7</td>
<td>1.0</td>
<td>1.79</td>
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<td>2.8</td>
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<tr>
<td>CLS</td>
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<td>2.9</td>
<td>18.3</td>
<td>18.3</td>
<td>18.3</td>
<td>1.6</td>
<td>16.79</td>
<td>2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>ELETTRA</td>
<td>DBA-12</td>
<td>2</td>
<td>7.4</td>
<td>7.4</td>
<td>7.4</td>
<td>1.3</td>
<td>9.12</td>
<td>1.4</td>
<td>3.0</td>
</tr>
<tr>
<td>TPS</td>
<td>DB-24</td>
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<td>1.7</td>
<td>1.7</td>
<td>1.7</td>
<td>1.0</td>
<td>1.08</td>
<td>2.7</td>
<td>2.9</td>
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<tr>
<td>NSLS-II</td>
<td>DBA-30</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1.0</td>
<td>3.78</td>
<td>2.0</td>
<td>3.1</td>
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<tr>
<td>MAX-IV</td>
<td>7BA-20</td>
<td>3</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>1.9</td>
<td>0.40</td>
<td>18.1</td>
<td>1.2</td>
</tr>
<tr>
<td>PEP-X (TME)</td>
<td>4×8TME-6</td>
<td>4.5</td>
<td>0.095</td>
<td>0.095</td>
<td>0.095</td>
<td>1.0</td>
<td>0.34</td>
<td>3.3</td>
<td>1.7</td>
</tr>
<tr>
<td>PEP-X (USR)</td>
<td>8×7BA-6</td>
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<td>0.029</td>
<td>0.029</td>
<td>1.0</td>
<td>0.10</td>
<td>5.3</td>
<td>1.4</td>
</tr>
<tr>
<td>TeVUSR</td>
<td>30×7BA-6</td>
<td>11</td>
<td>0.031</td>
<td>0.031</td>
<td>0.031</td>
<td>2.4</td>
<td>0.02</td>
<td>12.0</td>
<td>1.4</td>
</tr>
<tr>
<td>TeVUSR</td>
<td>30×7BA-6</td>
<td>9</td>
<td>0.029</td>
<td>0.029</td>
<td>0.029</td>
<td>2.7</td>
<td>0.02</td>
<td>18.4</td>
<td>1.4</td>
</tr>
</tbody>
</table>
The NSLS-II “Wind Tunnel” (BNL, 2006)

=> self-consistent: numerical simulations/analysis and analytic techniques applied to the same (realistic) model.
The NSLS-II “Wind Tunnel” (cont.)

Implementation (~50,000 lines of C++, C, and FORTRAN code; two different codes, Tracy-2 in C and Thor in C++, at the time).

- **Lattice File** (bare lattice)
- **Tracy-2 Library**
- **“Real” Lattice** (Flat File)
- **Thor (PTC)**

**C Program:**
- lattice errors
- global orbit correction
- control of IDs
- control of V. Emittance

**Lattice Functions**
- Emittance ("real" lattice)
- Tracking Data
- FFT Results
- Dynamic Aperture
- Frequency Maps

**Taylor Maps**
- Lie Generators
- Map Normal Form
- Tune Scans
- Chromatic Correction
Lessons Learnt, ALS: Control of Orbit

- Only 2 sextupole families.
- Orbit control not robust; not “tied down” in the sextupoles (BPM placement based on linear optics).
- For validation of the nonlinear model (Tracy-2), see J. Bengtsson et al (PAC 1994).
Closing-the-Loop (EPAC 1994)

Fig. 2  Estimated Beta Functions

<table>
<thead>
<tr>
<th>component</th>
<th>order</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracy-2 (no sextupole)</td>
<td>1</td>
<td>-24.89</td>
<td>-26.84</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>33.97</td>
<td>66.68</td>
</tr>
<tr>
<td>improved Tracy (1/(1 + δ))</td>
<td>1</td>
<td>-24.89</td>
<td>-27.88</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>33.97</td>
<td>70.64</td>
</tr>
<tr>
<td>Krakpot prot</td>
<td>1</td>
<td>-24.59</td>
<td>-27.68</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>32.66</td>
<td>74.18</td>
</tr>
<tr>
<td>Krakpot (prot, n.l. drift, quad.fringe)</td>
<td>1</td>
<td>-24.78</td>
<td>-27.66</td>
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<td></td>
<td>2</td>
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<table>
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<th>component</th>
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<th>x</th>
<th>y</th>
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<td>all syst. higher order multipole</td>
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<td>only syst. octupole in Bend.</td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td>-45.03</td>
<td>-57.10</td>
</tr>
</tbody>
</table>
Lessons Learnt, SLS: Seven-BA-6

For a perspective see:

1. A. Streun “Nonlinear Dynamics at the SLS Storage Ring” [LER 2010](#) (4 phase tromb. and 33 sext. fam.).
2. P. Kaltchev et al “Lattice Studies for a High Brightness Light Source” [PAC 1995](#).
Lessons Learnt, SLS: Seven-BA-6 -> TBA-12

G. Mülhaupt et al (NIM 404, 1998)

A. Streun et al (PAC01)

This level of agreement between model & measurements is expected; for single particle dynamics. A matter of a first principles approach.

Resonance guesses

example: set

\[ h_{10020} = 6 \cdot 10^{-9} \cdot e^{2\pi/3} \ m^2 \]

with auxiliary sextupoles and pinger magnets

\[ aQ_x + bQ_y = n \]

<table>
<thead>
<tr>
<th>peak [mm]</th>
<th>Tune</th>
<th>Guess</th>
<th>min.dist.</th>
<th>[ a ]</th>
<th>[ b ]</th>
<th>[ n ]</th>
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<td></td>
<td>0.02222</td>
<td>20.25797</td>
<td>20.25803</td>
<td>[3]</td>
<td>[0]</td>
<td>61</td>
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<tr>
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<td>[3]</td>
<td>[0]</td>
<td>61</td>
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<td>[1]</td>
<td>[2]</td>
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<td>[1]</td>
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<td>0.03584</td>
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<td></td>
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<td>8.83160</td>
<td>[1]</td>
<td>[2]</td>
<td>38</td>
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</tbody>
</table>

1000 turn FFT sine window peak interpolation

A. Streun, PSI

NLBD-II, DIAMOND, Nov 2-4, 2009
Closing-the-Loop (2009)

A. Streun et al 2009

5. Best results up to now

Normalized life time as function of RF voltage

- Normalized to bunch current and vertical beam size
- Without 3rd harmonic cavity

Theoretical comparison:
- Theory for ideal lattice (6D TRACY-simulation)
- Skew quads and aux. sextupoles
- ON and OFF

Normalized life time vs. RF voltage

- Normal operation
Observation, SOLEIL: Alpha Buckets

D. Robin, E. Forest, C. Pellegrini, A. Amiry

\[ \alpha_c^{(1)} \sim \frac{1}{v_x^2} \]

SOLEIL PAC 1999; validation by 6D phase-space tracking.

\[ H(\phi, \delta; s) = \frac{\eta^{(1)}h\omega_0}{2c_0}\delta^2 + \frac{\eta^{(2)}h\omega_0}{3c_0}\delta^2 + \frac{\omega_0 eV_{rf}}{2\pi c_0 E_0}(\cos(\phi + \phi_s) + \phi \sin(\phi_s)) \]

\[ \phi' = \partial_\delta H = \frac{h\omega_0\eta^{(1)}}{c_0}\delta + \frac{h\omega_0\eta^{(2)}}{c_0}\delta^2, \quad \delta' = -\partial_\phi H = \frac{\omega_0 eV_{rf}}{2\pi c_0 E_0}(\sin(\phi + \phi_s) - \sin(\phi_s)) \]
NSLS-II: Initial Concept (EPAC 2003)

Linear scaling of SLS:

TBA-12, $C = 288$, $= 5.5 \text{ nm} \cdot \text{rad} @ 2.4 \text{ GeV}$

to “2×SLS”:

TBA-24, $C = 523 \text{ m} @ 3.0 \text{ GeV}$

gives

$$\varepsilon_x = \left(\frac{3.0}{2.4}\right)^2 \cdot \frac{1}{2^3} \cdot 5.5 = 1.1 \text{ nm} \cdot \text{rad} @ 3.0 \text{ GeV}$$

However, dynamic aperture does not scale: $\tilde{\eta}_x \sim \phi_b$ (J. Bengtsson EPAC 2006).


S. Krinsky, J. Bengtsson, S. Kramer “Consideration of a Double Bend Achromatic Lattice for NSLS-II” EPAC 2006.

**NSLS-II: Lattice Evolution**

**TBA-24 EPAC 2004**

![Graph 1]

**TBA-24 EPAC 2006**

![Graph 2]

**DBA-30+4 DWs EPAC 2006**

![Graph 3]

J. Bengtsson EPAC06

\[
\begin{align*}
\frac{\xi}{\text{Cell}} &= [3.8, \, 1.2], \, C = 630 \, \text{m} \\
\frac{\xi}{\text{Cell}} &= [2.1, \, 1.1], \, C = 758 \, \text{m} \\
\frac{\xi}{\text{Cell}} &= [3.3, \, 1.4], \, C = 780 \, \text{m}
\end{align*}
\]
NSLS-II: Parametric Evaluation (CDR, 2006)

Table 4.2.3 Storage Ring Parameters for Number of DBA Lattice Cells Varying from 32 to 24.

<table>
<thead>
<tr>
<th>Lattice</th>
<th>DBA32</th>
<th>DBA30</th>
<th>DBA28</th>
<th>DBA26</th>
<th>DBA24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>822</td>
<td>780</td>
<td>739</td>
<td>697</td>
<td>656</td>
</tr>
<tr>
<td>Bend magnet radius [m]</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Straight sections [n x (m)]</td>
<td>16x(8, 5)</td>
<td>15x(8, 5)</td>
<td>14x(8, 5)</td>
<td>13x(8, 5)</td>
<td>12x(8, 5)</td>
</tr>
<tr>
<td>Horizontal emittance, $\varepsilon_x$ (bare) [nm-rad]</td>
<td>1.7</td>
<td>2.1</td>
<td>2.6</td>
<td>3.2</td>
<td>4.1</td>
</tr>
<tr>
<td>Horizontal emittance, $\varepsilon_x$ (full set of damping wigglers) [nm-rad]</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Straight Section Utilization

<table>
<thead>
<tr>
<th>8 m straights</th>
<th>RF and injection</th>
<th>Damping wigglers</th>
<th>Undulators</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>5 m straights</td>
<td>Undulators</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>15</td>
<td>14</td>
</tr>
</tbody>
</table>

- $\varepsilon^\text{IBS}_x = 0.2 - 0.25 \text{ nm-rad}$.  
- $C: \sim$1 M per m.
NSLS-II: Parametric Evaluation (CDR, 2006, cont.)

**Figure 6.1.2** The fractional reduction of the ring emittance and the increase in energy spread for dipole magnets of bend radii $p_0 = 25$ m (proposed for NSLS-II) and $p_0 = 16.7$ m dipole that could yield a shorter circumference lattice.

**Figure 6.1.3** Emittance reduction for NSLS-II as 0, 1, 2, 3, 5, and 8 DW (7 m each) are installed and operated at 1.8 T peak field.

**Table 6.1.3** Effect of Three and Eight 7 m Damping Wigglers on Beam Properties at 3 GeV.

<table>
<thead>
<tr>
<th></th>
<th>Zero DWs</th>
<th>Three 7 m DWs (21 m)</th>
<th>Eight 7 m DWs (56 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy loss [keV]</td>
<td>287</td>
<td>674</td>
<td>1320</td>
</tr>
<tr>
<td>RF voltage (3% bucket) [MV]</td>
<td>2.5</td>
<td>3.1</td>
<td>3.9</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.0079</td>
<td>0.00876</td>
<td>0.0096</td>
</tr>
<tr>
<td>Natural emittance: $\delta_x$, $\delta_y$ [nm-rad]</td>
<td>2.1, 0.01</td>
<td>0.91, 0.008</td>
<td>0.50, 0.005</td>
</tr>
<tr>
<td>Damping time: $\tau_x$, $\tau_y$ [ms]</td>
<td>54, 27</td>
<td>23, 11.5</td>
<td>12, 6</td>
</tr>
<tr>
<td>Energy spread [%]</td>
<td>0.05</td>
<td>0.089</td>
<td>0.099</td>
</tr>
<tr>
<td>Bunch duration [ps]</td>
<td>10</td>
<td>15.4</td>
<td>15.5</td>
</tr>
</tbody>
</table>
Connect EPICS to a virtual accelerator simulated with Tracy-3 by Virtual IOCs; aka J.M.S. (James’ Model Server).
Closing-the-Loop (M. Böge, SLS, PAC 2001)

- Re-use accelerator design model (Tracy-2) as on-line model: by machine translating (with p2c) ~10,000 lines of Pascal code to C.

- Feasible because the code is organized as a library and the internal beam dynamics model is: architectured, layered, and recursive.
Client-Server Architecture for HLA

- In collaboration with B. Dalesio.

Improved by G. Shen et al (PAC 2011): Name Srv, Twiss Srv, etc.
### NSLS-II: Storage Ring Commissioning (APS, 2015)

#### SR COMMISSIONING

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-Mar-14</td>
<td>1st turn around SR is complete.</td>
</tr>
<tr>
<td>31-Mar-14</td>
<td>3 turns complete</td>
</tr>
<tr>
<td>3-Apr-14</td>
<td>Wrong kicker polarity is found and fixed. Circulating beam</td>
</tr>
<tr>
<td>5-Apr-14</td>
<td>Beam up to 200 turns. Turned on the sextupoles, retuned the BTS/orbit almost 300 turns, RF is ON. Stored beam 10k+ turns</td>
</tr>
<tr>
<td>8-Apr-14</td>
<td>Storing up to about 0.25mA (70% injection efficiency)</td>
</tr>
<tr>
<td>16-Apr-14</td>
<td>0.5mA one-shot injection with on-axis injection; accumulated &gt; 2.6mA</td>
</tr>
<tr>
<td>23-Apr-14</td>
<td>Local vertical bump in BPMs 62/63 shown an obstacle in vacuum chamber</td>
</tr>
<tr>
<td>25-Apr-14</td>
<td>After opening up the 3rd bellows, an RF contact spring was found in cell 10</td>
</tr>
<tr>
<td>29-Apr-14</td>
<td>25 mA</td>
</tr>
<tr>
<td>11-May-14</td>
<td>Phase I commissioning complete</td>
</tr>
<tr>
<td>11-Jul-14</td>
<td>SC RF is commissioned; 50 mA is accumulated</td>
</tr>
<tr>
<td>23-Oct-14</td>
<td>First project beamline’s first light</td>
</tr>
<tr>
<td>08-Dec-14</td>
<td>Insertion Device and Front End commissioning complete</td>
</tr>
<tr>
<td>01-Apr-15</td>
<td>Beam emittance is 1 nm rad and 7 pm rad</td>
</tr>
</tbody>
</table>
NSLS-II: Predictable Results (APS, 2015)

**NSLS-II Design Parameters: High current**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Design</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy [GeV]</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Beam Current [mA]</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>Horizontal Emittance [nm-rad]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Vertical Emittance [pm-rad]</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>Beam transverse Stability [beam size]</td>
<td>10%</td>
<td>&lt;10%</td>
</tr>
</tbody>
</table>

- 100 mA with all IDs closed
- Injection efficiency was > 90%.
- Beam lifetime is ~4 hrs.
NSLS-II: Predictable Results (APS, 2015)

**NSLS-II Design Parameters: Beam Emittance**

- **Design Emittance Achieved**
  \[ \varepsilon_x^{0\text{dw}} = 2.05 \text{ nm\cdot rad}, \quad \varepsilon_x^{3\text{dw}} = 1 \text{ nm\cdot rad}, \]
  \[ \varepsilon_y = 7 \text{ pm\cdot rad}, \text{ reach the diffraction value of 8 pm\cdot rad, which also was verified by HXN x-ray beam image size (change by 33%)} \]
“Outside the Box”: MAX User Mtg 2008 (M. Eriksson)

Question: What is fundamentally different from previous designs?

1. Small magnets => strong lenses => short magnets
   But: How to do it? Never done before.
   Ask Lars Johan Lindgren and Bengt Anderberg!

2. But you need new types of lattices?
   Ask Simon Leeman, Johan Bengtsson (Brookhaven) and Andreas Streun (PSI) to develop codes and number-crunch!

3. The vacuum chamber bore is to small for pumping?
   Ask Erik Wallén, Magnus Berglund, Anders Hansson and Roberto Kersevan (ESRF) to develop and characterize a linear pumping system (NEG-coated)!

4. Ultra-small emittance=>no beam life-time!
   Ask Lars Malmgren, Per Lilja, Robert Nilsson, Ake Andersson to make 100 MHz RF system with huge energy acceptance!
Ignore TME, instead, focus on $1/N^3$. Provide space (by innovative magnet design). Introduce octupoles to improve (=> direct) control of the second order sextupolar driving terms (M. Eriksson et al PRST-AB 12, 120701, 2009).

See also V. Litvinenko FLS 1999

MAX-IV Project Status Report, 2010:

“Committee consider MAX-IV an innovative and daring project and concluded that

...DDR (Detailed Design Report) has addressed all the issues relevant to achieving the performance goals... tolerance requirements... are demanding but not beyond what is reachable...”
Colliders: The FODO Cell

The linear optics for a FODO cell

is well known (for \( k_{Qf} = -k_{Qd} \))

\[
\beta_{x_{\text{max}}} = \frac{2 \rho \sin(\phi) (1 + k \rho \sin(\phi))}{\sin(\mu_x)} \rightarrow \frac{2L_b (1 + k L_b)}{\sin(\mu_x)} + O(\phi^3) = \frac{2L_b (1 + \sin(\frac{\mu_x}{2}))}{\sin(\mu_x)} + O(\phi^3),
\]

\[
\eta_{x_{\text{max}}} = \frac{2 \rho \sin^2\left(\frac{\phi}{2}\right) (2 + k \rho (2 \sin(\phi)))}{\sin^2\left(\frac{\mu_x}{2}\right)} \rightarrow \frac{\rho \phi^2 \left(1 + \frac{1}{2} k L_b\right)}{\sin^2\left(\frac{\mu_x}{2}\right)} + O(\phi^4) = \frac{L_b^2 \left(1 + \frac{1}{2} \sin\left(\frac{\mu_x}{2}\right)\right)}{\rho \sin^2\left(\frac{\mu_x}{2}\right)} + O(\phi^4)
\]

where we have used \( \sin\left(\frac{\mu_x}{2}\right) = \pm \frac{k L_b}{2} \).
If it was considered being used for e.g. a damping ring, the hor. emittance would be

\[ \varepsilon_x = C_q \gamma^2 \frac{\langle H/|\rho|^3 \rangle}{J_x \langle 1/\rho^2 \rangle}, \]

where \( H \) is the linear dispersion action

\[ H = \| \tilde{\eta} \| = \tilde{\eta}^T \tilde{\eta}, \quad \tilde{\eta} = A^{-1} \tilde{\eta}, \quad A^{-1} = \begin{bmatrix} 1/\sqrt{\beta_x} & 0 \\ \alpha_x/\beta_x & \beta_x \end{bmatrix}, \]

which to leading order is

\[ \langle H(s) \rangle = \frac{\rho \phi_b^3}{\sin^3(\mu_x/2)} \left[ 1 - \frac{(kL_b)^2}{16} \right] + O(\phi_b^4) \]

and has a min for

\[ \Delta \mu_x = 180^\circ, \quad kL_b = 2, \quad \langle H(s) \rangle = \rho \phi_b^3. \]
However, this is a leading order result. An exercise in algebra leads to the rather neat result (Helm, Wiedemann SLAC PEP Note 303, 1973)

\[
\langle \mathcal{H}(s) \rangle = \frac{\rho \phi^3}{\sin^3 \left( \frac{\mu_x}{2} \right) \cos \left( \frac{\mu_x}{2} \right)} \left( 1 - \frac{3}{4} \sin^2 \left( \frac{\mu_x}{2} \right) + \frac{1}{60} \sin^4 \left( \frac{\mu_x}{2} \right) \right) + O(\phi^5)
\]

which has a min for

\[
\mu_x = 2 \tan \left( \frac{1}{2} \sqrt{\frac{75 + 3 \sqrt{1905}}{8}} \right) \approx 0.38 \cdot 2\pi, \quad \langle \mathcal{H}(s) \rangle_{\text{min}} = \frac{1}{60} \sqrt{\frac{16075 + 381 \sqrt{1905}}{6}} \approx 1.23 \cdot \rho \phi_b^3.
\]

However, a formula is (to our knowledge) not provided for the linear chromaticity. One can show that

\[
\xi_x = -\frac{1}{\pi} \tan \left( \frac{\mu_x}{2} \right)
\]

and it follows that

\[
\begin{align*}
\xi_x = \begin{cases} 
-1/\pi, & \mu_x = 90^\circ \\
-0.81, & \mu_x = 137^\circ
\end{cases}
\end{align*}
\]
“R&D”: The OFODOFO Cell

The linear dispersion action has a min for

\[ \eta_{xc} = \frac{L_b \phi}{24}, \quad \eta'_{xc} = 0, \]

\[ \alpha_{xc} = 0, \quad \beta_{xc} = \frac{L_b}{2 \sqrt{15} \sqrt{1 - \frac{3}{8} k_d L_b + \frac{3}{80} k_d^2 L_b^2}}, \]

\[ \langle H(s) \rangle_{\text{min}} = \frac{L_b \phi^2}{12 \sqrt{15} \sqrt{1 - \frac{3}{8} k_d L_b + \frac{3}{80} k_d^2 L_b^2}}. \]
One can also show that

\[ \mu_x = 2 \arctan \left( -\frac{3}{\sqrt{15}} \frac{1 - \frac{1}{4} k_d L_b}{\sqrt{1 - \frac{3}{8} k_d L_b + \frac{3}{80} k_d^2 L_b^2}} \right) \]

and

\[ \xi_x = \frac{12}{8 \pi \sqrt{15}} \frac{1 - \frac{1464}{3072} k_d L_b + \frac{254}{3072} k_d^2 L_b^2 - \frac{13}{3072} k_d^3 L_b^3}{1 - \frac{1}{8} k_d L_b + \frac{3}{80} k_d^2 L_b^2} \]

\[ \xi_y = \frac{1}{\left(4 \pi \sqrt{15}\right)} \left( 43008 + 24672 k_d L_b - 25200 k_d^2 L_b^2 + 6330 k_d^3 L_b^3 - 609 k_d^4 L_b^4 + 20 k_d^5 L_b^5 \right) \]

\[ \sqrt{-242810880 - 91594752 k_d L_b + 163349504 k_d^2 L_b^2 - 15035392 k_d^3 L_b^3 - 34034880 k_d^4 L_b^4 - 17085840 k_d^5 L_b^5 - 3894596 k_d^6 L_b^6 + 500032 k_d^7 L_b^7 - 37141 k_d^8 L_b^8 + 1490 k_d^9 L_b^9 - 25 k_d^{10} L_b^{10}} \]
The horizontal linear chromaticity is essentially flat and the vertical has a min for
\[ k_d L_b \approx -1.24088 \]
which gives
\[ k_d \approx \frac{-1.24088}{L_b}, \quad L_1 \approx 0.88121 \cdot L_b, \quad k_f \approx \frac{2.86572}{L_b} \]
with
\[ \beta_{yc} \approx 13.1 \cdot L_b, \quad \nu_x \approx 0.781, \quad \nu_y \approx 0.220, \quad \xi_x \approx -1.195, \quad \xi_y \approx -1.718 \]
and the total cell length is
\[ L = (1 + 2L_1)L_b \approx 2.76242 \cdot L_b. \]

For an example, we may choose
\[ \phi_b = 3^\circ, \quad L_b = 1.0 \text{ m}, \quad \rho_b = \frac{L_b}{\phi_b} \approx 19.1 \text{ m} \]
and scale it by a factor 0.1.
Interestingly, the linear chromaticity is not increased.
“R&D”: The OFODOFO Cell - Scaling Laws (cont.)
We will now return to our initial example:

\[ \phi_b = 3^\circ, \quad L_b = 1.0 \text{ m}, \quad \rho_b = \frac{L_b}{\phi_b} \approx 19.1 \text{ m}, \]

reduce \( \varepsilon_x \) by a factor of \( \varepsilon_r = 13 \) to \( \varepsilon_x = 0.615 \text{ nm\cdotrad @3 GeV} \) for minimum horizonal/vertical linear chromaticity, and compare it with the MAX-IV unit cell, i.e., for the same linear dispersion action \( \mathcal{H} \).

In particular, the MAX-IV unit cell has \( \varepsilon_x = 0.334 \) but \( J_x \approx 2 \) because the \( Q_d \) gradient is integrated into the dipole.
3D Parametric Plot of Hor/Ver Linear Chromaticity

\[ \xi_x(k_{Qd}, \beta_{xc}) \]

\[ \xi_y(k_{Qd}, \beta_{xc}) \]
Reality Check: A Min Emittance Cell for MAX-IV (cont.)

MAX-IV Unit Cell

ME Cell

Horizontal Dispersion
The tune and linear chromaticity are

\[ \nu_x \approx 0.244, \quad \nu_y \approx 0.089, \quad \xi_x \approx -0.232, \quad \xi_y \approx -0.232 \]

whereas the MAX-IV unit cell has

\[ \nu_x \approx 0.265, \quad \nu_y \approx 0.082, \quad \xi_x \approx -0.270, \quad \xi_y \approx -0.241. \]

To summarize, the MAX-IV unit cell it is well (numerically) optimized for the given parameters.

It can be scaled according to the scaling properties summarized on slide 32, without affecting the linear chromaticity; but the peak beta functions and horizontal linear dispersion will change.
Conclusions

- Hamiltonian dynamics, perturbed by classical radiation and quantum fluctuations, and related numerical and analytical methods provide the foundation for self-consistent, realistic modeling of modern ring-based synchrotron light source.

- In other words: predictable results.

- Applications include: conceptual design, engineering design, simulation of the accelerator for testing and validation of controls algorithms (aka “high level applications”), and model based control for commissioning.

Thank You.