Progress Towards Diffraction Limited Storage Ring Light Sources

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March 2013
Outline

- Optimization of brightness and emittance
- Challenges of low emittance
  - Nonlinear dynamics
  - Collective effects
- Early ideas for diffraction-limited or “ultimate” light sources
- Trends in light source design
- Progress in next-generation designs
- Conclusion
X-ray Brightness

- The quality of a beam is expressed by the brightness

$$B \propto \frac{N\gamma}{(\Delta \lambda/\lambda) \Delta t \Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}}$$

- Approximate description of single-electron undulator radiation distribution

$$\sigma_{r'} \approx \sqrt{\frac{\lambda}{2L}} \quad \sigma_r \approx \frac{1}{2\pi} \sqrt{2\lambda L}$$

$$\epsilon_r = \sigma_r \sigma_{r'} \approx \frac{\lambda}{2\pi} \quad \beta_r = \frac{\sigma_r}{\sigma_{r'}} \approx \frac{L}{\pi}$$

Electron Beam Contribution

- Electron beam distribution must be convolved with single-electron distribution, giving

\[ E_q = \sum_q \sum_{q'} = \sqrt{\sigma_q^2 + \sigma_{q'}^2} \sqrt{\sigma_{q'}^2 + \sigma_{r'}^2} \]

- Smallest photon beam emittance obtained when

\[ \beta_q = \frac{\sigma_q}{\sigma_{q'}} = \beta_r \]

\[ \epsilon_q = \sigma_q \sigma_{q'} \lesssim \epsilon_r \]

“diffraction-limited source”
Example

- 8 keV is sometimes taken as defining the lower boundary of “hard x-rays”

\[ \lambda = 1.5 \AA \rightarrow \epsilon_r = 24 \text{pm} \]

- For typical 3rd-generation rings

\[ \epsilon_x : [1, 5] \text{nm} \quad \epsilon_y : [4, 40] \text{pm} \]

so we are several orders of magnitude away from DL performance in horizontal.

- For an undulator filling a typical 5-m-long straight

\[ \beta_r = 1.6 \text{m} \]

which is feasible, but not commonly delivered.
Emittance in Electron Rings

- Equilibrium emittance is given by\(^1,2\)

\[
\epsilon_0 = C_q \frac{F(\nu_x, \text{lattice}) \gamma^2}{N_d^3} \frac{P_d}{P_d + P_w}
\]

- Naively want
  - Low energy
  - Many weak dipoles
  - Judicious choice of lattice type and tune
  - Strong damping wigglers

- A number of issues impede our ability to capitalize on this scaling

\(^1\)H. Wiedemann, Particle Accelerator Physics, Vol. 1 (1993)
\(^2\)J. Murphy, NSLS Light Source Data Book (1989).
Challenges of Low Emittance

- If we increase $N_d$ to reduce emittance
  - Bending angle per dipole decreases like $1/N_d$
  - Dispersion decreases like $1/N_d$
  - Chromaticity sextupole strength increases like $N_d$
    - Dynamic aperture decreases like $1/N_d$
    - Second order chromaticities increase like $N_d$

- If we optimize tune to reduce emittance
  - Must increase horizontal tune
    - Dispersion smaller
    - Chromaticity larger
  - Means stronger sextupoles...

- The essential challenge: stronger sextupoles lead to difficult non-linear dynamics
  - This means greater difficulty injecting and worse lifetime

1:L. Emery, private communication.
Optimization of Nonlinear Dynamics

- These issues present even for early 3rd generation sources
  - Led to introduction of “geometric sextupoles”
  - Emphasis on reducing amplitude-dependent tune shifts
- Resonance driving term (RDT) minimization
  - Supports tuning larger numbers of sextupole and octupole families
  - Many successful applications
  - Weights assigned to individual RDTs based on experience
  - Must check and iterate with tracking


The program OPA is one of several used for RDT minimization.
Direct Optimization of Nonlinear Dynamics\textsuperscript{1-6}

- Optimize quantities determined by tracking, e.g.,
  dynamic acceptance, momentum acceptance,
  Touschek lifetime, diffusion rates
- Often used with multi-objective optimization
- Tune linear lattice as well as sextupoles, octupoles

Example of direct optimization of APS dynamic acceptance and Touschek lifetime

Intrabeam scattering (IBS)

- Multiple electron-electron scattering in a bunch
  - Leads to increased emittance and energy spread
- Worse with higher bunch density, i.e., lower emittance
  - Motivates having many low-intensity bunches
- Nominally worse with lower energy
  - Fights the beneficial $E^2$ scaling of emittance

![Graph showing APS emittance at 200 mA as a function of energy with and without IBS.](image)
Touschek scattering

- Hard electron-electron scattering leading to large longitudinal momentum kicks
- Strongly impacted by local momentum acceptance
- Normally thought of as worse for low emittance
  - However, if beam is very “cold”, Touschek lifetime increases!

Touschek lifetime for NSLS II assuming emittance can be arbitrarily reduced (lattice courtesy W. Guo)
In 1995, Einfeld et al. described a diffraction-limited light source based on a multi-bend achromat (MBA)

- 7 bends per achromat
- TME-like cells in the center
- Defocusing in dipoles to save space
- Small beta values at IDs
- 0.5 nm emittance at 3 GeV
- Only 400m circumference

The “Ultimate Storage Ring”

- In 2000, Ropert et al. described\(^1\) an Ultimate Storage Ring Light Source
  - 7 GeV, 2 km circumference, four-bend achromatic cells
    - 0.3 nm emittance
  - 7-m-long undulators
  - 500 mA
  - \(~100\times\) increase in brightness
- Suffered from comparison with ERL concepts\(^2\)
  - Emittance much larger, giving less coherence
  - High power loads
- Many misinterpreted these problems as fundamental

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1: A. Ropert et al., EPAC 2000, 83-87; Figs. courtesy L. Farvacque.
PETRA III Facility

- In 2004, PETRA III was proposed
- Conversion of 2.3-km high-energy physics ring
- Replaced one arc with DBA cells for IDs
  - Beta functions approaching the ideal values $L/\pi$
- 80 m of wigglers reduce emittance 4.5-fold to 1 nm
- Now in operation at 6 GeV, 100 mA

NSLS Upgrade: NSLS II

- Shares features with PETRA III
  - Large ring (792 m) for its energy (3 GeV)
  - Damping wigglers planned
    - Will reduce emittance up to 4-fold
    - 0.5 nm emittance with 8 DWs

- Beta functions in short straights within factor of two of ideal values

- Challenging nonlinear dynamics tuned with 10 sextupole families

- Touschek lifetime helped by “cold” beam

- Commissioning in 2014

NSLS-II lattice file courtesy W. Guo.
MAX IV Light Source

- MAX IV will be the first MBA-based light source
  - 3 GeV, 528 m circumference
  - 20 7BA cells
    - Relaxed from TME condition to improve nonlinear dynamics
  - $\varepsilon_0 = 263$ pm with 4 wigglers
  - In construction

Magnets are built with common yokes to reduce cost while improving relative alignment and stability.

1: S.Leemann et al., PRSTAB 12, 120701 (2009). Figures courtesy S. Leemann.
**MAX IV Light Source**

- Nonlinear dynamics tuned using RDT minimization
  - 5 sextupole families
  - 3 octupole families
    - First light source to use octupoles
    - Directly address tuning of amplitude-dependent tune shifts

Figures courtesy S. Leemann.
MAX IV Light Source

- Touschek lifetime improves significantly as emittance is lowered
- IBS at 500 mA (5 nC/bunch) controlled using
  - 100 MHz main rf
  - bunch-lengthening cavity
- 50 mm (170 ps) rms bunch length unusually long for a storage ring light source
- In spite of the very low emittance, still not “diffraction-limited”

Figures courtesy S. Leemann.
Next-Generation Designs: XPS7

- 7 GeV, 1.1 km circumference (APS replacement)
- 40x6BA cells, giving $\varepsilon_0 = 78$ pm
- Feasibility not shown
  - Poor nonlinear dynamics performance
  - Strong combined function quad/sextupole magnets
- First attempt to challenge ERLs
  - 0.5 $\mu$m normalized emittance
  - Too extreme for a 1.1-km circumference
- However, revived some earlier ideas
  - Operation with “round beams” to reduce IBS and increase lifetime
  - Use of on-axis injection and “swap-out” mode to deal with small dynamic aperture

2: L. Emery et al., PAC 2003, 256-258.
Operation with “Round Beams”

- Present rings have $\kappa = \frac{\varepsilon_y}{\varepsilon_x} \ll 1$
  - Improves brightness
  - Essential for accumulation with small gap chambers
  - Accumulation requires large horizontal acceptance
    - This becomes hard as we strive for lower emittance
- When we make $\varepsilon_x$ very small, $\kappa \ll 1$ is pointless
  - Brightness dominated by single-electron radiation distribution
  - Drives up IBS and Touschek scattering rates
- Better approach$^{1,2}$
  - Run with $\kappa = 1$ (“round beams”)
  - Inject on-axis
    - Greatly reduces acceptance requirements
  - Use swap-out mode of operation:
    - Upon injection, old bunch (trains) are ejected and replaced

1: L. Emery et al., PAC 2003, 256-258.
Injection Issues

- All present-day ring light sources use beam accumulation
  - Each stored bunch/train is built up from several shots from the injector
  - Incoming beam has a large residual oscillation after injection
    - Requires typical horizontal DA of ~10 mm or more
  - In the presence of x-y coupling, residual oscillations result in loss on vertical small-gap chambers
    - Incompatible with large x-y coupling
  - Top-up doesn’t help here because the injection efficiency is likely to be very low

- We proposed to use “swap-out” injection\(^1,2\)
  - Kick out depleted bunch or bunch train
  - Simultaneously kick in fresh bunch or bunch train

- This was the operating mode of the first dedicated SR source, TANTALUS\(^3\)

\(^1\)M. Borland, “Can APS Compete with the Next Generation?”, APS Strategic Retreat, May 2002.
\(^3\)E. M. Rowe and F. E. Mills, Particle Accelerators 4, 211 (1970).
ID Gap Benefit

- Present-day rings have insertion devices with relatively wide horizontal gaps
  - Necessary in order to preserve injection aperture
  - Prevents use of helical devices
  - Makes production of vertically- or elliptically-polarized radiation more difficult

- If injection is on-axis, this problem goes away
  - Can use round ID chambers
  - Use helical devices for broader tuning range and polarized radiation
Next-Generation Designs: Tsumaki et al.

- 6 GeV, 2 km circumference
- 32x10BA cells, giving $\varepsilon_0 = 35$ pm
- First feasible <100 pm design
  - DA suitable for beam accumulation
  - Several hour Touschek lifetime
  - Workable magnet designs with 20mm bore radius
  - With full coupling and IBS, 21 pm in both planes
- However
  - Large beta functions in straights not ideal for brightness
  - Straight sections only 4m long

Figures courtesy K. Tsumaki.
Next-Generation Designs: USR7

- 7 GeV, 3.1 km circumference
- 40x10BA, giving $\varepsilon_0 = 30$ pm
  - 10 m straight sections
  - Beta functions in straights better, but still not ideal
- Feasible design
  - DA suitable for on-axis injection
  - Momentum aperture of $\pm 2\%$
  - Workable magnet designs with 20mm bore radius

Next-Generation Designs: USR7

- IBS and Touschek controlled using full coupling at 200mA with 4200 bunches

~100-fold increase in brightness compared to APS
Bunch Pattern and Fill Rate

- If we inject bunch trains, the fractional droop in intensity among trains is
  \[ D \approx \Delta T_{inj} N_{trains} \frac{1}{\tau} \]

- The required injector current is
  \[ I_{inj} \approx \frac{I_{ring} L_{ring}}{c \tau D} \]

- We probably want \( D < 0.1 \)
- We are considering a very large ring (3.16 km) with up to 200 mA
- For 4000-bunch beam, 20 bunches per train, and 2 hour lifetime
  - Inject a bunch train every 3.6 s
  - 3 nA average current from the injector (APS injector: 4 nA)
  - Each train has 11 nC (APS injector: 3 nC/bunch).
**Indiana University 10pm USR design**

Twiss parameters for one superperiod with dispersion function magnified by 100 times.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>2663m</td>
</tr>
<tr>
<td>Energy</td>
<td>5GeV(4-7GeV)</td>
</tr>
<tr>
<td>Natural chromaticities</td>
<td>-595.339(horizontal)</td>
</tr>
<tr>
<td></td>
<td>-148.741(vertical)</td>
</tr>
<tr>
<td>Qx</td>
<td>202.9</td>
</tr>
<tr>
<td>Qy</td>
<td>33.884</td>
</tr>
<tr>
<td>dE/E</td>
<td>3.8e-4</td>
</tr>
<tr>
<td>Momentum compaction factor</td>
<td>1.223e-5</td>
</tr>
<tr>
<td>Natural emittance</td>
<td>9.1pm(before coupling)</td>
</tr>
</tbody>
</table>

Large natural chromaticities are induced by large number of dipoles and small beta functions.

Dynamic acceptance suitable for on-axis injection. Momentum acceptance >±1.5%

2: Y. Jing et al., PAC 2011, 781-783.

Content courtesy Y. Jing.
Next-Generation Designs: PEP-X

- Would use PEP-II tunnel
  - 4.5 GeV, 2.2 km circumference
  - 48x7BA, giving $\epsilon_0 = 22$ pm
  - 5 m straight sections
  - 90m damping wigglers
  - With full coupling and IBS, 11 pm emittances

- Patterned on MAX IV
  - More aggressive tuning for low emittance

- Long straights use up 30% of circumference

PEP-X USR Design

- PEP-X group at SLAC has developed a robust 7BA lattice for a proposed light source in the PEP tunnel\(^1,2\)

Choose cell phase advance to make +I transform for each arc of \(N\) cells:
- \(\nu_x = 2 + \frac{m}{N}\) and \(\nu_y = 1 + \frac{n}{N}\)
- This results in cancellation of many 2nd-order geometric and chromatic aberrations\(^3,4\)
- For PEP-X, \(N=8\) and \(m=n=1\)

\(^1\)M.-H. Wang \textit{et al.}, Proc IPAC11, THPC074.
\(^2\)Y. Nosochkov \textit{et al.}, Proc. IPAC11, THPC075.
Illustration of Effect of Right Phase Advance

Distortion of phase-space ellipse in PEP-X arc with 8 cells

\[ \nu_x = 0.100 \]

\[ \nu_x = 0.125 \]

\[ \nu_x = 0.150 \]

\[ \nu_x = 0.175 \]
Performance of PEPX scheme

PEPX Baseline design (160pm)

PEPX USR design (23pm)

Figures courtesy Y. Cai.
See also, Y.Cai, FLS2012.
Application of MOGA to PEP-X

- Sextupoles have been optimized using MOGA algorithm\(^1\), providing a dramatic increase in lifetime\(^2\).

- Just what MOGA does to make this improvement is yet to be understood.

\(^1\)M. Borland et al., APS LS-319, August 2010.
\(^2\)M.H. Wang et al., Proc IPAC11, THPC074.
SPring-8 II Preliminary 6-BA Lattice

67 pm emittance without damping wigglers or undulator damping

DA with errors suitable for on-axis injection.

New injection scheme planned with on- and off-axis modes
Next-Generation Designs: SPring-8 II

- In early 2012, Ishikawa et al., published a preliminary upgrade report for SPring-8¹
  - Replace existing 1.4-km ring in 2019 (1-year shutdown)
  - Use existing tunnel and x-ray hutches
  - ~1000x brightness

<table>
<thead>
<tr>
<th></th>
<th>SPring-8 (present)</th>
<th>SPring-8 II (planned)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>8 GeV</td>
<td>6 GeV</td>
</tr>
<tr>
<td>Current</td>
<td>100 mA</td>
<td>300 mA</td>
</tr>
<tr>
<td>Emittance</td>
<td>3.4 nm</td>
<td>67 → 10 pm</td>
</tr>
<tr>
<td>Coupling</td>
<td>0.2%</td>
<td>~2%</td>
</tr>
<tr>
<td>Bunch length</td>
<td>13 ps</td>
<td>&gt;20 ps</td>
</tr>
<tr>
<td># beamlines</td>
<td>62 max.</td>
<td>62+ max</td>
</tr>
</tbody>
</table>

¹T. Ishikawa et al., Jan. 2012. (Google “Spring-8 upgrade plan”.)

Graphics and content courtesy T. Watanabe.
The ESRF Hybrid Multi-Bend (HMB) lattice

- multi-bend for lower emittance
- dispersion bump for efficient chromaticity correction => “weak” sextupoles (<0.6kT/m)
- no need of “large” dispersion on the three inner dipoles => small $H_x$ and $E_x$

\[ \beta_x = 75.600 \quad \delta p/p = 0.000 \]
\[ \beta_z = 27.600 \quad 1 \text{ period, } C = 843.972 \]

Courtesy A. Franchi, ESRF
Nonlinear optics: the HMB lattice

Phase advance between pairs of (chrom.) sextupoles:

\[ \Delta \phi_x = (2n+1)\pi \quad \Delta \phi_y = n\pi \]

\( \Delta \phi_x = (2n+1)\pi \) to minimize at the cell ends the Resonance Driving Terms from \( x^3 \) \( (f_{3000} \text{ and } f_{1200} \approx 0) \) => elliptical horizontal phase space

+ \( \Delta \phi_y = n\pi \) minimize those from \( xy^2 \) \( (f_{1020} \text{ and } f_{0120} \approx 0) \) rendering vertical phase space elliptical too \( [f_{0111} \approx 0 \text{ from } \Delta \phi_x = \pi] \) …

… provided that second-order (octupolar-like) RDTs are kept low

Courtesy A. Franchi, ESRF

no harmonic sextupoles
Optimizing dynamic aperture

HMB lattice (V172-F)
- octupole component in QD0/QF0
- long. gradient in dipoles
- lower cross-term detuning

\[
d\frac{Q_x}{dj_x} = -4 \times 10^3 \quad d^2\frac{Q_x}{dj_x^2} = 0.5 \times 10^9 \\
d\frac{Q_y}{dj_x} = -3 \times 10^3 \quad d^2\frac{Q_y}{dj_x^2} = 0.1 \times 10^9 \\
d\frac{Q_y}{dj_y} = -5 \times 10^3 \quad d^2\frac{Q_y}{dj_y^2} = 1.0 \times 10^9
\]

V172F: Tunes Vs horizontal position

\[\Delta \phi_x < 3\pi\]
ESRF Hybrid MBA Scheme

- Dynamic aperture compatible with existing injector
- Momentum aperture about +/- 3%
- Natural emittance is 160 pm, lower than 320 pm possible with MAX-IV type lattice
  - Longitudinal dipole gradients
  - Much stronger gradients in dipoles ($K_1$ as high as 2.2 m$^{-2}$)
- Quads are also strong, up to 100 T/m, as are sextupoles (up to 2 kT/m$^2$)
- Very promising concept
Possible Lattice Upgrades for APS

- APS is presently being upgraded, but not for lower emittance
  - New insertion devices (revolvers, APPLEs, SCUs)
  - Improved beamline optics and detectors
  - Improved beam stability
  - Short-pulse x-rays (L. Emery’s talk)
  - 50% higher beam current

- Following this upgrade, another upgrade might be worthwhile to improve the emittance

- In addition to lattice design and dynamics, need to investigate
  - Best beam energy (less than present 7 GeV?)
  - Magnet designs and tolerances
  - Instability thresholds and impact on timing users

- This is on-going R&D and we present a few snapshots
Gradient Dipole Limits

- MBA lattices rely on defocusing gradient dipoles
  - Allows eliminating many quadrupoles
  - Changes damping partition to further reduce emittance
- Matching experience shows that the gradient limit is an important parameter
- We estimated the max. gradient given
  - 12 mm beam pipe radius (same as MAX-IV)
  - Rough relationship of pole radius R and good field region (1.44R)
  - Saturation limits
  - Desire to build magnet with shorting plate (cheaper)
- For the 25-40m bending radii needed at APS, we find generous limits of
  - 39 T/m gradient
  - $K_1 = 1.7$ at 7 GeV
MAX-IV-like APS Lattice at 6 GeV

- 150 pm natural emittance
- Significantly reduced beta functions at straights compared to MAX-IV
- MOGA using tunes, 8 chromatic sext. families
  - Octupoles no help so far
- DA small, but as expected from scaling MAX-IV DA

**1.8 h Touschek lifetime for 200 mA/324 bunches and 4pm vertical emittance**

Swap out 4 bunches every 8s (1.1 nA av. current)

Easily compatible with existing 100 pm booster emittance for on-axis injection
Additional Lattice Ideas for APS

- Working on ESRF-like HMBA
  - Using less ambitious magnet parameters
  - About half the emittance of MAX-IV-like design
  - Work continues on DA and momentum aperture

- Also exploring the PEP-X approach in combination with both types of MBA design
  - E.g., cell tunes of 2.2 and 1.1 with extra quads every 10\textsuperscript{th} straight to move total tune away from integer
  - Requires using 4 straight sections for tune adjustment, so won’t be used unless it provides significant benefit
What to do with Tevatron tunnel now?

Exploratory light source design
- Roughly match 6-straight, 6-arc geometry
- Use PEP-X optics modules
  - 6 arcs with 30 cells of 7BA giving $N_d = 1260$
  - Relax cell tunes, giving $\epsilon_0 = 2.9$ pm at 9 GeV
- Preliminary MOGA gives
  - Adequate DA for on-axis injection, 4.5 h gas-scattering lifetime
  - Adequate LMA for 4 h Touschek lifetime for 0.5nC/bunch
Collective Effects vs Energy

- Bunch lengthening helps improve lifetime and MWI threshold at low energy
- Energy spread
- Microwave threshold
- Touschek lifetime
Expected Performance

Emittance with IBS shows broad minimum between 9 and 11 GeV.

Brightness is spectacular for 10 keV and above

(Calculations assume superconducting undulators.)
Superconducting Ring

- At FLS2012, W. Guo et al. described a USR based on superconducting magnets
  - High fields possible
  - Combined function bend/quad/sextupole
  - Implies a very compact source
- Exploratory linear optics design
  - All magnets have gradient
  - 828 m circumference
  - $\epsilon_0 = 6.4$ pm
- Dynamic aperture is small as of yet
  - Trying lumped chromaticity correction
- Promising idea for bigger rings as well

1:W.Guo et al., Superconducting Ultimate Storage Ring Design, FLS2012. Figure courtesy W. Guo.
Conclusion

- In 1995, Einfeld et al. proposed a concept for a diffraction-limited storage ring light source.
- In spite of this, it was widely assumed ~10 years ago that storage ring light sources had reached their limit.
- MAX IV will soon test the MBA concept in the real world.
- Several existing light sources are exploring possible MBA upgrades or new facilities.
  - Brazil has funded a new MBA facility (SIRIUS).
  - China has funded R&D into a new MBA facility near Beijing.
- We can expect a 100-1000-fold brightness increase across a wide spectral range.

Thanks to K. Balewski, Y. Cai, D. Einfeld, L. Farvacque, A. Franchi, W. Guo, Y. Jing, S. Leemann, K. Tsumaki, and T. Watanabe for materials used in this talk.