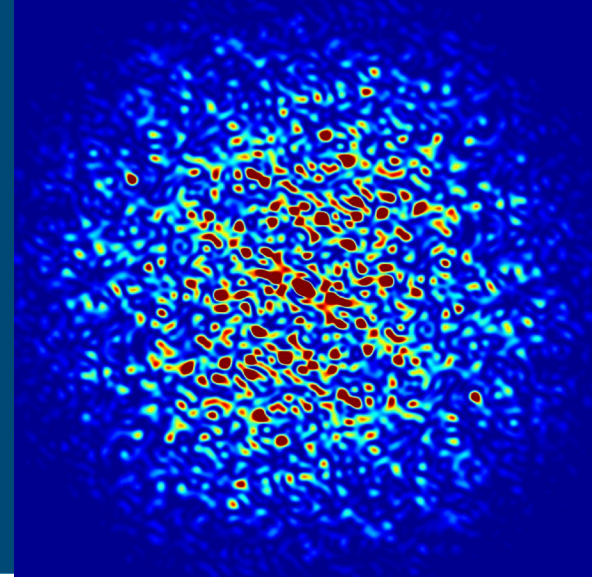# Physics of multi-bend achromat lattices

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September 3, 2019 in Lansing, Michigan

Acknowledgments

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  - Michael Borland for suggestions and material
  - Joe Calvey, Vadim Sajaev, and Yipeng Sun for slide material
  - Tim Berenc, Jeff Dooling, Louis Emery, Kathy Harkay, Uli Wienands, Kent Wootton, Aimin Xiao
- Colleagues from other institutions
  - Gabriele Bassi (NSLS-II), Alexei Blednykh (NSLS-II), Marco Venturini (ALS/ALS-U)
  - ESRF-EBS physics team
- Computing resources at ANL's Blues and Bepop clusters, and ASD's weed cluster
- Funding from the DOE Office of Basic Energy Sciences

Motivation: X-rays for science

- X-rays have played an important role in scientific discovery since their discovery

- X-rays are now used to probe many systems:
  - Electronic and magnetic materials
  - Chemical science
  - Life science and medicine
  - Biology and biochemistry
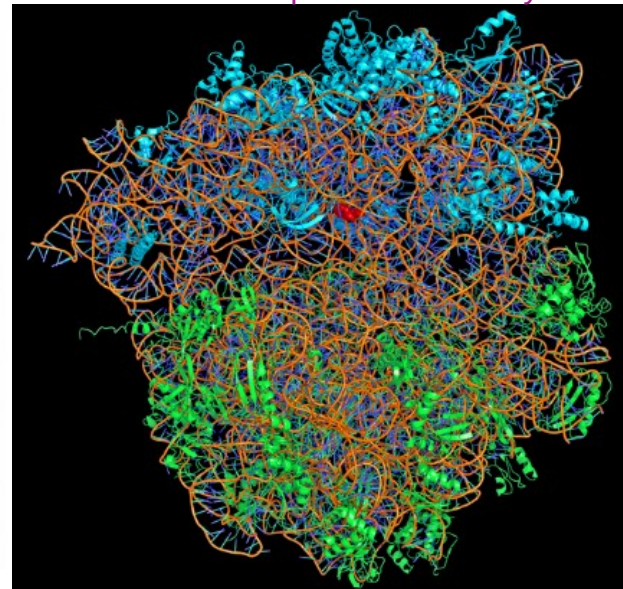 - Geological and planetary science
  - Nanomaterials
  - ...
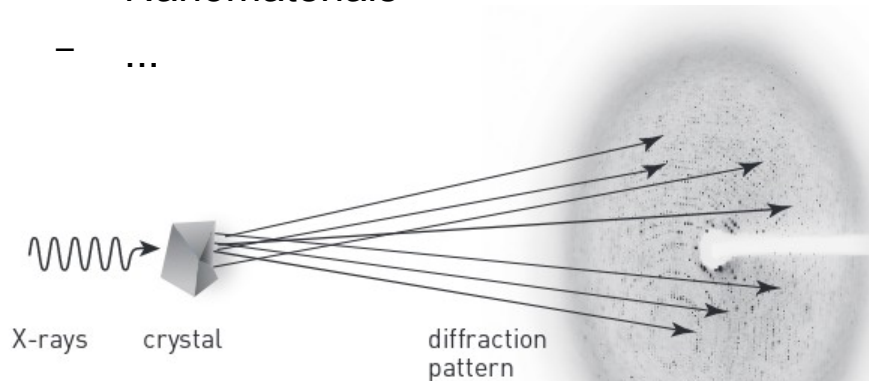
F. Shen et al., ACS Energy Lett. 3, 1056 (2018). ©2018 American Chemical Society
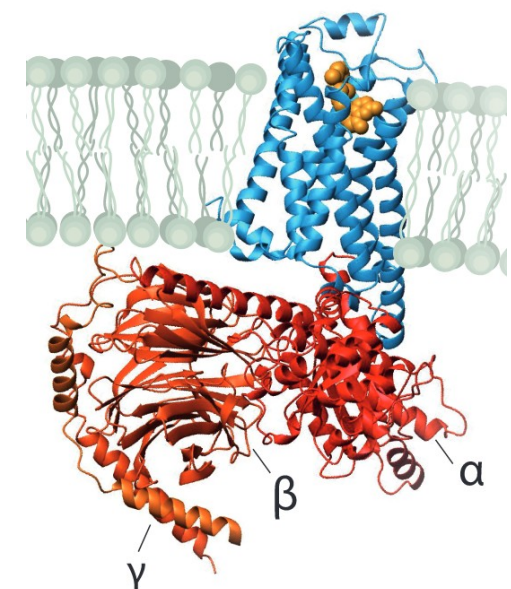Microstructure-driven failure in Lithium ion batteries
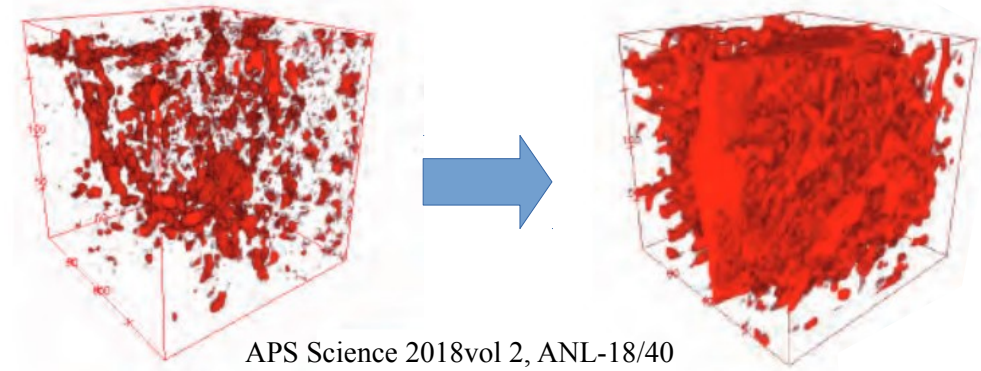
APS Science 2018vol 2, ANL-18/40

V. Ramakrishnan, T.A. Steitz,and A.E. Yonath
2009 Nobel prize in chemistry

R.J. Lefkowitz and B. Kobilka
2012 Nobel prize in chemistry

Press release. NobelPrize.org. Nobel Media AB 2019. Fri. 30 Aug 2019.

Ryan Lindberg -- Physics of MBA lattice -- NAPAC 2019 -- September 3, 2019

3

Brief history of storage ring-based light sources

First generation sources

- Storage ring was primarily built and used for high energy physics
- Scientists used bending magnet radiation parasitically

Second generation sources

- Specifically built as a light source
- Primarily relied on bending magnets, with some space for wigglers and undulators

Third generation sources

- Optimized for x-ray production
- Contains long (several meter) straight sections for undulators

Increasing x-ray spectral flux

Increasing x-ray brightness $\mathcal{B}$

$$\mathcal{B} = \frac{\text{Number of photons}}{\text{6D phase space volume}} = \frac{\text{photons/time}}{(\text{2D area})_x (\text{2D area})_y (\text{Spectral bandwidth})}$$

High brightness → Ability to focus large numbers of photons to a small spot
→ Large photon flux through an aperture
→ High level of transverse coherence (coherent fraction)
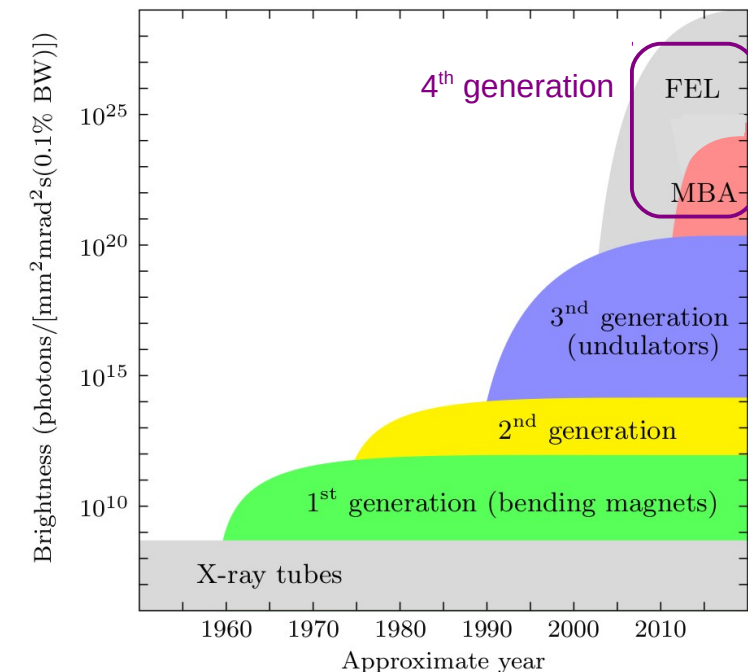
Undulator brightness depends on electron beam emittance

$$\mathcal{B} = \frac{\text{Number of photons}}{\text{6D phase space volume}} = \frac{\text{photons/time}}{(\text{2D area})_x (\text{2D area})_y (\text{Spectral bandwidth})}$$

- Due to its wave nature, radiation has an intrinsic $(\text{2D area})_x = (\text{2D area})_y = 2\pi\frac{\lambda}{4\pi} = 2\pi\varepsilon_{\text{rad}}$

- X-rays are emitted from a collection of electrons with differing angles and positions, so that the total transverse phase space area is obtained as a convolution of the electron and x-ray phase spaces
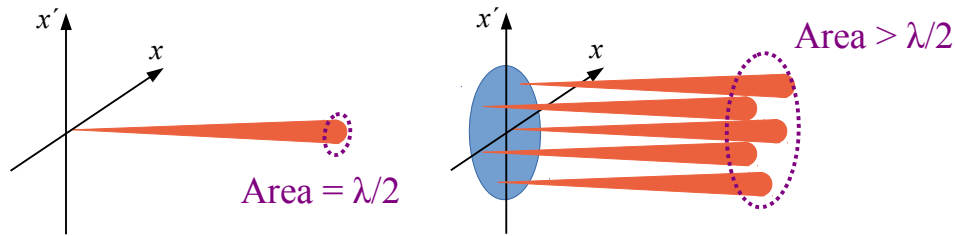
$$\mathcal{B} = \begin{cases} N_{\text{electron}}\mathcal{B}_0 & \text{if } \varepsilon_x, \varepsilon_y \ll \varepsilon_r = \dfrac{\lambda}{4\pi} \\[2ex] \dfrac{\varepsilon_r^2}{\varepsilon_x\varepsilon_y}N_{\text{electron}}\mathcal{B}_0 & \text{if } \varepsilon_x, \varepsilon_y \gg \varepsilon_r = \dfrac{\lambda}{4\pi} \end{cases}$$

- For a simplified (Gaussian) model of the radiation and $\varepsilon_x = \varepsilon_y$, we find that

$$\mathcal{B} = \frac{N_{\text{electron}}\mathcal{B}_0}{1 + \left(\dfrac{\beta_x^*}{Z_R} + \dfrac{Z_R}{\beta_x^*}\right)(\varepsilon_x/\varepsilon_r) + (\varepsilon_x/\varepsilon_r)^2}$$

When we also want to match electron and photon beams such that $\beta_x^*, \beta_y^* \to Z_R \sim \dfrac{L_u}{\pi} \sim 1\text{ m}$

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Equilibrium emittance

- The emittance reaches an equilibrium when radiation damping is balanced by diffusion[1]

- The equilibrium emittance is computed by integrating "curly-$\mathcal{H}$" around the ring

Emittance ~ (energy)^2

$C_q \approx 3.84 \times 10^{-4}$ nm

ρ = bending radius

$$\varepsilon_{x,0} = \gamma^2 \frac{55}{32\sqrt{3}} \frac{\hbar c}{mc^2} \frac{\oint ds\, \mathcal{H}(s)/\rho(s)^3}{J_x \oint ds\, 1/\rho(s)^2}$$

J_x = "damping partition" that quantifies the amount of radiation damping in the horizontal plane.

Typically $J_x = 1$, but with suitable design we can set $1 \leq J_x < 3$.

$$\mathcal{H}(s) = \beta_x(s)\eta_x'(s)^2 + 2\alpha_x(s)\eta_x(s)\eta_x'(s) + \frac{1+\alpha_x^2(s)}{\beta_x(s)}\eta_x(s)^2$$

Curly-$\mathcal{H}$ gets contributions from the dispersion and its derivative weighted by the respective lattice functions.

Curly-$\mathcal{H}$ adds to the emittance when the trajectory is bent.

[1] M. Sands, SLAC Report No. 8, 1969.

Using small emittance requirement for lattice design

- For a constant field bending magnet, one can solve for the lattice functions that result in the smallest equilibrium emittance: the Theoretical Minimum Emittance (TME) cell[2]

- The dispersion in a TME cell is at its minimum at the middle of the dipole, but having zero dispersion in the straight sections is often desired
  - Avoid emittance increase due to quantum diffusion in the undulator
  - Avoid beam size increase and the resulting increase in effective emitance in undulator

- Double bend (2 dipoles) achromat (zero dispersion going in and coming out) has become standard for 3rd generation light sources[3,4]

$$\text{TME}: \quad \varepsilon_{x,0} = \frac{C_q \gamma^2 \Theta^3}{12\sqrt{15}}$$

Minimum
$$\text{DBA}: \quad \varepsilon_{x,0} = \frac{C_q \gamma^2 \Theta^3}{4\sqrt{15}}$$
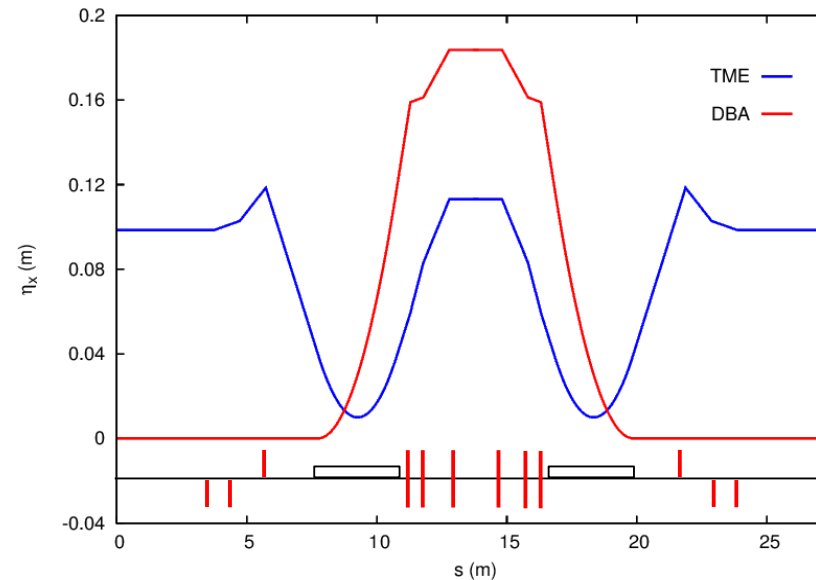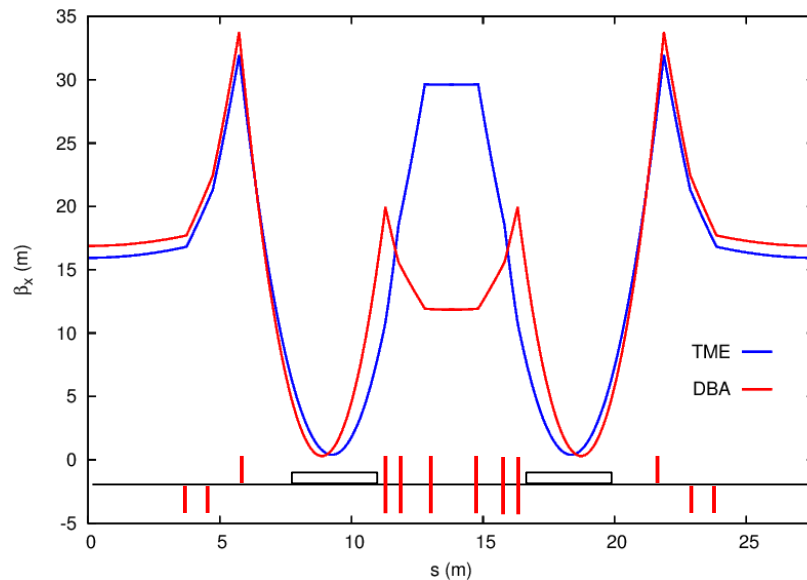
IMPORTANT NOTE:
No effort has been made to use realistic quadrupole strengths or to keep the vertical plane under control.

Meeting these criteria and achieving other performance goals generally requires some trade-offs in emittance!

[2] L.C. Teng. "Minimum emittance lattice for synchrotron radiation storage rings," Argonne National Laboratory Tech. Rep. No. LS-17 (1985).
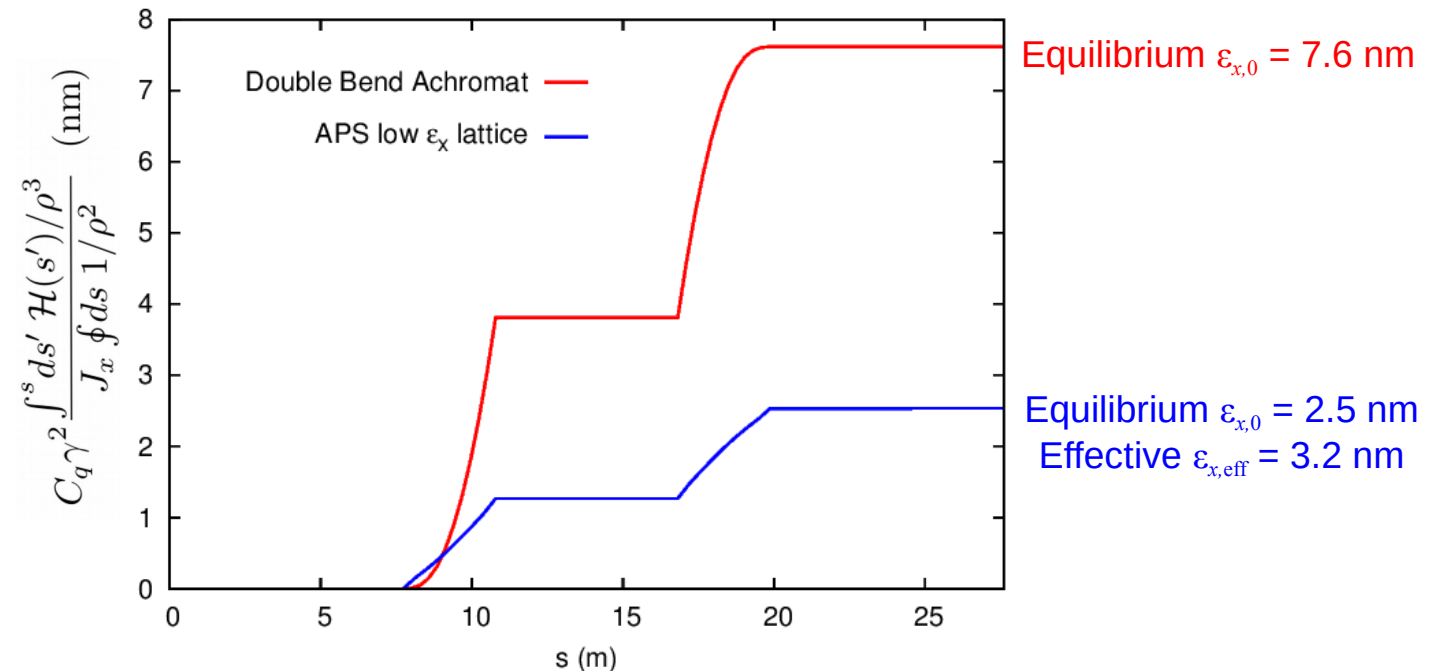[3] W.H.K. Panofsky in *High Energy Beam Optics*, ed. by K.G. Steffen (Wiley, New York) p. 117 (1965).
[4] R. Chasman, G.K. Green, and E.M. Rowe. "Preliminary Design of a Dedicated Synchrotron Radiation Facility." IEEE Trans. Nucl. Sci. **22**, 1765 (1975).

Double bend lattice used at APS
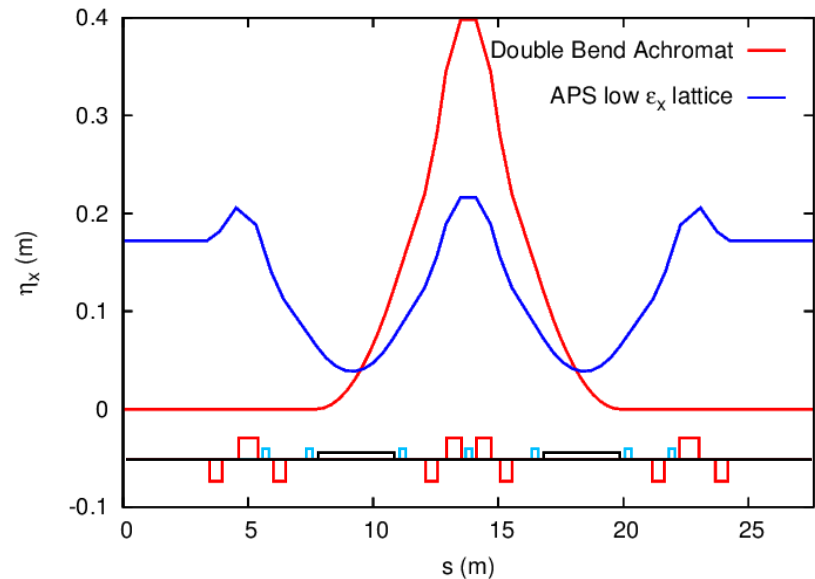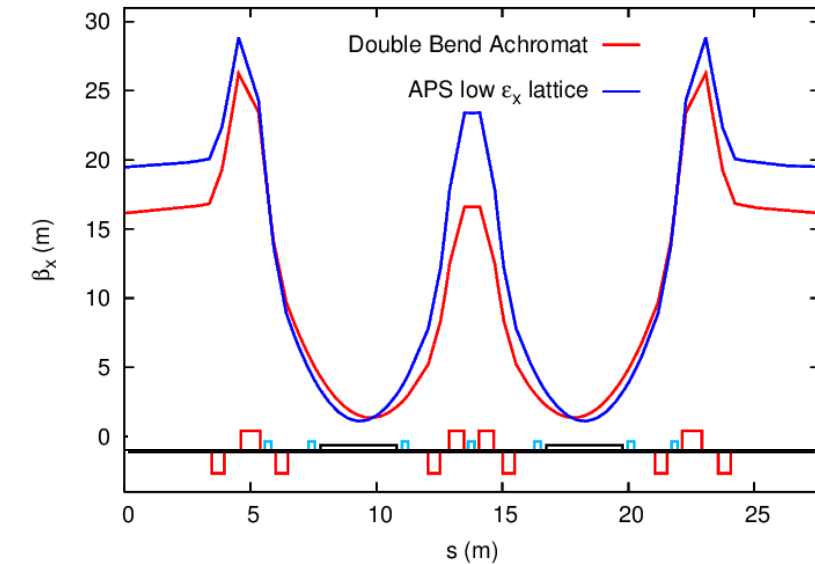
- First lattice used by APS was a double bend achromat

- ESRF showed that one could reduce the emittance below that of a DBA by allowing some dispersion in the straight sections

- APS followed their example ~2001 to decrease its emittance

- Change at APS was enabled by top-up injection: the lifetime of the lower emittance lattice was too short for fill and decay operation

Equilibrium $\varepsilon_{x,0}$ = 7.6 nm

Equilibrium $\varepsilon_{x,0}$ = 2.5 nm
Effective $\varepsilon_{x,\text{eff}}$ = 3.2 nm

Emittance scaling

The equilibrium emittance generally scales in the following way:

$$\varepsilon_{x,0} = C_q \gamma^2 \begin{pmatrix} \text{Factor depending upon} \\ \text{lattice function design} \\ \text{and magnetic field profile} \end{pmatrix} \begin{pmatrix} \text{Bend angle} \\ \text{per dipole} \end{pmatrix}^3$$

$$\frac{1}{\begin{pmatrix} \text{Number of} \\ \text{dipoles} \end{pmatrix}^3} = \frac{1}{N_D^3}$$

1. Minimize curly-$\mathcal{H}$ directly with lattice design

$$\mathcal{H}(s) = \beta_x(s)\eta_x'(s)^2 + 2\alpha_x(s)\eta_x(s)\eta_x'(s) + \frac{1+\alpha_x^2(s)}{\beta_x(s)}\eta_x(s)^2$$

�→ Having small dispersion η_x in dipole
➤ Having small envelope function β_x in dipole

2. Minimize $\oint ds\, \mathcal{H}(s)/\rho(s)^3$ by designing dipoles with specific bend radius profiles (longitudinal gradients)

3. Increase x-damping (J_x) by using dipoles with transverse gradients (focusing)

Favors using as many bending magnets per periodic sector
→ **Multi- (>3) Bend Achromat**

Einfeld and Plesko[5] proposed a rings that take advantage of this favorable MBA scaling in early to mid 90's.

No MBA projects began until > 15 years later.

WHY?

[5] D. Einfeld and M. Plesko. "A modified QBA optics for low emittance storage rings," NIMA **335**, 402 (1993); "Design of a diffraction limited light source (DIFL)," Proc. of PAC 95, pp. 177.

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MBA scaling for magnet requirements are less attractive

We can study this easily with a simple model of a ring whose circumference is C_R that is composed of idealized TME-like cells.

Similar results apply for MBA sectors
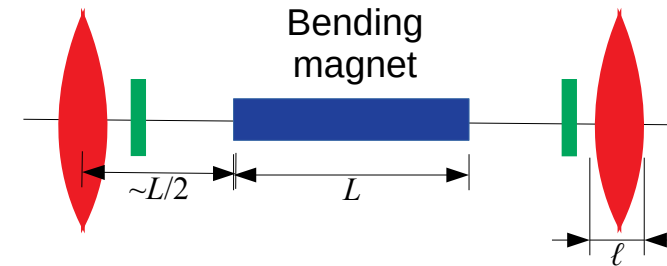
- The required **quadrupole strength** scales as $k_Q = \dfrac{1}{f\ell} \sim \dfrac{1}{L}\dfrac{1}{\ell} \sim \dfrac{N_D}{C_R}\dfrac{N_D}{(\ell/L)C_R} \sim N_D^2 \dfrac{1}{(\ell/L)C_R^2}$

- This results in a **natural chromaticity** of $\xi_{x,\mathrm{nat}} = \dfrac{1}{4\pi}\oint ds\, \beta_x(s)k(s) \sim N_D\beta_x f \sim N_D \dfrac{C_R}{N_D}\dfrac{N_D}{C_R} \sim N_D$

- To correct this, each sextupole must contribute of order 1 unit of chromaticity,

$$\xi_{\mathrm{sext}} = \frac{1}{4\pi}\int ds\, \beta_x(s)\eta_x(s)m(s) \sim \frac{\beta_x\eta_x}{4\pi}\int ds\, m(s) \sim 1$$

- So that the **integrated sextupole strength** scales as $\int ds\, m(s) \sim \dfrac{4\pi}{\beta_x\eta_x} \sim \dfrac{N_D}{C_R}\dfrac{4\pi N_D}{C_R\Theta} \sim N_D^3 \dfrac{1}{C_R^2}$

MBAs require strong magnets with small apertures!

[6] M. Borland, G. Decker, L. Emery, V. Sajaev, Y. Sun, and A. Xiao. "Lattice design challenges for fourth-generation storage-ring light sources," J. Synchrotron Rad. **21**, 912 (2014).

Scaling laws for robustness and stability reveal challenges

1. Tolerances to errors can be illustrated by the beta-beating caused a sextupole at $s = 0$ displaced by Δx

$$\frac{\Delta \beta_x(s)}{\beta_x(s)} = \Delta x \frac{\beta_x(0)}{2\sin(2\pi\nu_x)} \cos[2\phi_x(s) - 2\phi_x(0) - 2\pi\nu_x] \int ds' \, m(s')$$

For $\sim N_D$ such displacements that are randomly distributed we have the rms variation

$$\left\langle \frac{\Delta \beta_x(s)}{\beta_x(s)} \right\rangle_{\text{rms}} \sim N_D^{1/2} \langle \Delta x \rangle_{\text{rms}} \langle \beta_x \rangle \int ds \, m(s) \sim N_D^{1/2} \langle \Delta x \rangle_{\text{rms}} \frac{C_R}{N_D} \frac{N_D^3}{C_R^2} \sim N_D^{5/2} \frac{\langle \Delta x \rangle_{\text{rms}}}{C_R}$$

2. Scaling of the dynamic aperture can be seen from the quad+sextupole equations of motion

$$\frac{d^2}{ds^2} x + k_0(s)x = -\frac{1}{2} m_0(s)x^2$$

Scale s by the number of dipoles, $s \rightarrow \sigma/N_D$, and apply the MBA scalings
$$k_0(s) \rightarrow N_D^2 k(N_D s) = N_D^2 k(\sigma) \qquad m_0(s) \rightarrow N_D^3 m(N_D s) = N_D^3 m(\sigma)$$

If the stability limit here is $x_{\max}$, then the stability limit after increasing dipole number by N_D is $x_{\max}/N_D$

$$\frac{d^2}{d\sigma^2}(N_D x) + k(\sigma)(N_D x) = -\frac{1}{2} m(\sigma)(N_D x)$$

$\Rightarrow$ **Dynamic aperture** $\sim \dfrac{1}{N_D}$

NOTE: Dynamic aperture scales as $1/N_D^2$ if sextupole lengths shrink like $1/N_D$ as number of dipoles is increased

[6] M. Borland, G. Decker, L. Emery, V. Sajaev, Y. Sun, and A. Xiao. "Lattice design challenges for fourth-generation storage-ring light sources," J. Synchrotron Rad. **21**, 912 (2014).
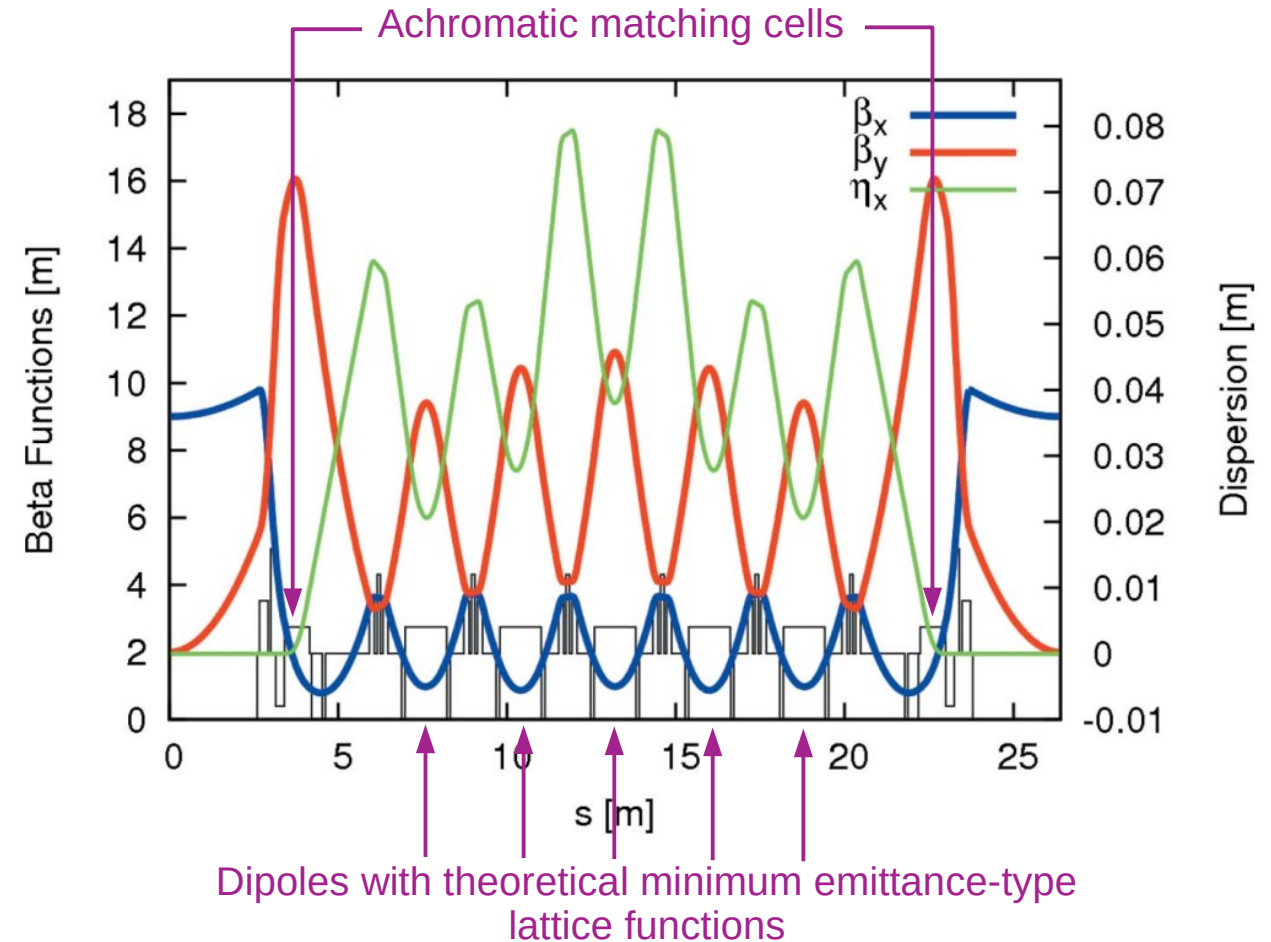
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Upgrade projects are underway around the world

- MAX-IV is serving users in Sweden

- ESRF-EBS (France) and SIRIUS (Brazil) are under construction

- The other MBAs are in various stages of development

- These developments have been driven by advances in
  - Technology
  - Lattice design
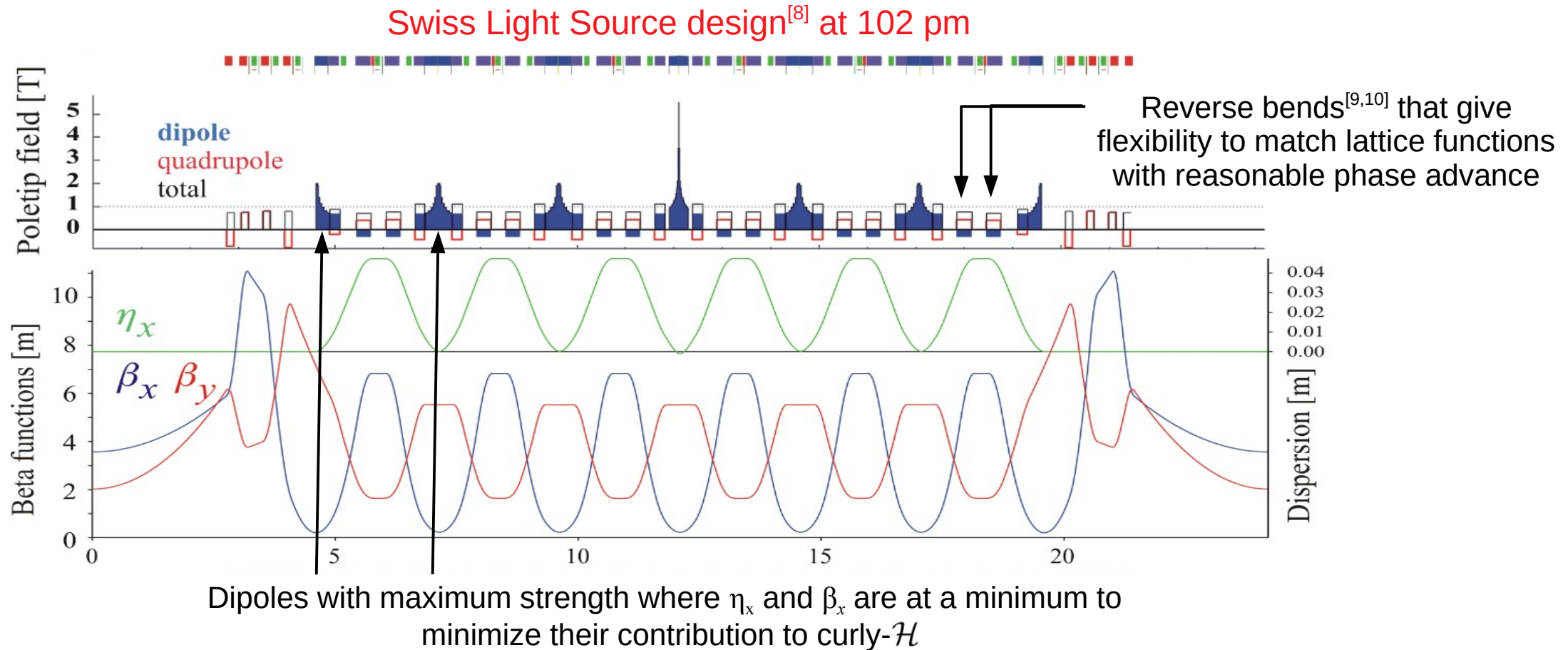 - Simulation capabilities
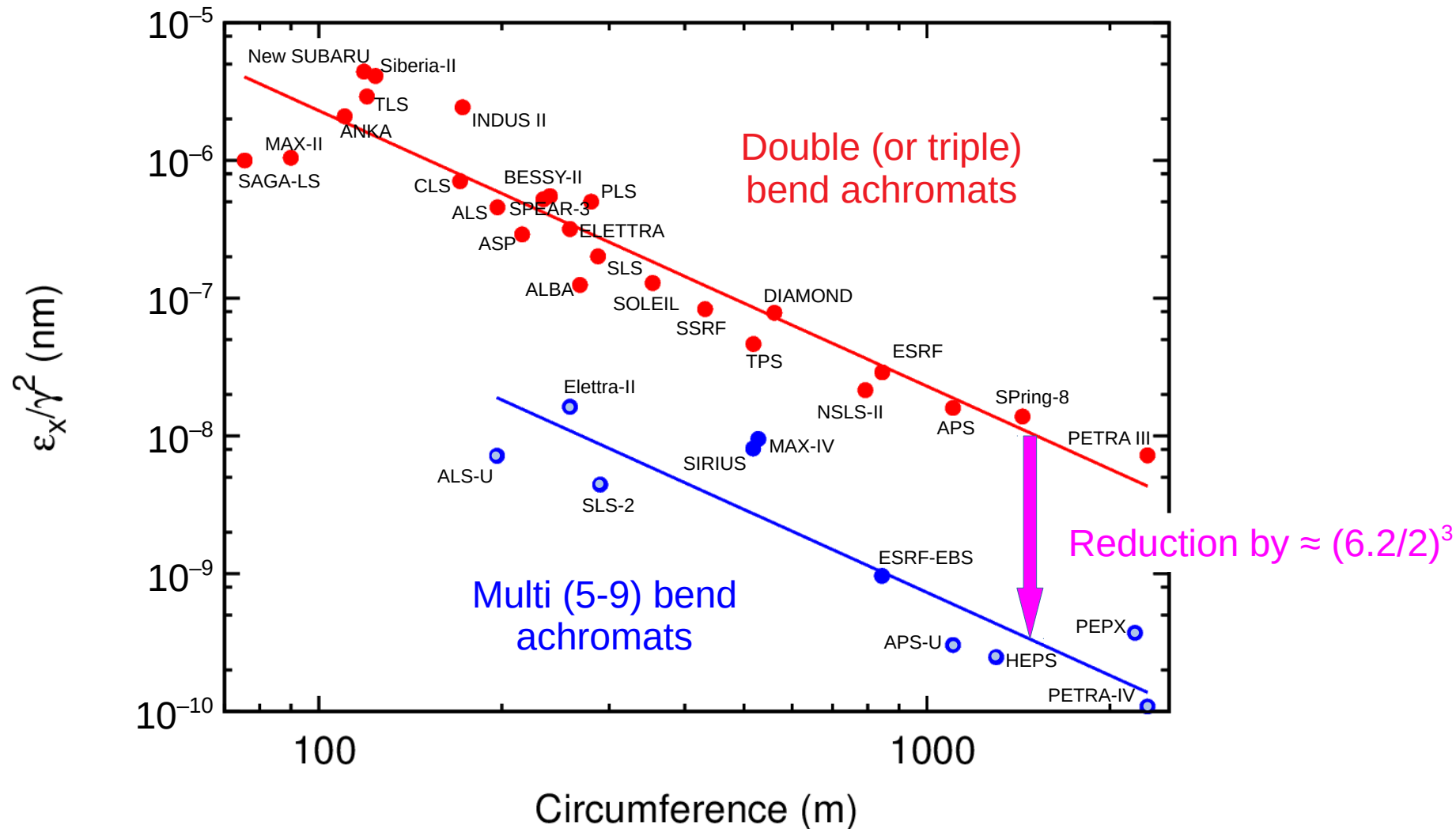
MAX-IV: the first MBA storage ring

- MAX-IV in Lund, Sweden, is the first MBA-based storage ring, and has been operational since 2017

- Natural emittance of 330 nm is ~10x smaller than similar DBA rings

- Two critical enabling technologies:

  1. NEG coating of vacuum chambers
     - Reduces photon-stimulated desorption
     - Provides distributed pumping
     - Enables ultra-low vacuum in small aperture vacuum chambers

  2. Utra-precise machining of magnet blocks as unified systems.
     - Reduced tolerances to 20 micron level

Achromatic matching cells

Dipoles with theoretical minimum emittance-type lattice functions

[7] P. F. Tavares, S. C. Leemann, M. Sjöström, and Å. Andersson, J. Synchrotron Rad. 21 862 (2014).
Reproduced with permission of the International Union of Crystallography

Reverse bends and longitudinal gradient dipoles can enable further emittance reduction
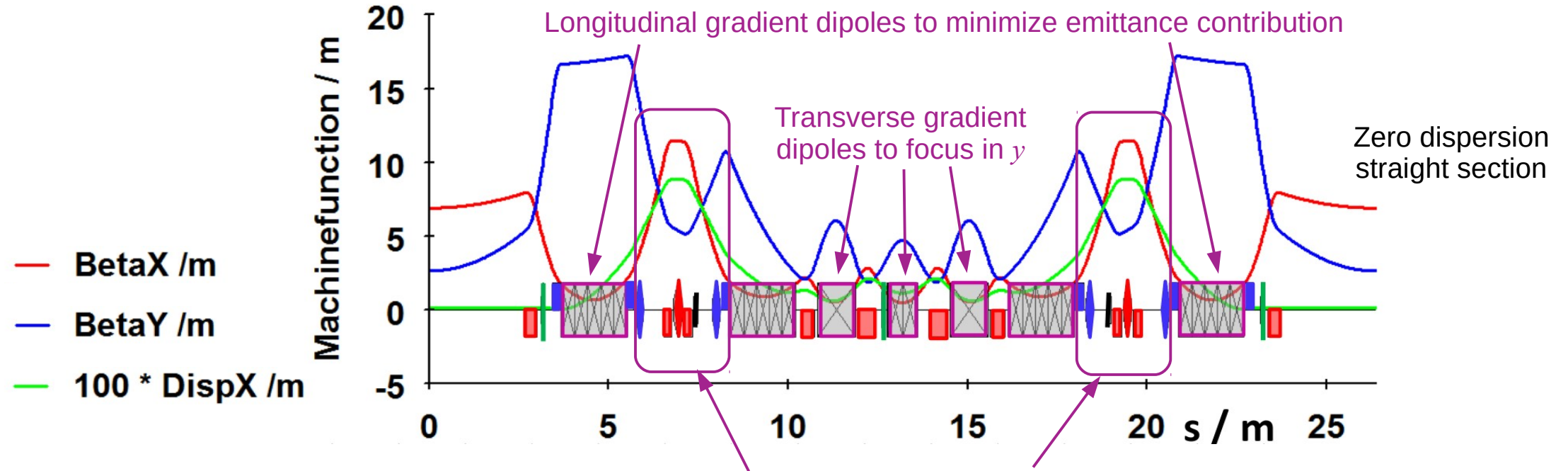
Swiss Light Source design[8] at 102 pm

Reverse bends[9,10] that give flexibility to match lattice functions with reasonable phase advance

Dipoles with maximum strength where η_x and β_x are at a minimum to minimize their contribution to curly-$\mathcal{H}$

[8] M. Aiba *et al.*, "SLS-2 Conceptual Design Report," ed. A. Streun (PSI, 2017), `http://www.lib4ri.ch/archive/nebis/PSI_Berichte_000478272/PSI-Bericht_17-03.pdf`.
[9] J.P. Delahaye and J.P. Potier, PAC 1989, pp. 1611.
[10] B. Riemann and A. Streun, Phys. Rev. Accel. Beams **22**, 021601 (2019).

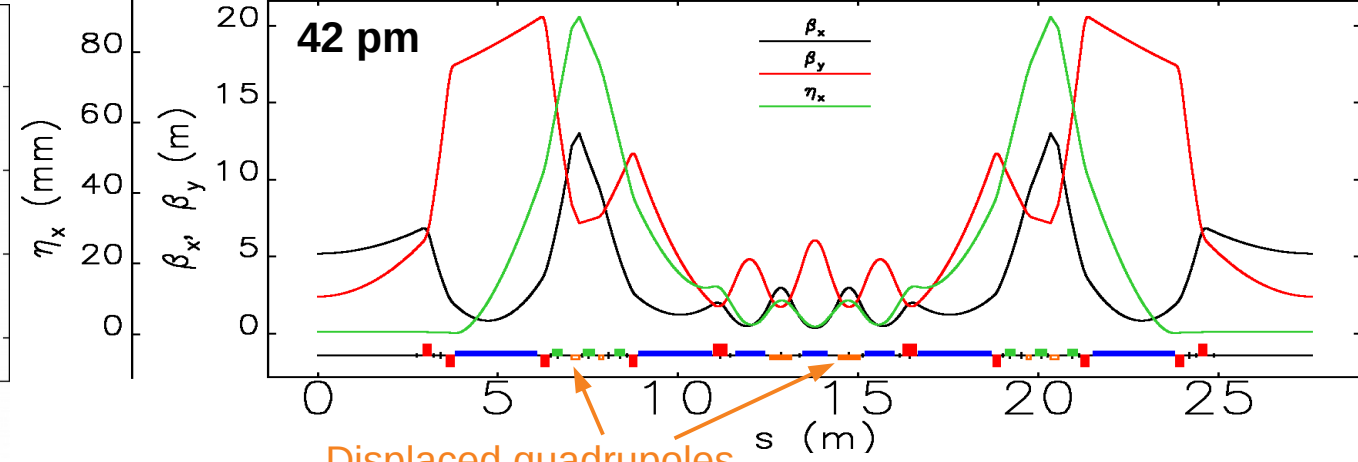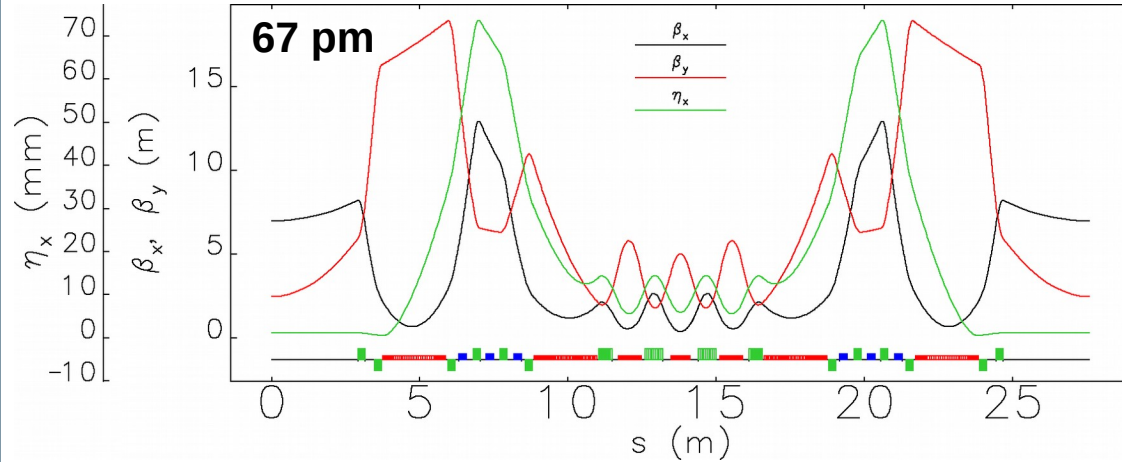# Hybrid MBA lattice has a number of different features

- Hybrid MBA lattice[11] was developed at the ESRF and is now being installed as part of their ESRF-EBS upgrade targeting 133 pm natural emittance

- Our simulations indicate that the hybrid MBA typically has better nonlinear dynamics for high energy storage rings
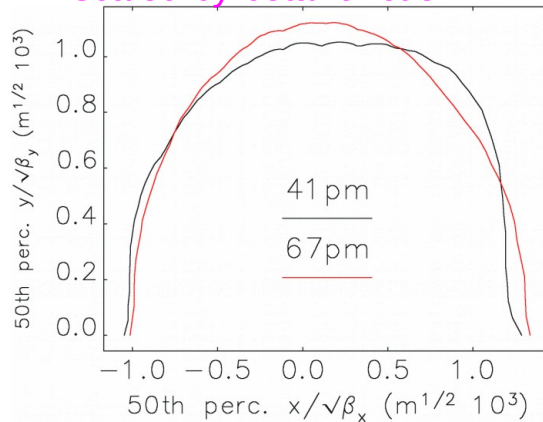
[11] L. Farvacque *et al.*, IPAC 2013, pp 79; L. Farvacque, *et al.,* "ESRF-EBS Design Report," ed. by D. Einfeld and P. Raimondi (The European Synchrotron, 2018).
https://www.esrf.eu/files/live/sites/www/files/about/upgrade/documentation/Design%20Report-reduced-jan19.pdf

Reverse bends enabled APS-U to further reduce emittance

67 pm

42 pm

Displaced quadrupoles
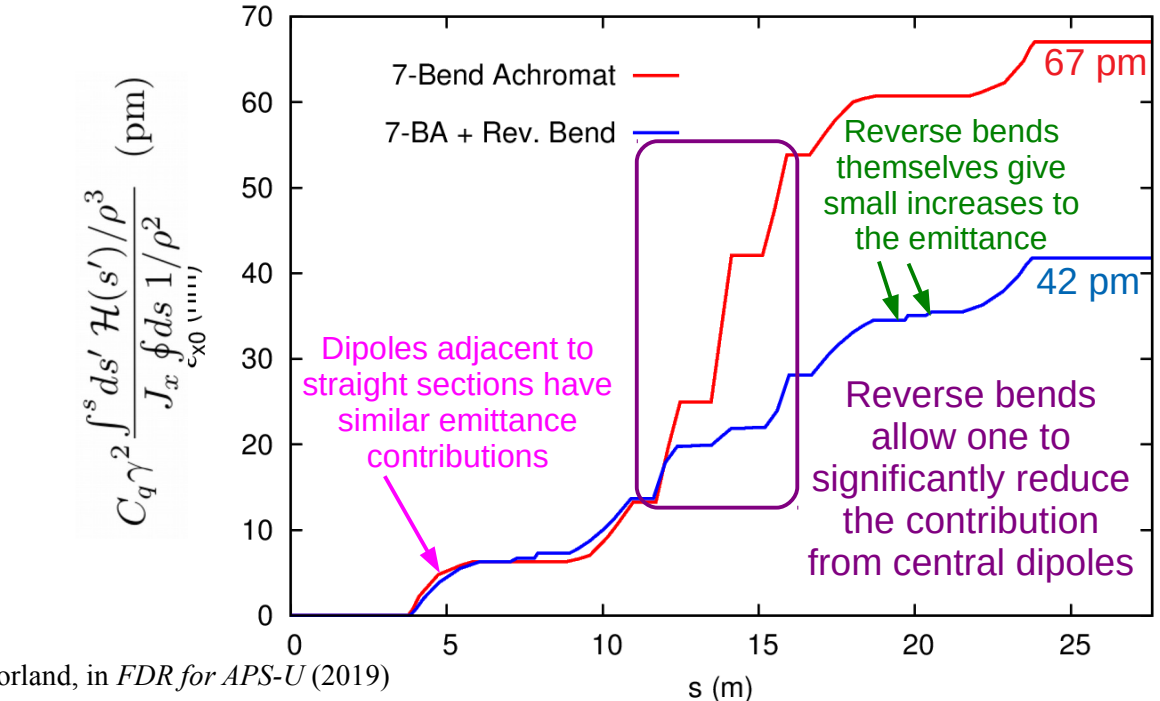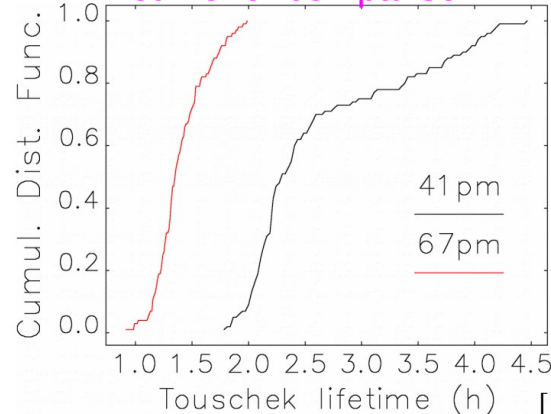(AKA reverse bending transverse gradient dipoles)

- One of the first versions of the APS-U lattices was a 7-bend achromat with 67 pm emittance

- Adding reverse bends allows for emittance reduction to 42 pm while maintaining (or even improving) the nonlinear dynamics
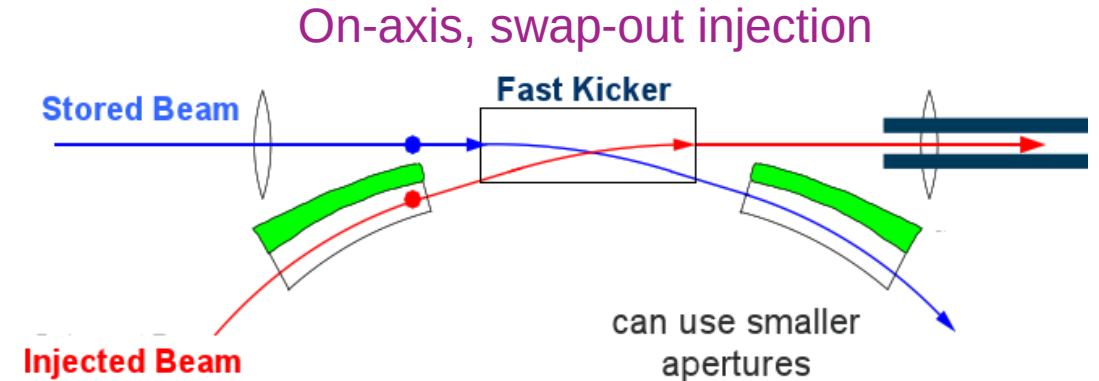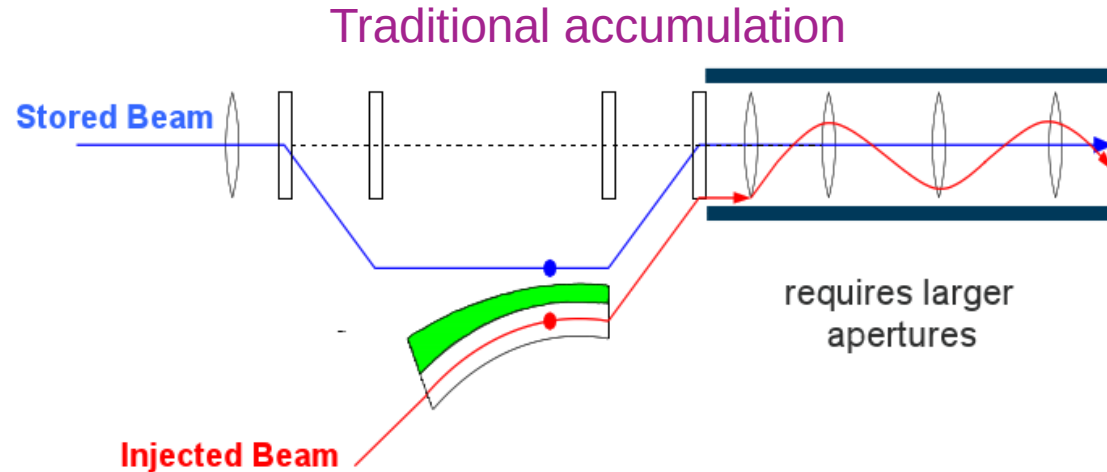
Median dynamic acceptance scaled by beta-function[12]

41 pm
67 pm

Approximate Touschek lifetime for comparison[12]

41 pm
67 pm

$$C_q \gamma^2 \frac{\int^s ds' \, \mathcal{H}(s')/\rho^3}{J_x \oint ds \, 1/\rho^2} \quad (pm)$$

7-Bend Achromat
7-BA + Rev. Bend

67 pm

42 pm

Reverse bends themselves give small increases to the emittance

Dipoles adjacent to straight sections have similar emittance contributions

Reverse bends allow one to significantly reduce the contribution from central dipoles

[12] M. Borland, in *FDR for APS-U* (2019)

Ryan Lindberg -- Physics of MBA lattice -- NAPAC 2019 -- September 3, 2019

Small dynamic acceptance can be partially overcome with advanced injection schemes

Traditional accumulation

On-axis, swap-out injection

Diagrams courtesy C. Steier (ALS/ALS-U)

- Swap-out injection[13,14] replaces a single bunch with minimal betatron oscillations
  - Possible with advances in fast pulser technology
  - Planned for APS-U and HEPS in Beijing
- ALS-U plans to combine a few nm-emittance accumulator ring with on-axis swap-out of bunch trains to allow for even tighter acceptance margins
- Many other possible injection schemes have been proposed including variants of longitudinal injection, schemes that use special magnets like an anti-septum or nonlinear kickers, etc.

[13] R. Abela, W. Joho, P. Marchand, S.V. Milton, and L.Z. Rivkin, EPAC 92, pp. 486.
[14] L. Emery and M. Borland, PAC03, pp. 256.

Double rf system can increase bunch length and lifetime

- A higher harmonic cavity (HHC) can lengthen bunch and reduce current density of low-emittance beam

- We model this in tracking including
  - Longitudinal impedance[15]
  - Beam-loaded main rf cavity with feedback[16]
  - Beam-loaded passive HHC

- Varying HHC detuning varies the voltage and thus the bunch length
  - "Ideal" HHC tuning flattens to rf potential, $V_{\parallel}(t) \sim t^4$.
  - "Overstretching" can make the bunch length ~2x "ideal" σ_t

- Touschek lifetime calculations[17] show that overstretching the bunch can significantly increase lifetime

[15] R. Lindberg et al., IPAC15, 1825.
[16] T. Berenc et al., IPAC15, 540.
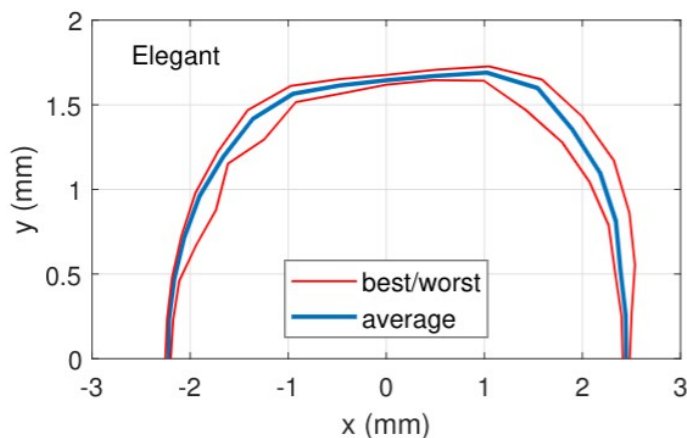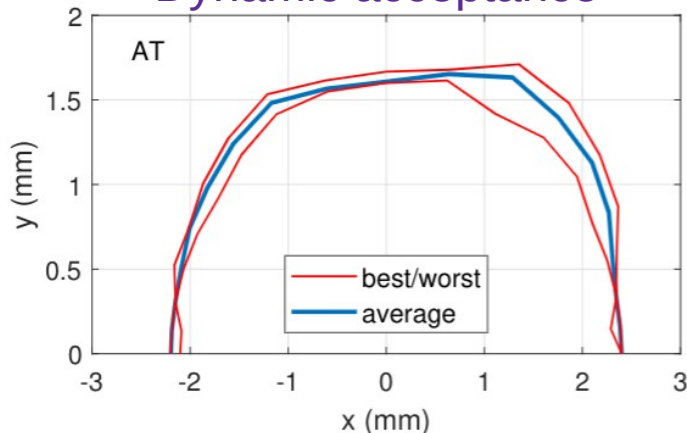[17] A. Xiao et al., IPAC15, 559.

200 mA average current in 324 bunches

200 mA average current in 48 bunches
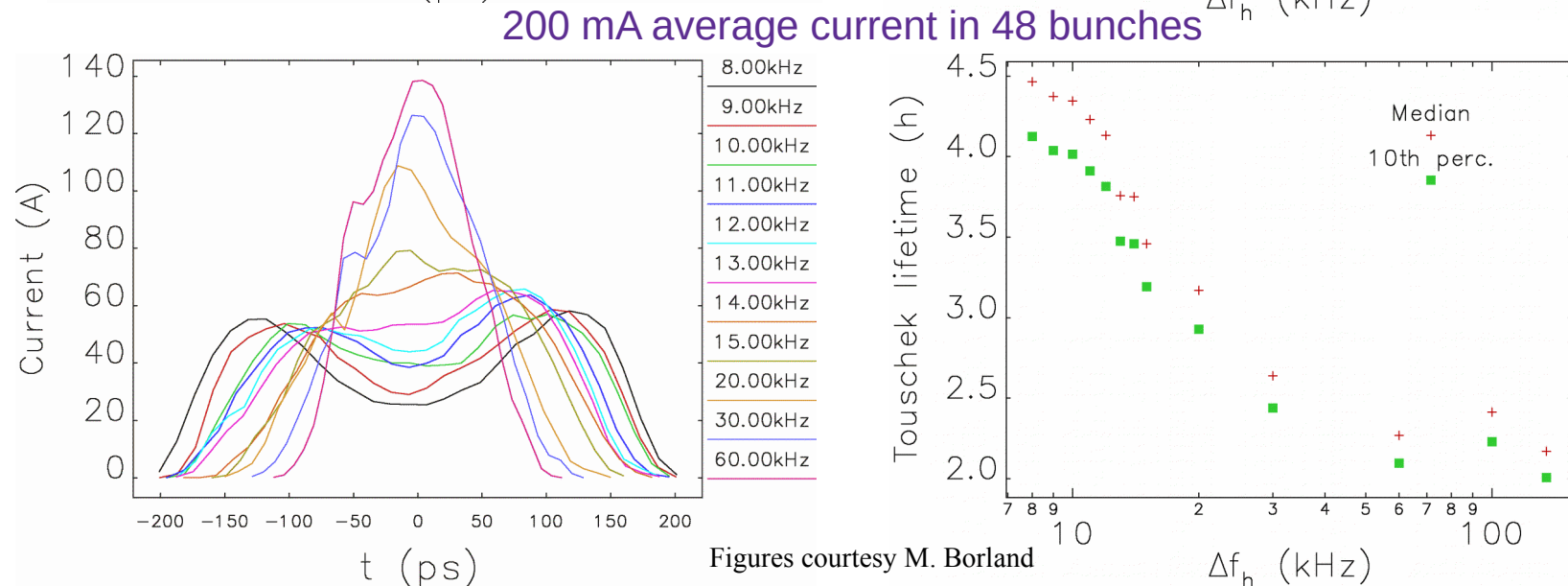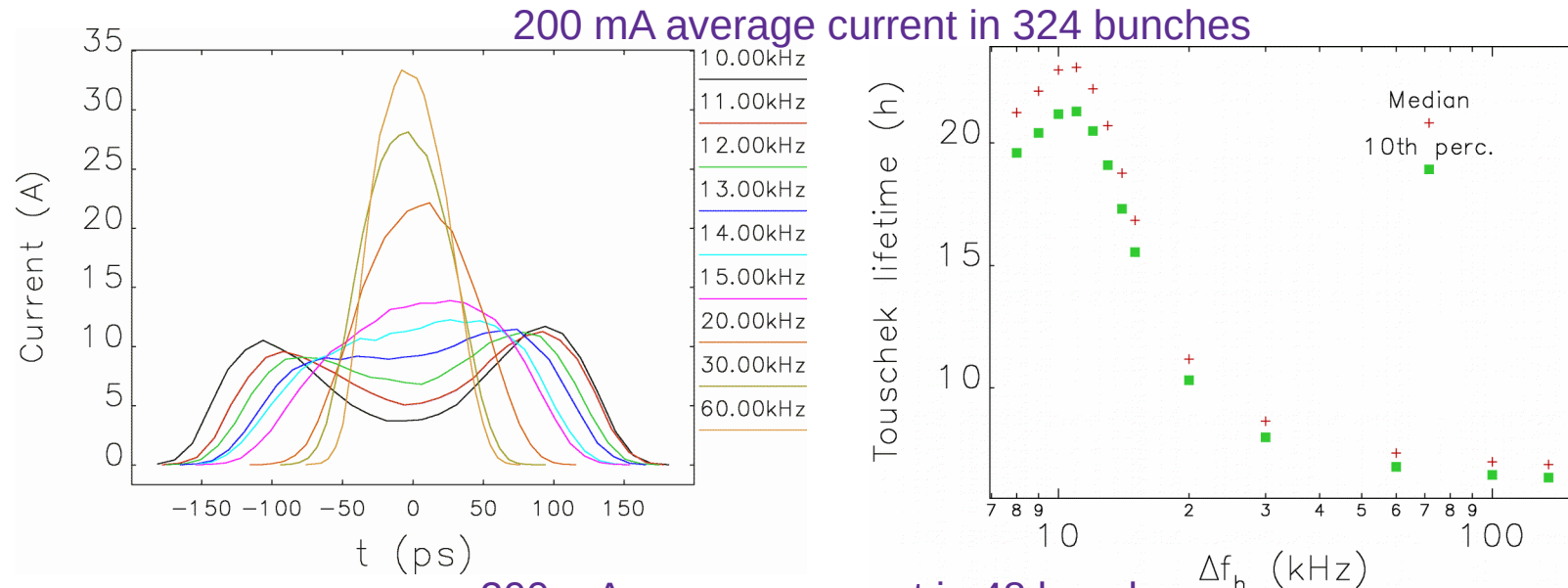
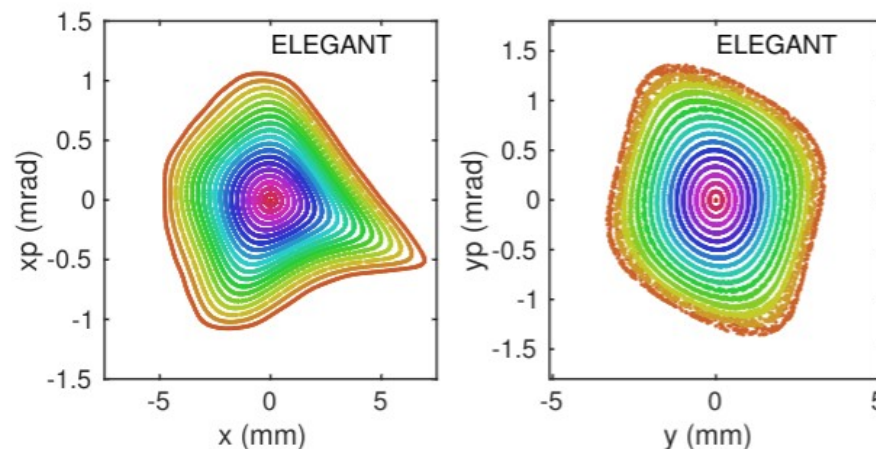Figures courtesy M. Borland
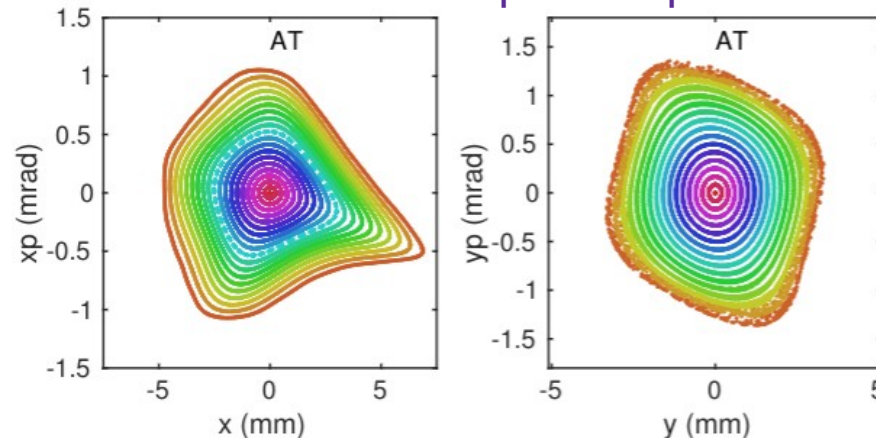
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High fidelity simulation tools are critical

- We rely heavily on simulations to predict complicated physics
- Making detailed comparisons between different codes is good for everyone

| Parameter	elegant	AT
Horizontal tune, ν_x	95.0999	95.0993
Vertical tune, ν_y	36.0999	36.1007
Momentum compaction, $\times 10^{-5}$	4.0406	4.0399
Chromaticity, ξ_x	8.1183	8.1704
Chromaticity, ξ_y	4.7221	4.8739
Natural chrom., ξ_x^{nat}	-133.6488	-133.5874
Natural chrom., ξ_y^{nat}	-111.6335	-111.4689
Emittance (pm)	41.6612	41.6434
Energy loss per turn (MeV)	2.8688	2.8700
Momentum spread, σ_δ, $\times 10^{-3}$	1.3499	1.3494
Damping partition, J_x	2.2497	2.2495
Damping time τ_x (ms)	6.8446	6.8424

Dynamic acceptance

Transverse phase space

Chromatic tune variation
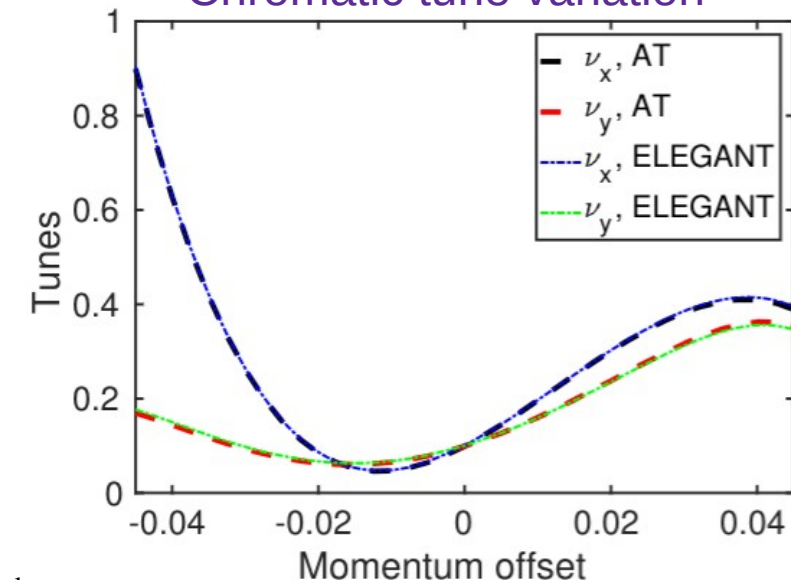
[18] M. Borland, Y.-P. Sun (ANL) and X. Huang (SLAC); unpublished

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Advanced algorithms enable robust optimization

- Lattice optimization a highly nonlinear problem with many variables

- APS pioneered use of tracking-based optimization[19] to rings[20,21]

- For APS-U, we use a multi-objective genetic algorithm[22] (MOGA) to evolve linear and nonlinear lattice properties, including

  - Particle tracking to determine injection aperture and lifetime

  - X-ray brightness calculation to determine performance at 10 keV

  - Constraints provided by engineering designs

  - Various error sets to insure robustness of solution

MOGA evolution from the START to the OPTIMAL

Improved optimization reduces spread in lifetime due to different error sets
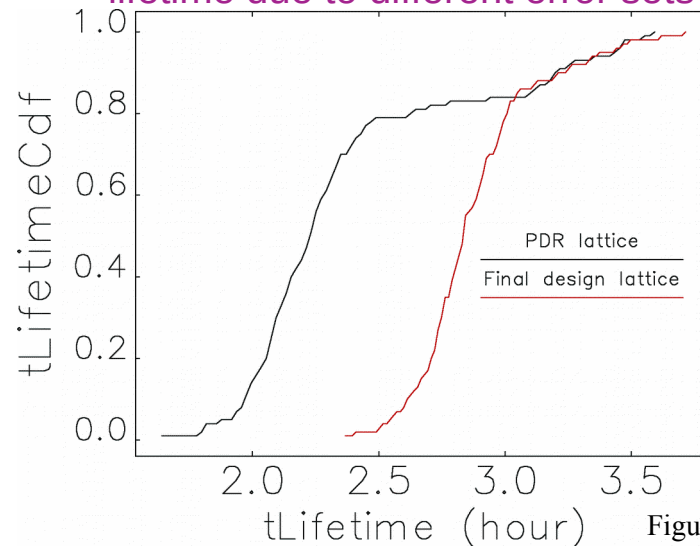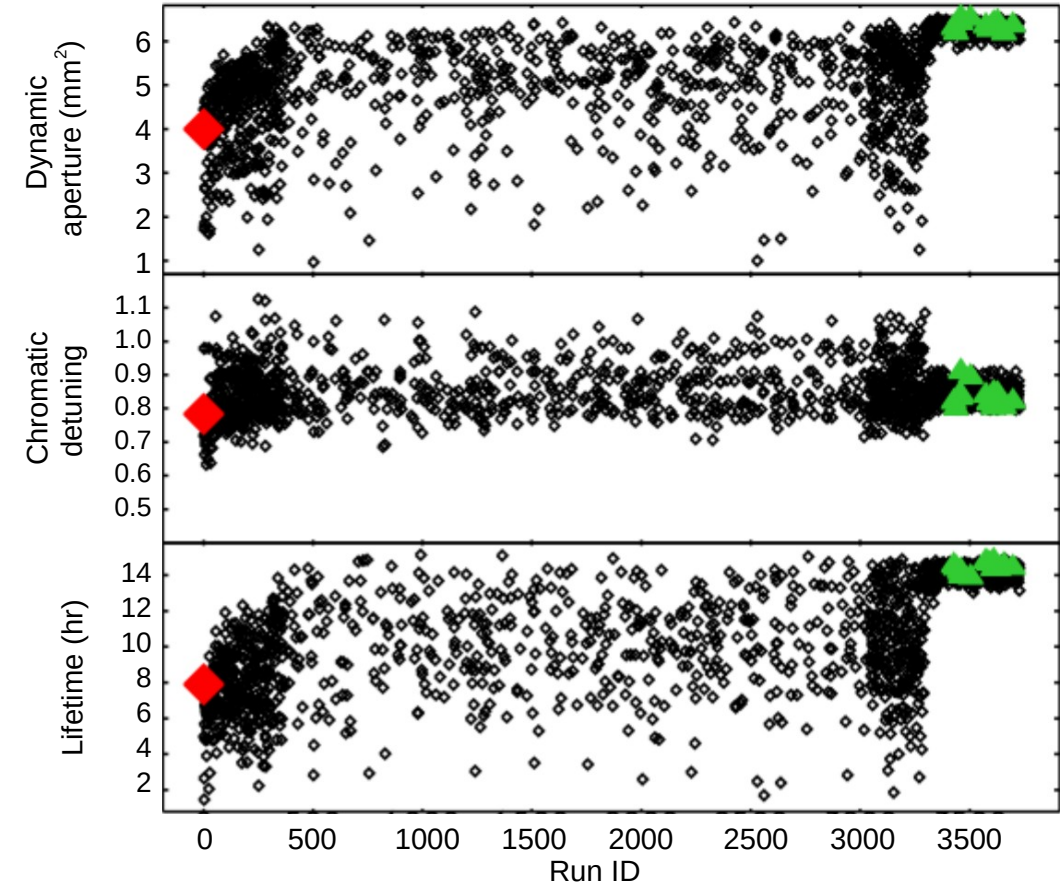
Figure courtesy M. Borland

Figure courtesy Y.-P. Sun

[19] I. Bazarov et al, PRSTAB **8**, 034202 (2005).
[20] H. Shang et al., PAC 2005, pp. 4230.
[21] M. Borland et al., PAC 2009, pp. 3850.
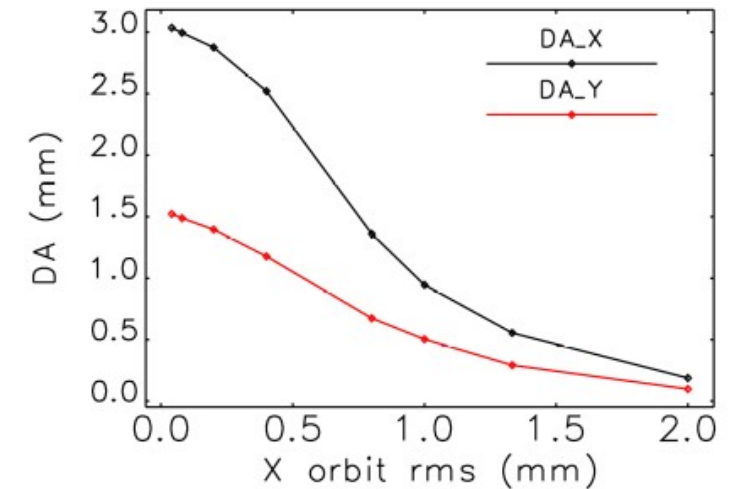[22] K. Deb et al., IEEE Trans. on Evol. Comp. **6**, 182 (2002).

Detailed commissioning simulations have become an important part of MBA design

Figures courtesy V. Sajaev

- Commissioning simulations are a more accurate way to derive error sets for subsequent lattice evaluation

- The main motivation behind commissioning simulations was the desire to minimize dark time during an upgrade
  - ESRF, APS-U, ALS-U, and SIRIUS have all developed automated commissioning tools[23]

- Our lattice commissioning simulations consist of
  1. Establishing first turn
  2. Multi-turn trajectory correction
  3. Orbit correction
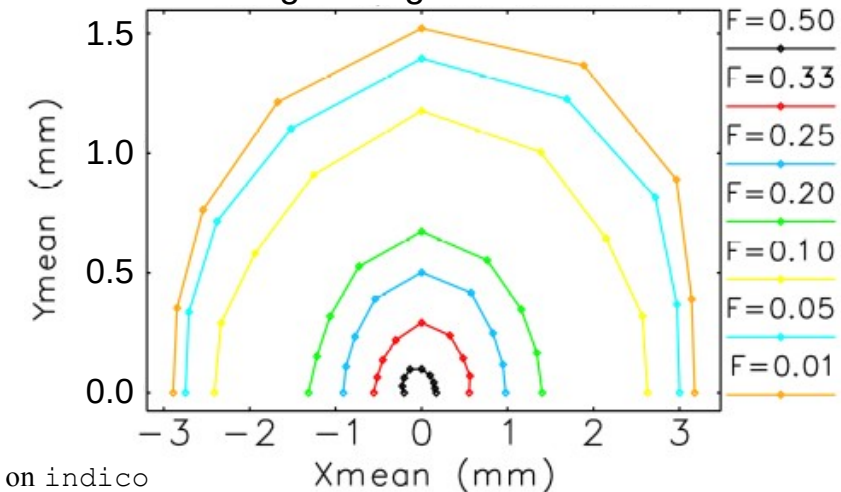 4. Beta function and coupling correction

All while including all sources of errors that we can think of: Magnet alignment, tilt, strength, BPM offset, calibration, ...

Median dynamic aperture for uncorrected lattice
F = scaling of magnet error tolerances

- Early simulations showed that the uncorrected dynamic aperture is expected to be smaller than the expected orbit errors
  - Trajectory is corrected to zero, but beam is not captured if (distance between trajectory and orbit) > (dynamic aperture)

- Sextupoles should be off until one achieves hundreds of turns, at which point they can be slowly powered up.

Recent successful tests at APS have helped validate our approach

[23] See, e.g., talks for the "Beam Tests and Commissioning Workshop," 2019 on indico

Conclusions

- Ultra-low emittance light sources can open new frontiers in x-ray science

- Multi-bend achromats can be the next generation low emittance machine

- Along with great potential comes great challenges/opportunities
  - Strong magnets and small vacuum chambers
  - Tight error tolerances on magnets and alignment
  - Highly nonlinear dynamics and small dynamic aperture

- These challenges can be met with a host of
  - Clever design (gradient magnets, reverse bends, dispersion bumps)
  - Improved injection schemes
  - Extensive simulation and experiments
  - Advanced optimization techniques

- There are also a rich set of physics IN multi-bend achromats not covered here
  - Possibility for both traditional and fast-ion-like instability
  - Collective dynamics in harmonic bunch lengthening system
  - Beam dump material damage by ultra-low emittance beams
  - And more...there are many posters covering these and similar topics

Thank you for your attention!