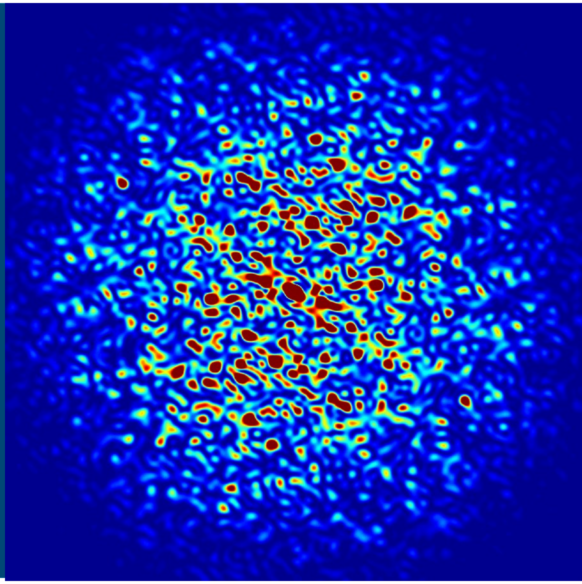
Physics of multi-bend achromat lattices



Ryan Lindberg
Physicist, Accelerator Systems Division
Advanced Photon Source, Argonne National Laboratory

NSCL/FRIB Nuclear Science Seminar
September 18, 2019 in East Lansing, Michigan

Acknowledgments

- Members of the APS-U physics team
  - 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
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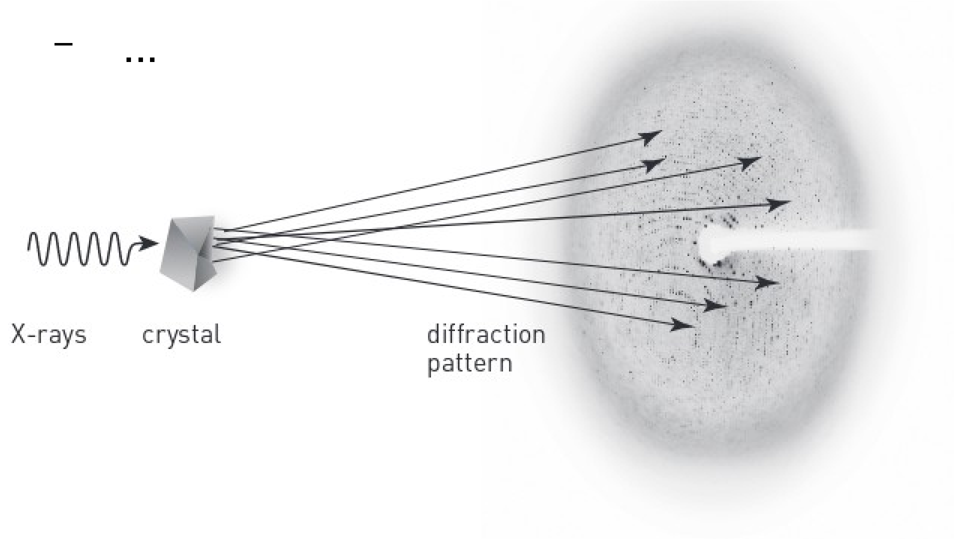

V. Ramakrishnan, T.A. Steitz,and A.E. Yonath
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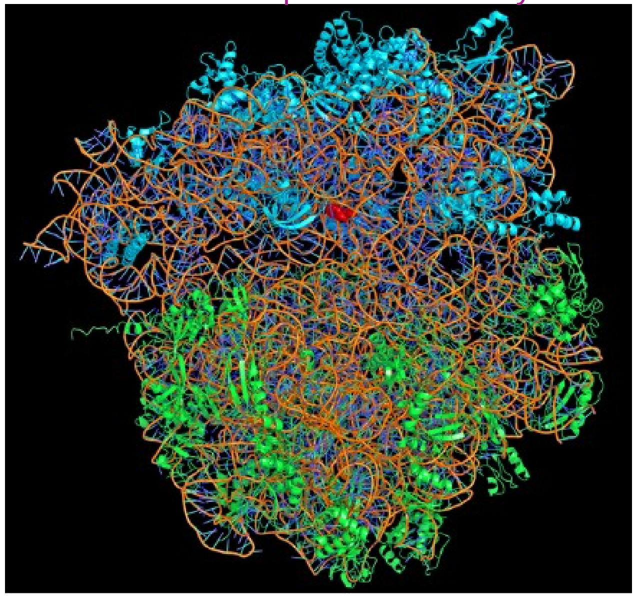

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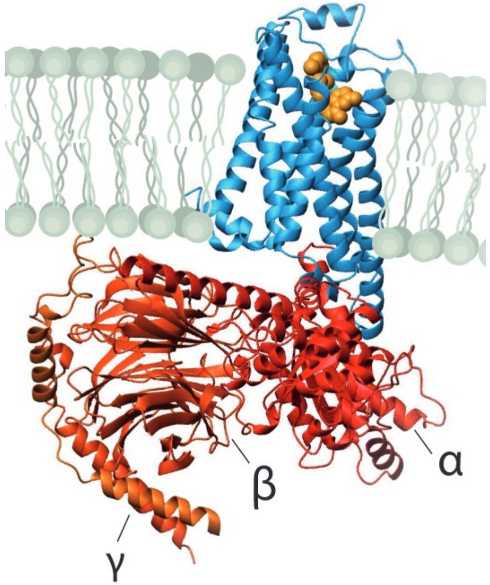

Press release. NobelPrize.org. Nobel Media AB 2019. Fri. 30 Aug 2019.

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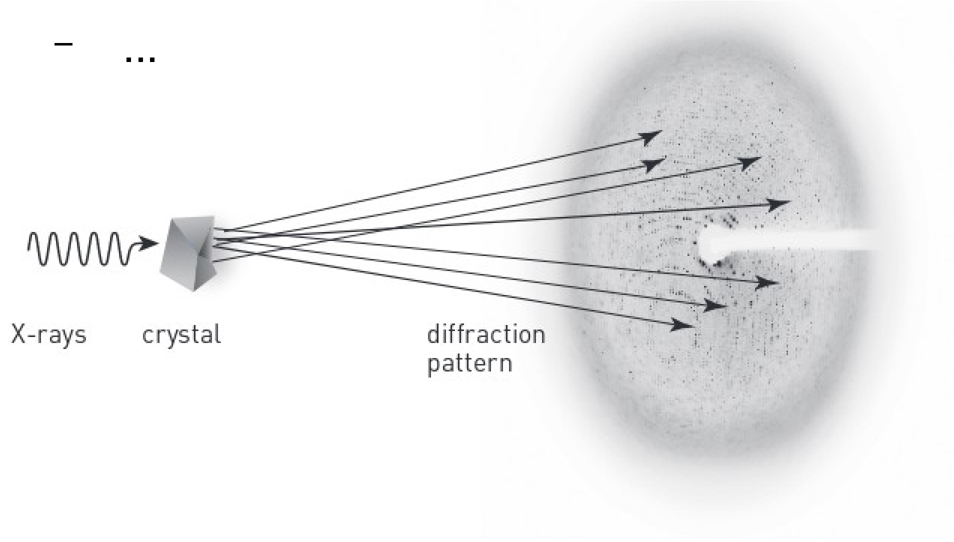
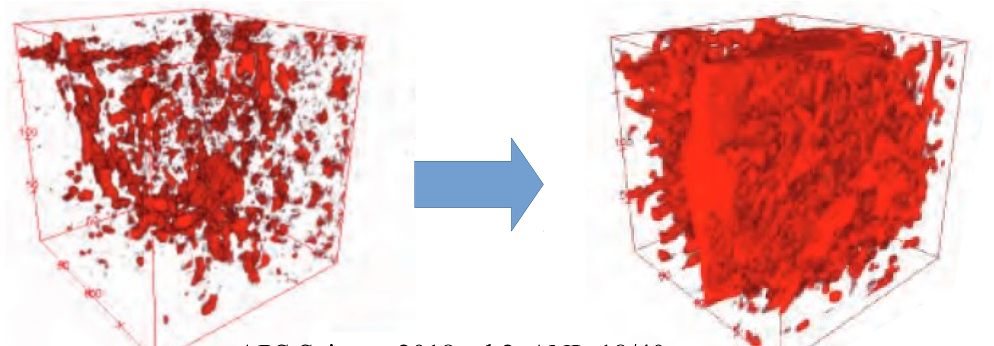


F. Shen et al., ACS Energy Lett. 3, 1056 (2018). ©2018 American Chemical Society
Microstructure-driven failure in Lithium ion batteries



APS Science 2018vol 2, ANL-18/40

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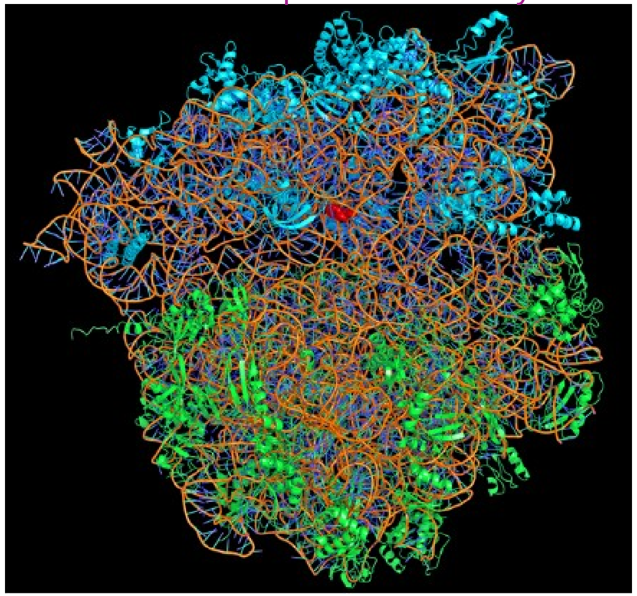

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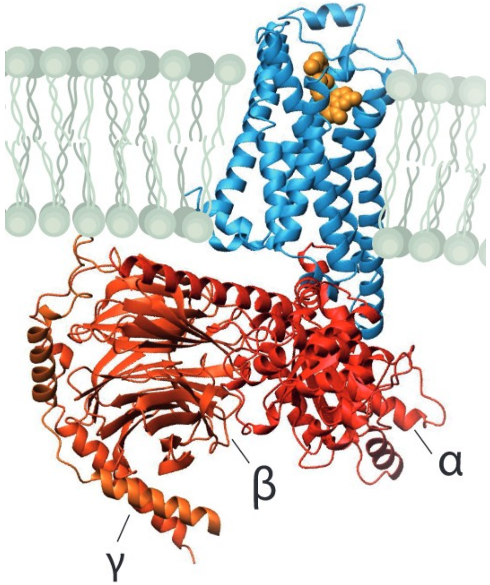

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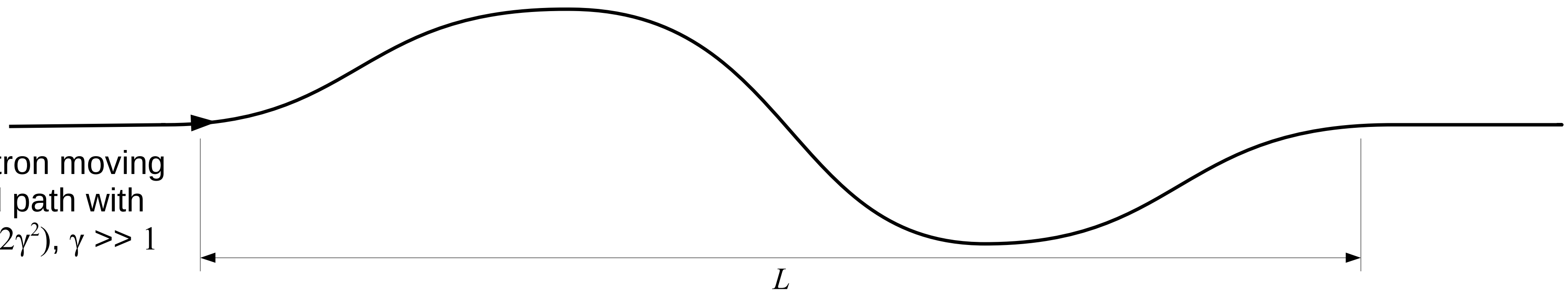
Synchrotron radiation is an intense source of x-rays



Relativistic electron moving along a curved path with speed $v \approx c(1-1/2\gamma^2)$, $\gamma >> 1$

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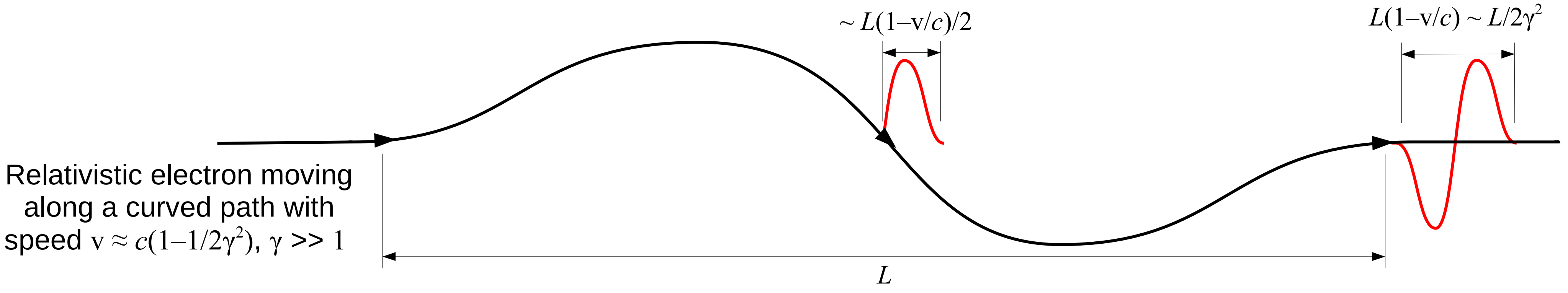

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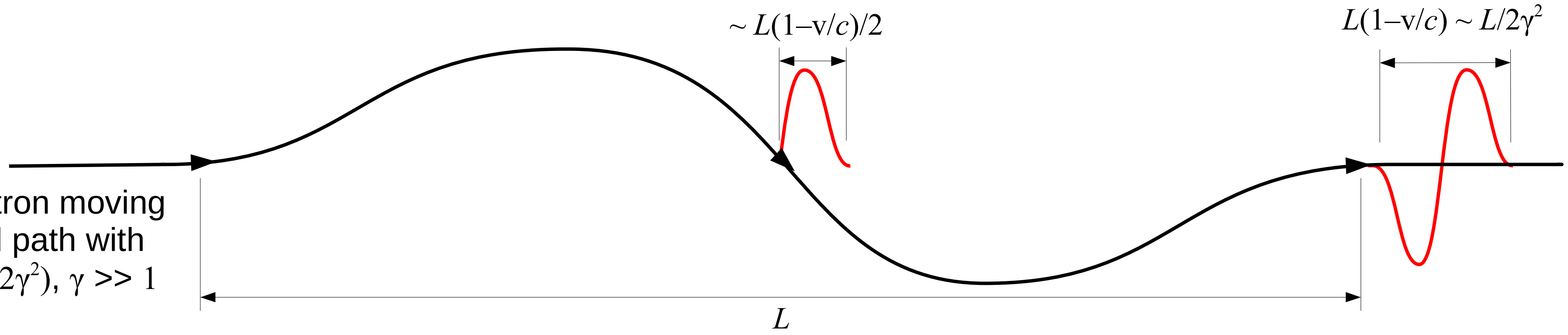

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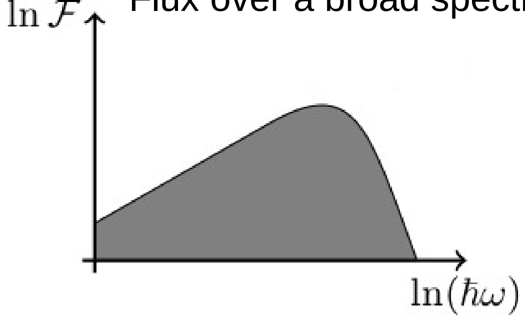
Flux over a broad spectrum



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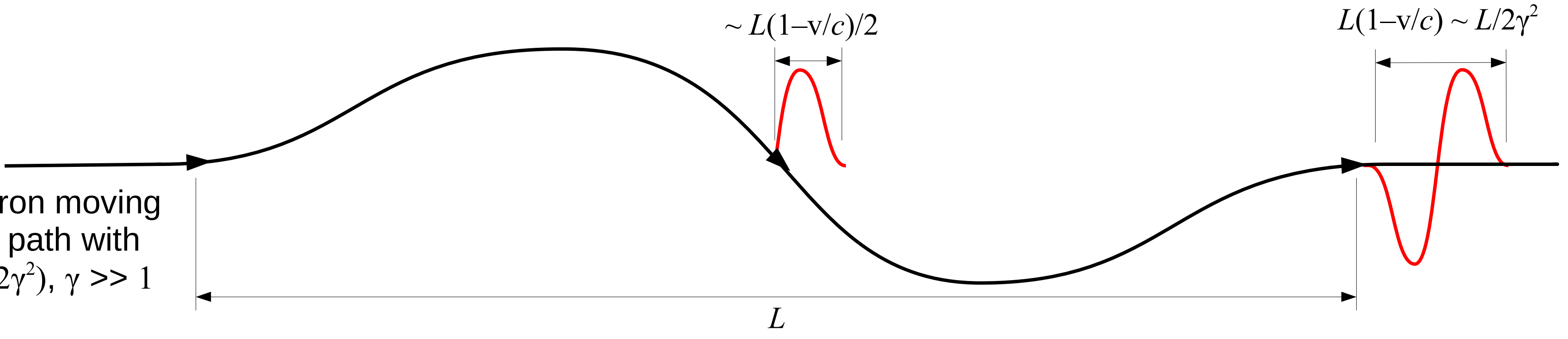

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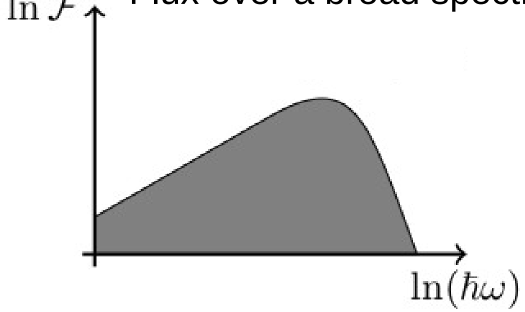
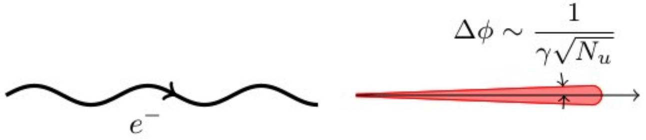
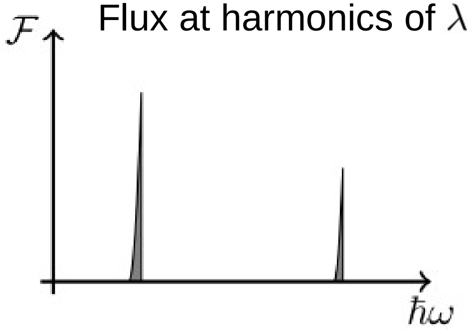
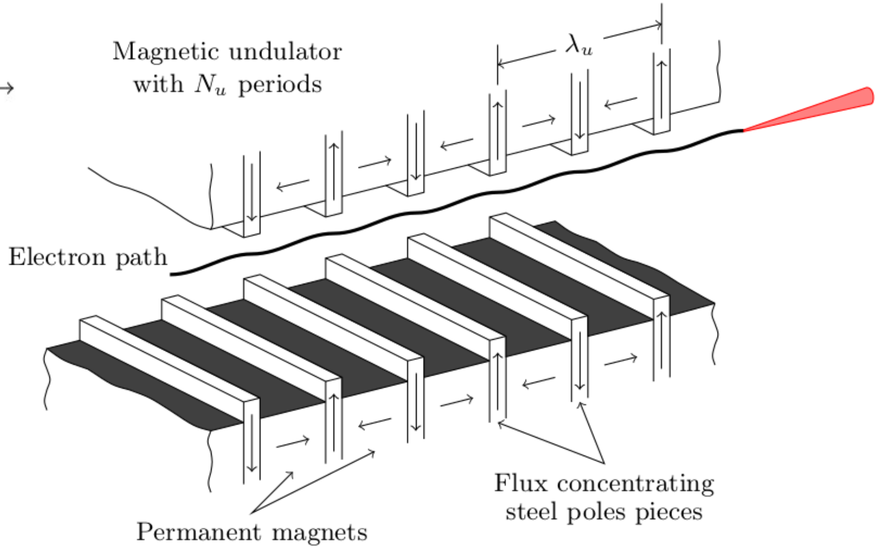


2. Undulators



Flux at harmonics of $\lambda \sim \frac{\lambda_u}{2\gamma^2}$





Light sources are located all over the world

FROM: APS Science 2014, ANL-15/03

The Advanced Photon Source at Argonne National Lab

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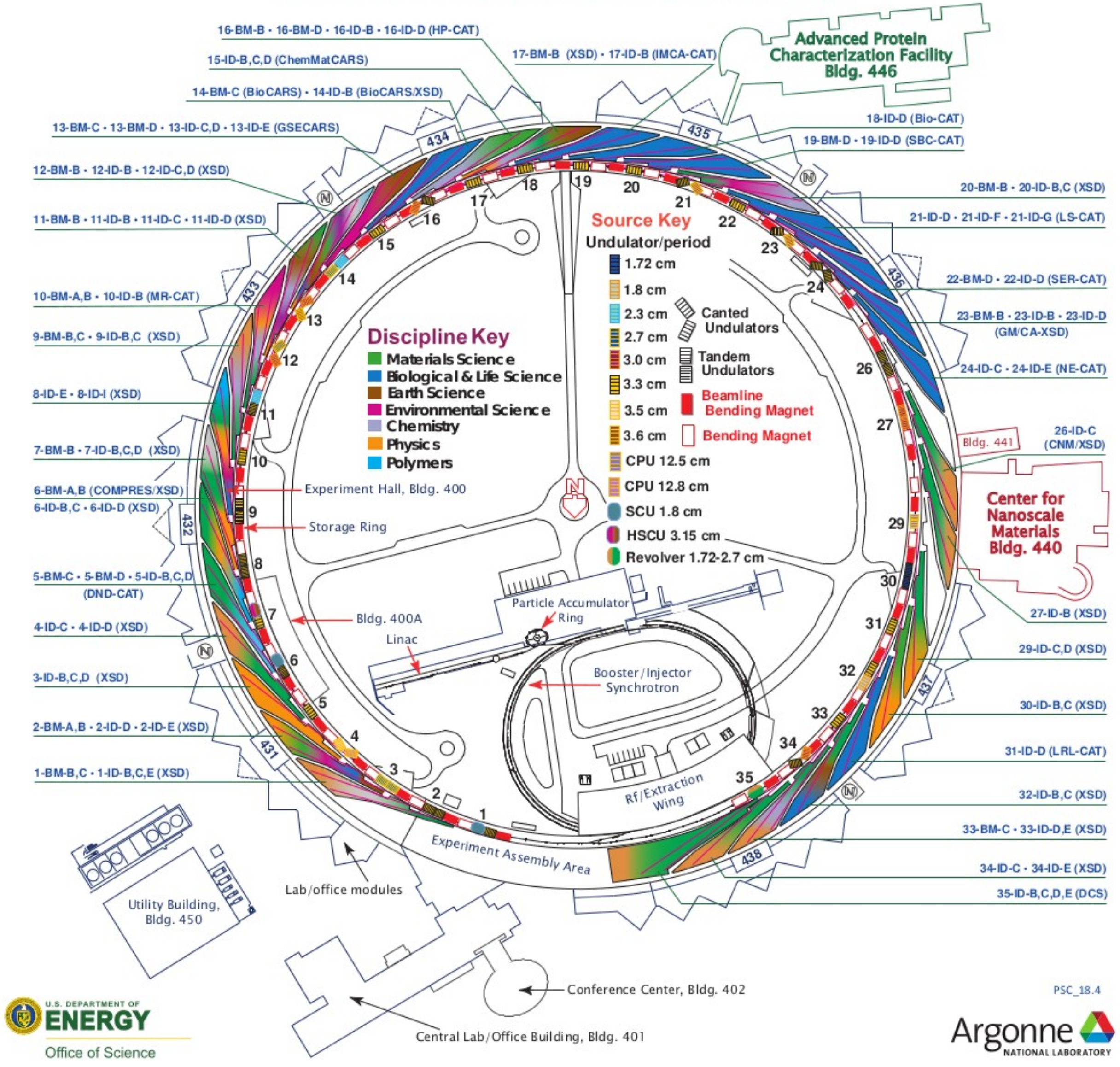

FROM: APS Science 2018 V1, ANL-18/40

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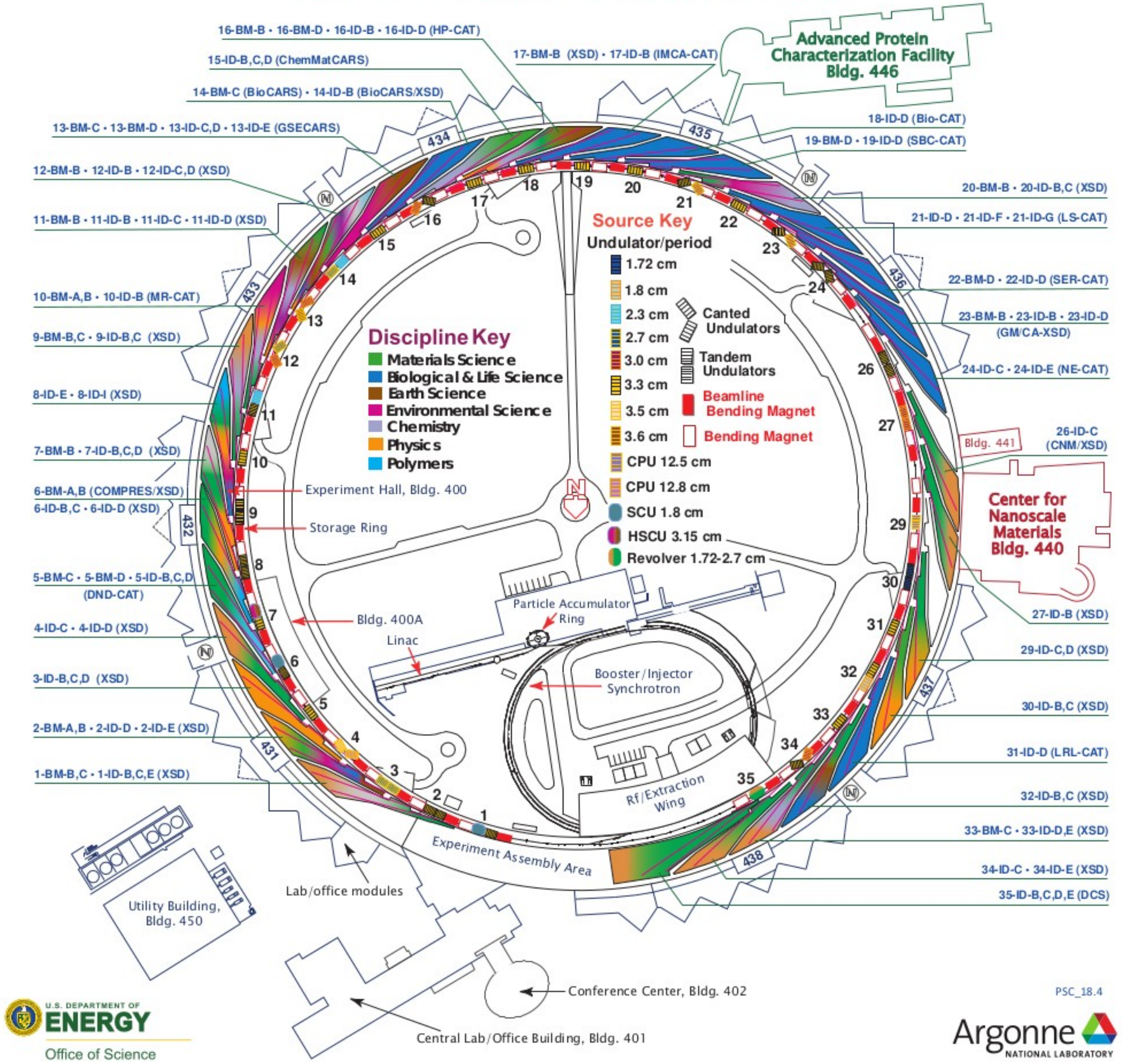

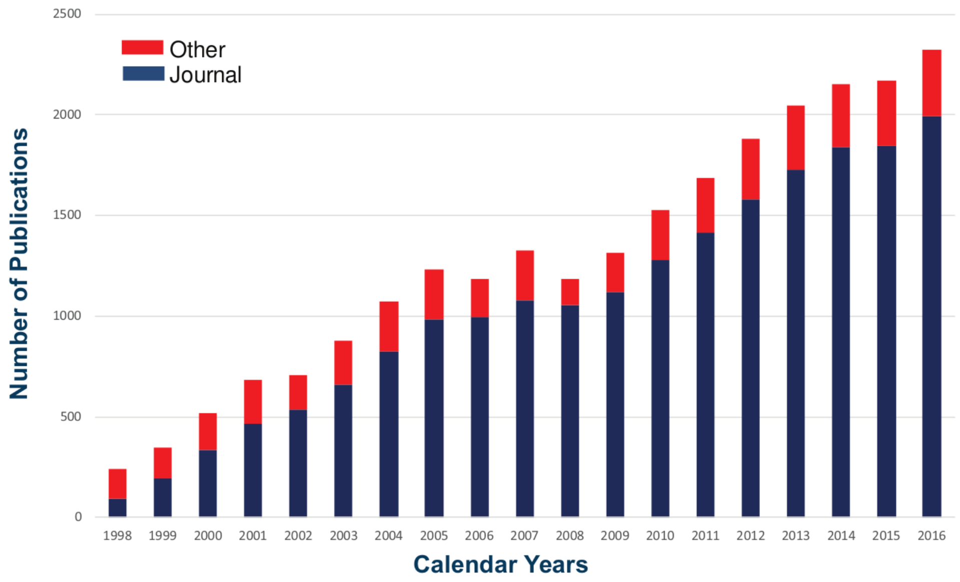

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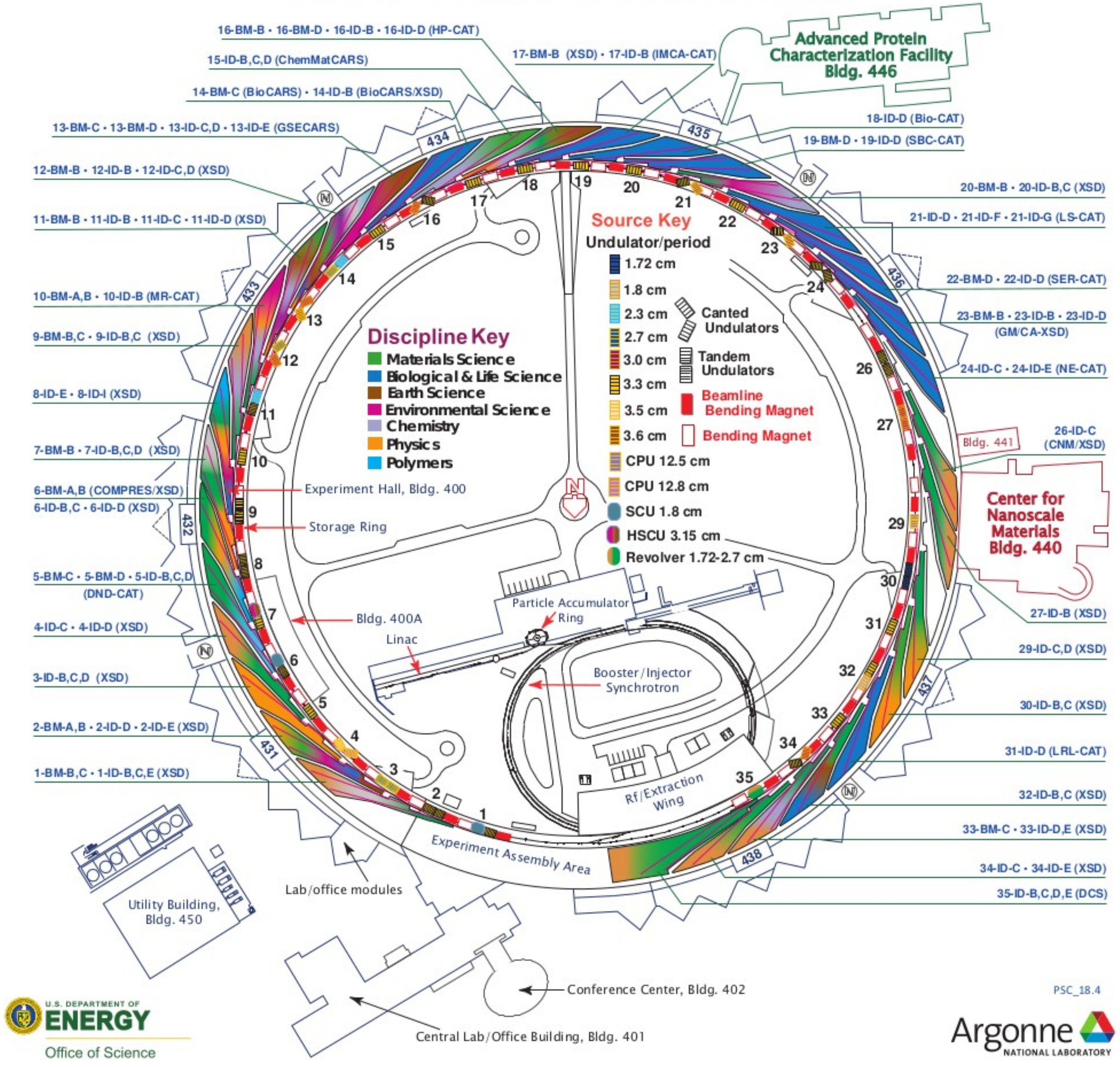

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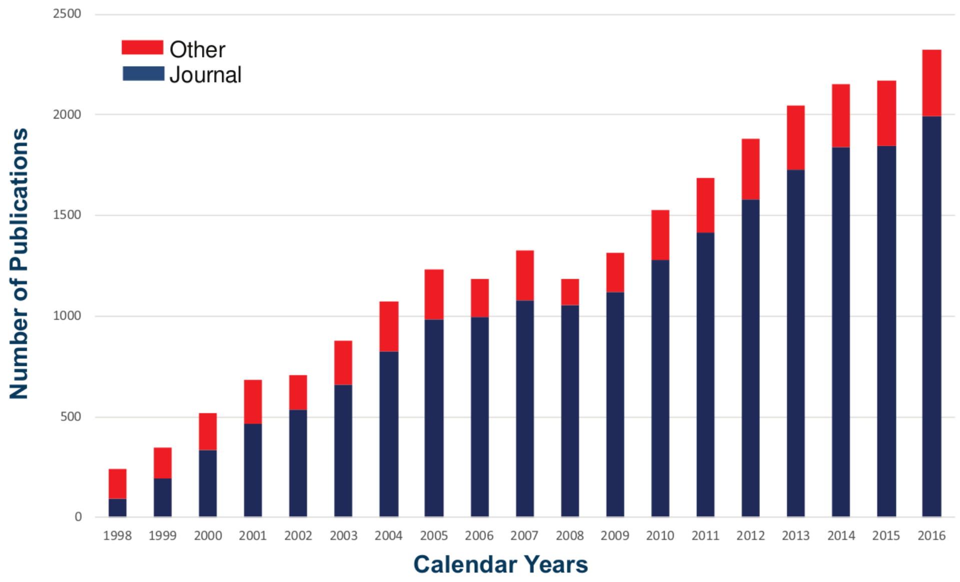

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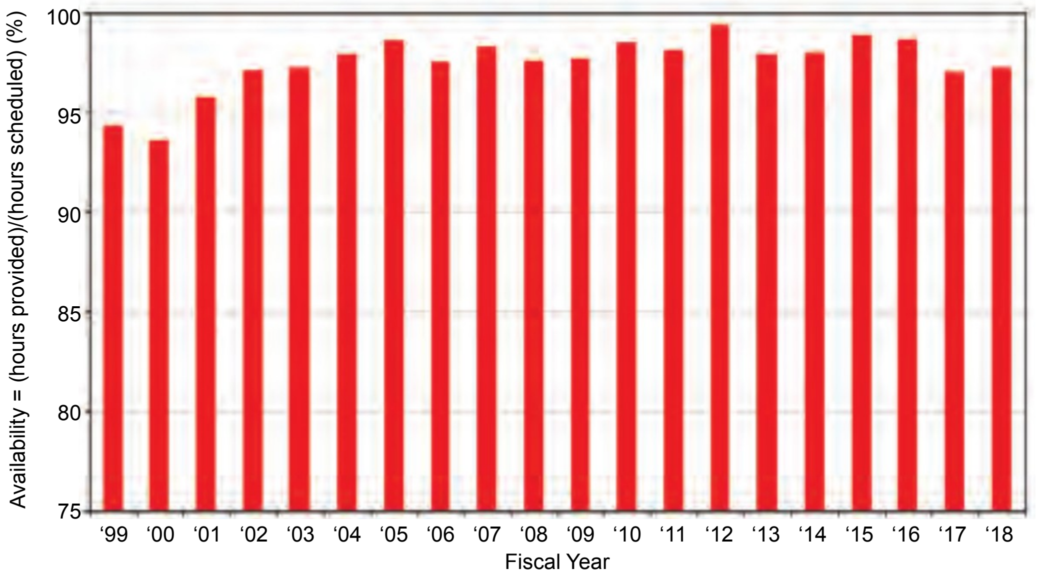

Brief history of storage ring-based light sources

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
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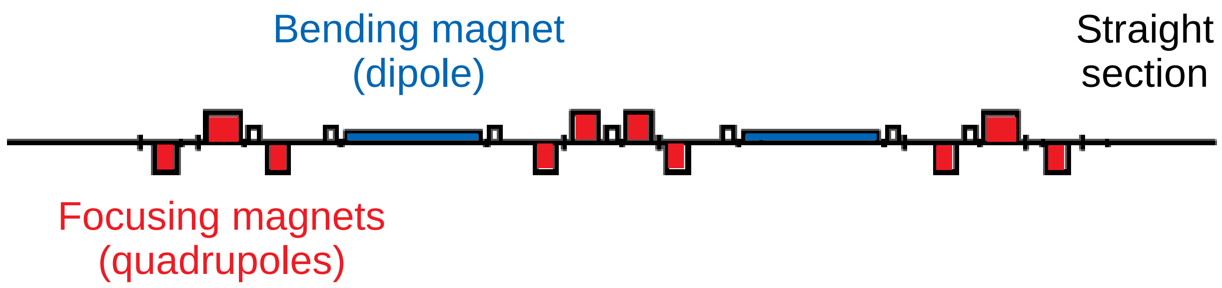

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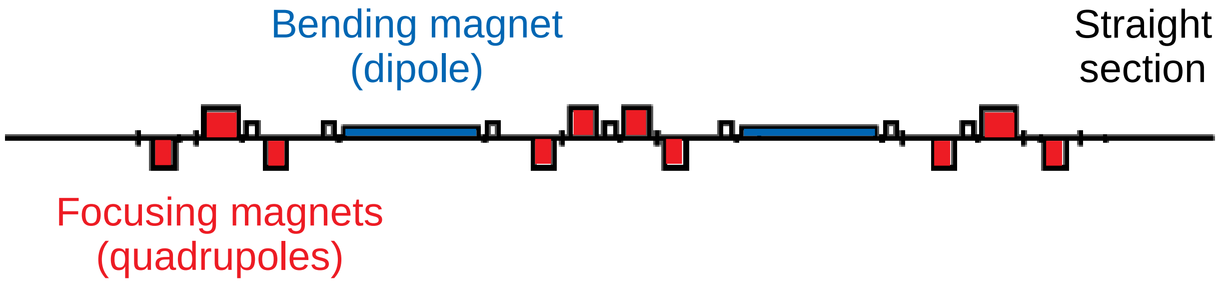

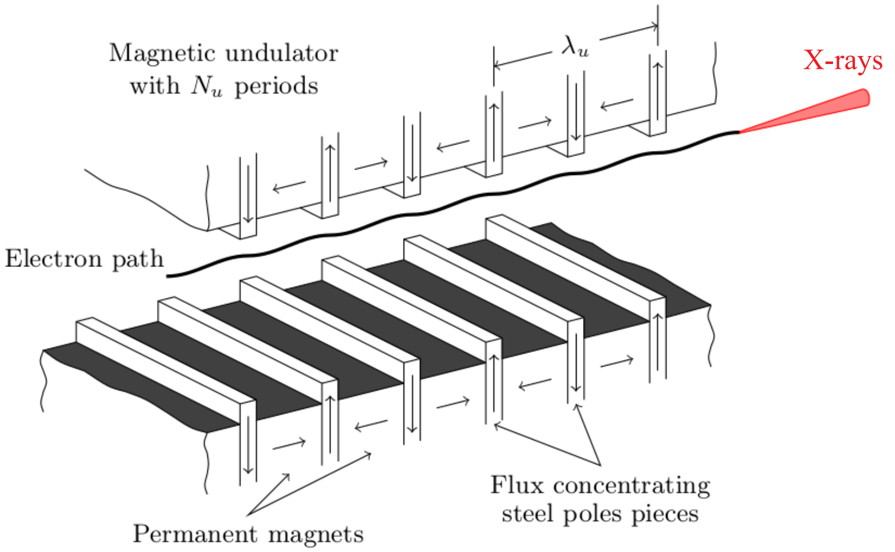

Repeat...

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Increasing x-ray spectral flux

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High brightness → Ability to focus large numbers of photons to a small spot
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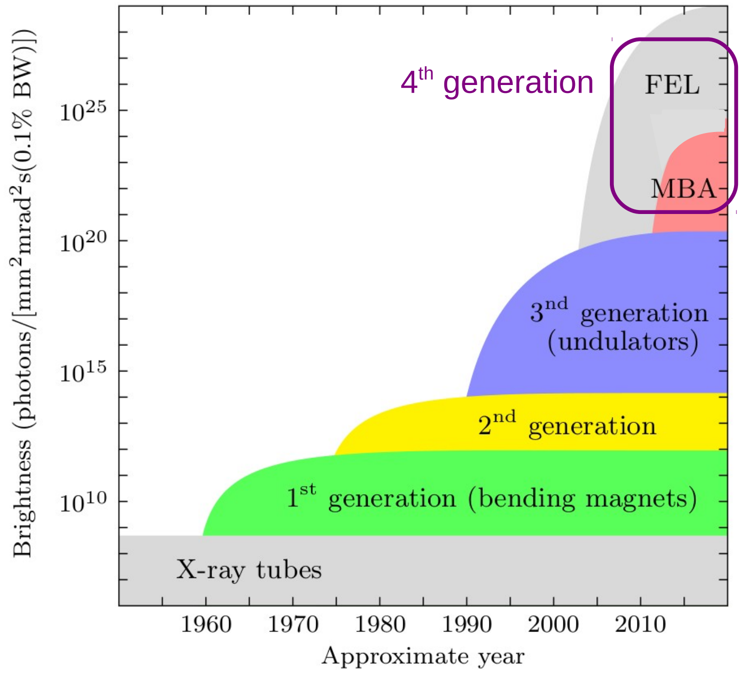

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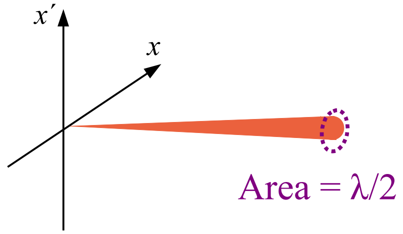

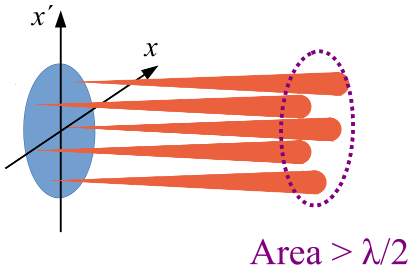

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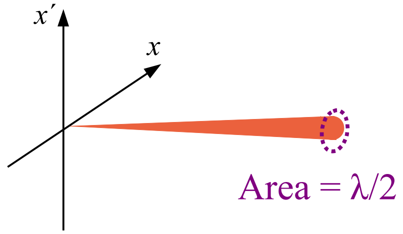

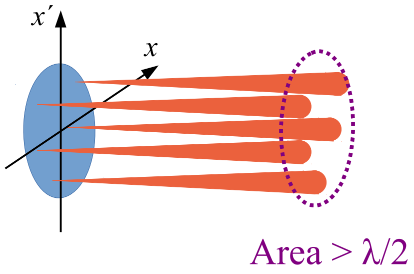

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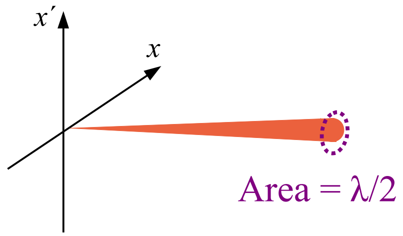

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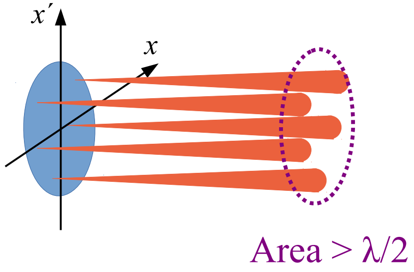

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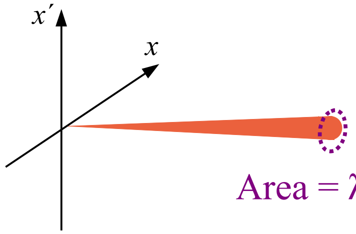

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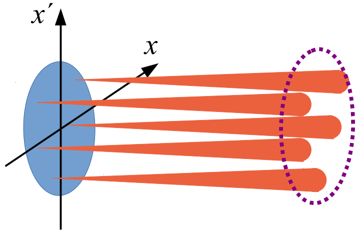

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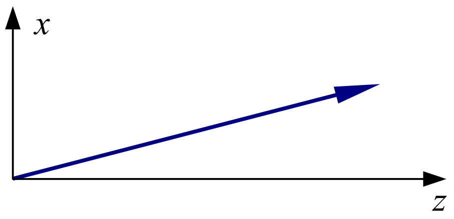
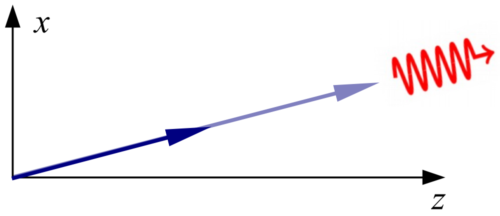
Maximizing the x-ray brightness at short wavelengths requires minimizing the emittance!

Equilibrium emittance in an electron storage ring is determined by emission of synchrotron radiation

- Synchrotron radiation leads to transverse damping:



Electron with initial momentum p at an angle ψ_i



Synchrotron emission along direction of motion reduces $|p|$

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

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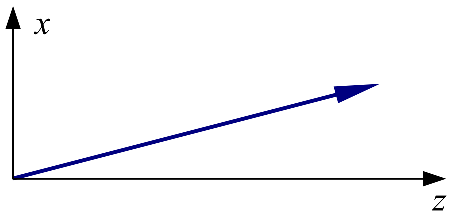

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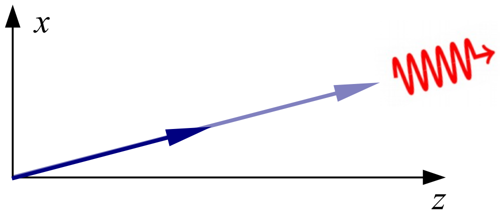

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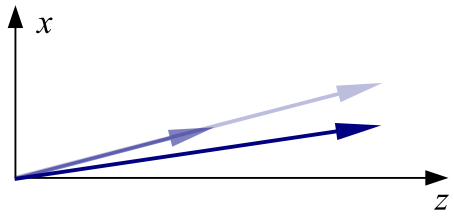

Acceleration in rf cavity restores only p_z, such that final angle $\psi_f < \psi_i$

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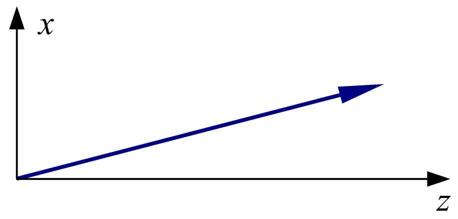

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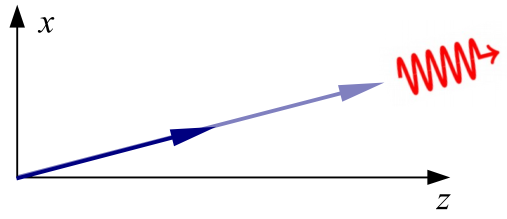

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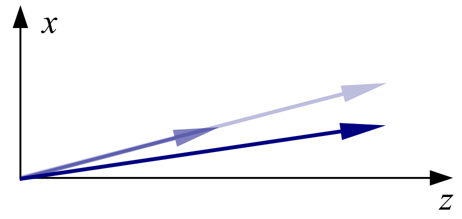

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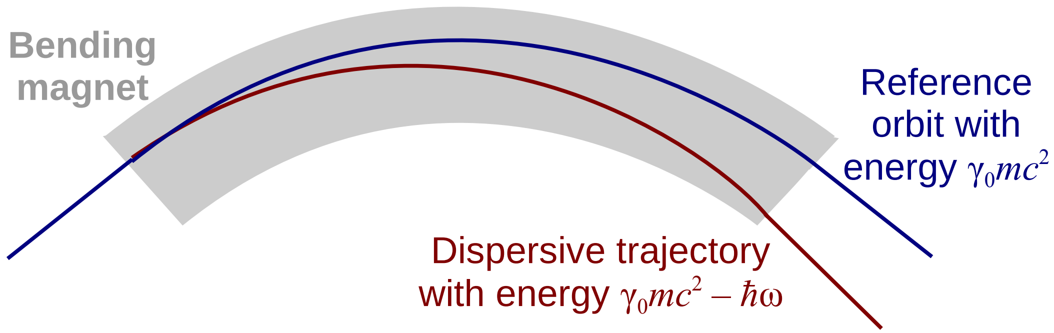
- Synchrotron emission also leads to diffusion



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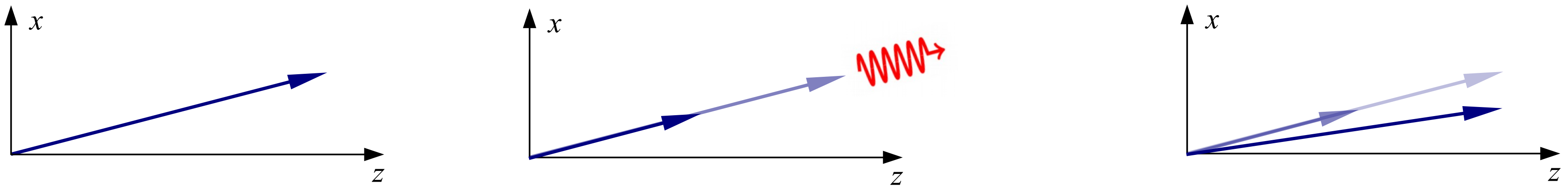

Electron with initial momentum p at an angle ψ_i

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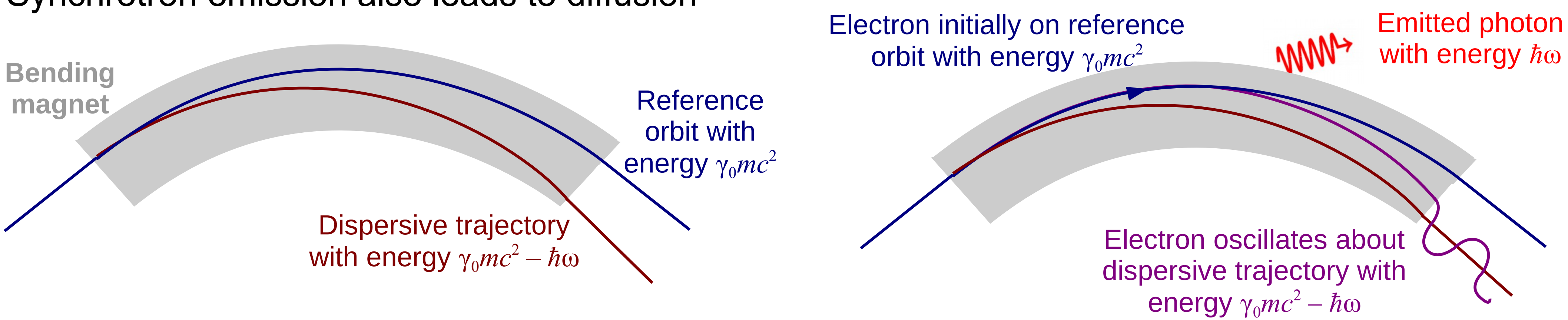

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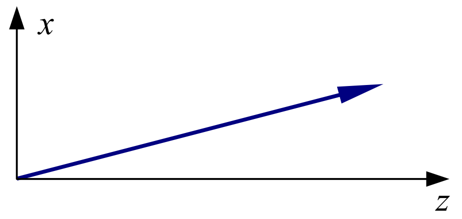

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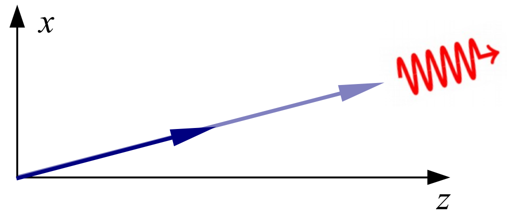

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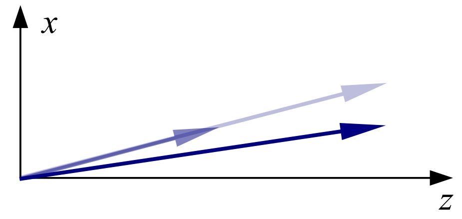

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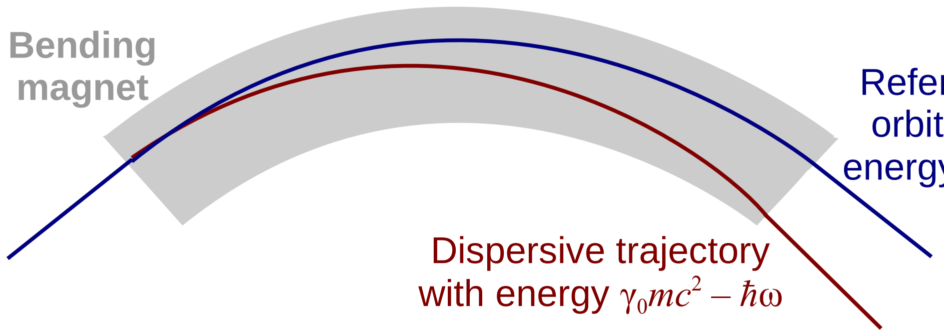

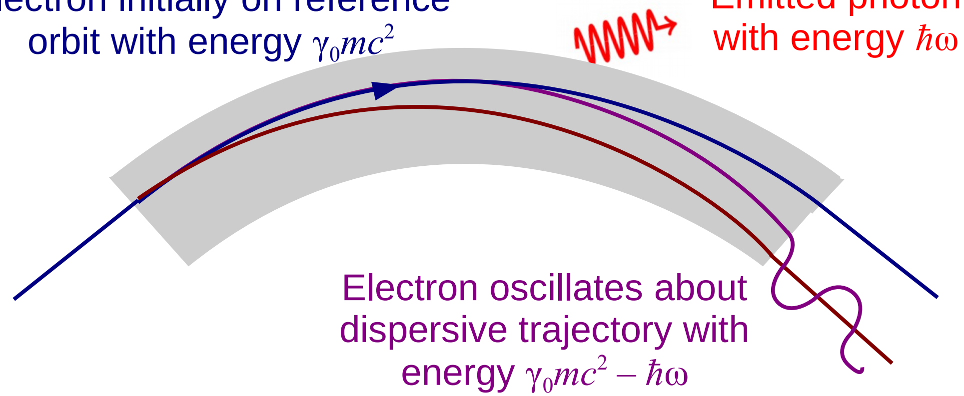

- Net result is Fokker-Planck dynamics that has a Gaussian equilibrium when damping balances diffusion

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Equilibrium emittance

- The properties of a linear lattice built of ideal quadrupoles (focusing elements) and dipoles (bending elements) are determined entirely by the lattice functions[2]
  - Orbit: Reference trajectory of on-axis electron that is at the design energy
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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.

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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[3]

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

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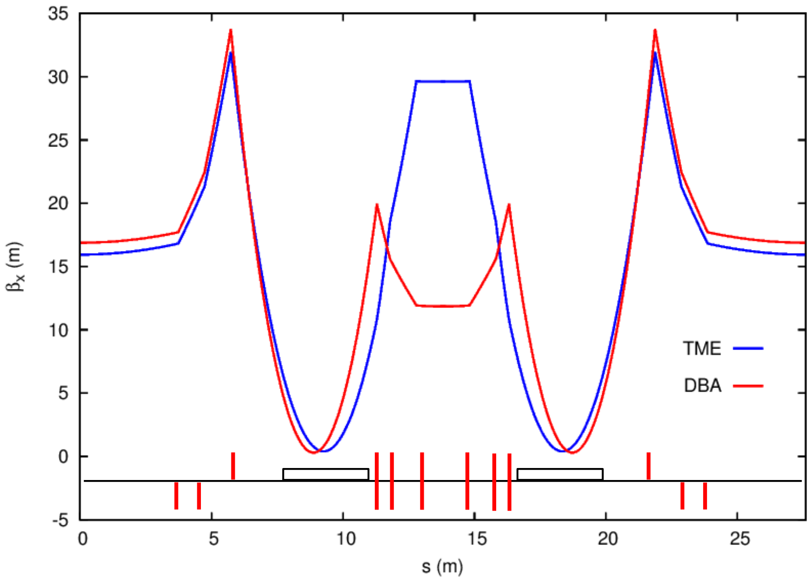

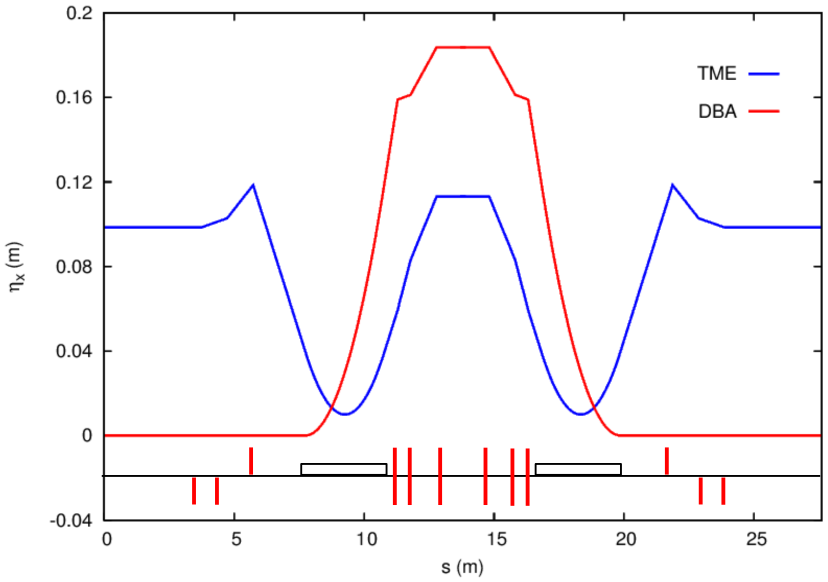

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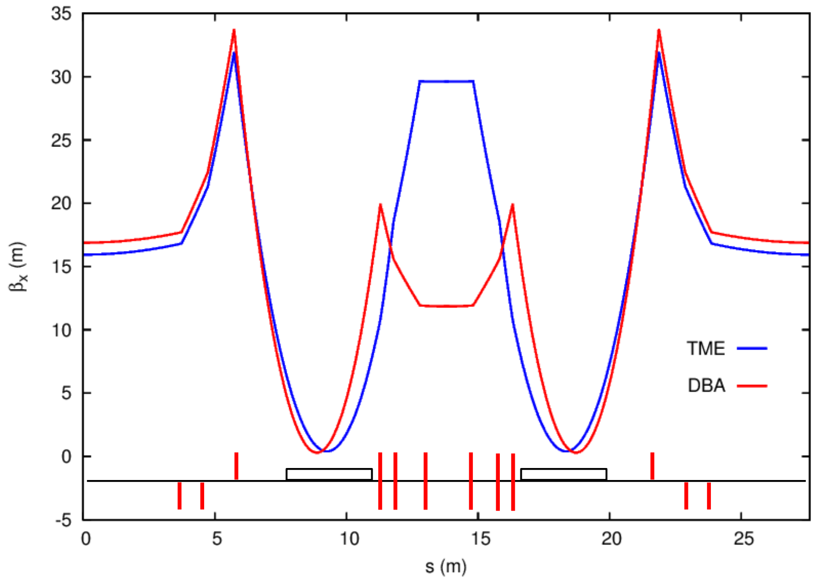

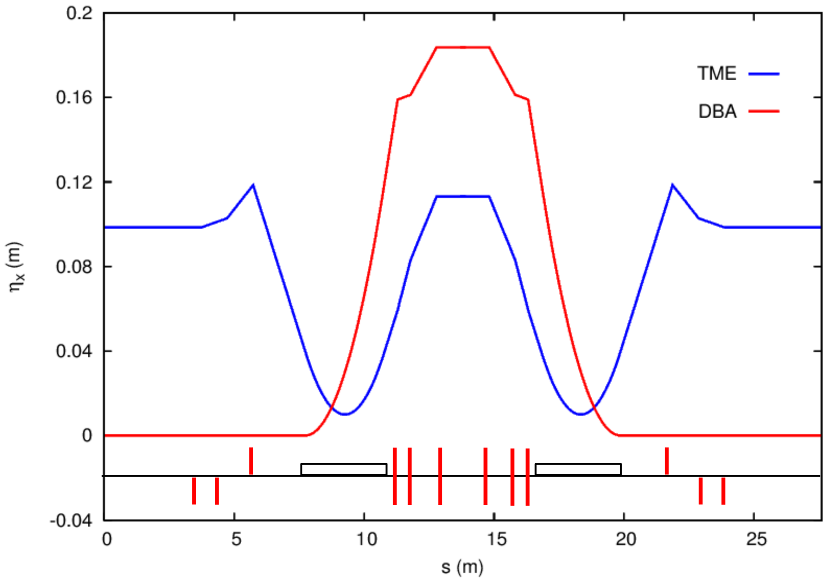

IMPORTANT NOTE:
No effort has been made to use realistic quadrupole strengths or to keep the vertical plane under control.

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

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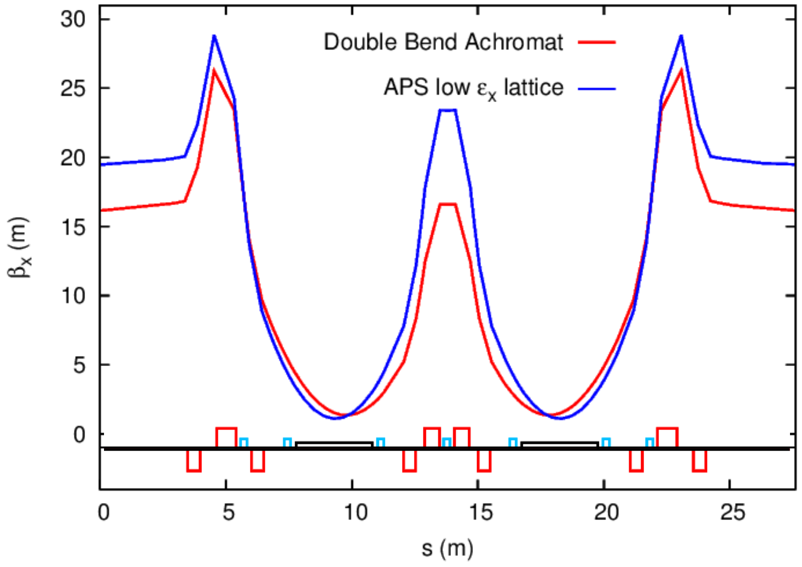

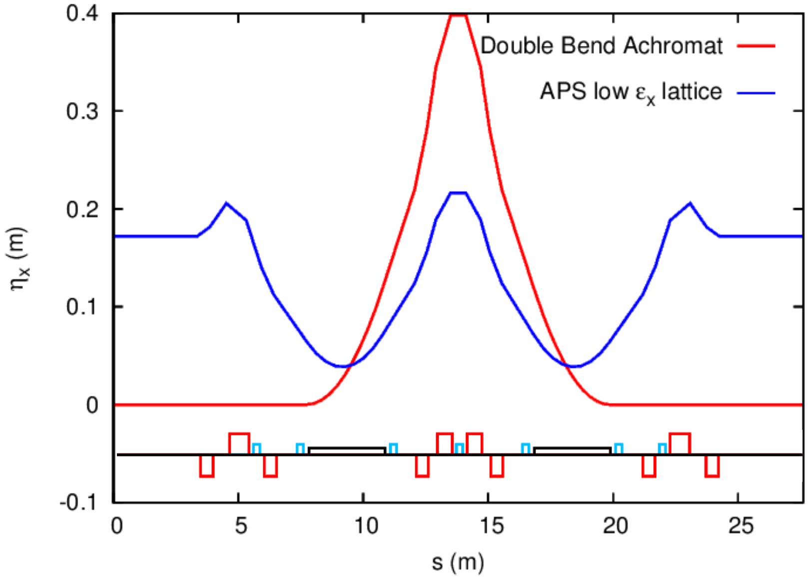

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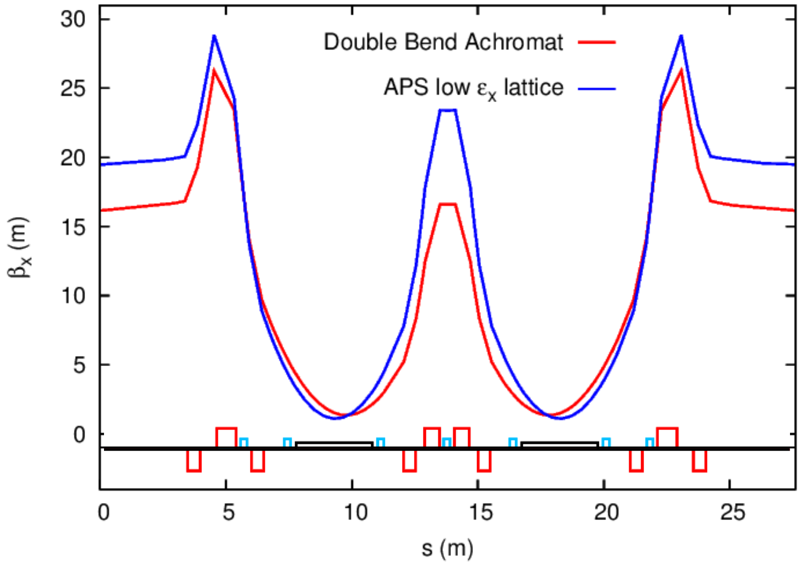

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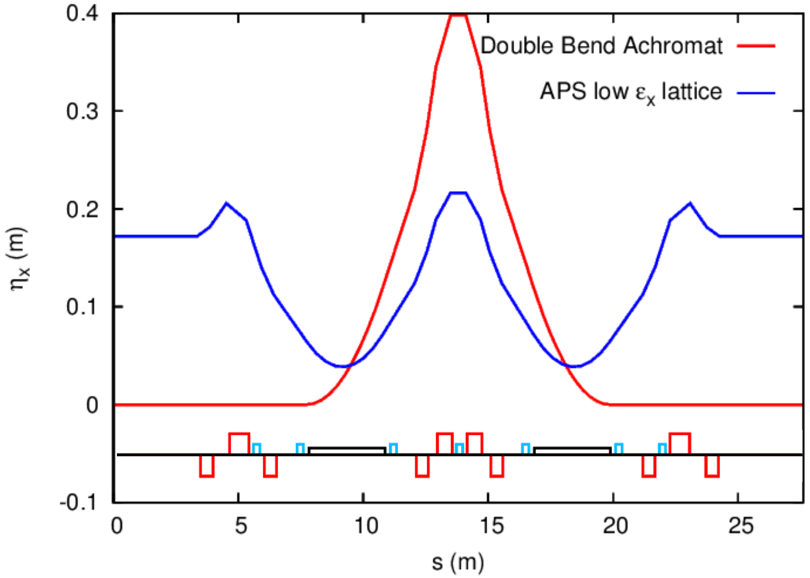

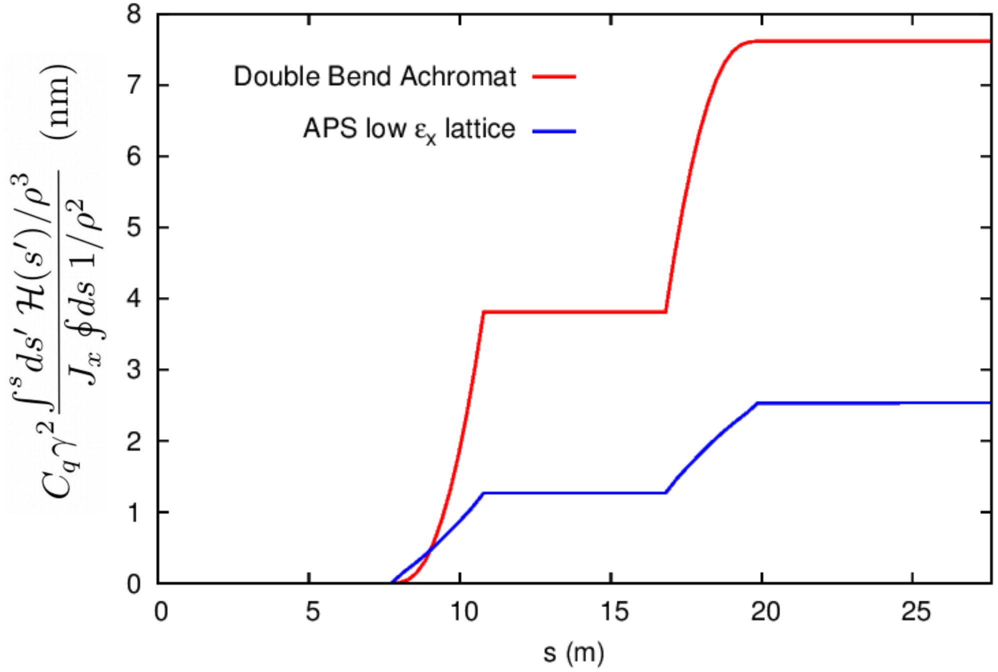

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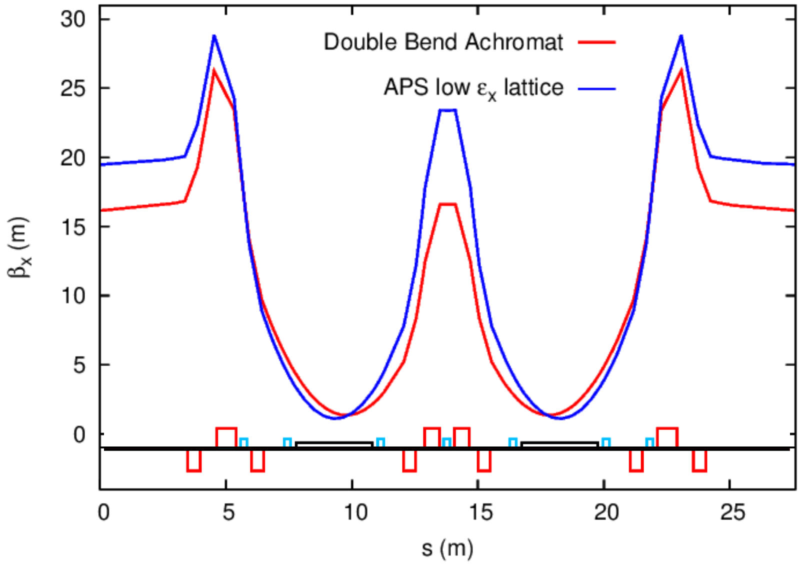

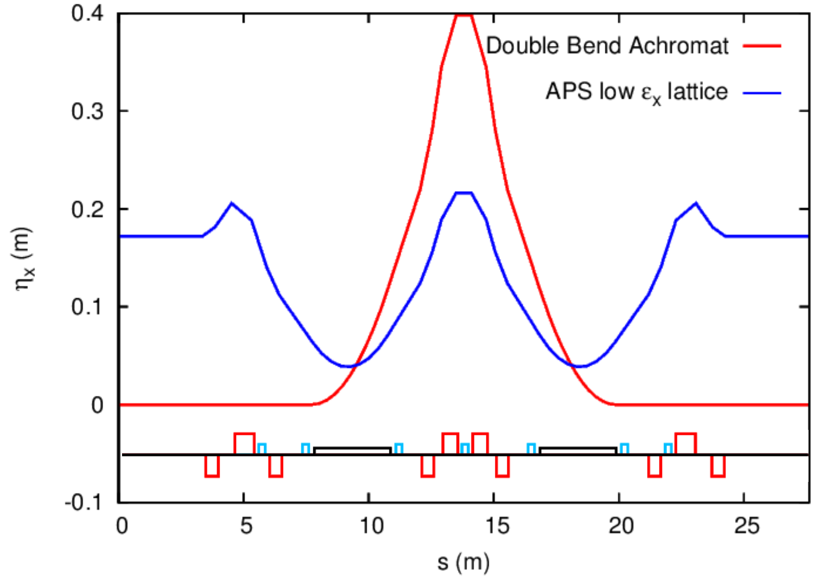

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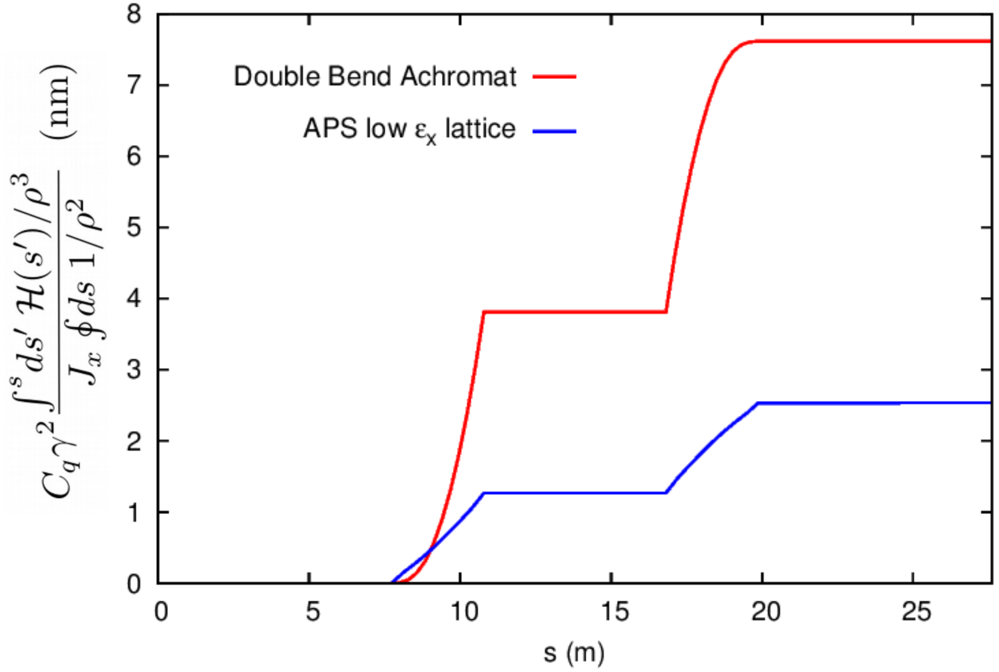
- Change at the APS was enabled by "top-up" injection
  - The short electron beam lifetime in the low-emittance lattice resulted in an untenable reduction in beam current between ring fills
  - Advances in lattice performance are often enabled by other factors



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The equilibrium emittance generally scales in the following way:

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

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Einfeld and Plesko[6] 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?

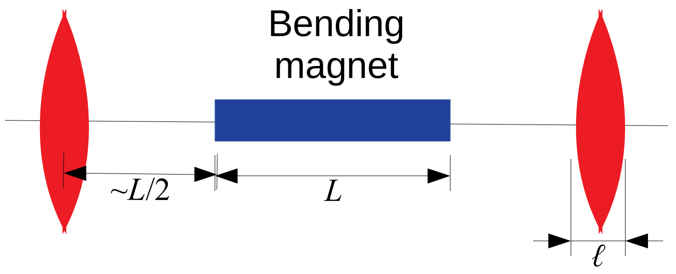
[6] D. Einfeld and M. Plesko. "A modified QBA optics for low emittance storage rings," NIMA **335**, 402 (1993); "Design of a diffraction limited light source (DIFL)," Proc. of PAC 95, pp. 177.

MBA scaling for magnet requirements are less attractive

- The favorable emittance scaling $\varepsilon_x \sim 1/N_D^3$ only obtains if we also add focusing magnets to reduce the quantum excitation in the bending magnets

We can study this in more detail using 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



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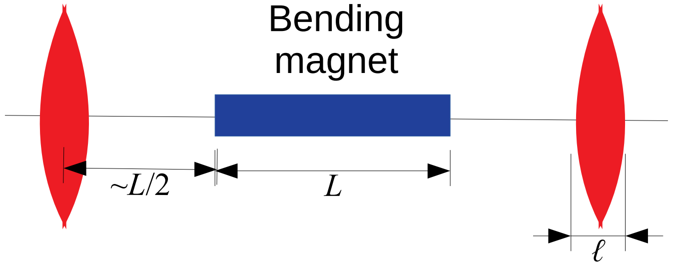

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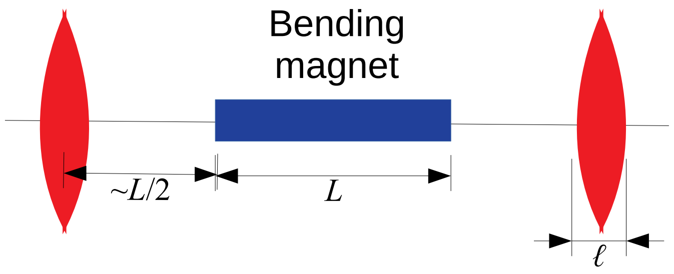

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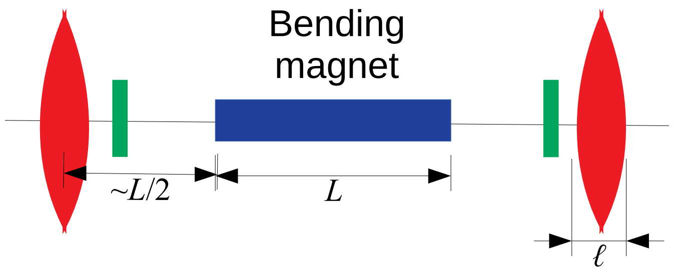

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MBA scaling for magnet requirements are less attractive

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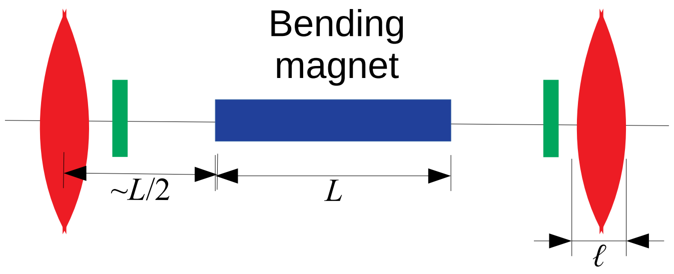

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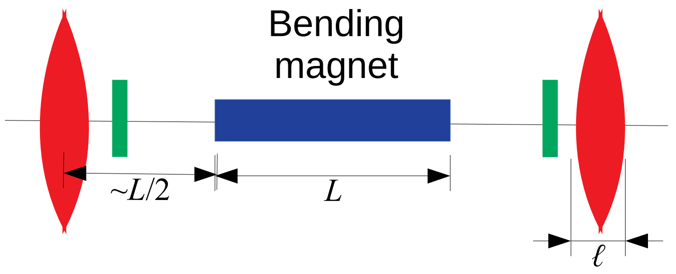

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MBAs require strong magnets with small apertures!

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Scaling laws for robustness and stability reveal challenges

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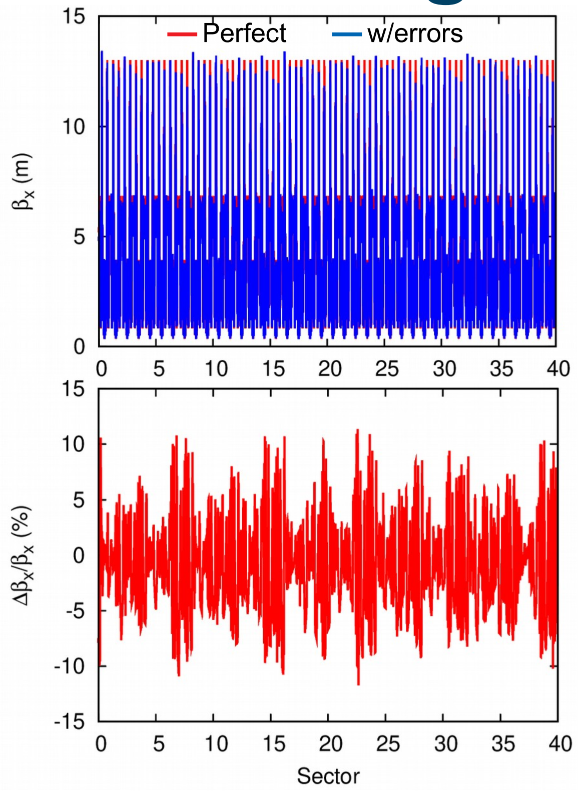

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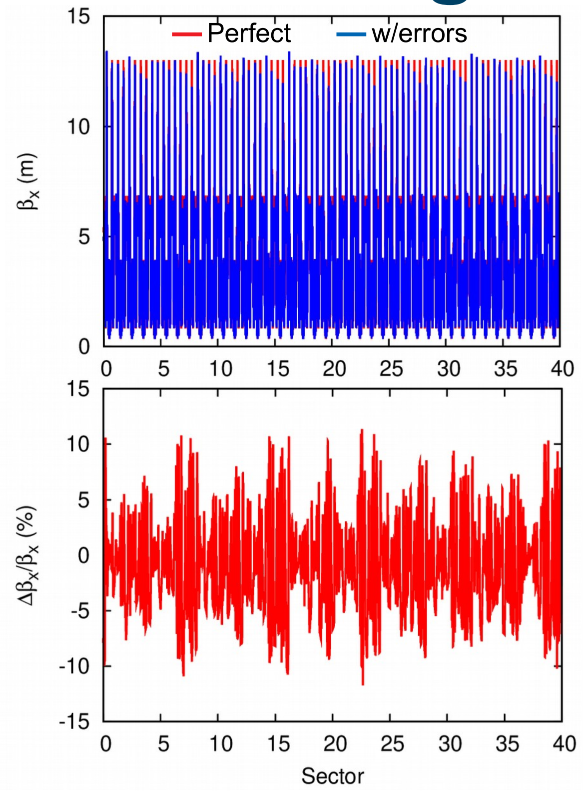

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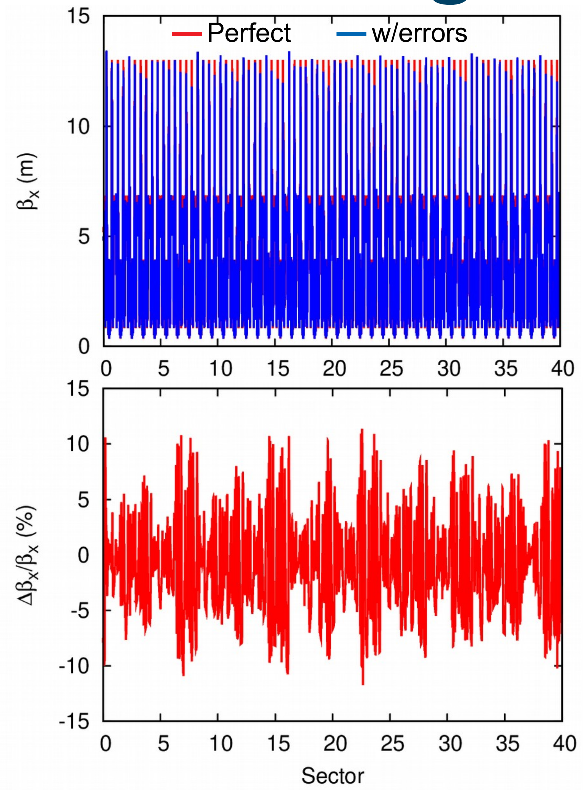

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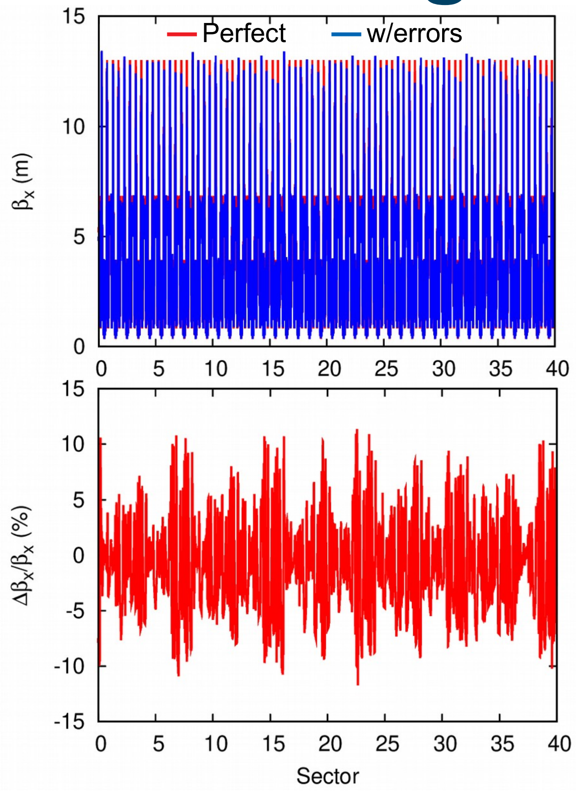

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   - Vacuum chambers provide the physical aperture
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   - Stability of nonlinear dynamics leads to the "dynamic" aperture, and the nonlinear dynamics associated with the strong sextupoles $\Rightarrow$ Dynamic aperture $\sim 1/N_D$

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

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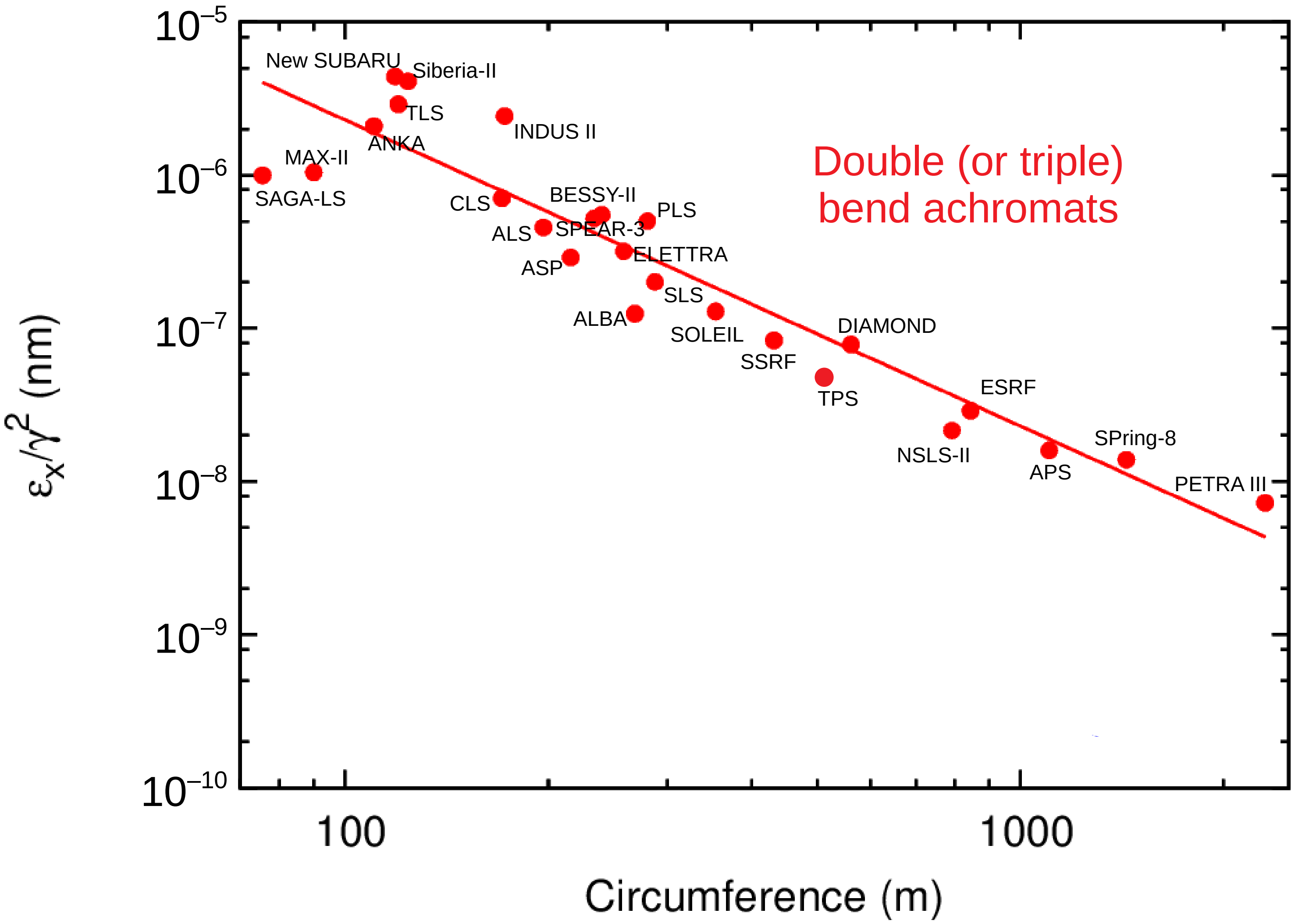
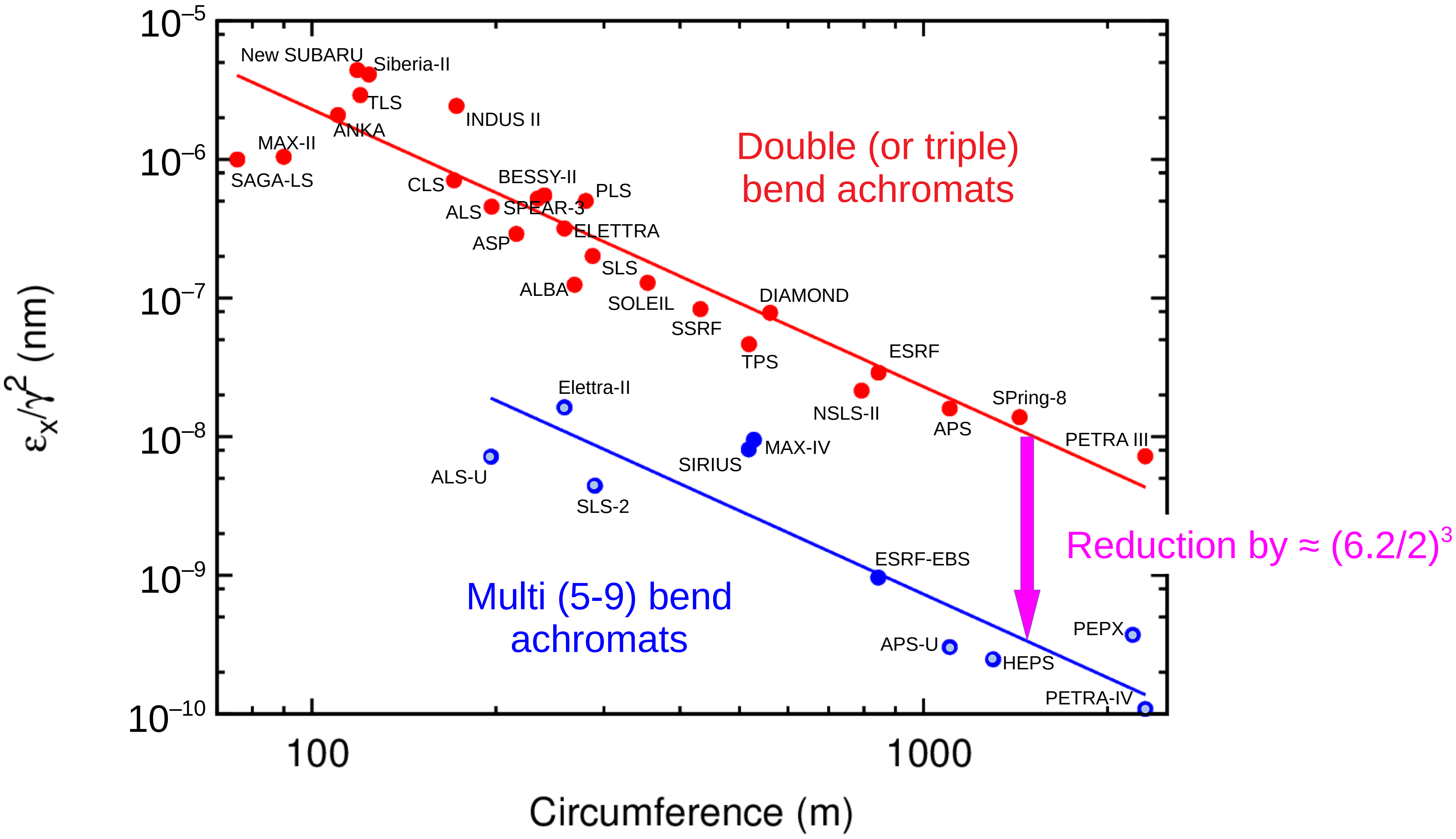
Upgrade projects are underway around the world



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



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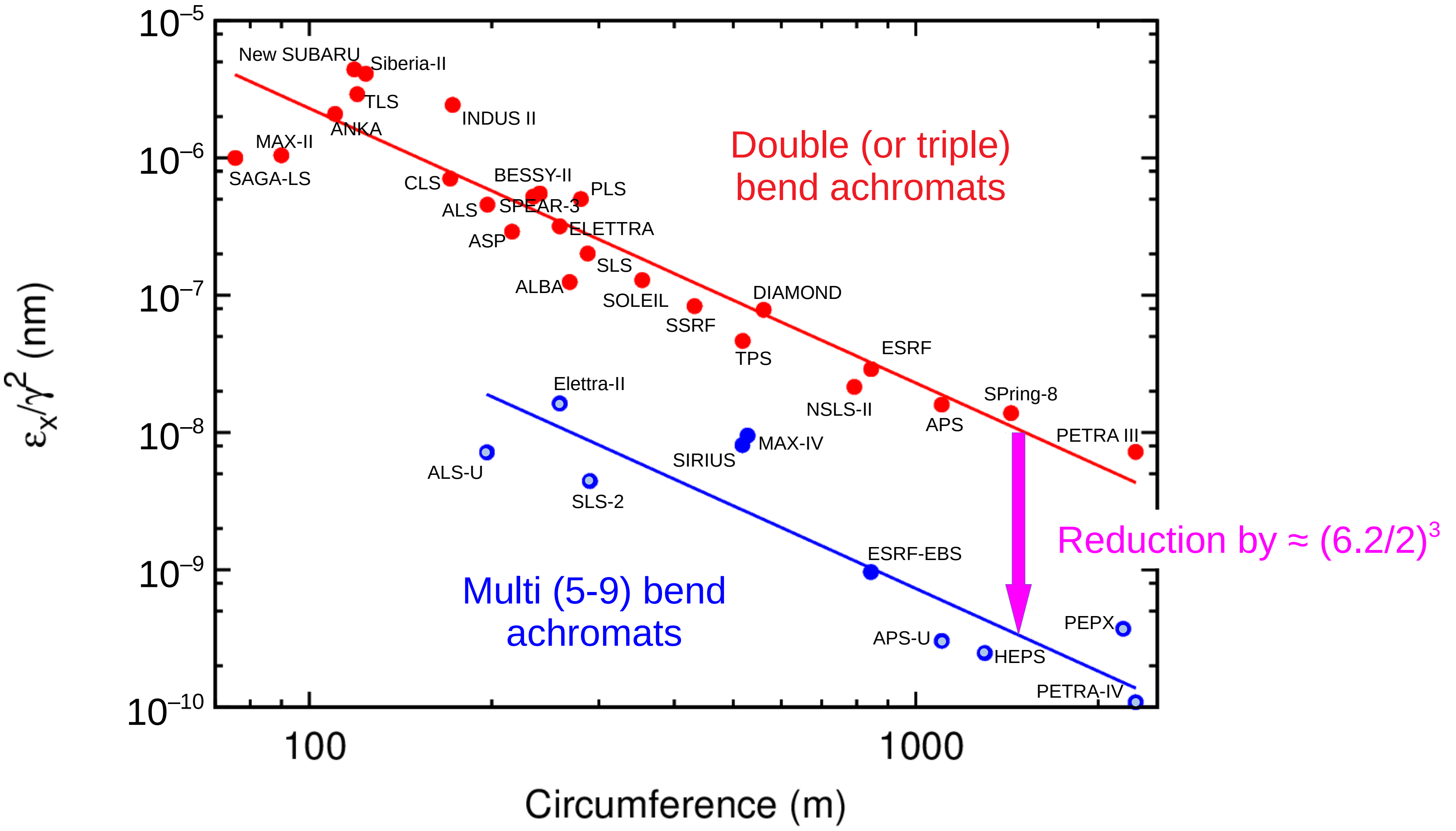
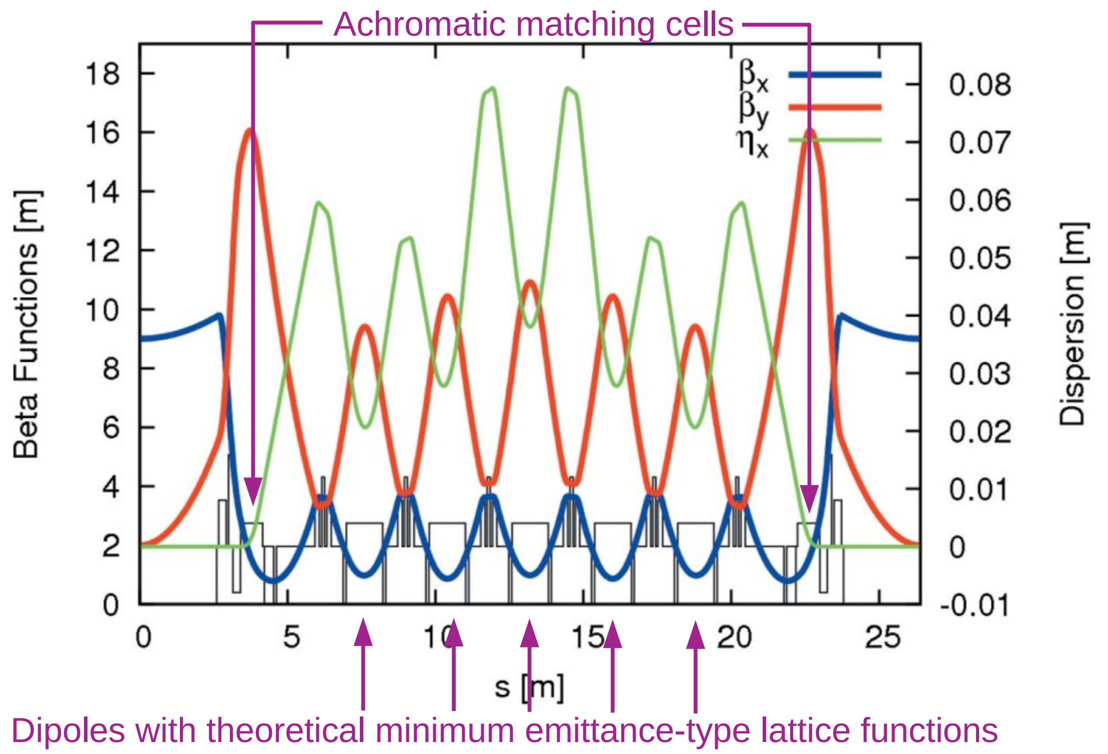
- These developments have been driven by advances in
  - Technology
  - Lattice design
  - Simulation capabilities



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



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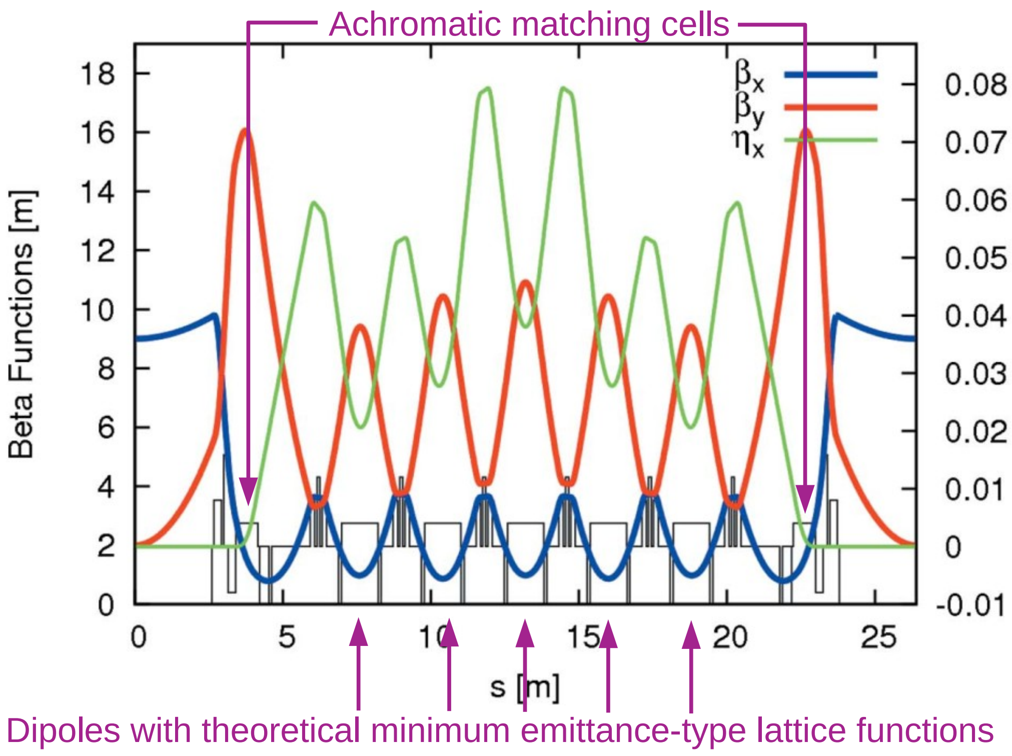
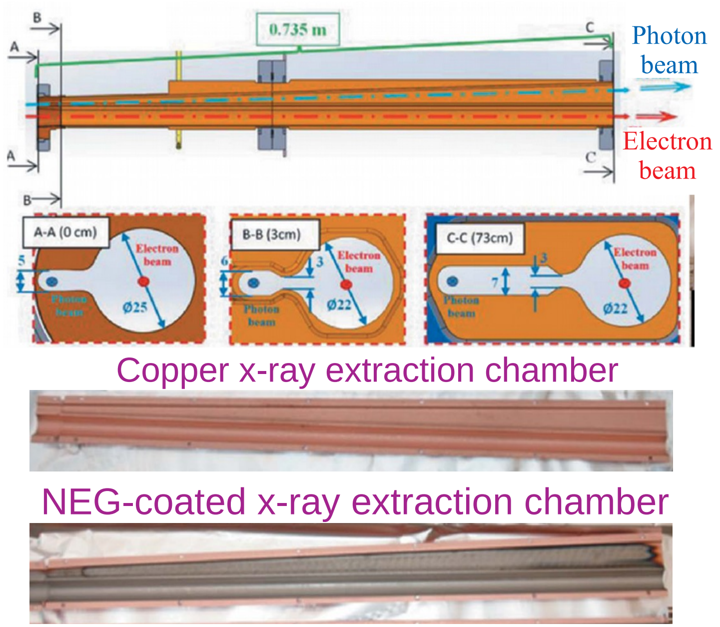
     - Reduces photon-stimulated desorption
     - Provides distributed pumping
     - Enables ultra-low vacuum in small aperture chambers





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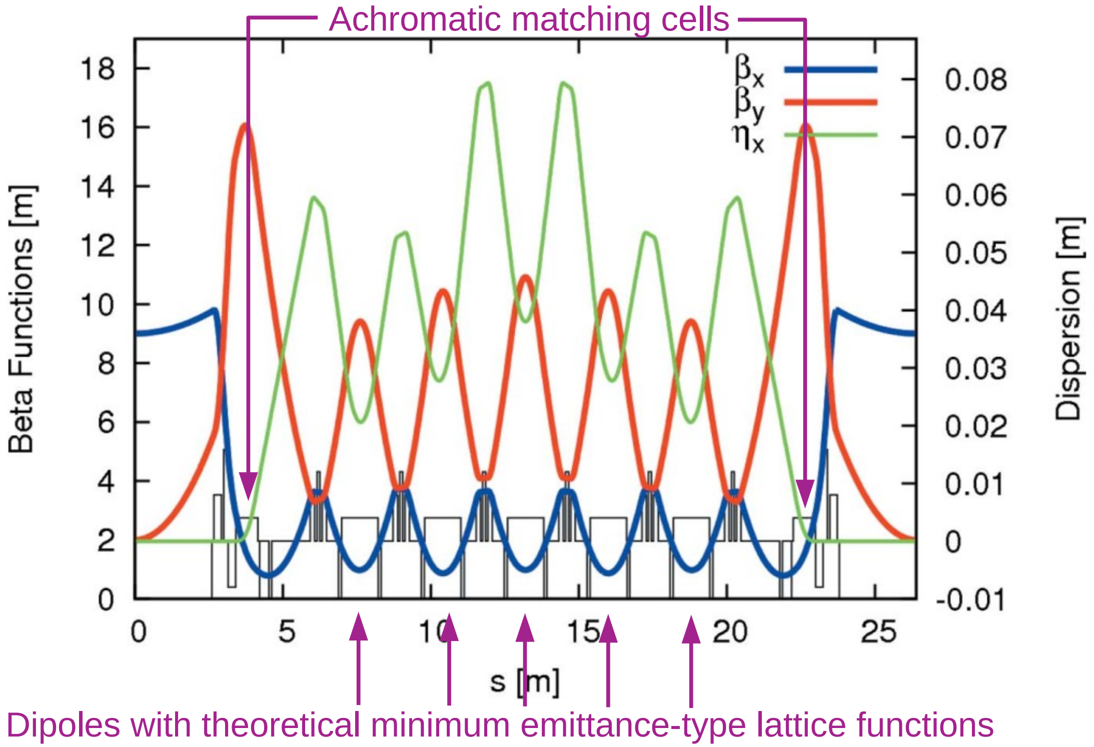

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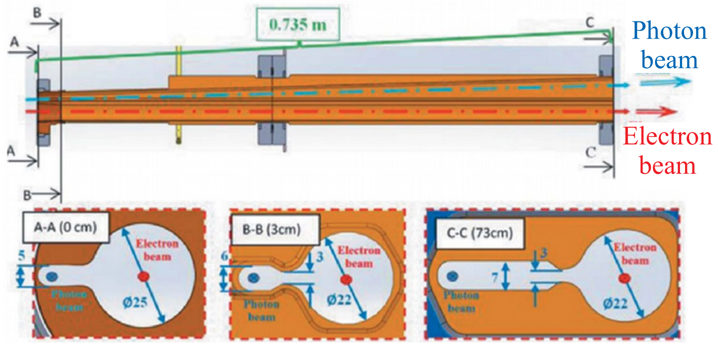
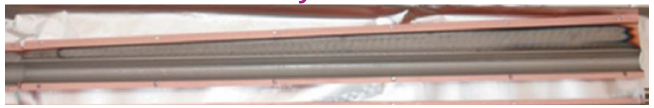
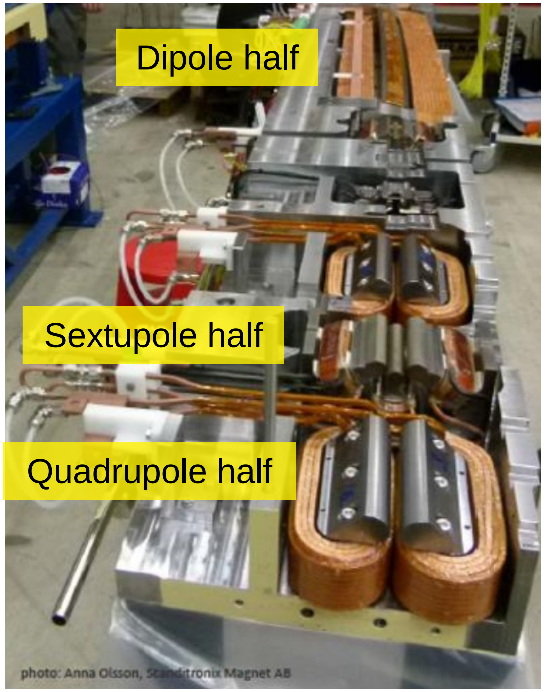
  2. Ultra-precise machining of unified magnet blocks.
     - Reduced tolerances to 20 micron level







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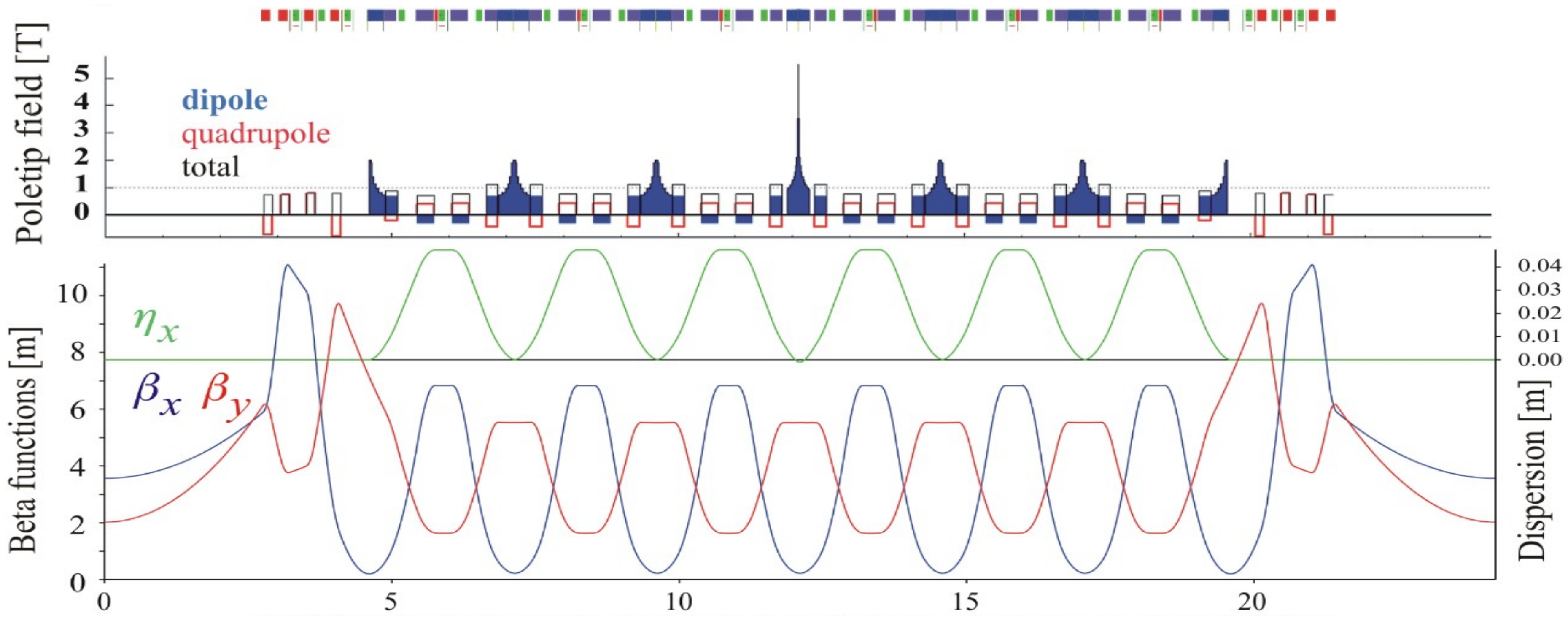
Reverse bends and longitudinal gradient dipoles can enable further emittance reduction

Swiss Light Source design[11] at 102 pm



[11] 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.

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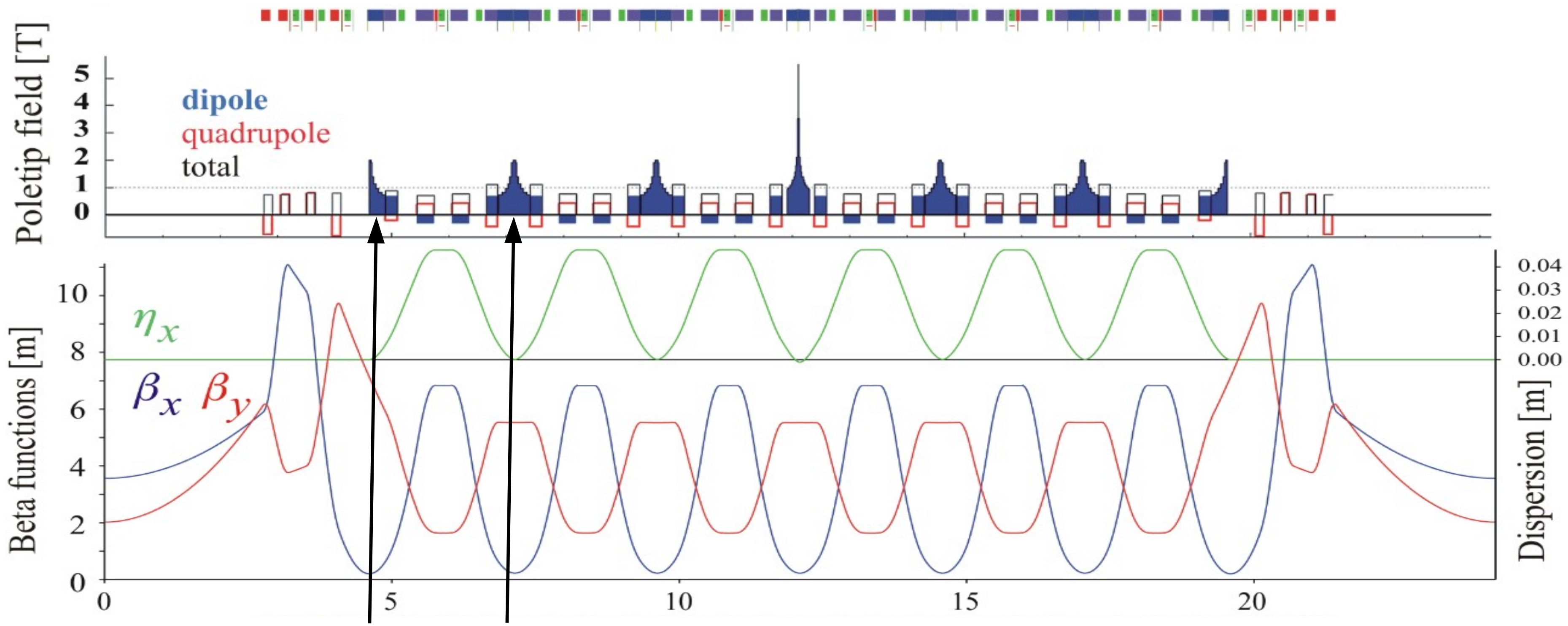

Dipoles with maximum strength where η_x and β_x are at a minimum to minimize their contribution to curly-$\mathcal{H}$

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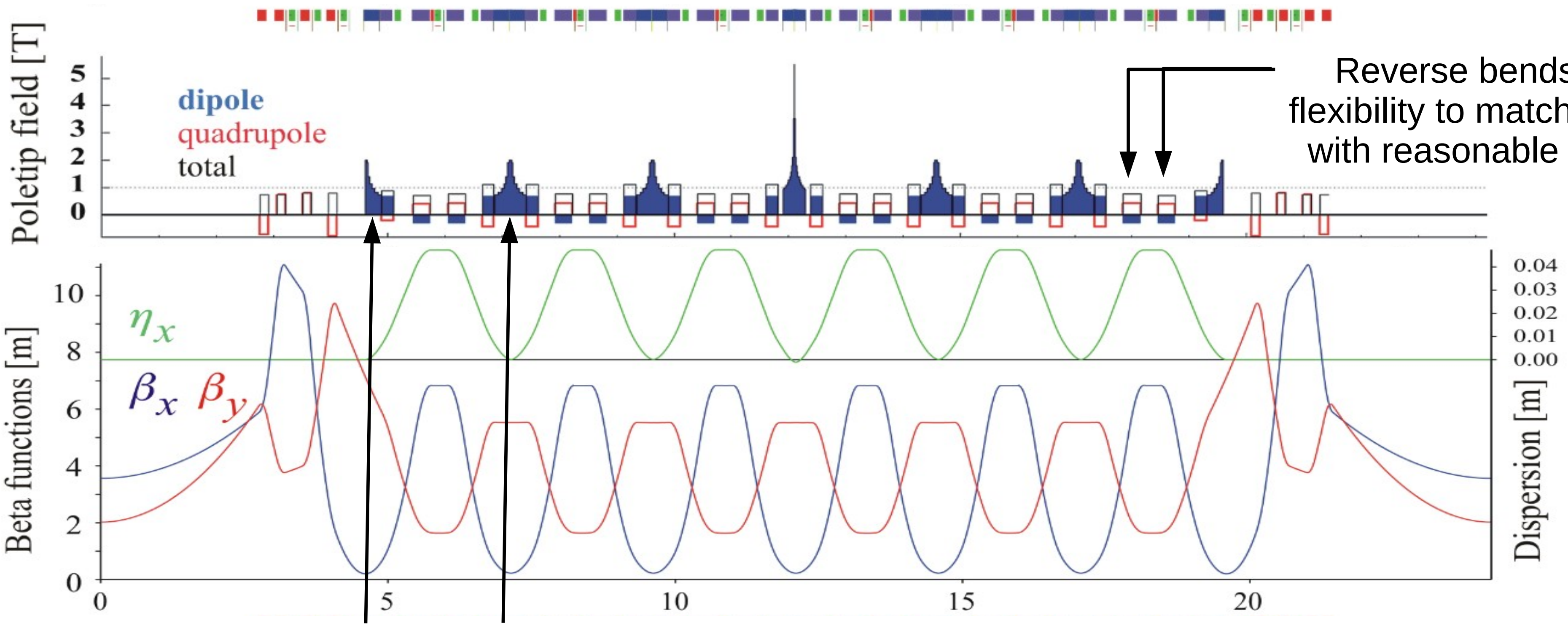

Reverse bends[12,13] that give flexibility to match lattice functions with reasonable phase advance

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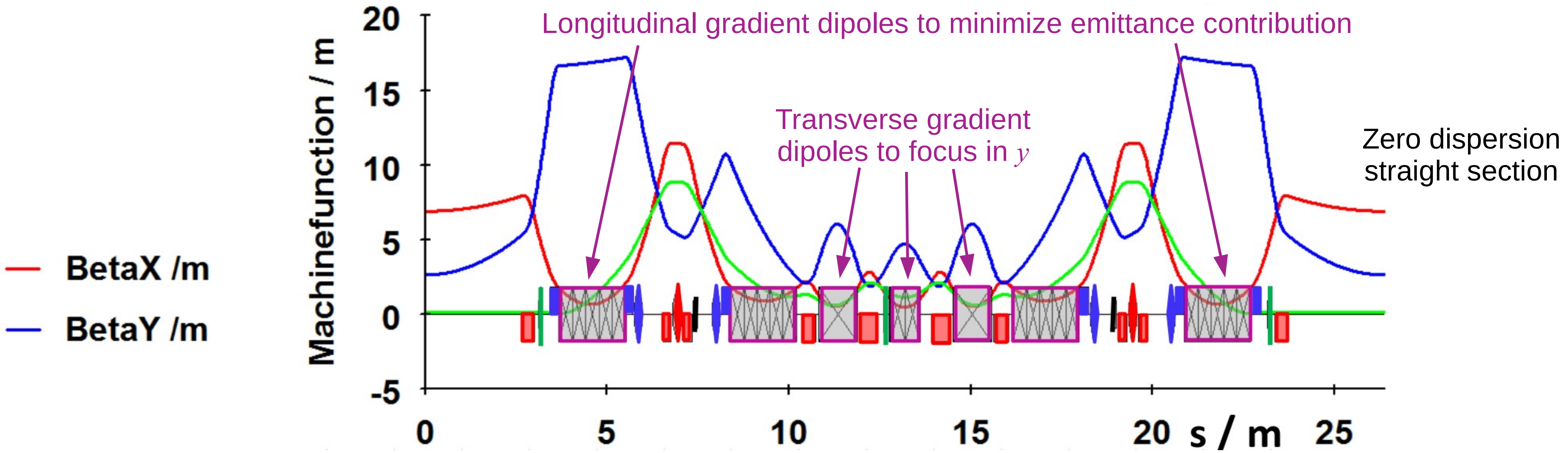
[12] J.P. Delahaye and J.P. Potier, PAC 1989, pp. 1611.
[13] B. Riemann and A. Streun, Phys. Rev. Accel. Beams **22**, 021601 (2019).

Hybrid MBA lattice has a number of different features



- Hybrid MBA lattice[14] was developed at the ESRF and is now being installed as part of their ESRF-EBS upgrade targeting 133 pm natural emittance

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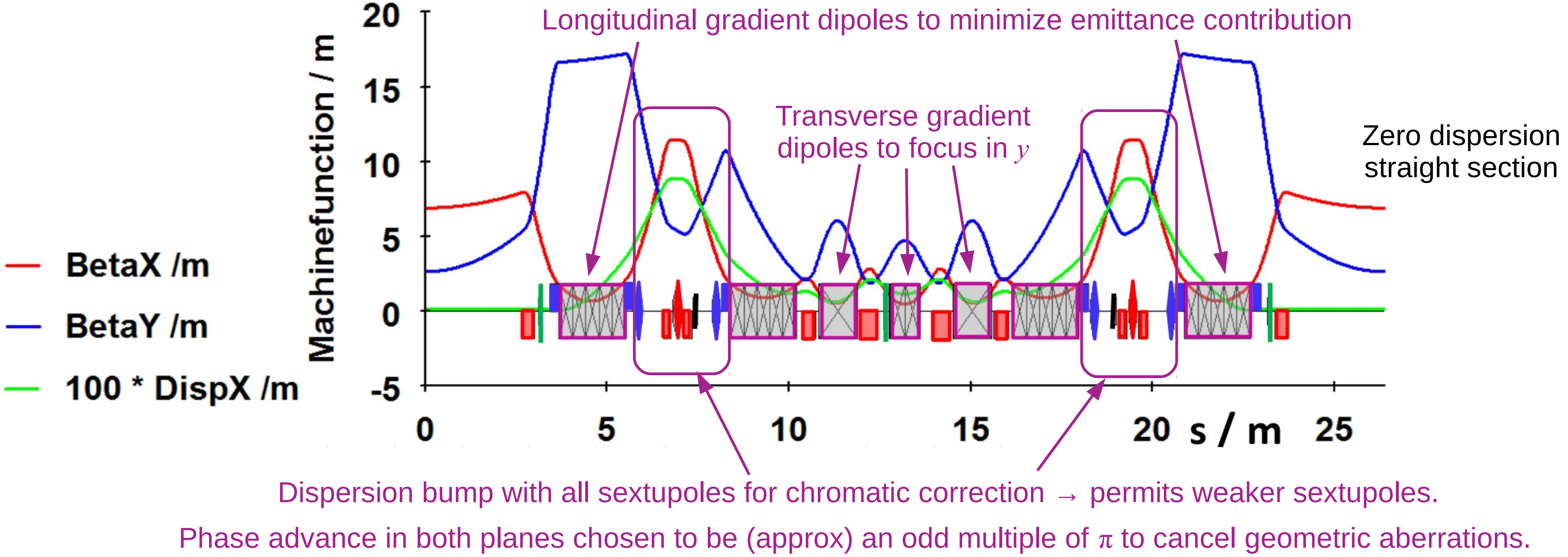

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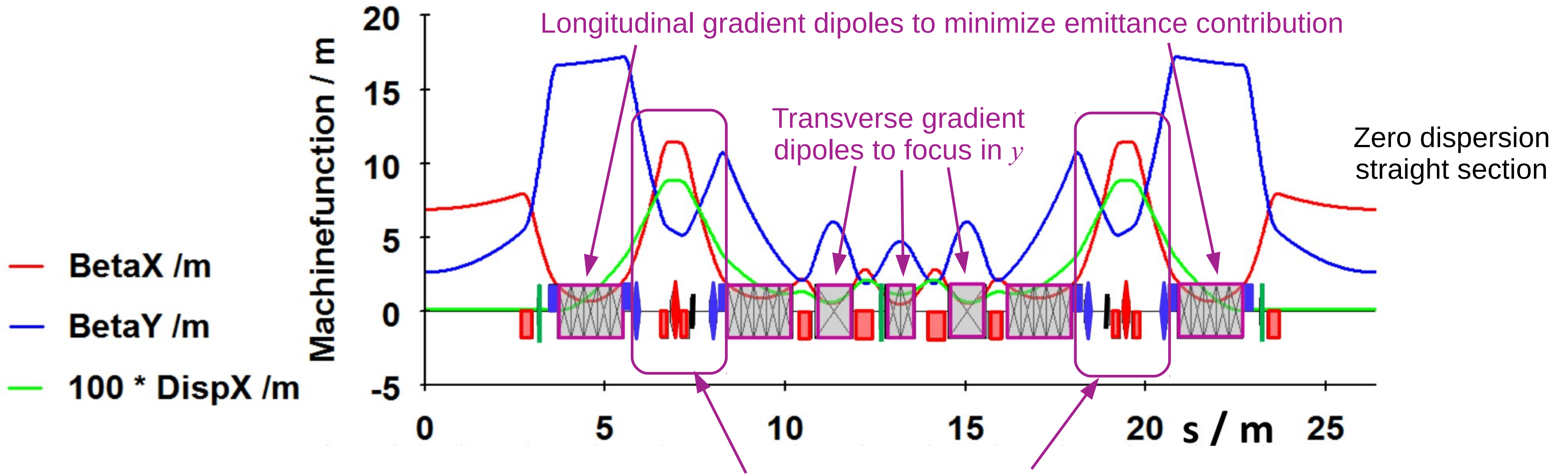

Dispersion bump with all sextupoles for chromatic correction → permits weaker sextupoles.

Phase advance in both planes chosen to be (approx) an odd multiple of π to cancel geometric aberrations.

- Hybrid MBA lattice[14] 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

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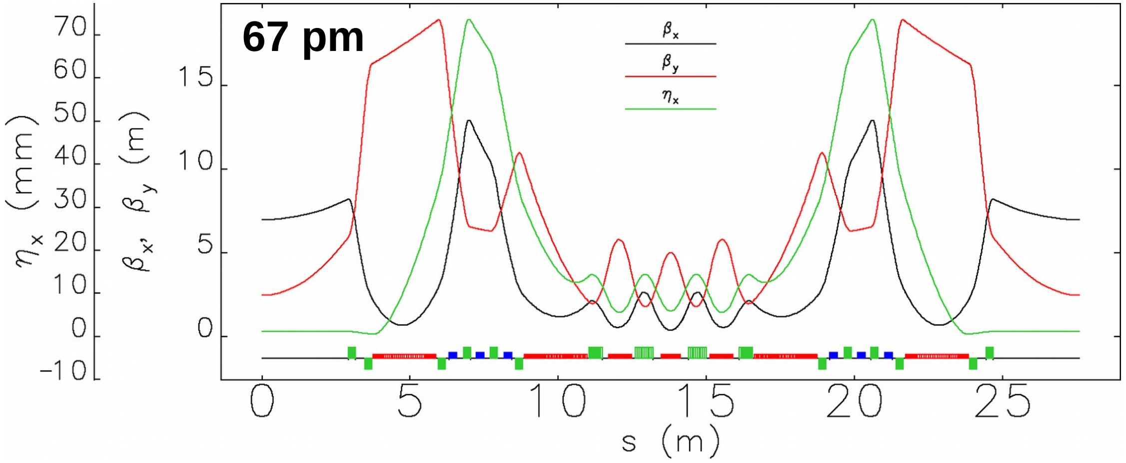
Reverse bends enabled APS-U to further reduce emittance



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

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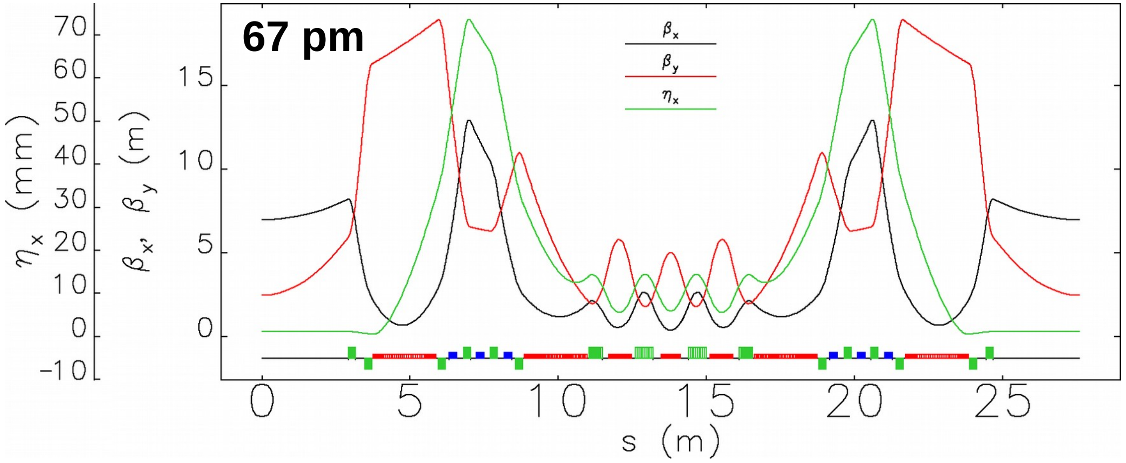

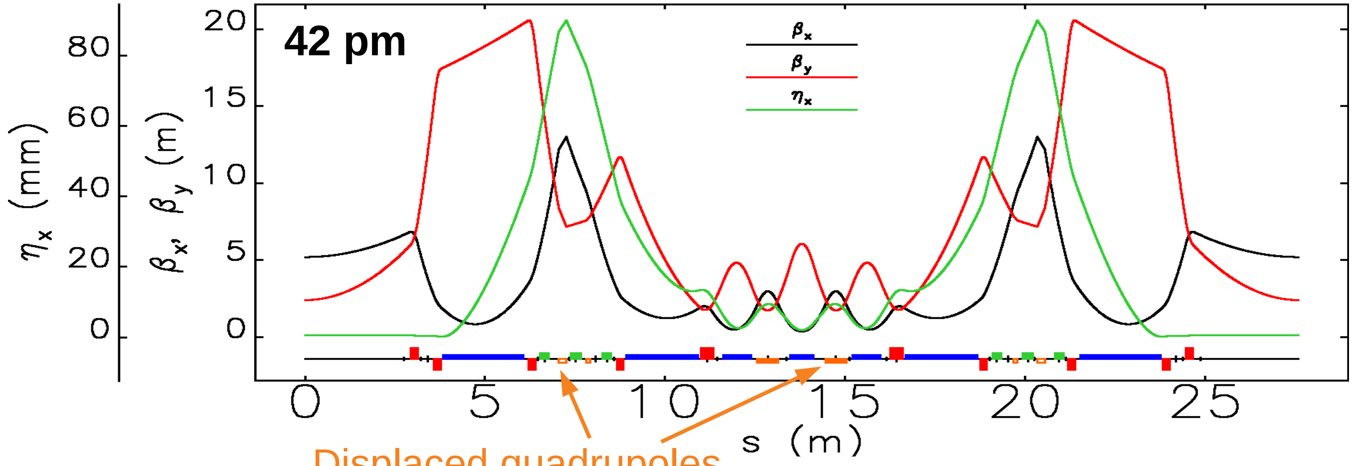

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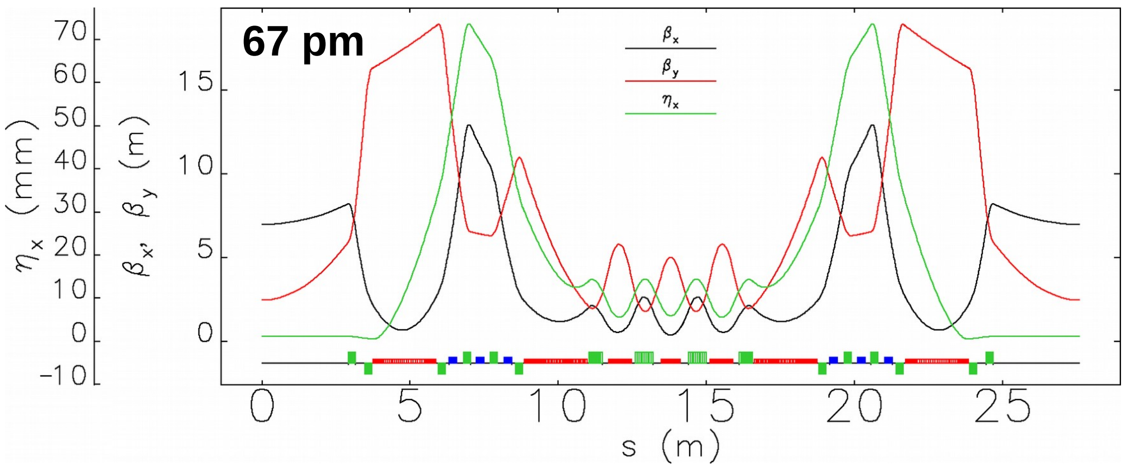

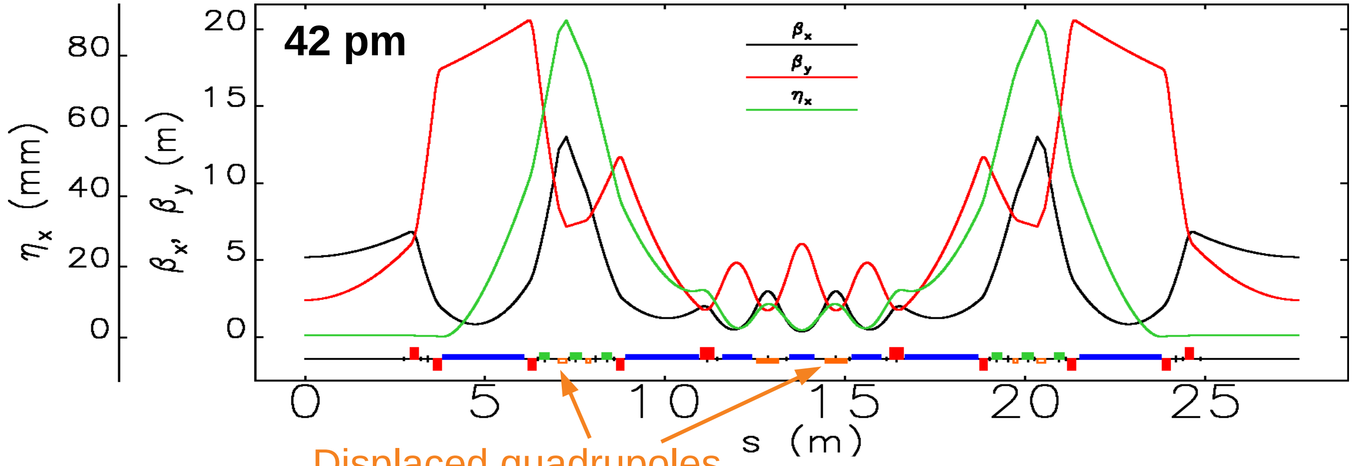

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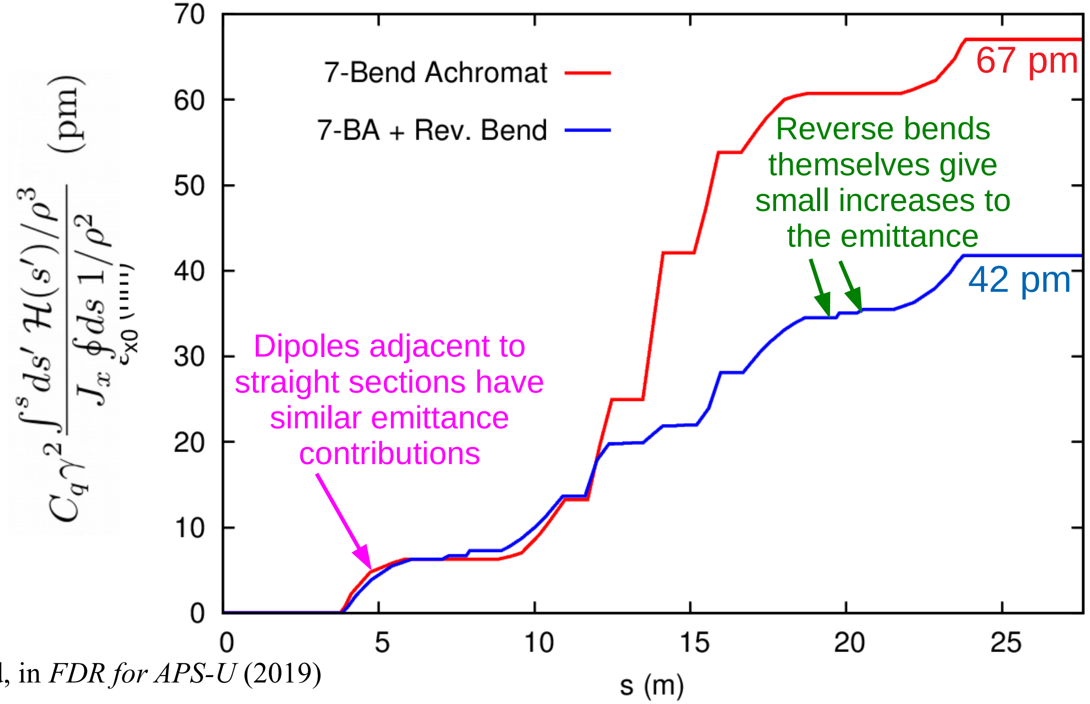

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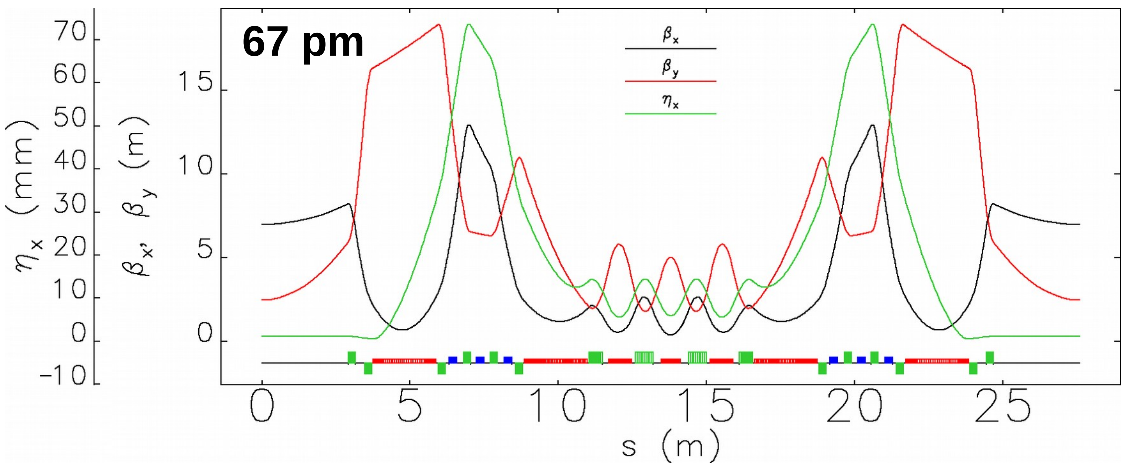

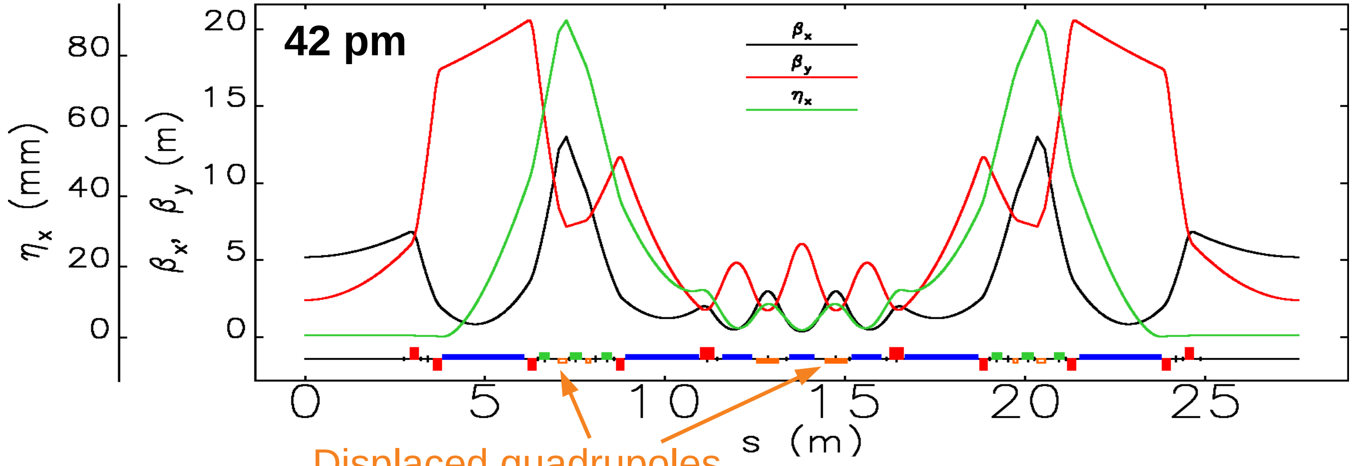

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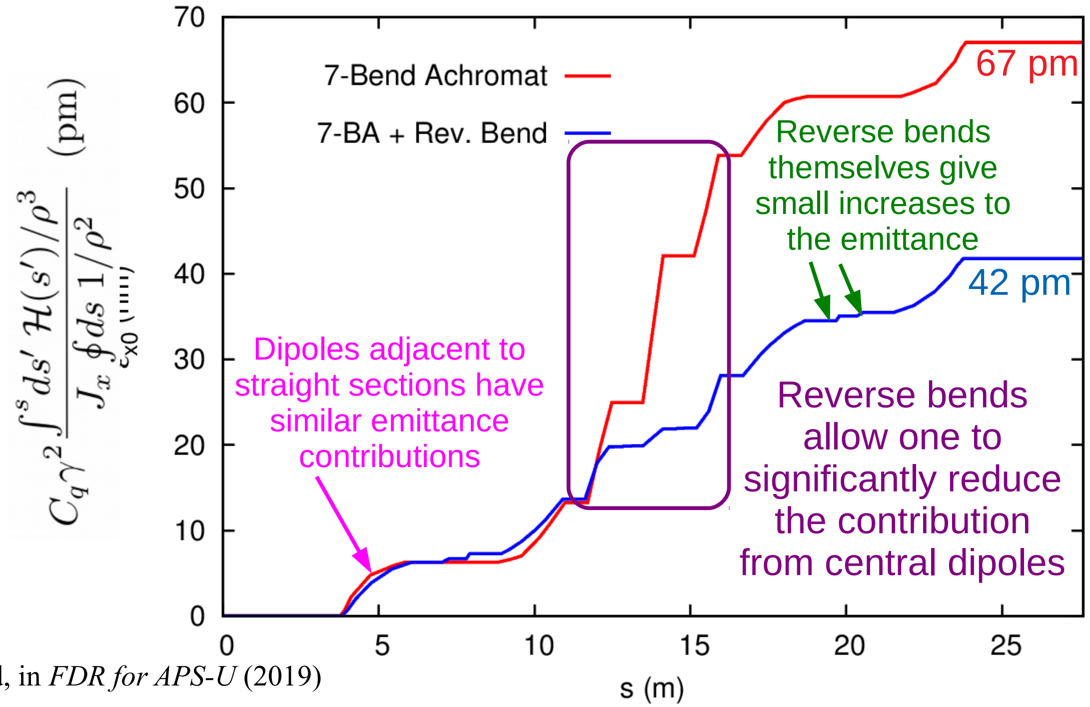

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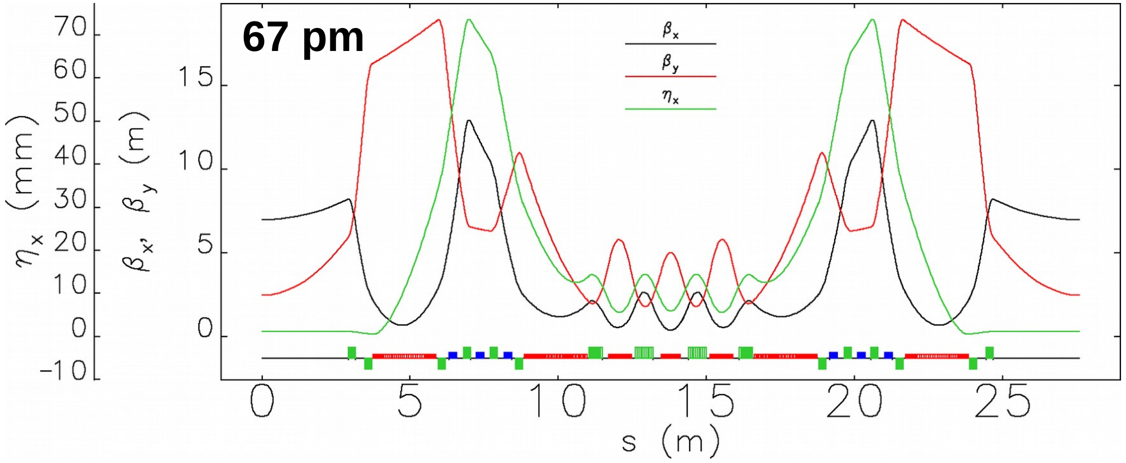

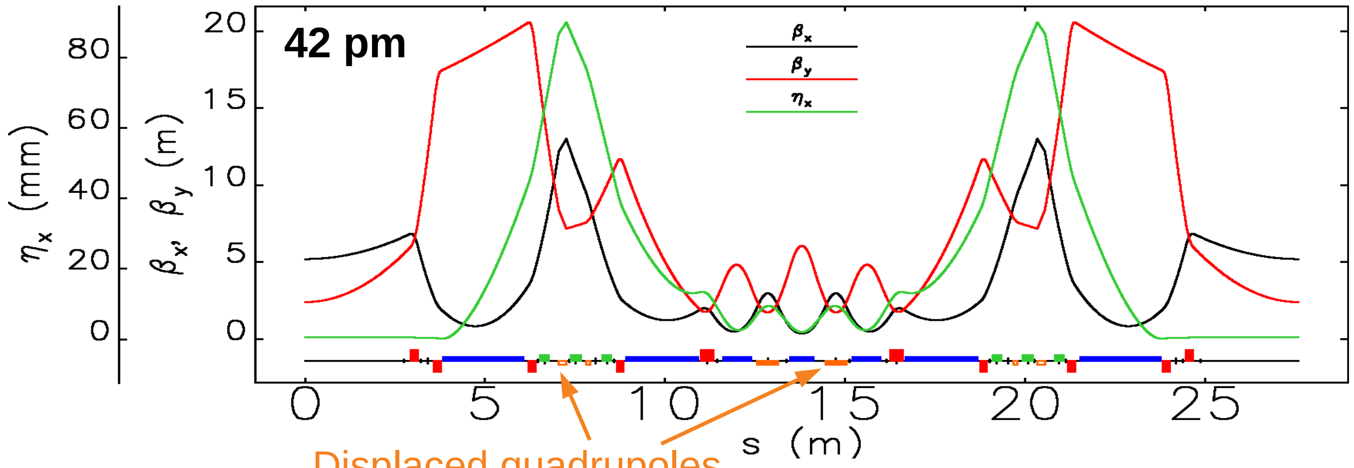

Displaced quadrupoles

(AKA reverse bending transverse gradient dipoles)

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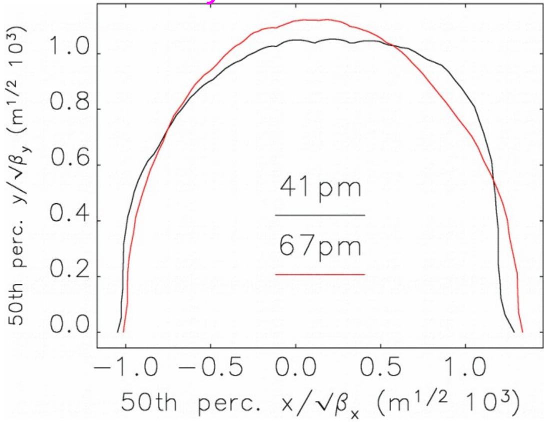
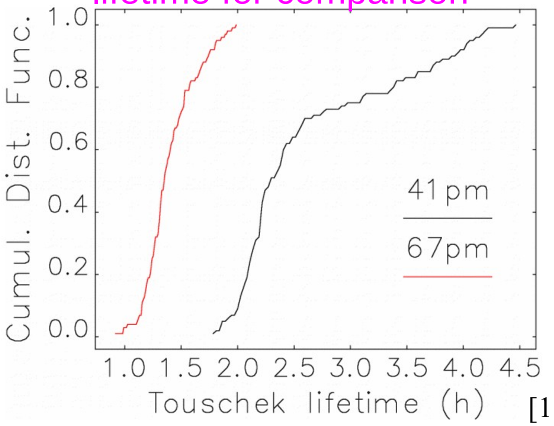
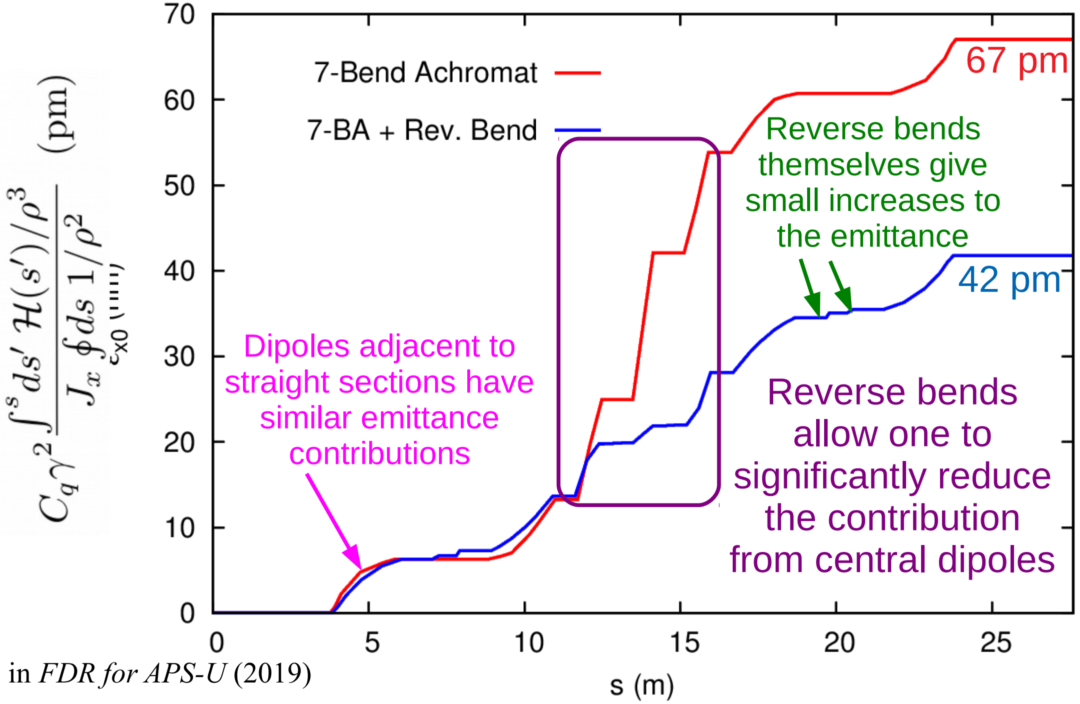
Median dynamic acceptance scaled by beta-function[12]



Approximate Touschek lifetime for comparison[12]





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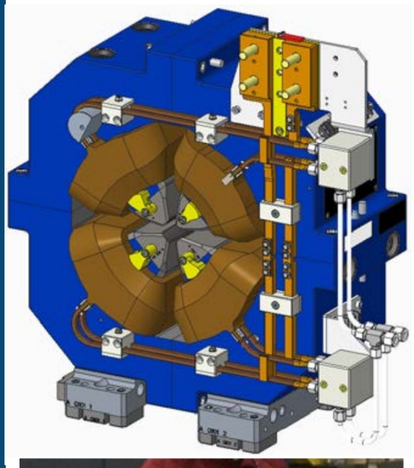
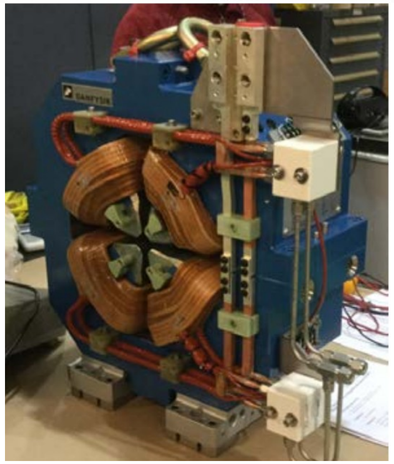
Examples of MBA magnets built for the APS-U

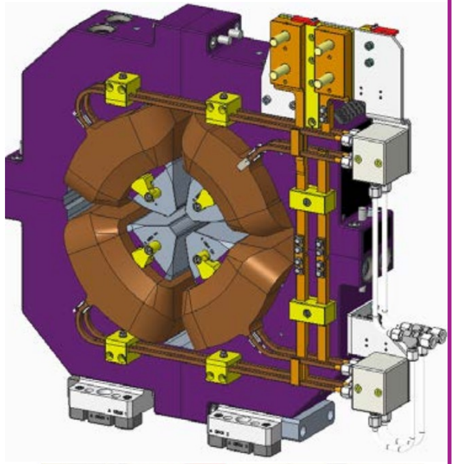
Quadrupole
CAD model





Quadrupole

Reverse bend
CAD model



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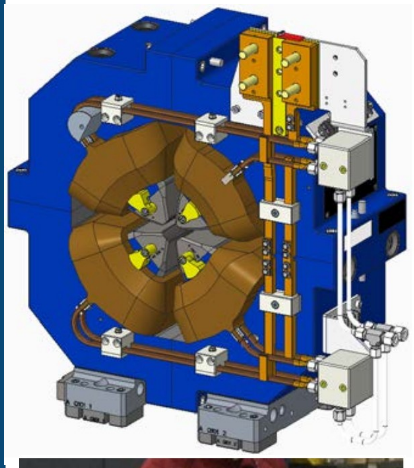
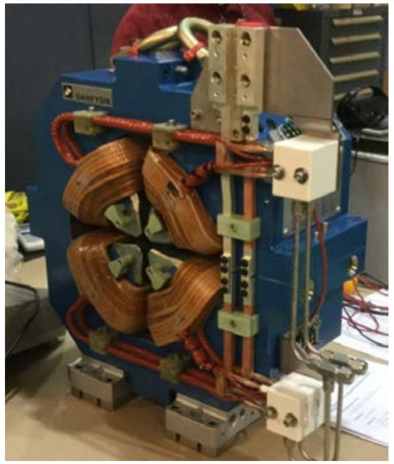
Pictures courtesy G. Decker and M. Jaski

Examples of MBA magnets built for the APS-U

Quadrupole
CAD model





Quadrupole

Reverse bend
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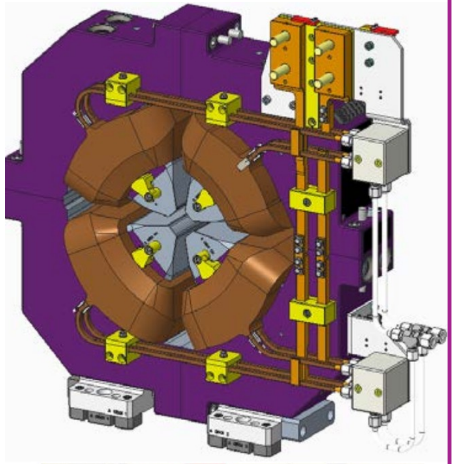
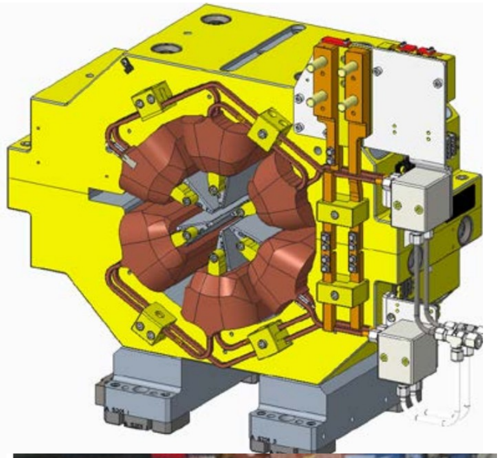


Reverse bend

Sextupole
CAD model



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Quadrupole
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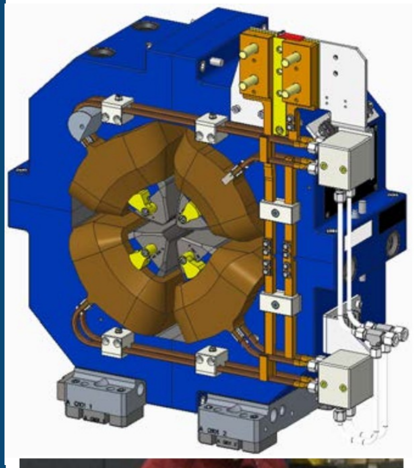

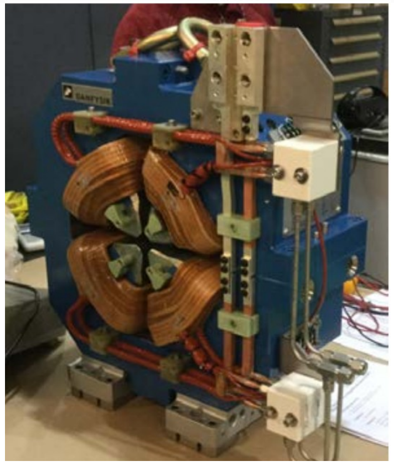

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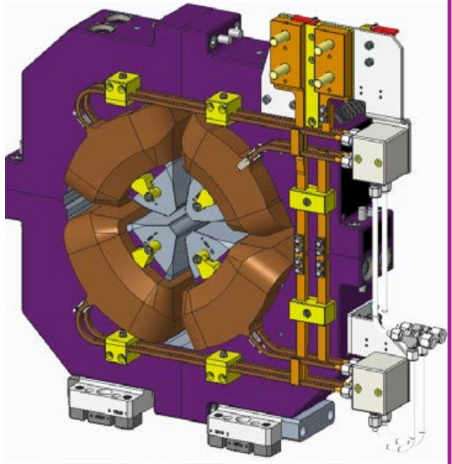

Reverse bend

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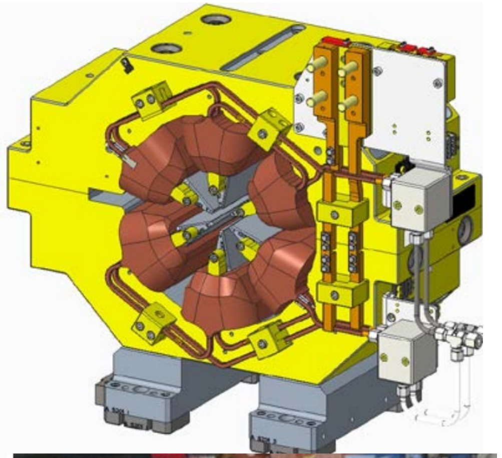
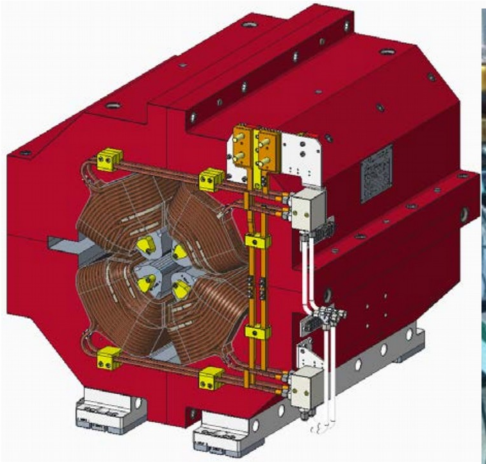


Sextupole

Transverse gradient
dipole CAD model



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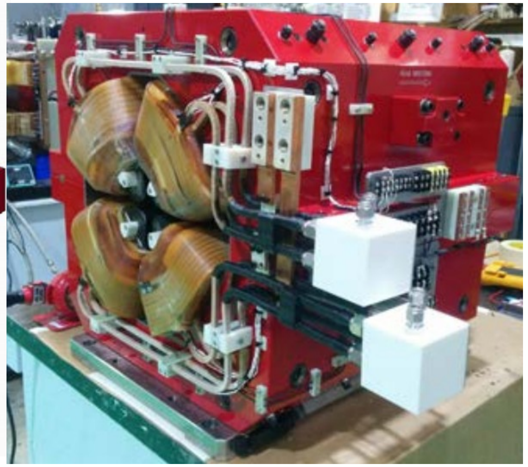
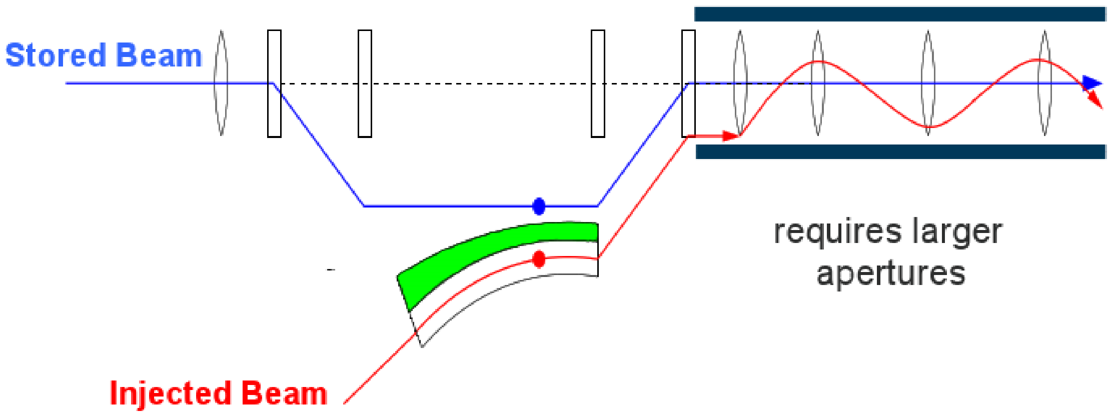


Longitudinal gradient dipole

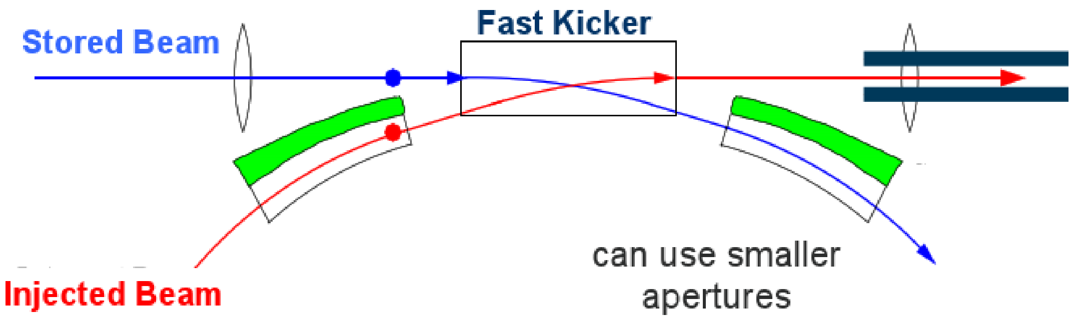
Pictures courtesy G. Decker and M. Jaski

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)

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  - Possible with advances in fast (~ns), pulsed power supply technology
  - Planned for APS-U and HEPS in Beijing

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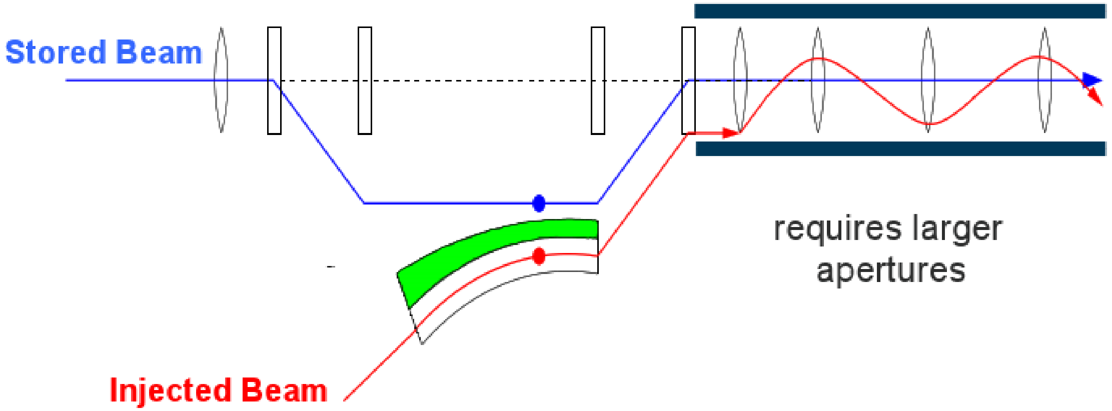

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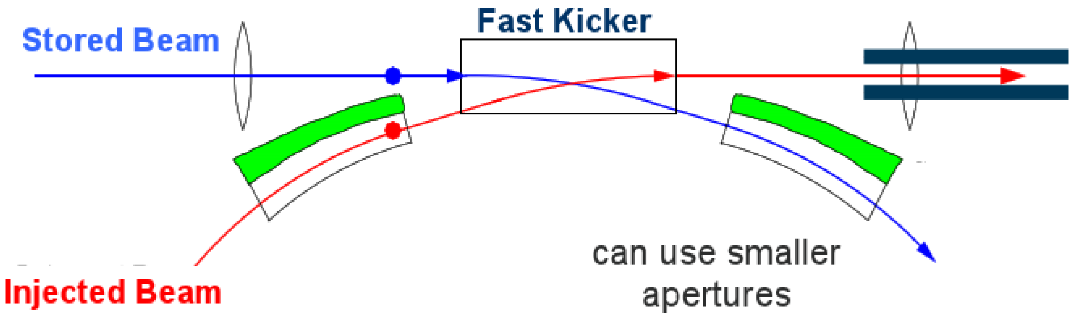

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  - Possible with advances fast (~ns), pulsed power supply technology
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- ALS-U plans to combine a few nm-emittance accumulator ring with on-axis swap-out of bunch trains to allow for even tighter 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.

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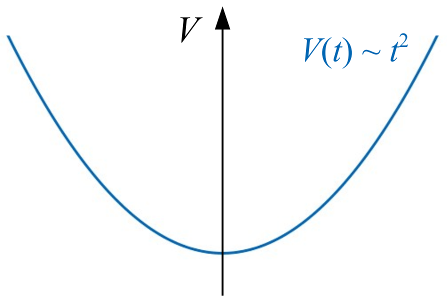
Double rf system can increase bunch length and lifetime

- A higher harmonic cavity (HHC) can lengthen bunch and reduce current density of low-emittance beam
  - Improve Touschek lifetime
  - Reduce intensity-dependent emittance growth and instabilities
- Varying HHC frequency changes the voltage and thus the bunch length



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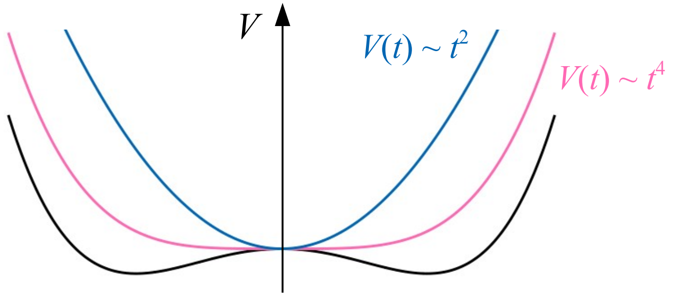

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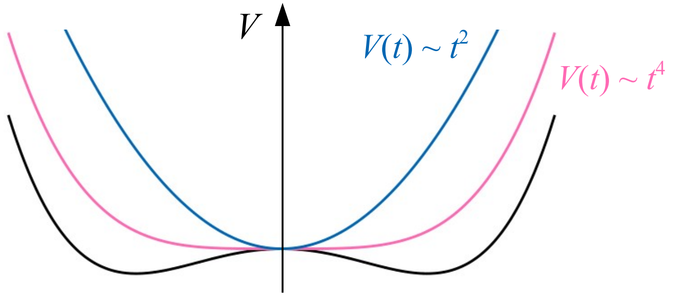
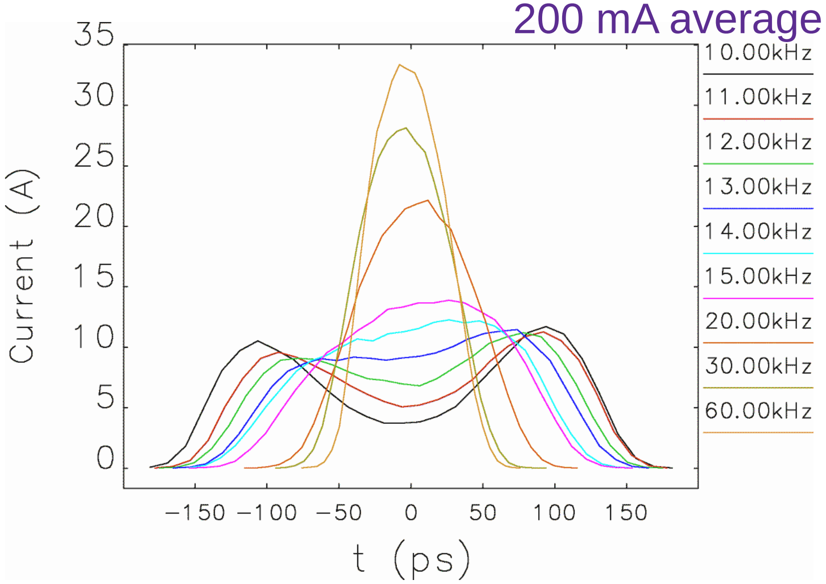
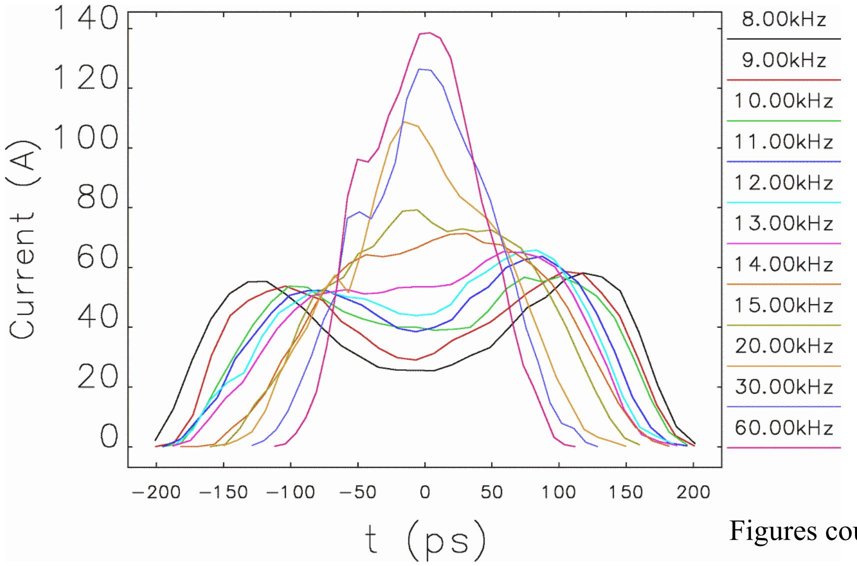


200 mA average current in 324 bunches



200 mA average current in 48 bunches



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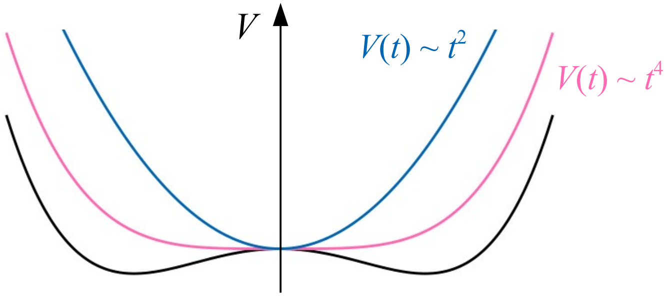

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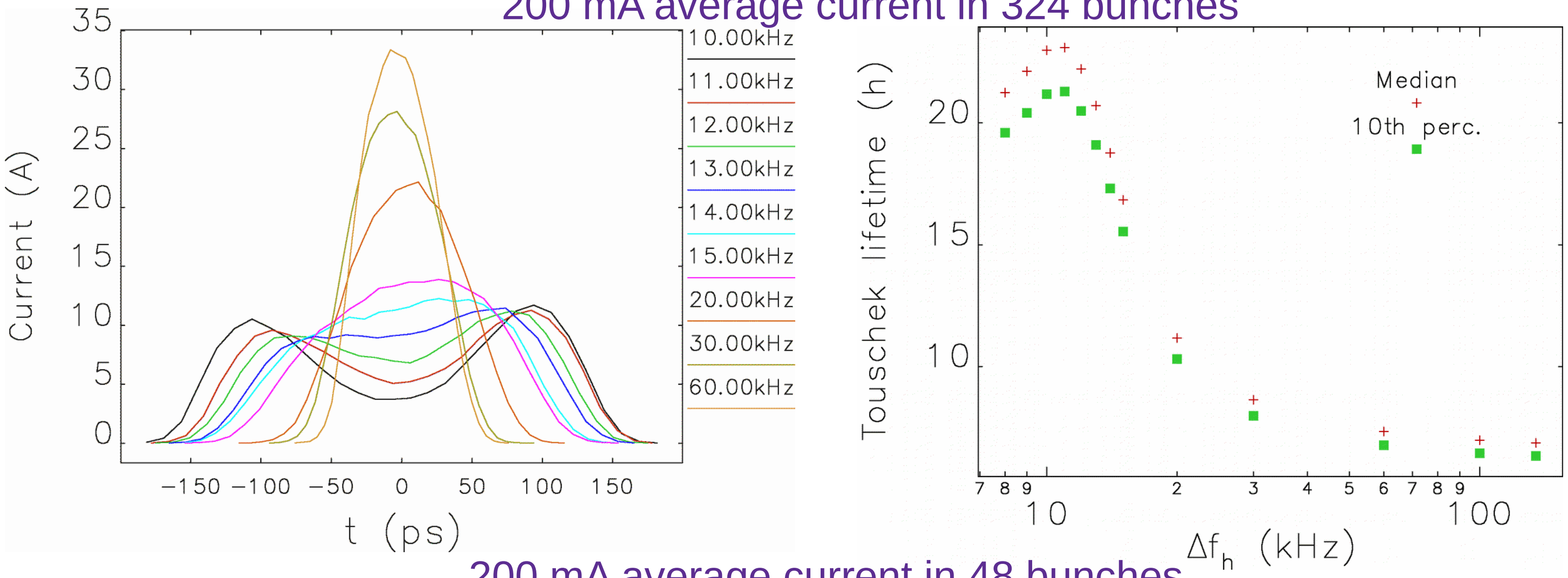

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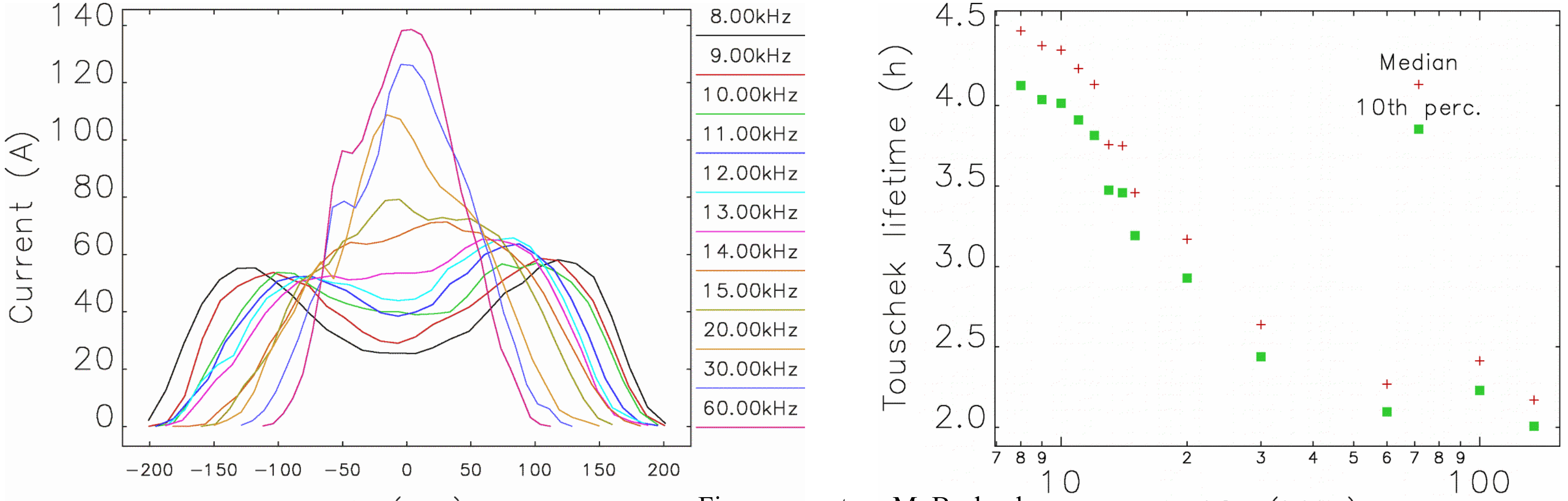

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High fidelity simulation tools are critical

- 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

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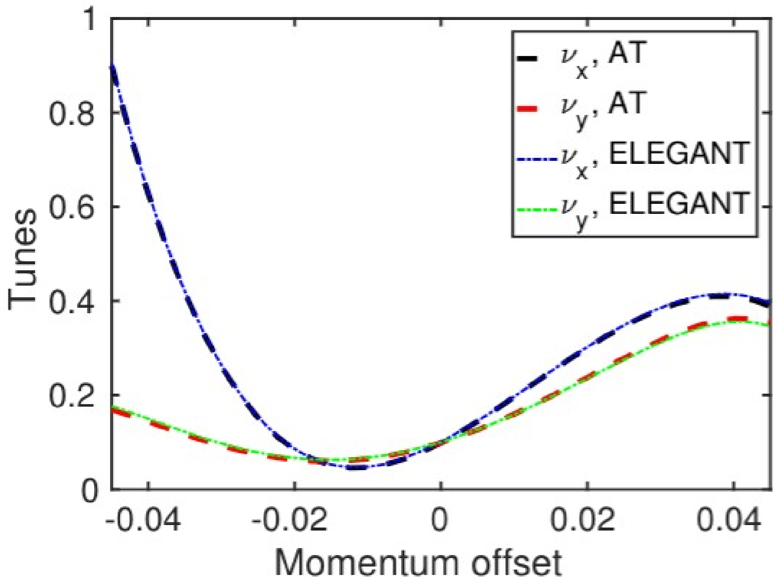
Variation of tune (fractional oscillation frequency)



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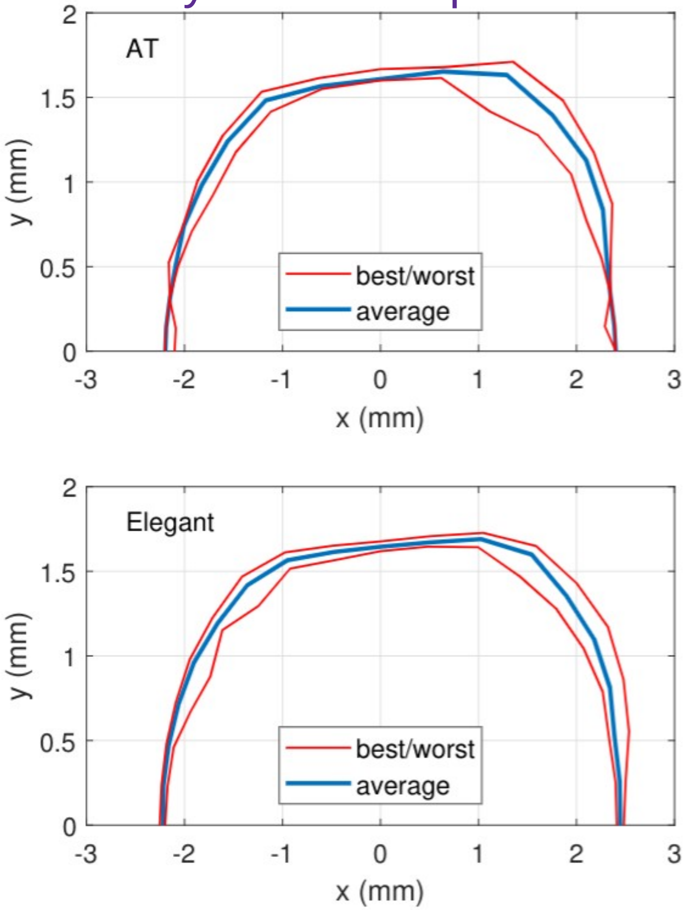
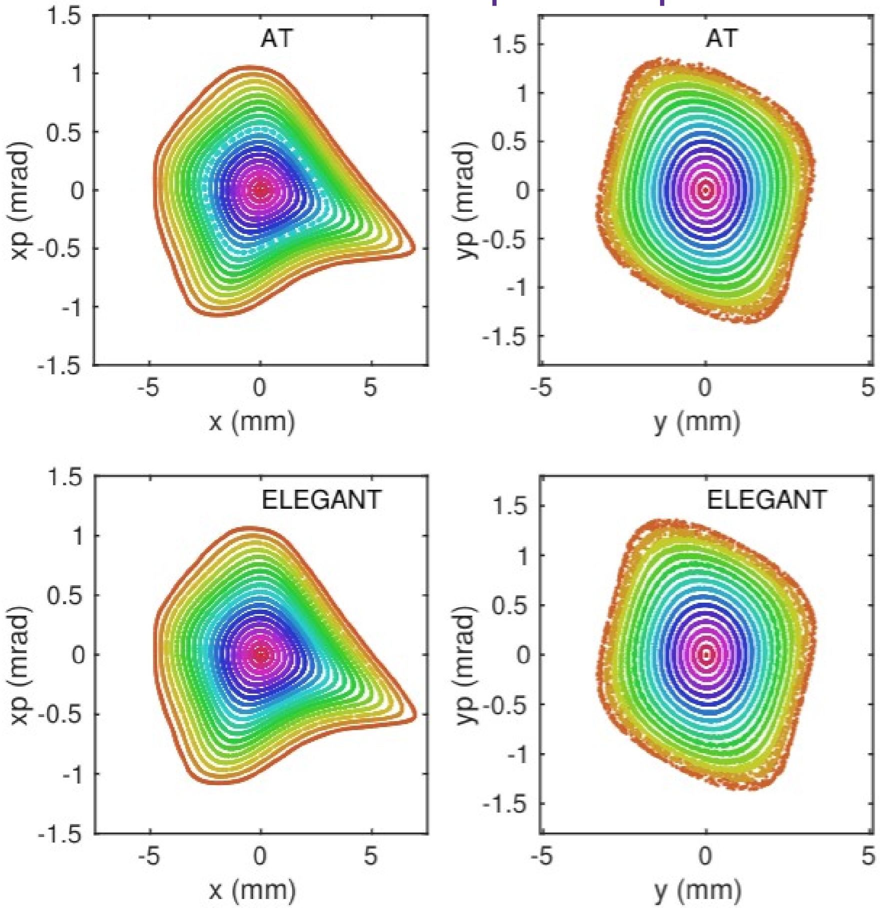
Dynamic acceptance



Transverse phase space



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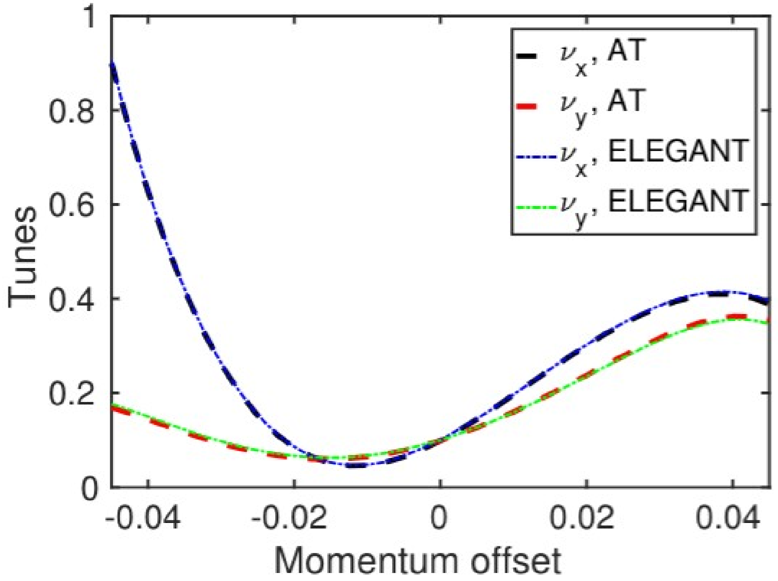

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Advanced algorithms enable robust optimization

- Lattice optimization a highly nonlinear problem with many variables
- APS pioneered use of tracking-based optimization[20] to rings[21,22]
- For APS-U, we use a multi-objective genetic algorithm[23] (MOGA) to evolve linear and nonlinear lattice properties, including
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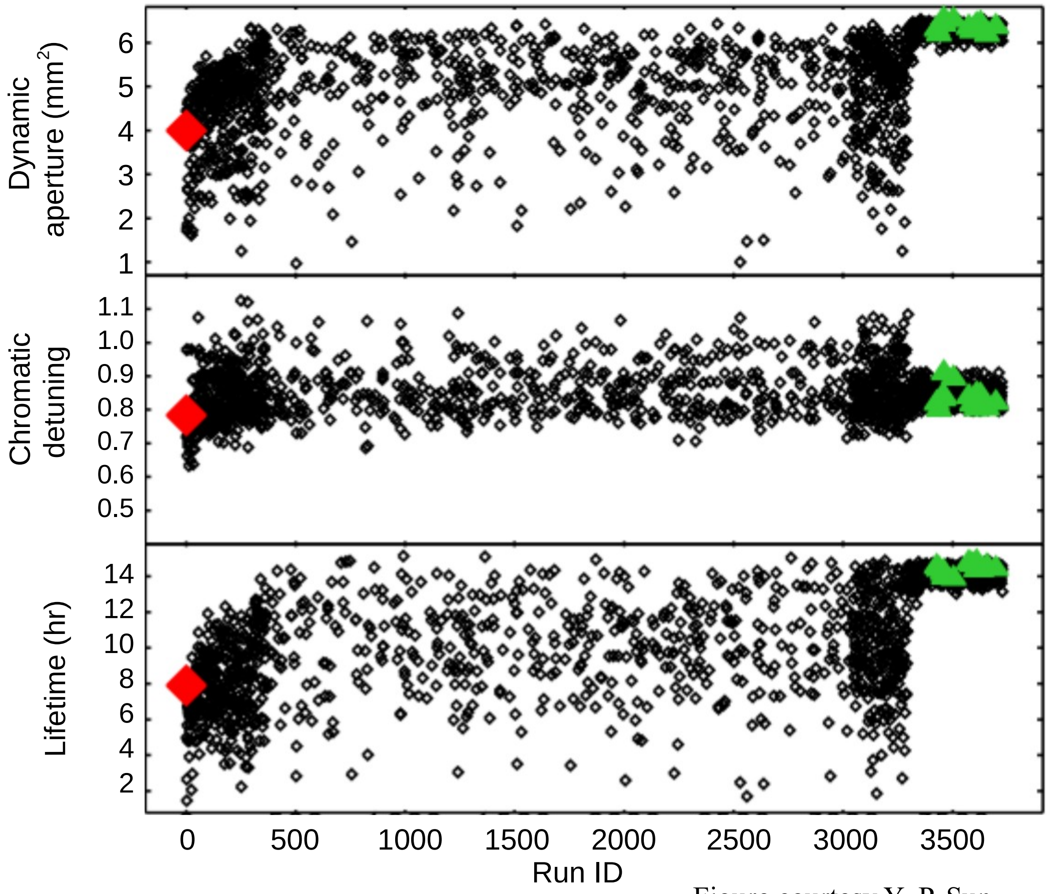
MOGA evolution from the START to the OPTIMAL



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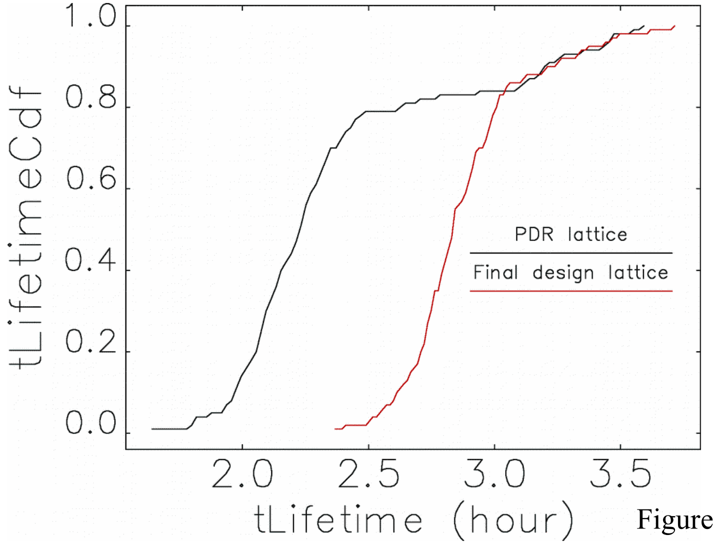
Improved optimization reduces spread in lifetime due to different error sets



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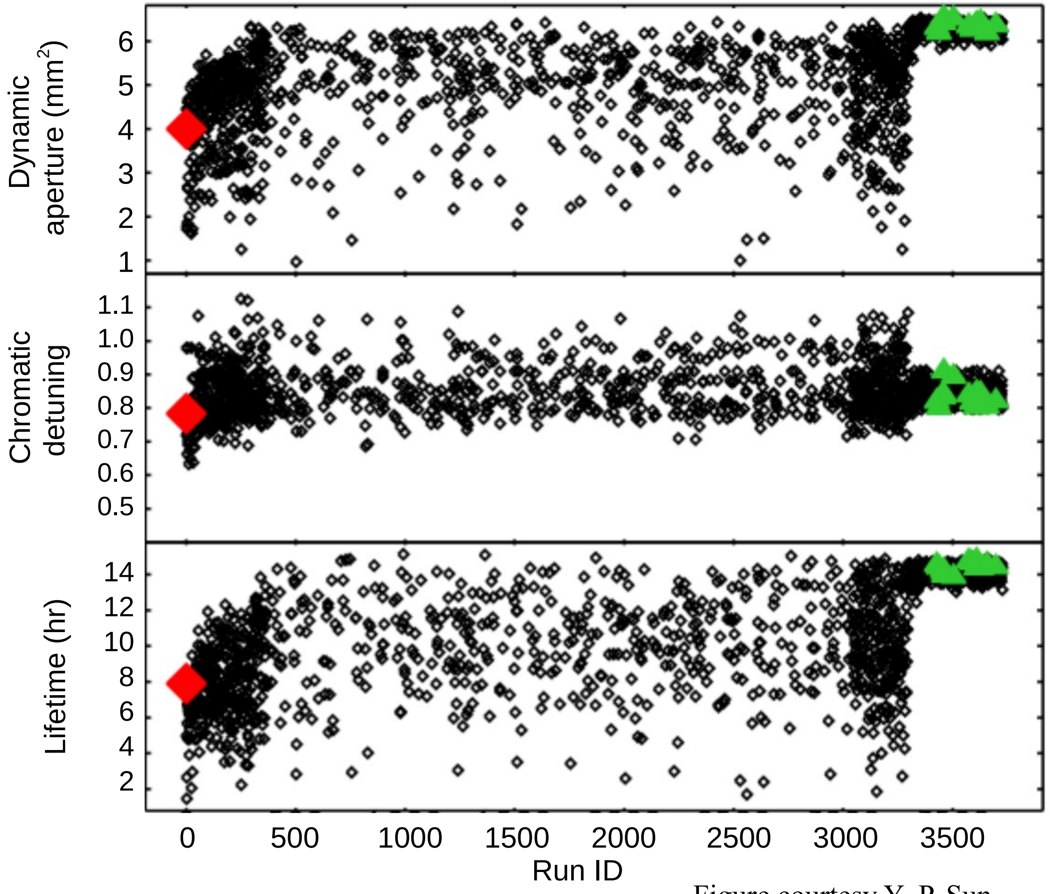

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Detailed commissioning simulations have become an important part of MBA design

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- The main motivation behind commissioning simulations was the desire to minimize dark time during an upgrade
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All while including all sources of errors that we can think of:
Magnet alignment, tilt, strength, BPM offset, calibration, ...

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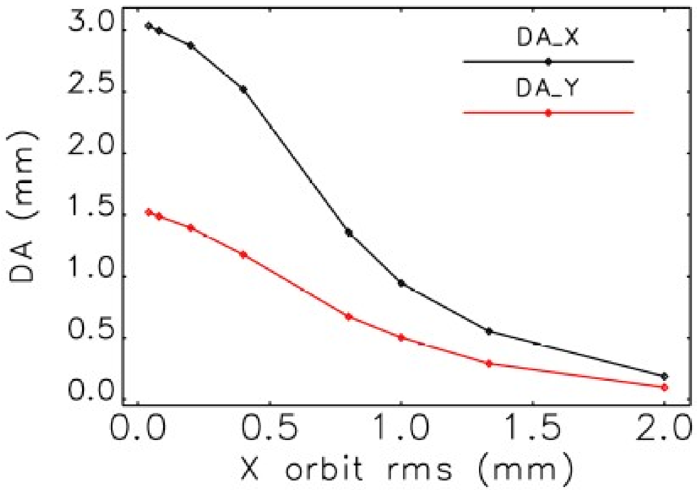
Figures courtesy V. Sajaev



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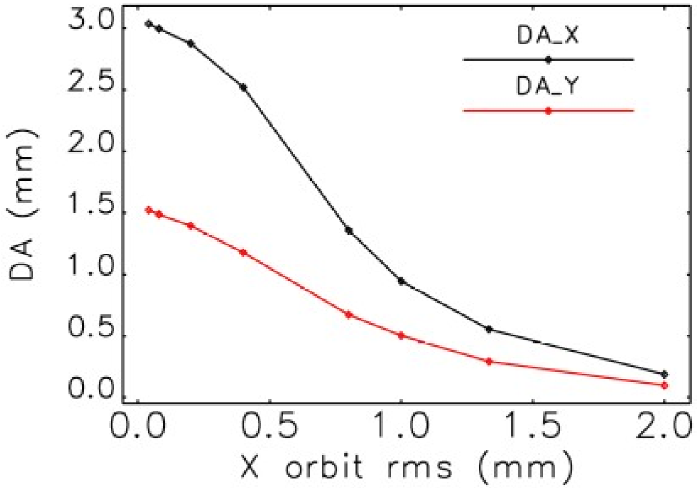
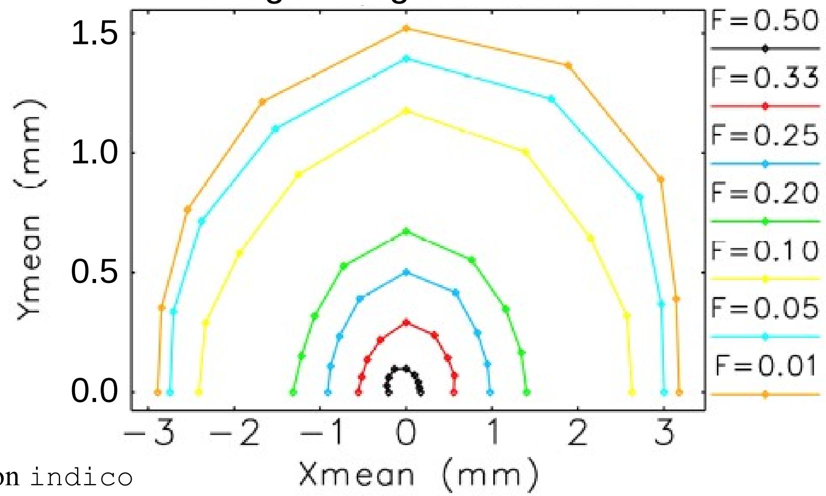


Median dynamic aperture for uncorrected lattice
F = scaling of magnet error tolerances



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Recent successful tests at APS have helped validate our approach

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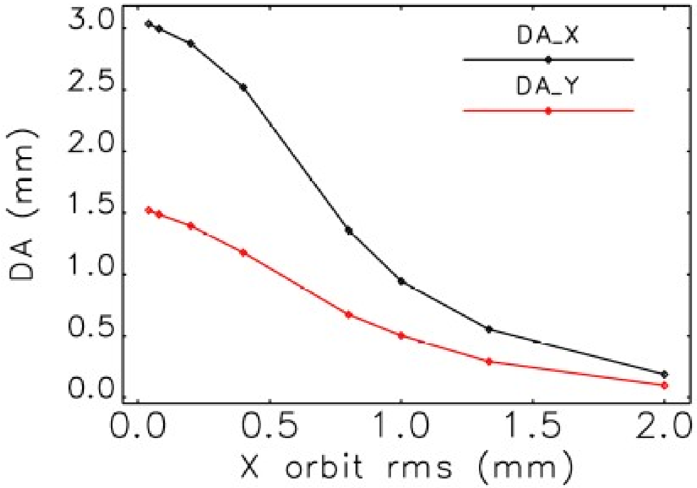

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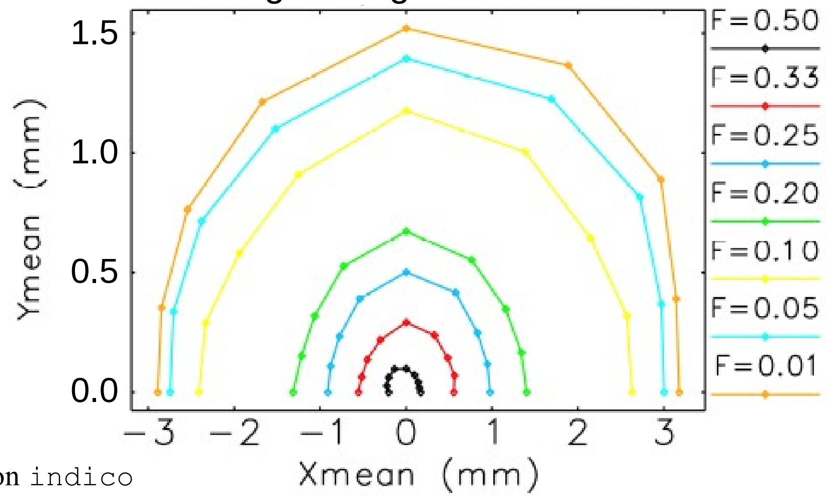

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Conclusions

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- 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

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  - Tight error tolerances on magnets and alignment
  - Highly nonlinear dynamics and small dynamic aperture
- These challenges can be met with a host of
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Thank you for your attention!