Low Emittance Storage Ring for Light Source

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- Radiative effect and emittance
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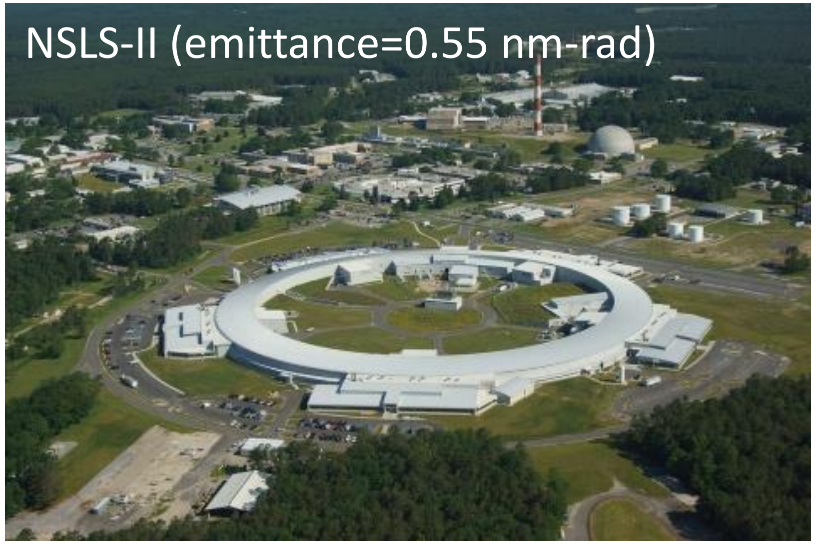
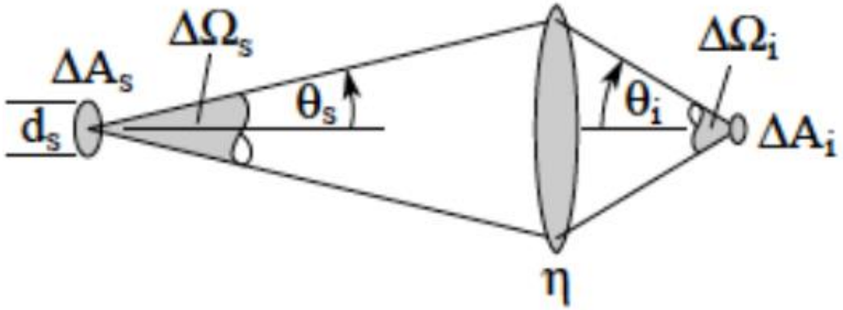
  - MAX IV (7BA)
- Upgrading of Synchrotron Storage Rings

Brightness and emittance



- All beamline experiments require high brightness of the light

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



which depends on emittance

  - Example: Undulator

$$\bar{B}_{\Delta\omega/\omega}(0) = \frac{7.25\times 10^6 \gamma^2 N^2 I(\mathrm{A})}{\sigma_x(\mathrm{mm})\sigma_y(\mathrm{mm})\left(1+\frac{\sigma_x'^2}{\theta_{\mathrm{cen}}^2}\right)^{1/2}\left(1+\frac{\sigma_y'^2}{\theta_{\mathrm{cen}}^2}\right)^{1/2}} \cdot \frac{K^2 f(K)}{\left(1+K^2/2\right)^2}\ \frac{\mathrm{photons/s}}{\mathrm{mm^2 mrad^2 (0.1\%BW)}}$$

where $\sigma = \sqrt{\varepsilon\beta}$ and $\sigma' = \sqrt{\varepsilon/\beta}$

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

Radiative Effects

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

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

where

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

which can be adjusted by vary magnetic strength

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

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

Radiative Effects

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

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

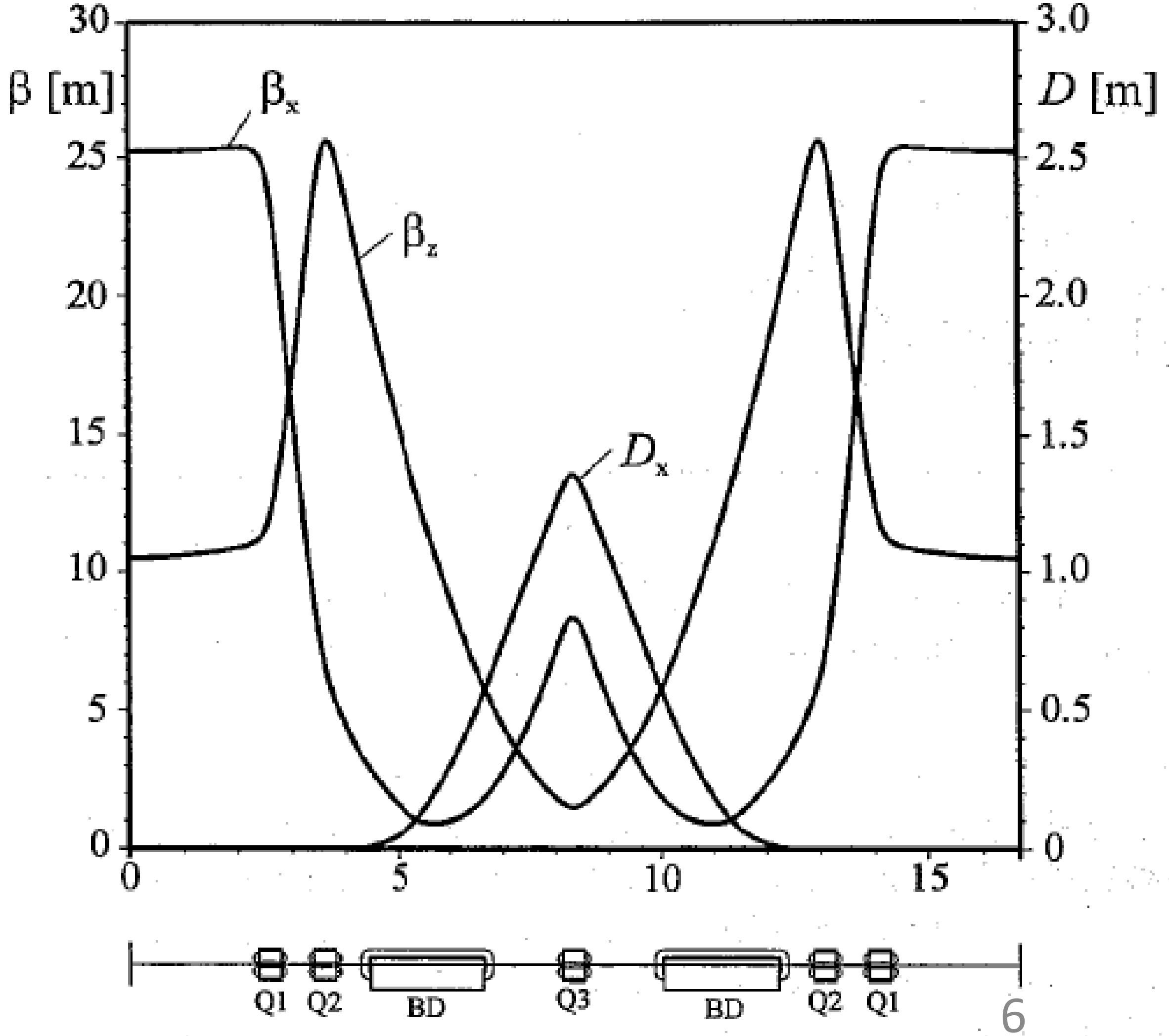
where l is length of bending magnets

- Optimize $H(s)$ to reduce the emittance

Klaus Wille, "The Physics of Particle Accelerators: An Introduction", Oxford University press

Chaseman-Green Lattice DBA

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



Klaus Wille, "The Physics of Particle Accelerators: An Introduction", Oxford University press

Evolution of optical parameters in Bending

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

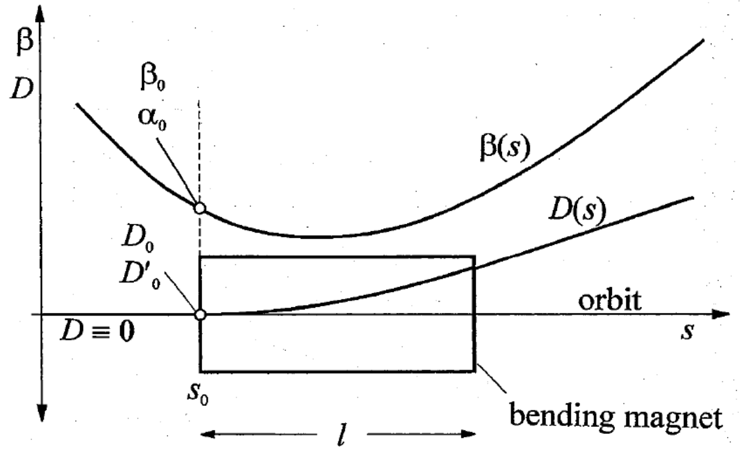
$$H(s) = \gamma D^2 + 2\alpha D D' + \beta D'^2$$

- For dispersion

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

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

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



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

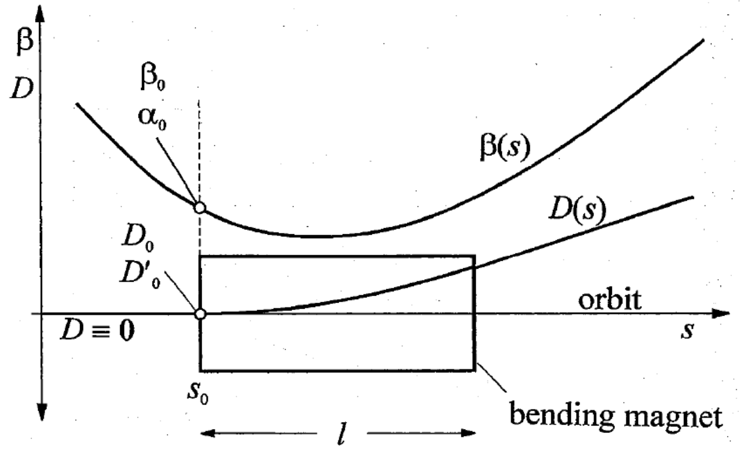
Evolution of optical parameters in Bending

For Betatron function (transformation Matrix for drift space)

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

gives

$$\beta(s) = \beta_0 - 2\alpha_0 s + \gamma_0 s^2$$
$$\alpha(s) = \alpha_0 + \gamma_0 s$$
$$\gamma(s) = \gamma_0$$



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

Emittance

Hence

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

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

Finally,

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

where $\Theta = l/\rho$

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

Minimum Emittance

Differentiate respects to initial condition

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

give

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

So

$$\beta_0 = \sqrt{\frac{12}{5}}\,l\,,\ \alpha_0 = \sqrt{15}$$

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

Minimum Emittance

For Chasman-Green lattice (double bend achromat)

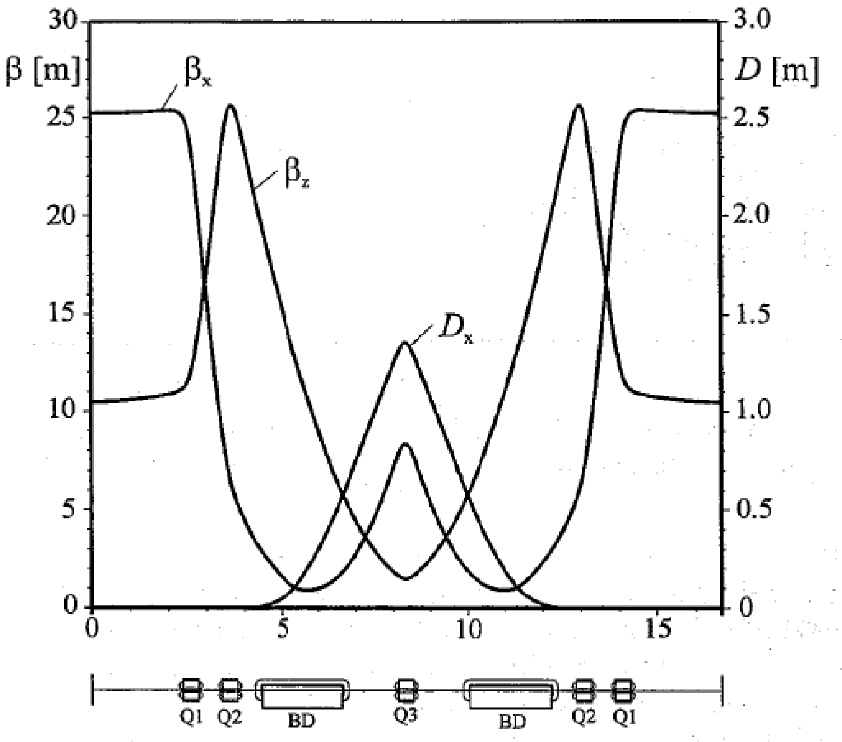
$$\varepsilon_x\ [\text{nm}-\text{rad}] = 94.7\ \Theta^3\ E^2[\text{GeV}]$$

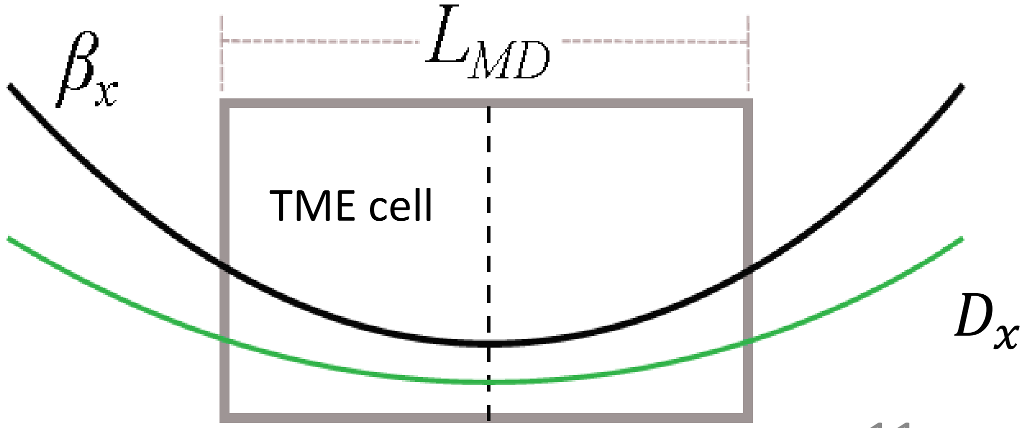
Note that if it's not Achromat lattice
when $D \neq 0$ and $D' \neq 0$

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

This is the theoretical minimum emittance (TME)

Double Bend Achromat lattice (DBA)





Dieter Einfeld (2014), "Multi-bend Achromat Lattices for Storage Ring Light Sources", Synchrotron Radiation News

Multi Bend Achromat (MBA)

- D. Einfeld *et al*. proposed the use of MBA in 1993.
- From

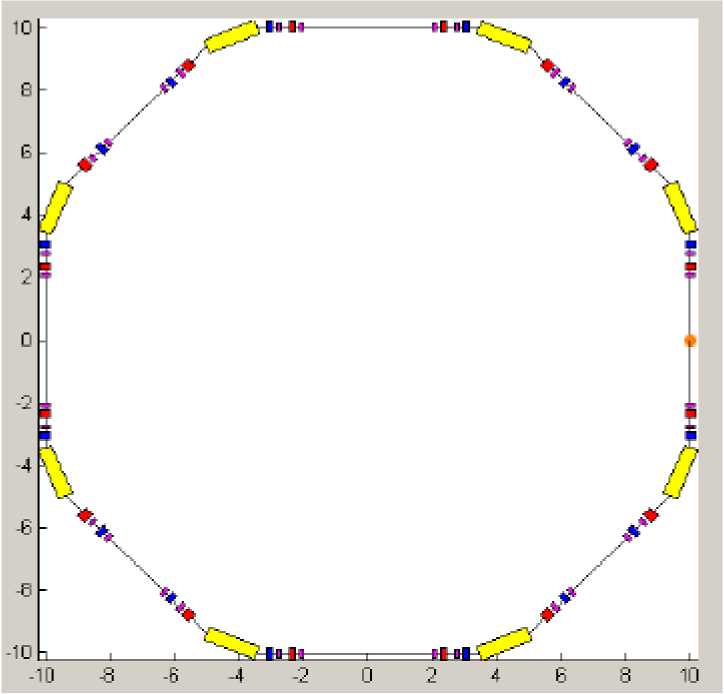
$$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \Theta^3 F,$$

where F is factor depends on Betatron function

- $\Theta = 2\pi/N$, N is number of bending
- Hence

$$\varepsilon_x \propto \frac{E^2}{N^3}$$

- Increase N -> reduce Θ -> reduce ε_x

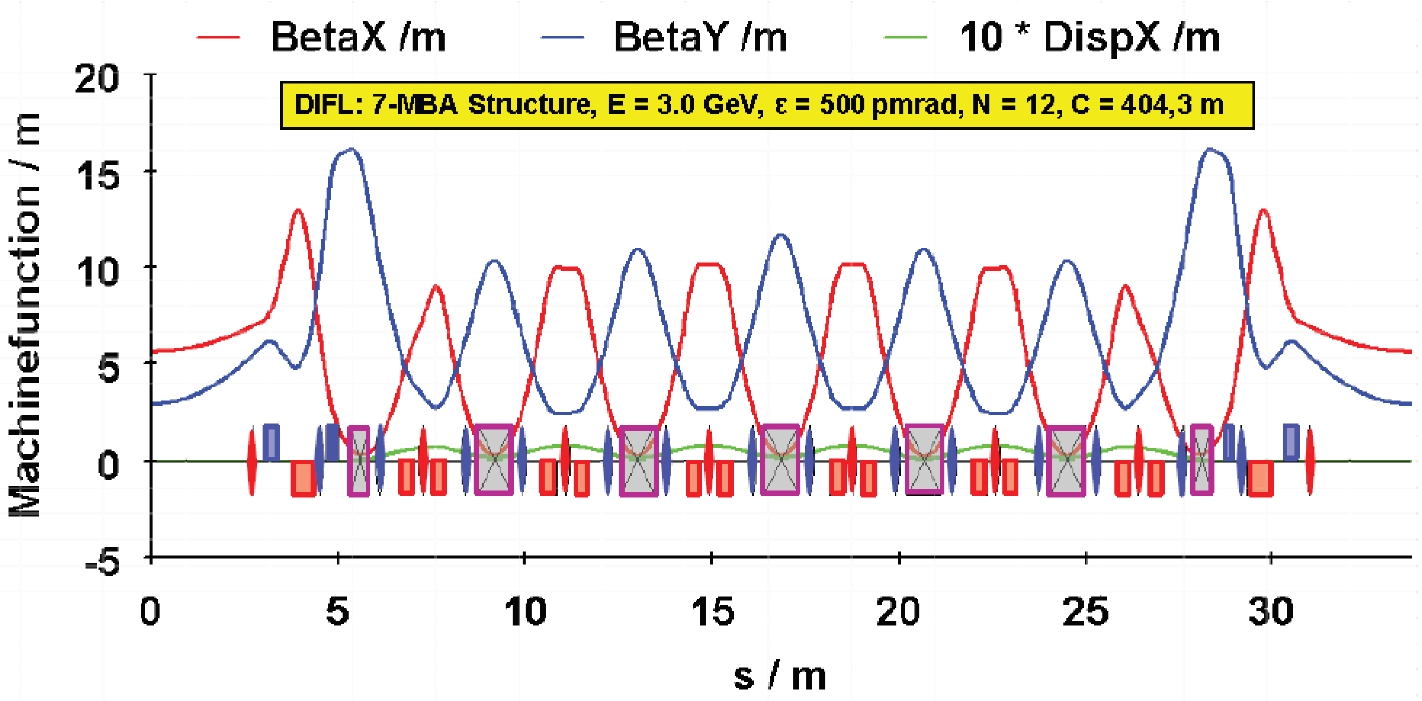


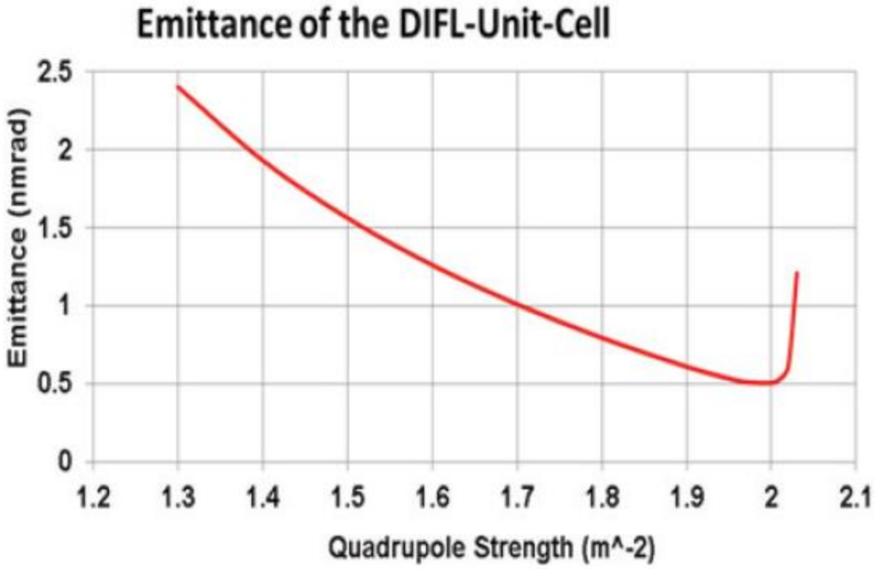
Thapakron Pulampong, “Ultra-low Emittance Lattice Design for Advanced Synchrotron Light Sources”, thesis submitted at the University of Oxford

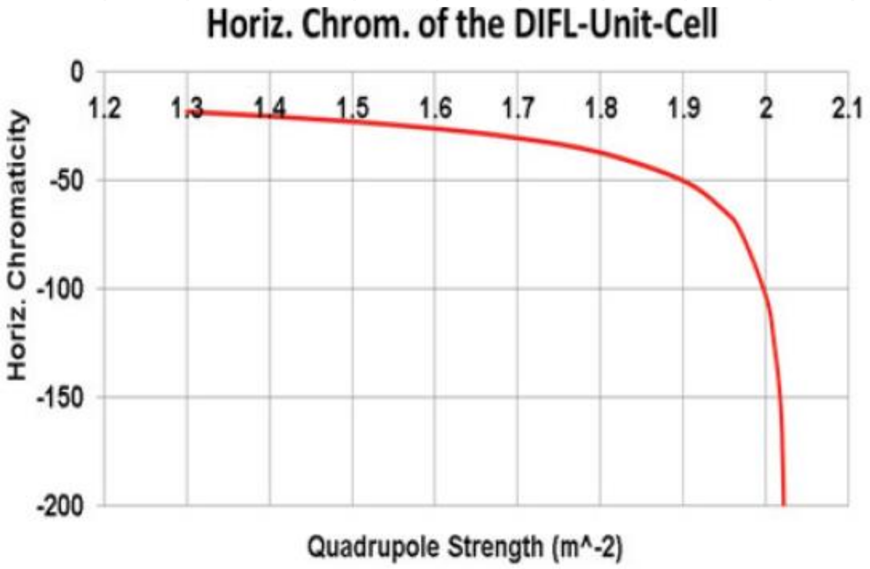
MBA

- Stronger focusing
- High Chromaticity (negative)

MAX IV (emittance ~200 - 330 pm-rad)







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

Dieter Einfeld (2014), “Multi-bend Achromat Lattices for Storage Ring Light Sources”, Synchrotron Radiation News

MBA

- More bending -> reduce space for IDs
- Require combine magnet -> increase J_x which reduce ε_x

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

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

Hence $J_x + J_E = 3$ constant

- Increase J_x will reduce J_E -> increase energy spread

MAX IV

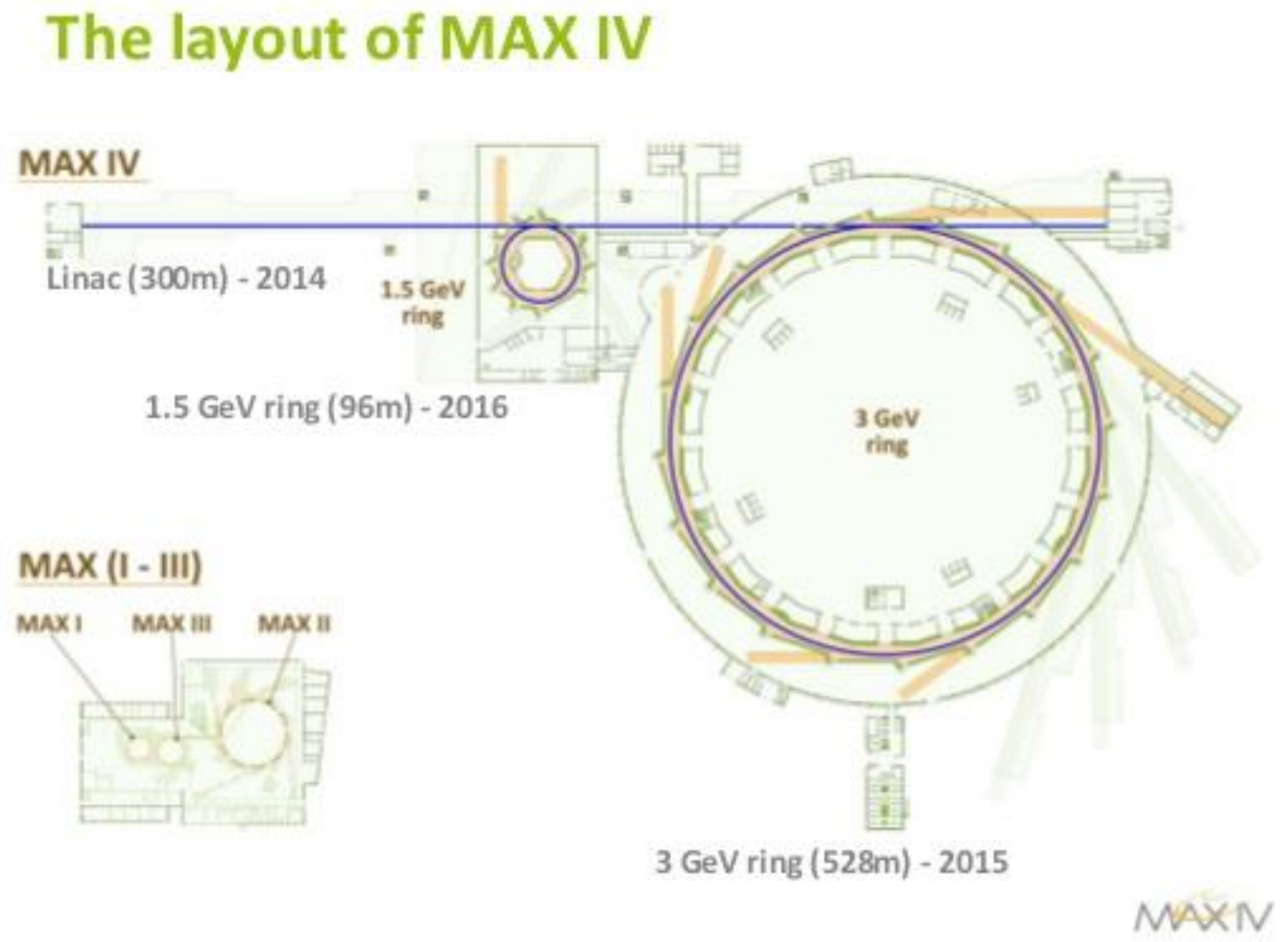
528 m circumference

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

MAX IV

Consists of

- 3 GeV LINAC (300 m)
  - 10 Hz for full energy injection
  - XFEL
- 1.5 GeV 96 m circumference
  - Soft x-ray and UV users
- 3 GeV: 528 m circumference
  - Hard x-ray users



MAX IV

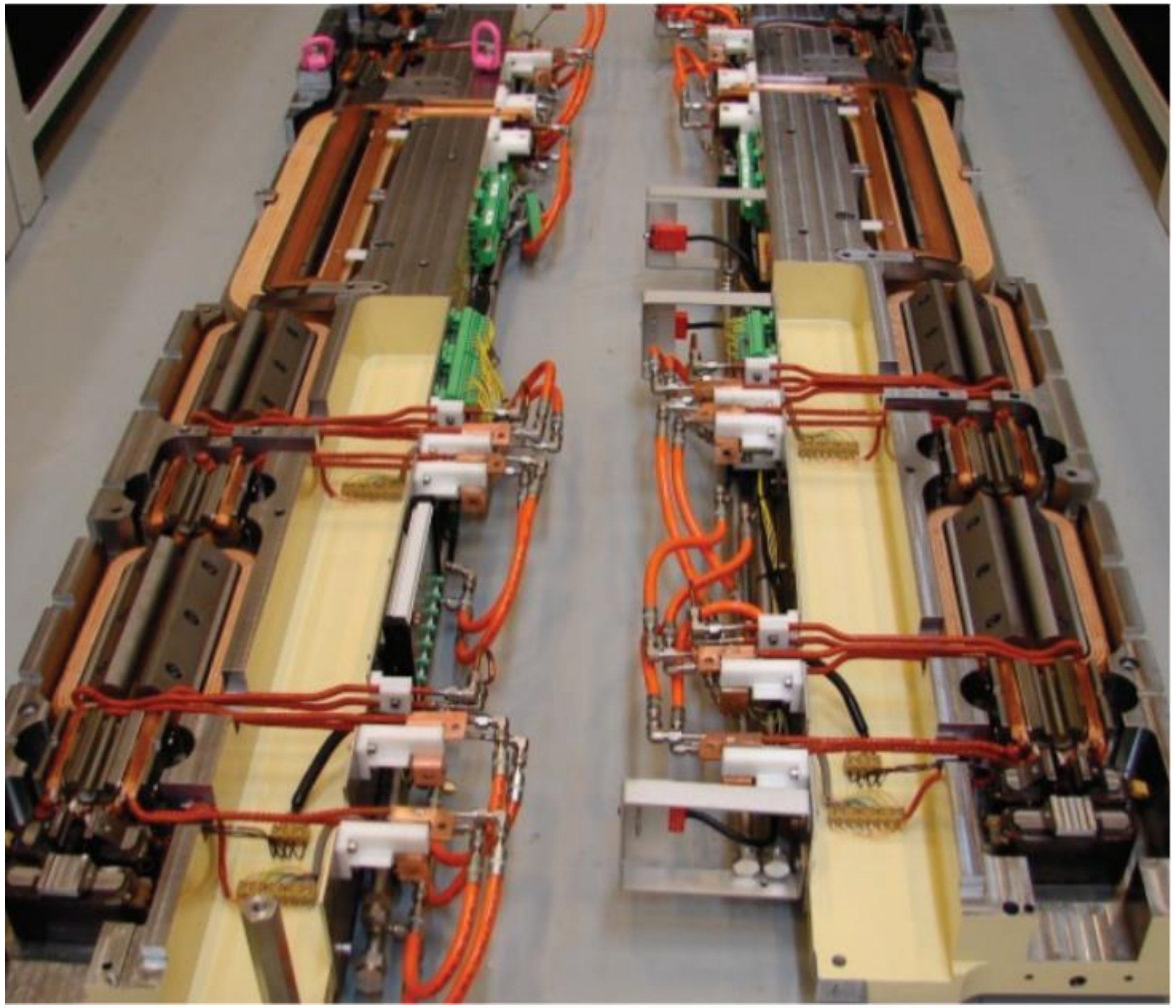
Comparison between

- NSLS-II
- MAX IV

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

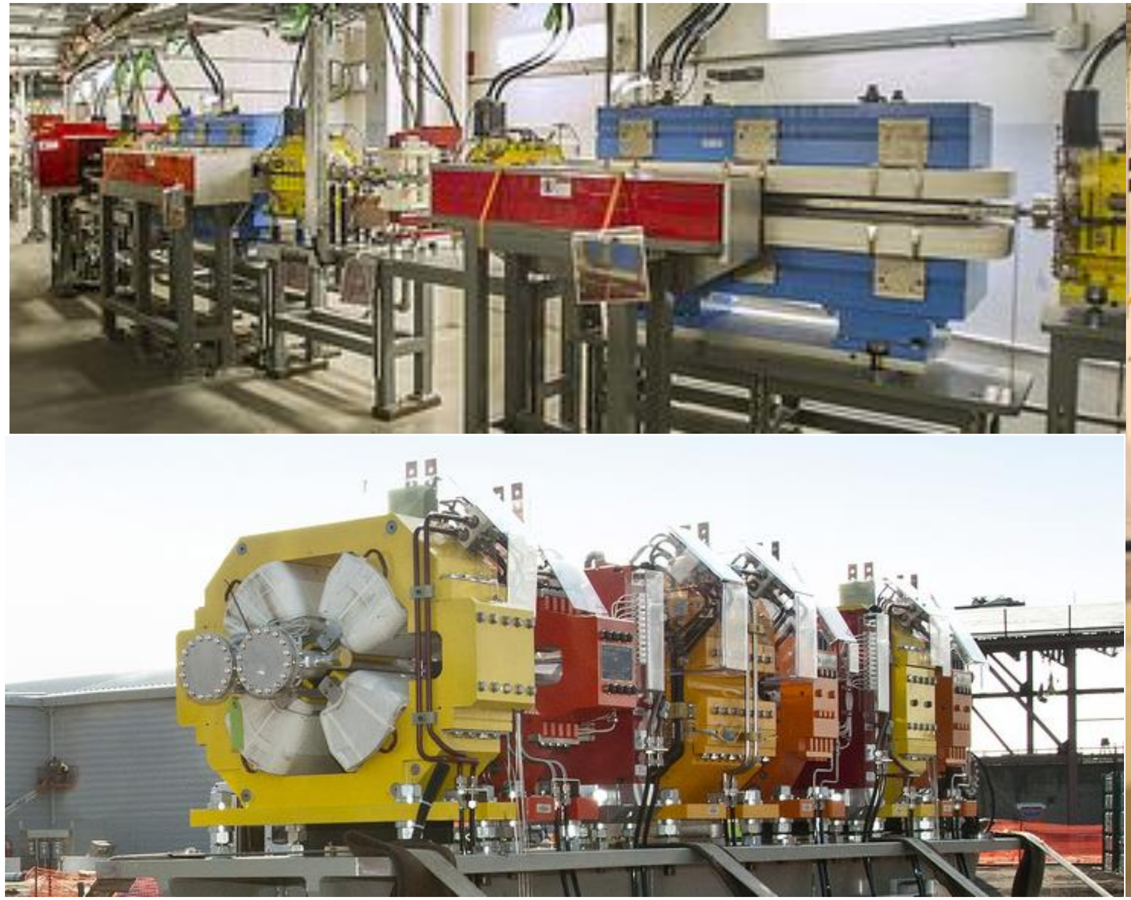
MAX IV: Magnets

- In order to reach low emittance with small circumference
  - Compact magnet
  - Reduce magnets gap -> Strong magnetic field
  - Shorter
- Integrated units
  - BM, QM pole are machined out of a pair of iron blocks
  - Each unit holding all the magnets of a complete cell



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

Magnets

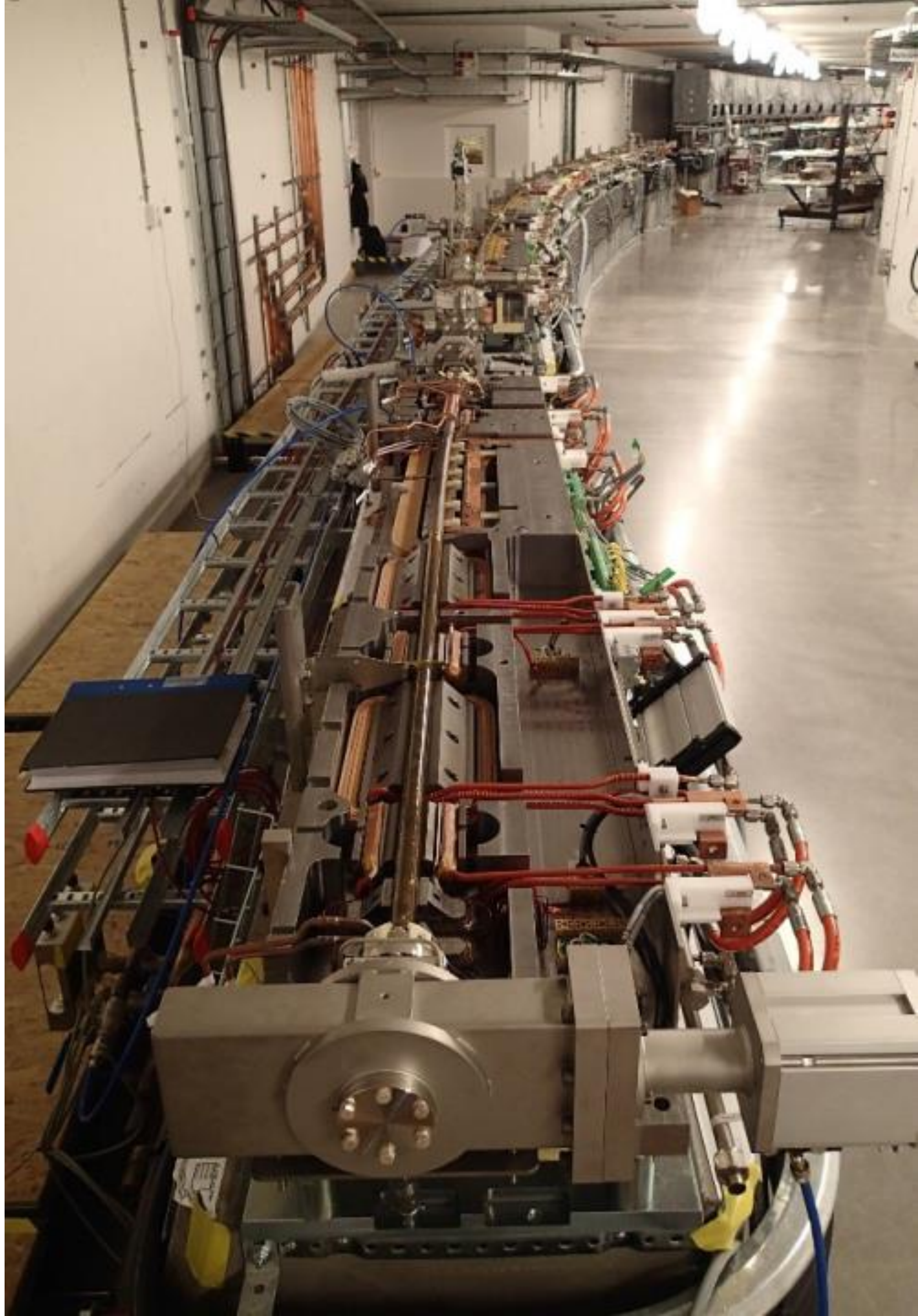


Separated function magnets (NSLS-II)

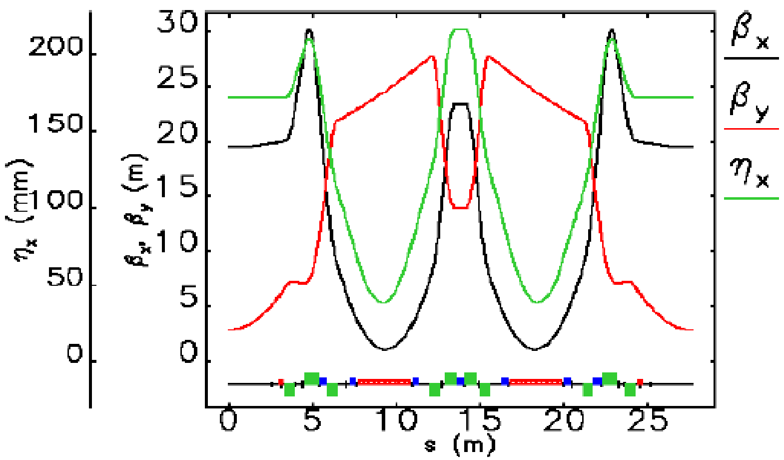
Two complete 7-bend achromats at MAX IV

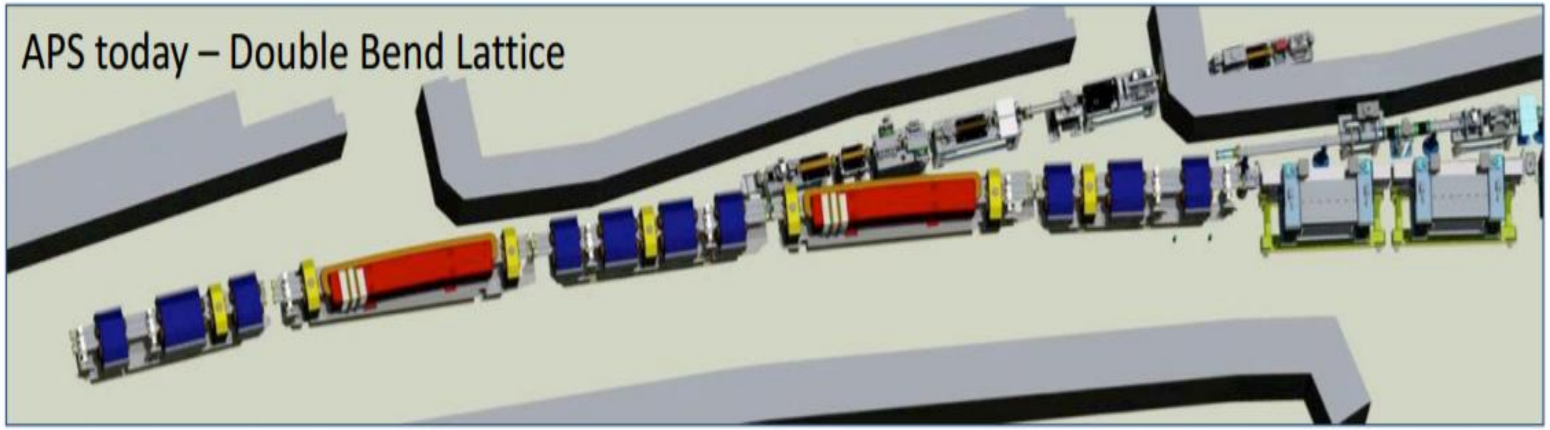
MAX IV: Chamber

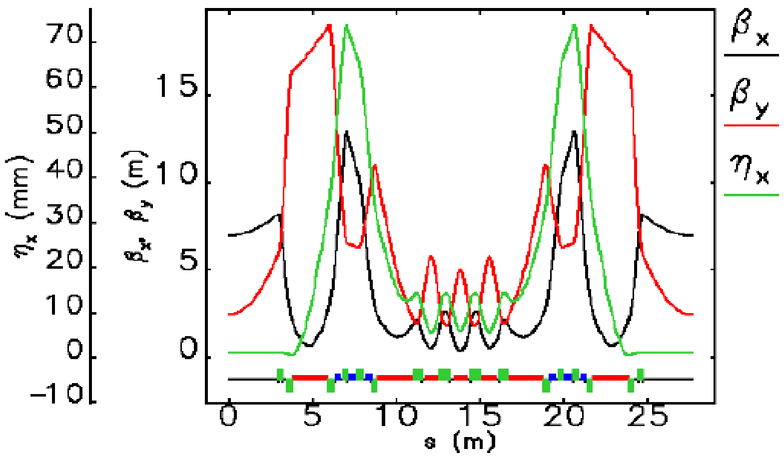
- Compact magnet design lead to narrow low-conductance vacuum chambers
  - Distributed pumping and heat load
- Heat load problem
  - Use copper as a chamber
  - Water cooling
- Pumping problem
  - Provide by non-evaporable getter (NEG) coating at the inner surface
  - Reduce number of pumps and absorbers

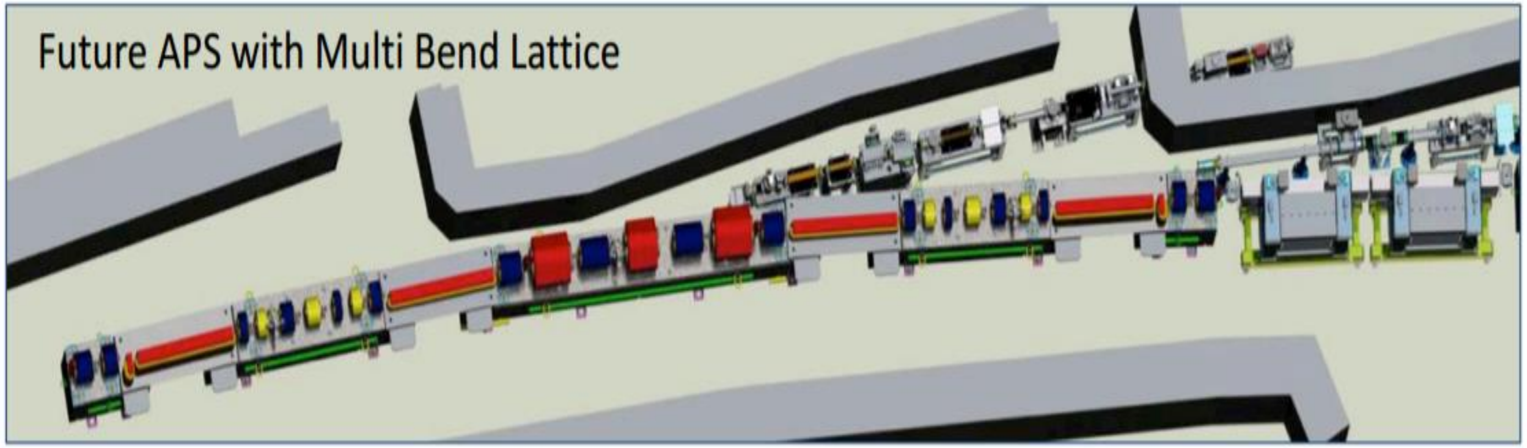


Advance Photon Source (APS) upgrading







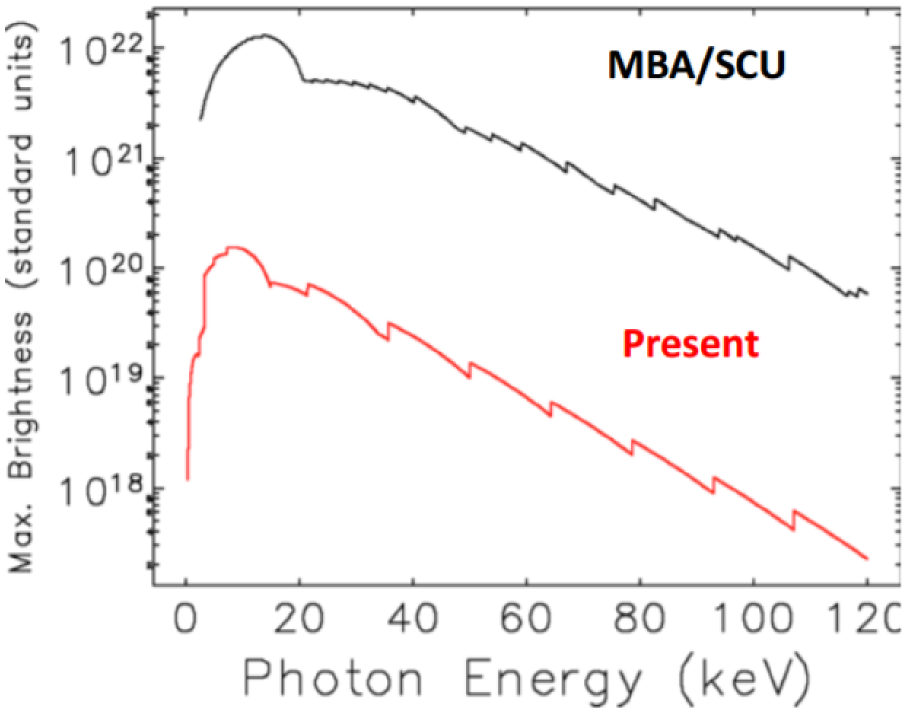


Stuart Henderson, “APS Upgrade Overview and Status”, APS Users Organization/Partner User Council Joint Meeting July 9, 2014

Advance Photon Source (APS) upgrading

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

	DBA	MBA	
Radiation-integral-related quantities			
Beam energy	7	6	GeV
Natural emittance	2527.5	66.9	pm
Energy spread	0.095	0.096	%



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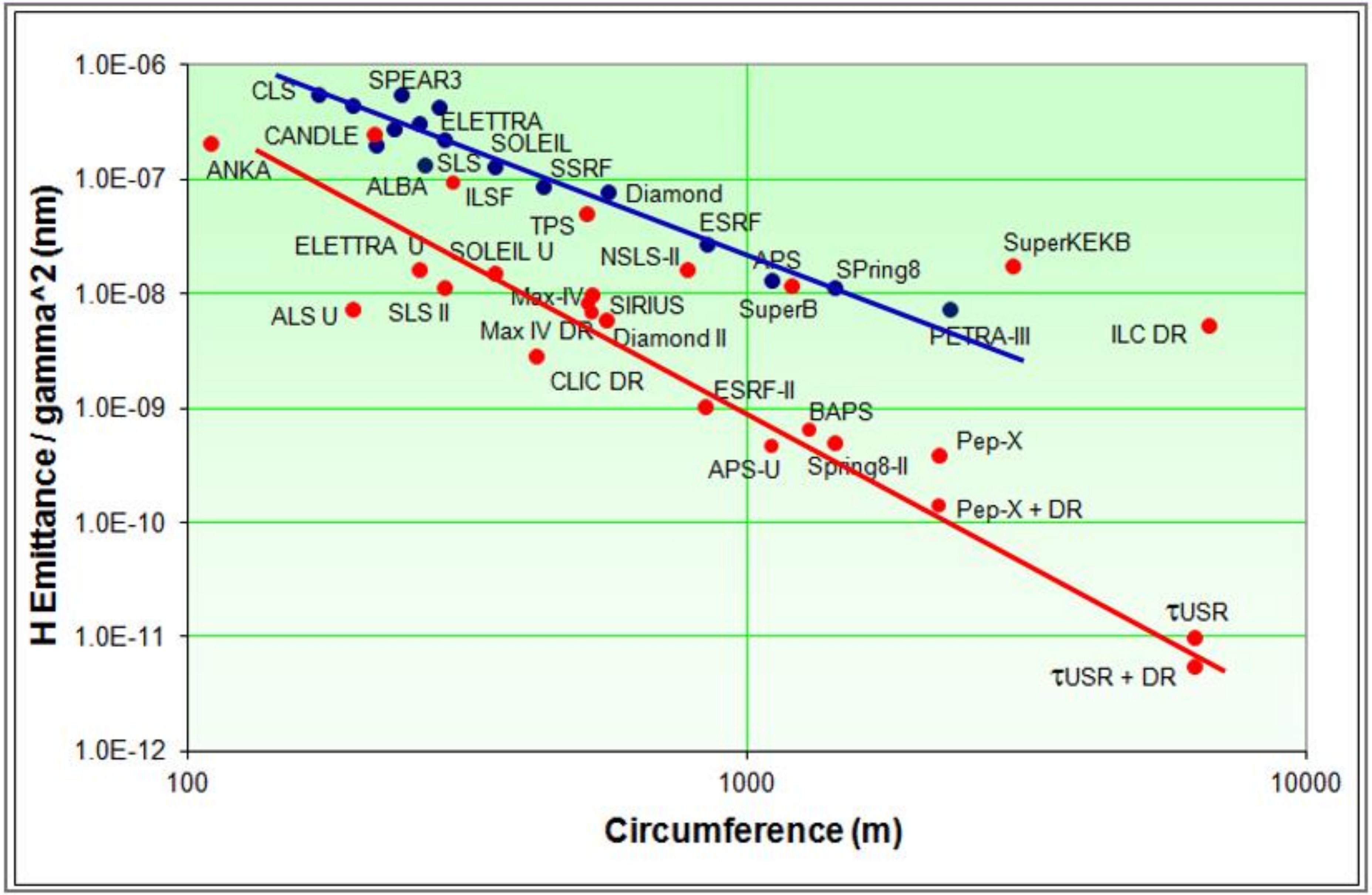
Survey of low emittance lattices



Credit: "Status of the Diamond Light Source upgrade", R. Bartolini, et al., EuCARD2 topical workshop Barcelona, 23 April 2015

Summary

- Theoretical Minimum Emittance (TME) consider only on emittance
  - Difficult to reach
- In reality, other parameters need to be considered
  - Non-linear term e.g. dynamics aperture
  - Space for IDs
  - Costs e.g. high-tech magnets
- MBA can reduce emittance because reduce the bending angle
- Many Synchrotrons around the world plan to upgrade to MBA

Reference

- PHY 554 CASE course, Stony Brook University, Fall 2016
- Klaus Wille, “The Physics of Particle Accelerators: An Introduction”, Oxford University press
- Dieter Einfeld (2014), “Multi-bend Achromat Lattices for Storage Ring Light Sources”, Synchrotron Radiation News, 27:6, 4-7, DOI: 10.1080/08940886.2014.970929
- Pedro F. Tavares, “The MAX IV storage ring project”, Journal of Synchrotron Radiation ISSN, 1600-5775
- Thapakron Pulampong, “Ultra-low Emittance Lattice Design for Advanced Synchrotron Light Sources”, thesis submitted at the University of Oxford
- R. Bartolini. A. Alekou, M. Apollonio, et al., “Status of the Diamond Light Source upgrade”, EuCARD2 topical workshop Barcelona, 23 April 2015
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Extra Slide: Chromaticity

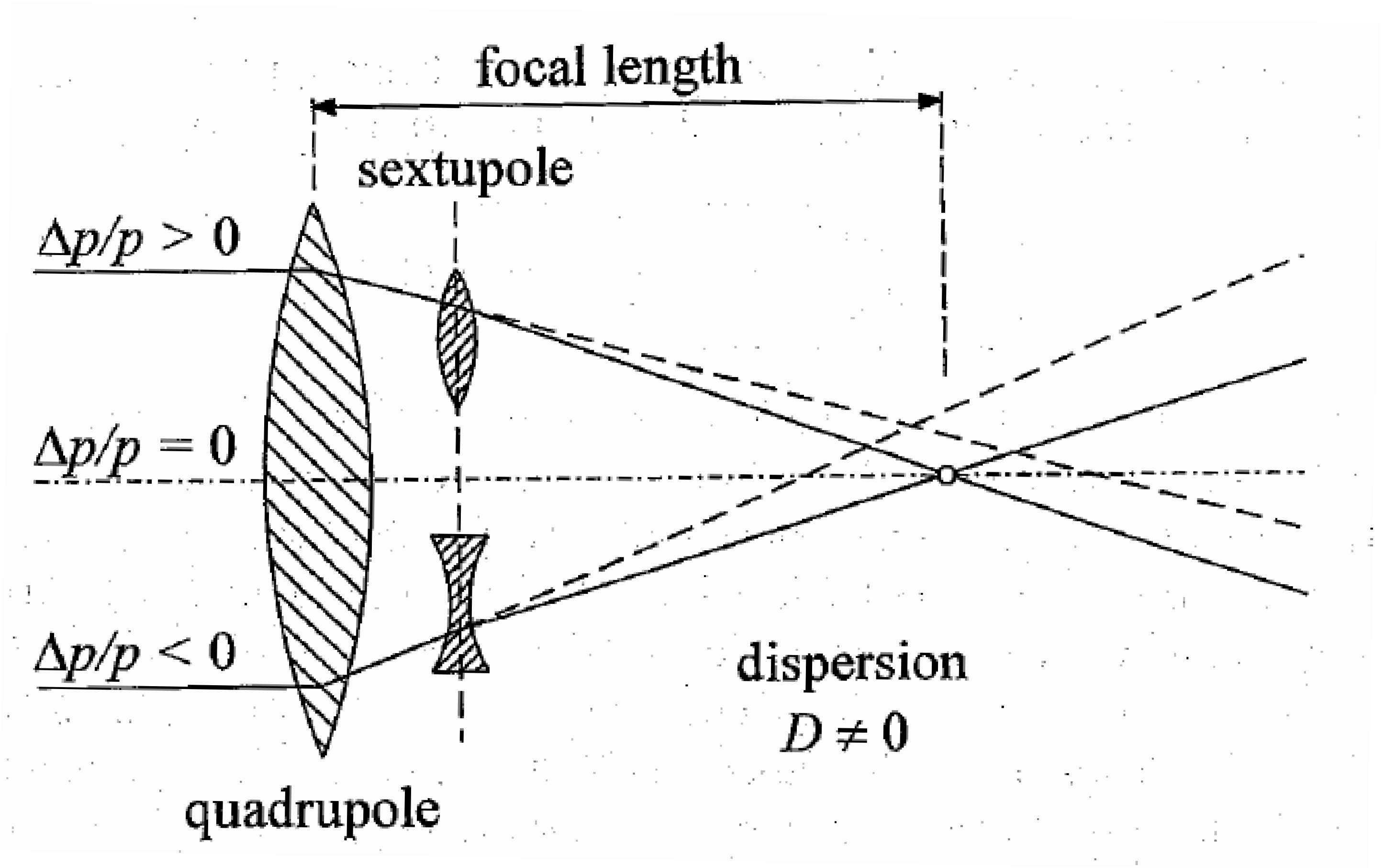
- Chromaticity leads to tune shifted

$$\xi \equiv \frac{\Delta Q}{\Delta p/p} = \oint k(s)\beta(s)ds$$

- Sextupole magnets
  - Compensate the Chromaticity

$$k_{\text{sext}} = m\,D\,\frac{\Delta p}{p}$$

Where m is sextupole strength



Extra Slide: NEG coating

- **Non evaporable getters** (NEG), based on the principle of metallic surface sorption of gas molecules, are mostly porous alloys or powder mixtures of Al, Zr, Ti, V and Fe. They help to establish and maintain vacuums by soaking up or bonding to gas molecules that remain within a partial vacuum.
- They are important tools for improving the performance of many vacuum systems.
- the NEG coating can be applied even to spaces that are narrow and hard to pump out, which makes it very popular in particle accelerators where this is an issue.
- The NEG acts as a getter or getter pump that is able to reduce the pressure to less than 10^{-7} Pa.