National Synchrotron Light Source II

Reaching Low Emittance in Synchrotron Light Sources by Using Complex Bends

Guimei Wang on behalf of Complex Bend design team

NSLS-II, Brookhaven National Lab

North American Particle Accelerator Conference: 1-6 September 2019

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Outline

- Introduction
- Trend in synchrotron light sources: today → tomorrow
- From Double-Bend Achromat to Multi-Bend Achromat lattice
- Complex Bend
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  - Prototype of Complex Bend
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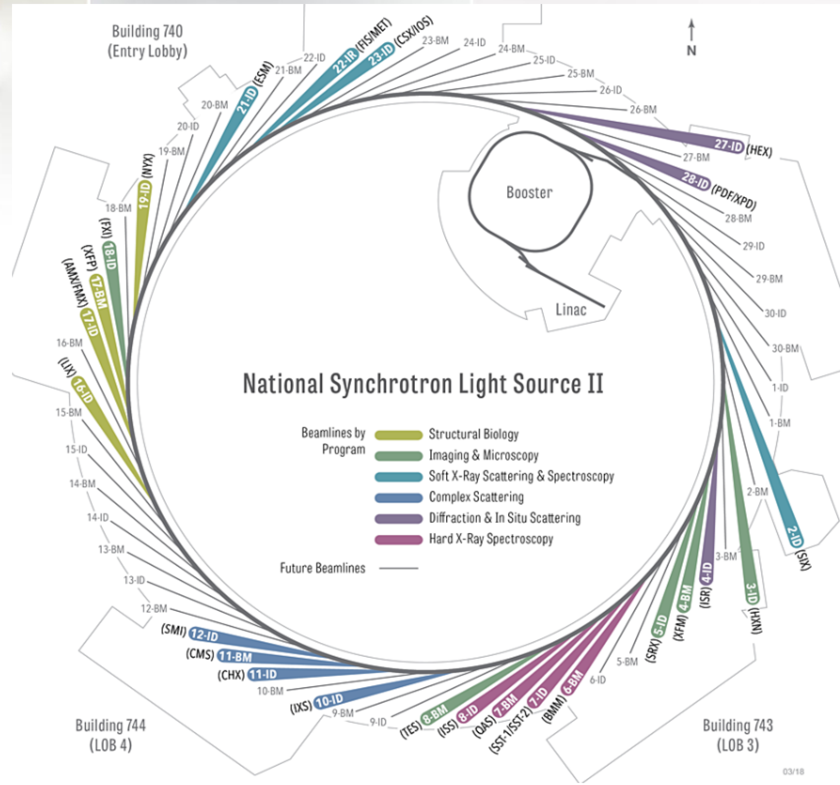
Introduction

NSLS II overview

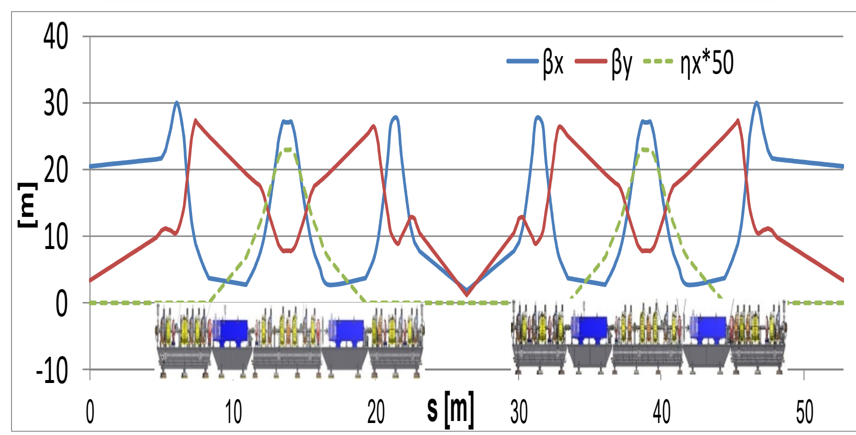
- National Synchrotron Light Source (NSLS-II) is a new 3 GeV, 500 mA, high-brightness synchrotron light source facility at the Brookhaven National Laboratory, funded U.S. Department of Energy (DOE).

- SR commissioning started in later March 2014
- Six project beamlines operated in Dec. 2014
- Top off routine operation started in October 2015
- 28 beamlines in top off operation at 400 mA
- Stored beam current up to 475 mA in Mar. 2019

- NSLS-II accelerator consists of a 200 MeV Linac, a full energy Booster and 3 GeV Storage Ring
- SR circumference is 792 m with 0.9 nm-rad horizontal and 8 pm-rad vertical emittance.
  - 15 long (9.3m) and 15 short (6.6m) straight sections
  - Top off injection for stable intensity (±0.5% variation)
  - High beam stability in position and angle



One super-period SR Lattice function



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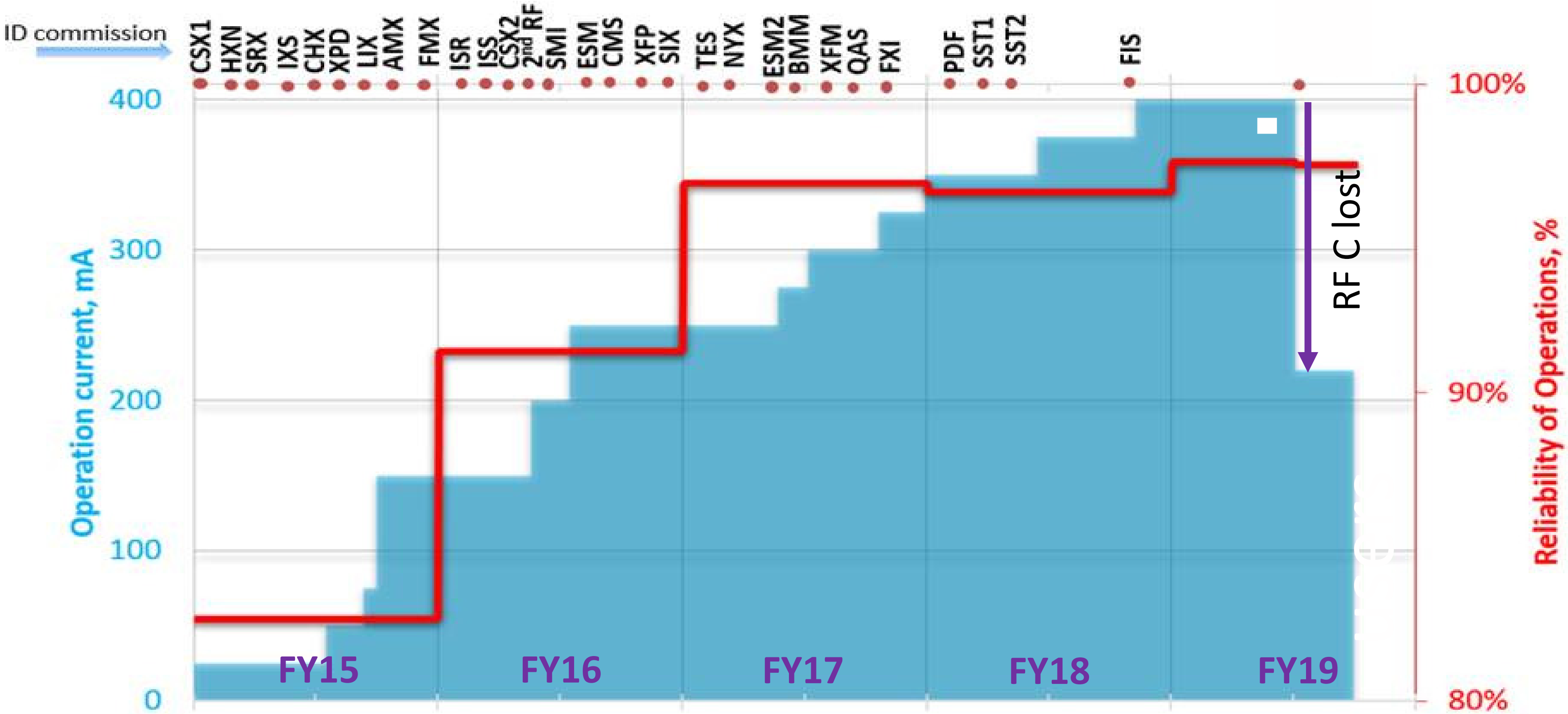
NSLS-II: 4½ years operations



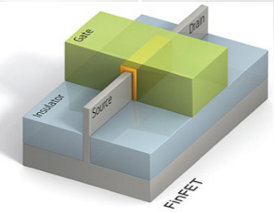
	FY15	FY16	FY17	FY18	FY19
Operating HRS per FY:	2100 hrs	3740 hrs	4500 hrs	4750 hrs	5000 hrs
Facility users per FY:	110	447	1037	1364	1182 (5/20)

- Commissioned 29 IDs (10 IVUs, 6 EPUs, 6 DWs, 5 3PWs, 1 BM and 1 PU)
- Steadily increase beam current and IDs sources while maintain operation high reliability

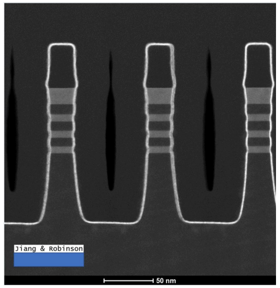
NSLS II: Brightness/Coherence driven science cases

- Brightness/coherence driven experiments
  - Experiments using a coherent X-ray beam or using diffraction limited focusing X-ray optics
  - ***Low emittance → resolution and scan time***
- Hard X-ray Nanoprobe Beamline:
  - cutting-edge multimodality 3D nano-tomographic with 5-10 nm resolution
  - Nano Diffraction from Nanosheet: study next-generation microprocessor, *e.g.* in IBM's new nanosheet technology, down to 7 nm thickness, state-of-the-art (10-14 nm commercial)
- Coherent Hard X-ray Scatting beamline: study real time thin-film growth, ~10 nm length scales and ms to μs time scales

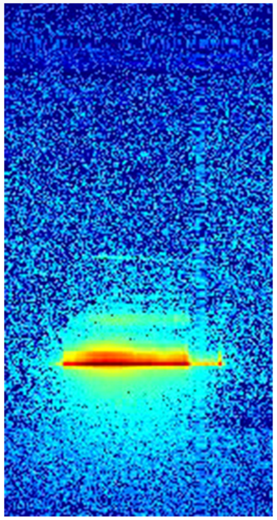
FinFET



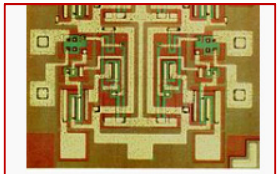
IBM



Nano-diffraction (5 sec/frame)

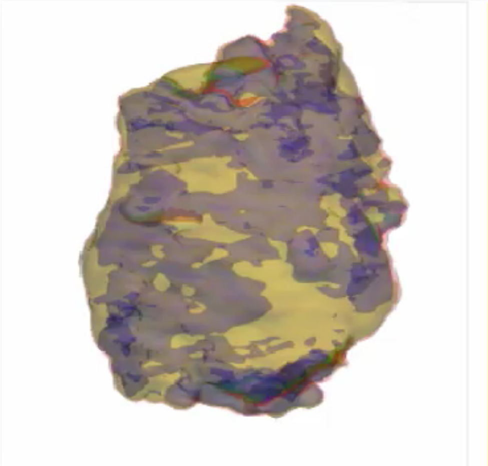


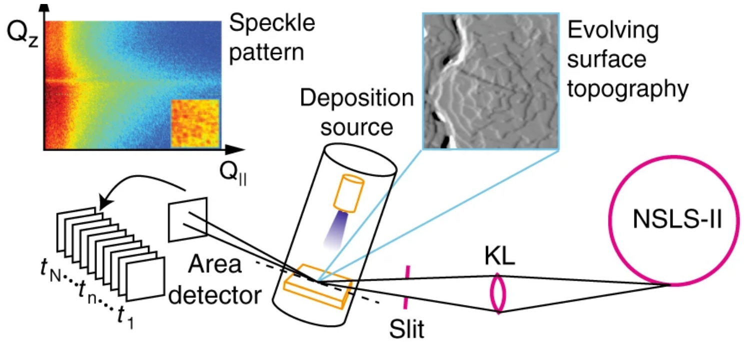
https://en.wikipedia.org/wiki/Semiconductor_device_fabrication



130 nm – 2001
90 nm – 2003
65 nm – 2005
45 nm – 2007
32 nm – 2009
22 nm – 2012
14 nm – 2014
10 nm – 2016
7 nm – 2018
5 nm – 2019

3D nano-tomographic





C_{60} film growth on polycrystalline graphene/SiO_2

Headrick et al. Nature Comm. (2019)
https://doi.org/10.1038/s41467-019-10629-8

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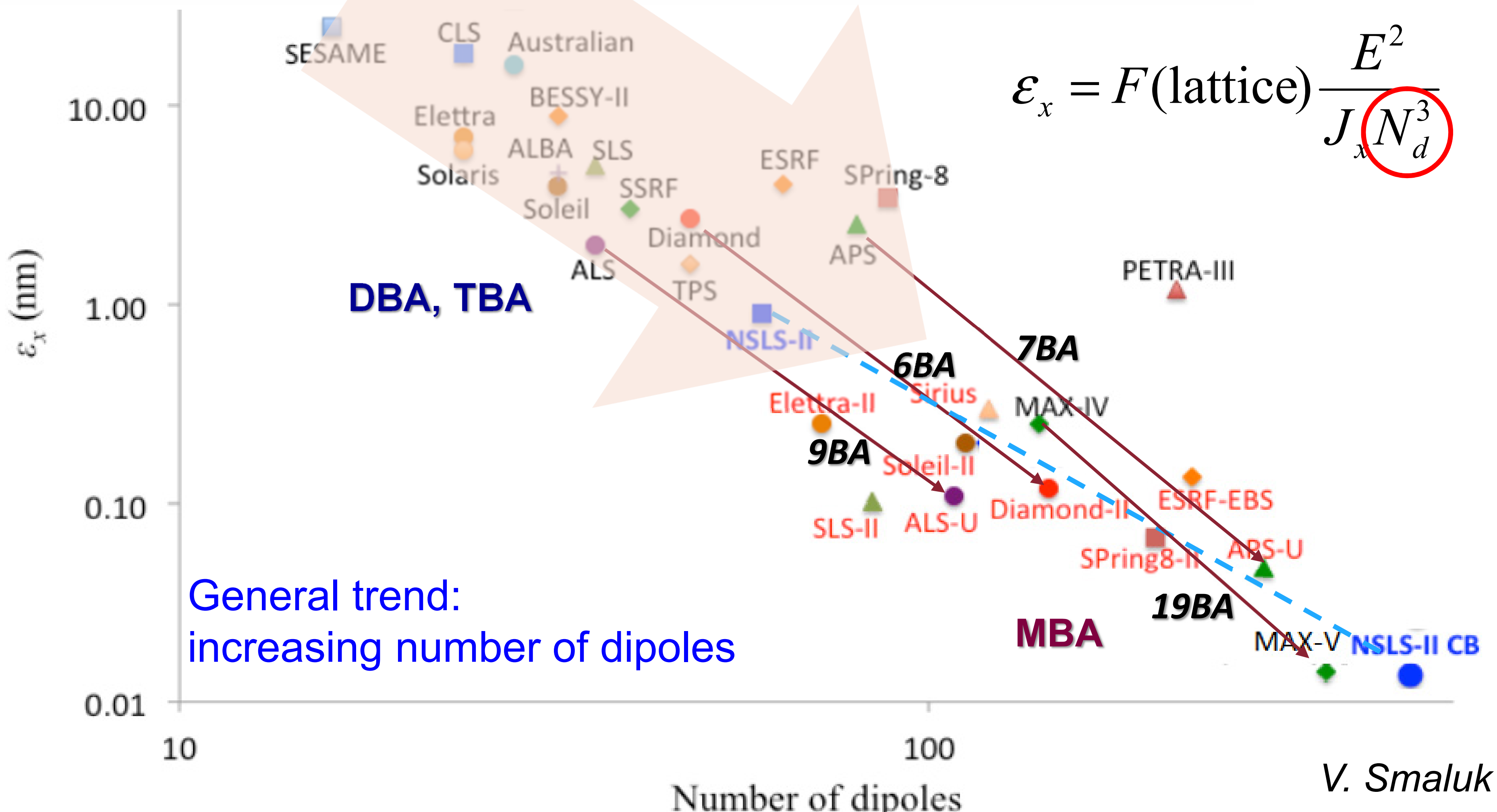
Synchrotron light source: today → tomorrow

Synchrotron light source: today and tomorrow

- Two order magnitude of emittance reduction: increasing brightness and coherence
- Transition from Double- and Triple-Bend Achromats to Multi-Bend Achromats
- All MBA-based projects consider significant increase of N_d

$$\varepsilon_x = F(\text{lattice})\frac{E^2}{J_x N_d^3}$$

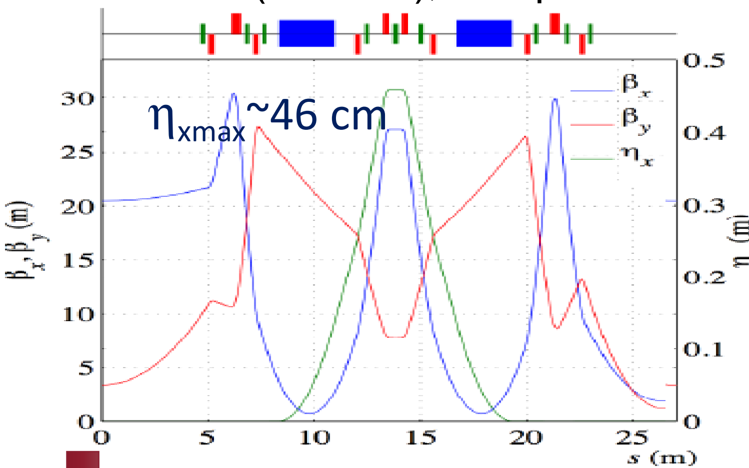


V. Smaluk

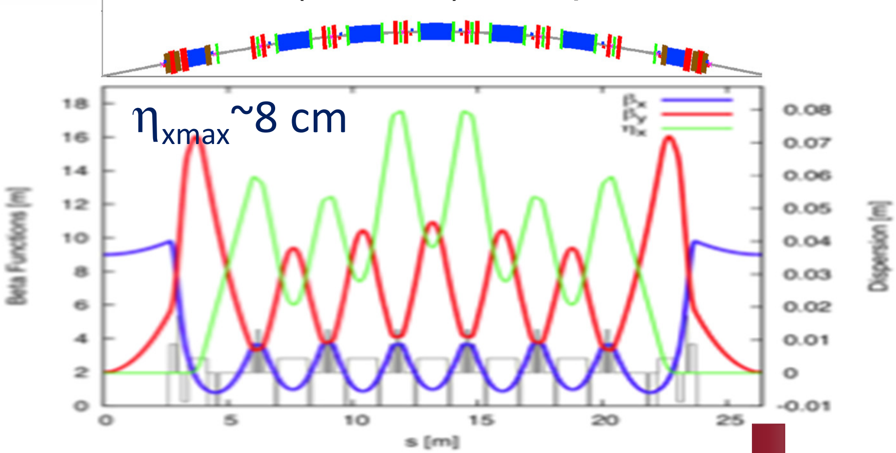
From DBA to MBA

- Trend of minimizing emittance of modern storage rings translates into reduction of η_x and β_x in their lattice dipoles
- Further reduction of emittance leads to dense and complex MBA lattices
- Complex Bend (CB): preserve substantial room for SR lattice elements

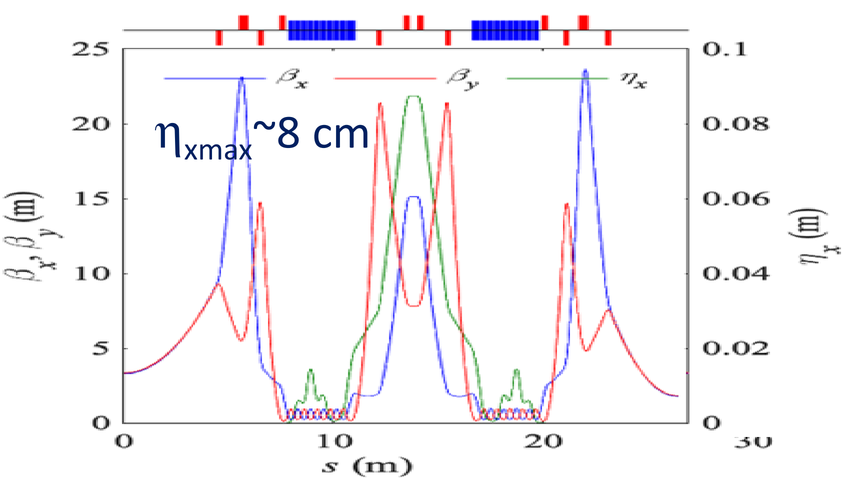
DBA (NSLS II), 900 pm·rad



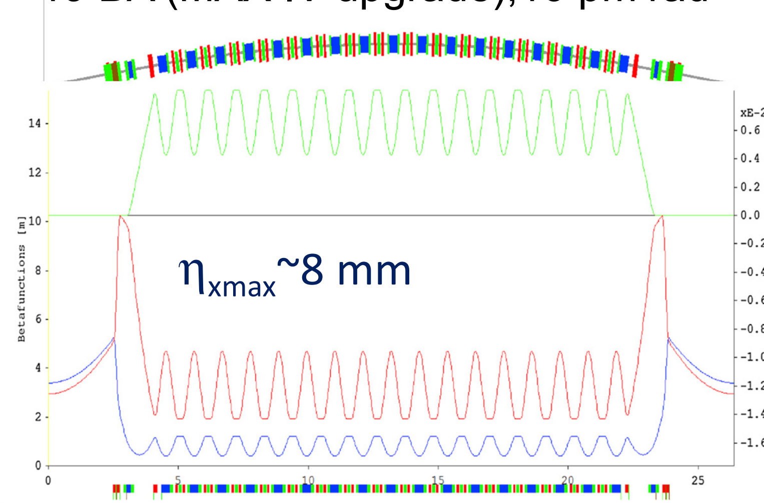
7BA (MAX IV), 250 pm·rad[1]



CB (NSLS II upgrade),19 pm·rad



19 BA (MAX IV upgrade),16 pm·rad[2]



1. P.F.Tavares et al., J. Synchrotron Radiat. 21 (2014) 862-877. 2. P.F.Tavares et al., J. Electron. Spectrosc. Relat. Phenom.224 (2018) 8-16.

Complex bend: Properties of the element

- Properties of the element
- Integration into lattice design
- Magnet design
- Prototype of Complex Bend
- Synchrotron radiation

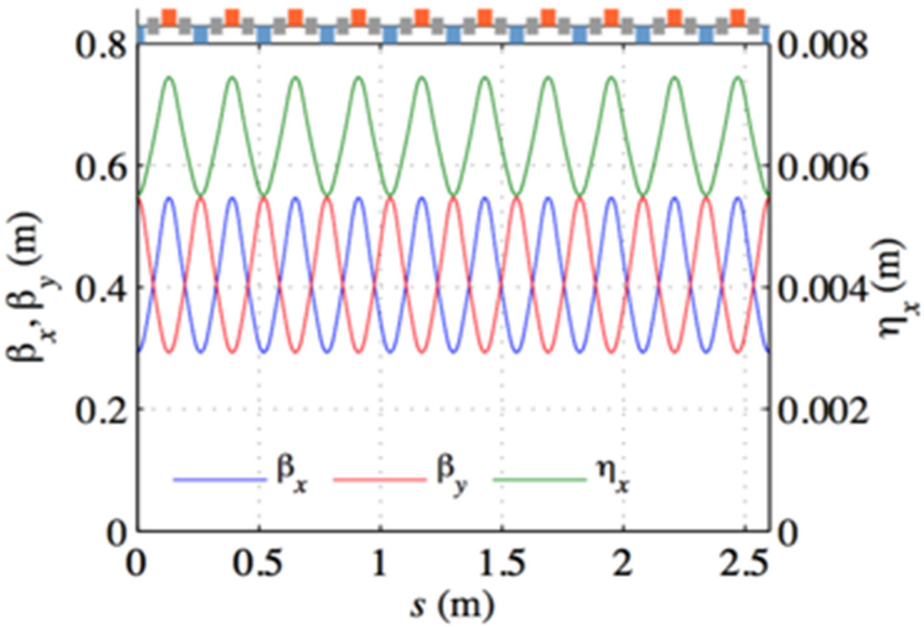
$$\varepsilon_x = F\frac{E^2}{J_x N_d^3} \overset{CB}{\Rightarrow} F\frac{E^2}{J_x [N_d N_p]^3}$$

Transition from individual dipoles to multiple dipole poles

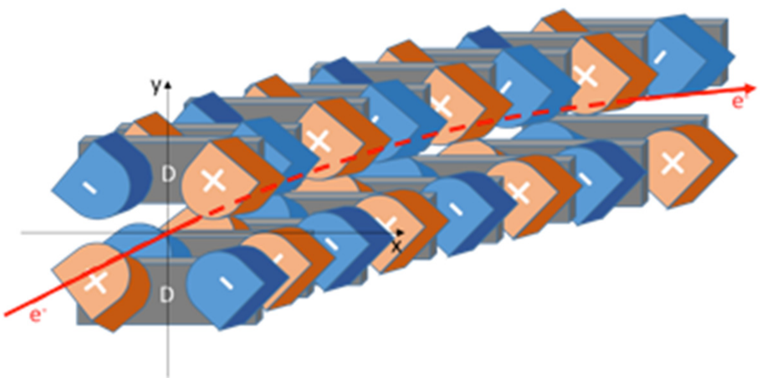
- APS DBA: 40x2=80 dipoles→
- APS-U MBA: 40x7=280 dipoles→
- NSLS-II upgrade: 30x2x10=600 poles

Complex Bend concept

- Complex Bend: a bending element consisting of dipole poles, interleaved with strong focusing and defocusing quadrupole poles, QF-D-B-D-QD-D-B-D (**CB**)
- Conventional long dipole → a sequence of short strong focusing poles
- Produce small beta-function and dispersion, resulting in substantially emittance reduction



Complex Bend I



G. Wang, , T. Shaftan *et al.*, Complex bend: Strong-focusing magnet for low-emittance synchrotrons, Phys. Rev. Accel. Beams 21, 100703

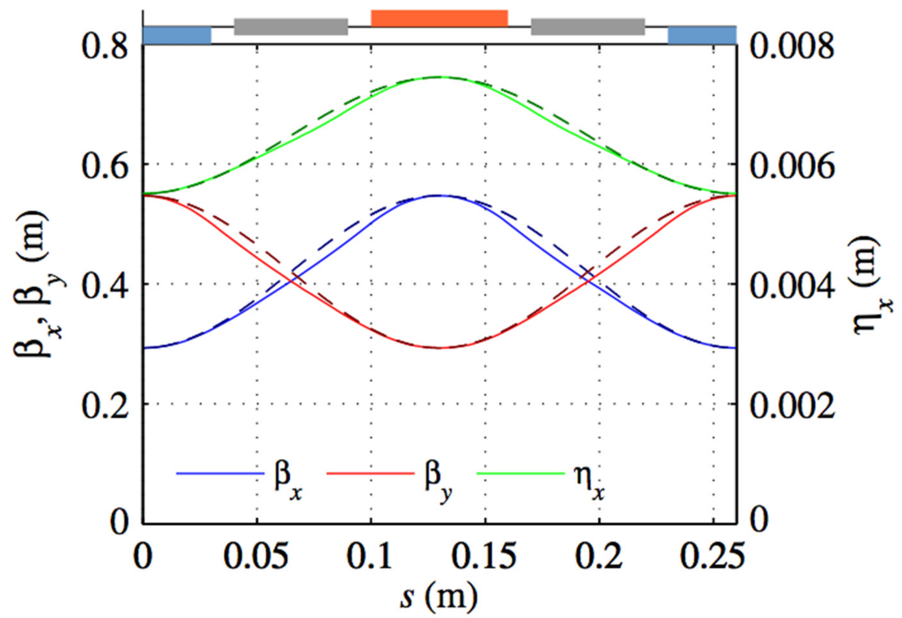
Analytic results of Complex Bend

Length of 1 cell $L_{CB} = 2(L_Q + L_B + 2L_D)$ $k_{CB} = \frac{2\pi}{L_{CB}}$

Beta function $\beta_x(s) \approx \overline{\beta_x} - \Delta\beta_x \cos(k_{CB} s)$

Dispersion $\eta_x(s) \approx \overline{\eta_x} - \Delta\eta \cos(k_{CB} s)$

Analytic expressions of $\overline{\beta_x}$, $\Delta\beta_x$ and $\overline{\eta_x}$, $\Delta\eta_x$ have been derived for $K_{1F} = -K_{1D} = K_1$



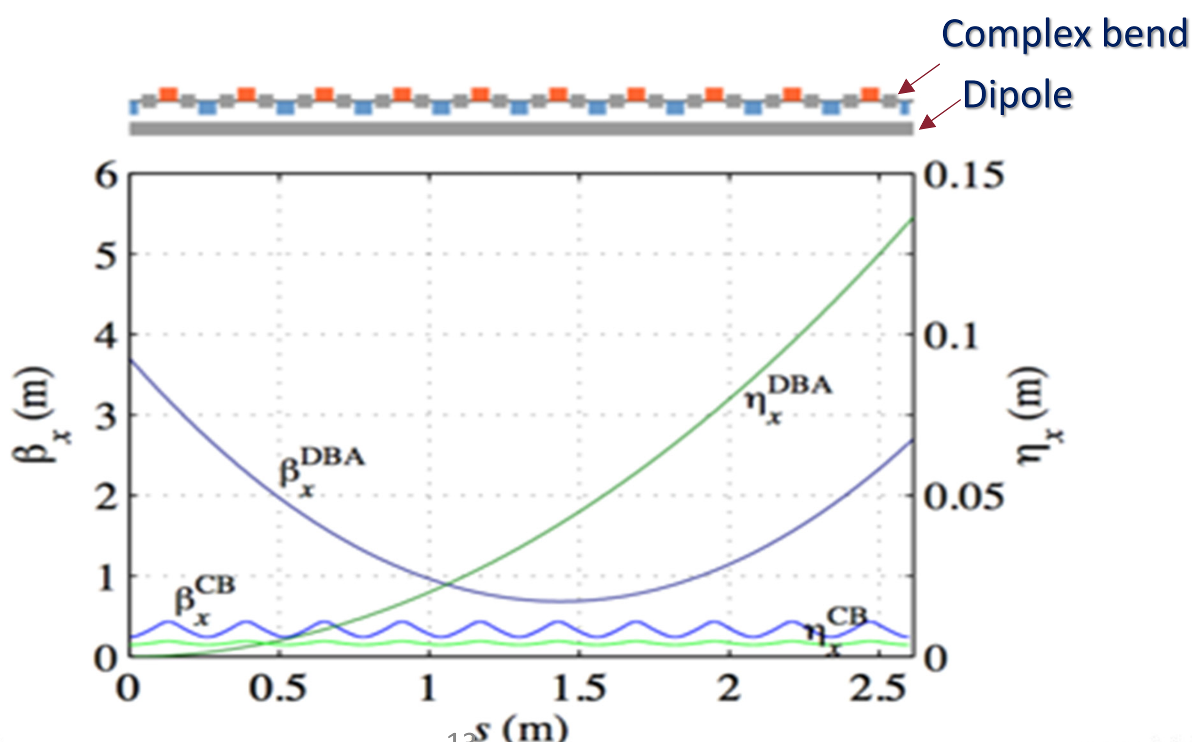
Emittance
$$\varepsilon_x \approx C_q \gamma^2 \frac{\overline{\eta}_x^{\,2}}{R_B \overline{\beta}_x}$$

Chromaticity
$$\xi \approx -\frac{N_p}{\pi} K_1 \frac{\Delta\beta}{k_{CB}} \sin\left(\frac{k_{CB} L_Q}{2}\right)$$

Complex bend vs DBA

- A Complex Bend magnet (10 periods): same total bending angle and length as NSLS-II dipole results in **70 pm-rad** emittance, 30 times lower emittance than NSLS-II DBA lattice
- Reach **13 pm-rad** emittance with 4.5 m CB
- Very strong quadrupole magnets (hundreds T/m) → *~1 mm horizontal shift introduce required dipole field*

	NSLS-II dipole	Complex bend I
Length, m	2.6	2.6 (0.26 per cell)
Bending field, T	0.4	1.05
Bending angle, rad	0.105	0.105
K_1, m^{-2}	0	+100 / –80
β_{max} / β_{min}, m	3.7 / 0.7	0.42 / 0.24
η_{max} / η_{min}, mm	137 / 0	4.7 / 3.6
Emittance, nm	**2.09**	**0.07**



Concept of Complex Bend II

- Complex Bend II: offer substantially reduce the device length by removing the dipole poles, QF-D-B-D-QD-D-B-D (CBII)
  - Longer quads with lower gradient strength
- Bending
  - Shifting the quadrupole poles along the curved horizontal axis
  - Permanent Magnet quadrupole poles installed into a wide gap of the conventional electromagnet

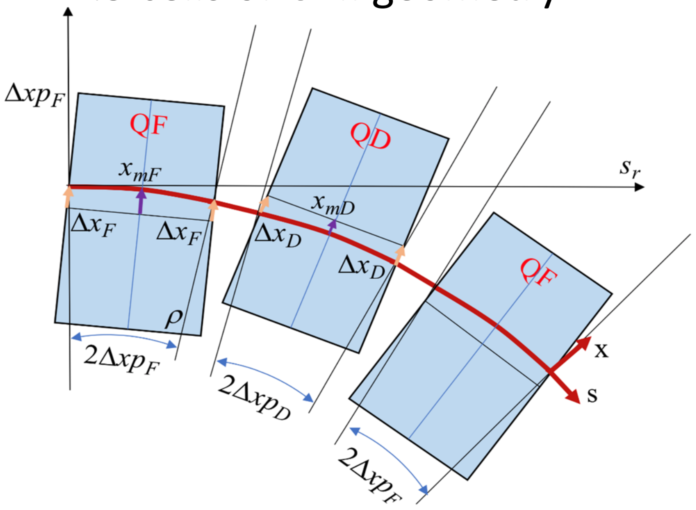
- The total angle per cell α_d is distributed between the two quadrupoles
- "angle ratio" parameter $0 < A < 1$.
- The entrance angles are

$$\Delta x_{pF} = \frac{\alpha_d}{2} A$$

$$\Delta x_{pD} = \frac{\alpha_d}{2}(1 - A)$$

$$2(\Delta x_{pF} + \Delta x_{pD}) = \alpha_d$$

1.5 cells of CBII geometry



G. Wang, T. Shaftan et al., Complex Bend II: A new optics solution , submitted to Phys. Rev. Accel. Beams

Stability constraint of ring beam dynamics

- CB II: synchrotron integral I_4, dominated from quads K_1 in each pole → specific condition to maintain positive partition numbers $J_{x/z}$
- Ring can be stable if a specific condition (Theorem) on the relationship between the shifts of focusing and defocusing poles is satisfied

$$I_4 = \oint \frac{\eta}{\rho}\left(\frac{1}{\rho^2} + 2K_1\right)ds \qquad I_2 = \oint \frac{ds}{\rho^2}$$

$$J_x = 1 - \frac{I_4}{I_2}, \qquad J_z = 2 + \frac{I_4}{I_2}, \qquad \varepsilon_x = F\frac{E^2}{J_x[N_d N_p]^3}$$

Periodic structure case, $N_F = N_D = N_Q$, $L_F = L_D = L_Q$

$$I_4 \approx \frac{N_p 2\eta_{Fav} K_{1F} L_Q}{\rho_{Fav}^3} - \frac{N_p 2\eta_{Dav} K_{1D} L_Q}{\rho_{Dav}^3}$$

Theorem: stability condition to maintain positive partition numbers

$$\eta_{Fav} K_{1F}^2 \Delta x_F + \eta_{Dav} K_{1D}^2 \Delta x_D \approx 0$$

G. Wang, T. Shaftan et al., Complex Bend II: A new optics solution , submitted to Phys. Rev. Accel. Beams

Complex Bend II – formulas for the whole ring

Required quads shift for bending

$$\Delta x_F = \Delta xp_F \frac{S_Q}{\sqrt{K_{1F}}(1 - C_Q)}$$

$$\Delta x_{mF} = \frac{\Delta x_F}{C_{0.5Q}}$$

$$\mu_{QF,D} = \sqrt{K_{1F,D}} \cdot L_Q, \mu_{F,D} = \sqrt{K_{1F,D}} \cdot s$$

$$C_Q = \cos(\mu_{QF}), S_Q = \sin(\mu_{QF})$$

$$Ch_Q = \cosh(\mu_{QD}), Sh_Q = \sinh(\mu_{QD})$$

$$C = \cos(\mu_F), S = \sin(\mu_F)$$

Beam trajectory in shifted quads

$$x_F = \Delta x_F C + \frac{\Delta xp_F}{\sqrt{K_{1F}}} S$$

Shifted quad transfer matrix

$$MF = \begin{vmatrix} C_Q & S_Q/\sqrt{K_{1F}} & -\frac{\Delta xp_F}{2}\left(L_Q C_Q - \frac{S_Q}{\sqrt{K_{1F}}}\right) + \frac{\Delta x_F}{2}\sqrt{K_{1F}} L_Q S_Q \\ -S_Q\sqrt{K_{1F}} & C_Q & \frac{\Delta x_F}{2}\left(\sqrt{K_{1F}} S_Q + K_{1F} L_Q C_Q\right) + \frac{\Delta xp_F}{2}\sqrt{K_{1F}} L_Q S_Q \\ 0 & 0 & 1 \end{vmatrix}$$

$$MD = \begin{vmatrix} Ch_Q & Sh_Q/\sqrt{K_{1D}} & \frac{\Delta xp_D}{2}\left(-L_Q Ch_Q + \frac{Sh_Q}{\sqrt{K_{1D}}}\right) - \frac{\Delta x_D}{2}\sqrt{K_{1D}} L_Q Sh_Q \\ Sh_Q\sqrt{K_{1D}} & Ch_Q & -\frac{\Delta x_D}{2}\left(\sqrt{K_{1D}} Sh_Q + K_{1D} L_Q Ch_Q\right) - \frac{\Delta xp_D}{2}\sqrt{K_{1D}} L_Q S_{hQ} \\ 0 & 0 & 1 \end{vmatrix}$$

Complex Bend II – formulas for the whole ring

Average bending radius and lattice functions

$$\rho_{F,D}(s) = \pm\frac{1}{x_{F,D}(s)K_{1F,D}} \quad \rho_{Fav,Dav} = \frac{1}{L_Q}\int_0^{L_Q}\rho_{F,D}(s)ds \quad \eta_{av} = \frac{2}{L_Q}\int_0^{\frac{L_Q}{2}}\eta(s)ds \quad \beta_{av} = \frac{2}{L_Q}\int_0^{\frac{L_Q}{2}}\beta(s)ds$$

$$I_2 = 2\pi\left(\frac{A}{\rho_{Fav}} + \frac{A}{\rho_{Dav}}\right) \qquad I_3 = 2\pi\left(\frac{A}{\rho_{Fav}^2} + \frac{1-A}{\rho_{Dav}^2}\right)$$

$$I_4 \approx \frac{N_p\eta_{Fav}L_Q}{\rho_{Fav}^3} + \frac{N_p\eta_{Dav}L_Q}{\rho_{Dav}^3} + \frac{N_p 2\eta_{Fav}K_{1F}L_Q}{\rho_{Fav}^3} - \frac{N_p 2\eta_{Dav}K_{1D}L_Q}{\rho_{Dav}^3}$$

$$I_5 \approx 2\pi\left(A\frac{\eta_{Fav}^2}{\rho_{Fav}^2\beta_{Fav}} + (1-A)\frac{\eta_{Dav}^2}{\rho_{Dav}^2\beta_{Dav}}\right)$$

Emittance and energy spread

$$\varepsilon_x = C_q\gamma^2\frac{I_5}{I_2 - I_4} \qquad \frac{dE}{E} = \gamma\sqrt{C_q\frac{I_3}{2I_2 + I_4}}$$

Complex bend: Lattice design

- Properties of the element
- Integration into lattice design
- Magnet design
- Prototype of Complex Bend
- Synchrotron radiation

Complex Bend II lattice for NSLS-II

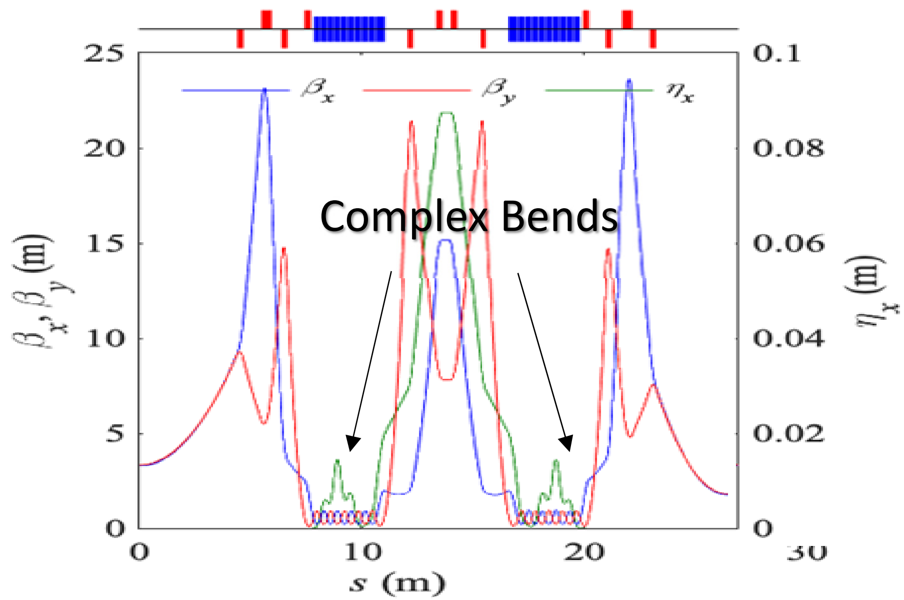
- "DBA"-like Complex Bend II lattice design for NSLS-II upgrade
- Comparable space as DBA lattice for SR other elements
- CB quadrupole gradient: 250 T/m, can be realized with Permanent Magnet Quadrupoles

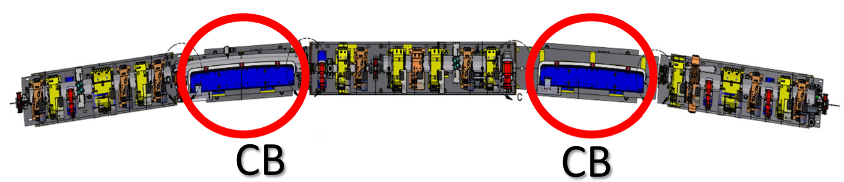
ε_x=18.7 pm rad

J_x=2

$\xi_{x,y}$ = -199/-260

NSLS-II upgrade lattice based on CBII design





Complex Bend II parameters

Parameters	Values
Number of CBII elements in the ring	60
Number of cells per CBII element	5
Total number of cells in the ring	300
Angle per CBII element, mrad	105
Quadrupole pole length, m	0.28
Drift length, m	0.03
Cell length, m	0.62
Complex Bend element length, m	3.1
Beam energy, GeV / unitless	3 / 5871
Field gradient, T/m	250, -250
Angle ratio, A	0.35

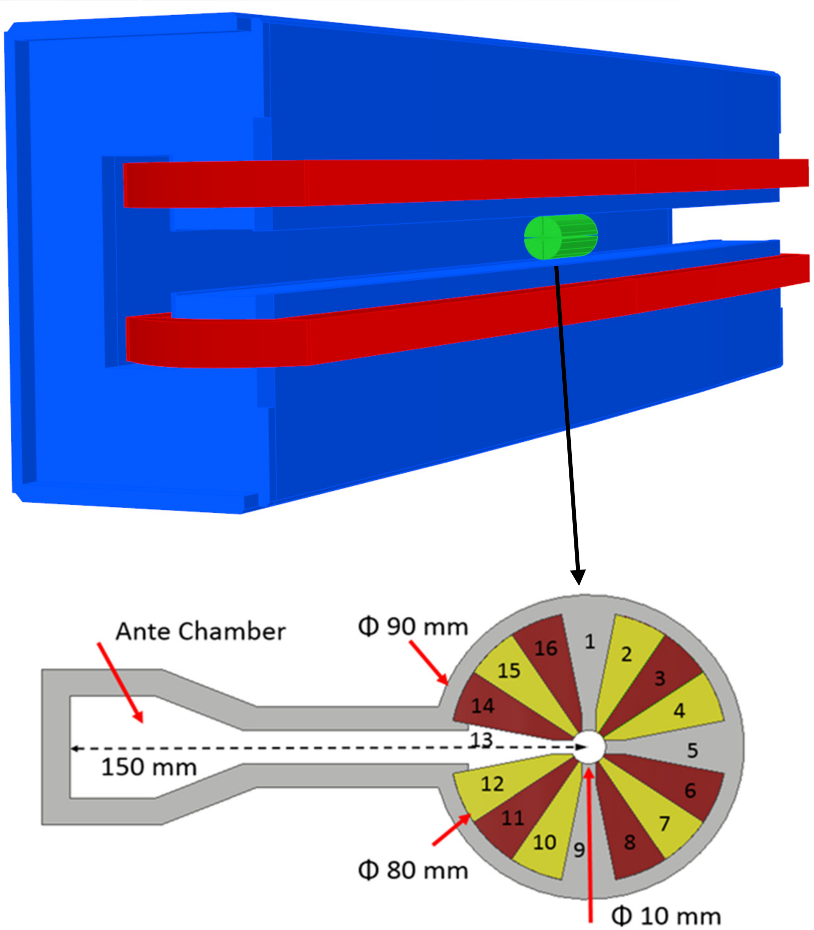
Complex bend: Magnet design

- Properties of the element
- Integration into lattice design
- Magnet design
- Prototype of Complex Bend
- Synchrotron radiation

Conceptual Design of a High Gradient CBII Quadrupole

- Require Quads offset by 1~2 mm for a dipole field, resulting in large unacceptable harmonic field of B_3 to B_6
- Superimpose Dipole and Quadrupole fields
- External H-shaped electromagnetic dipole with 90 mm aperture
- Halbach PMQ assembled inside a round 90-mm aluminum vacuum chamber
- Ante-chamber for the extraction of x-rays and for pumping via NEG strips.

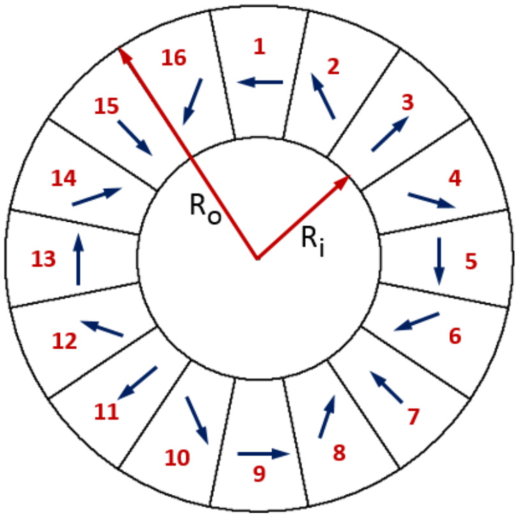
External H-shaped electromagnet dipole for Complex Bend II



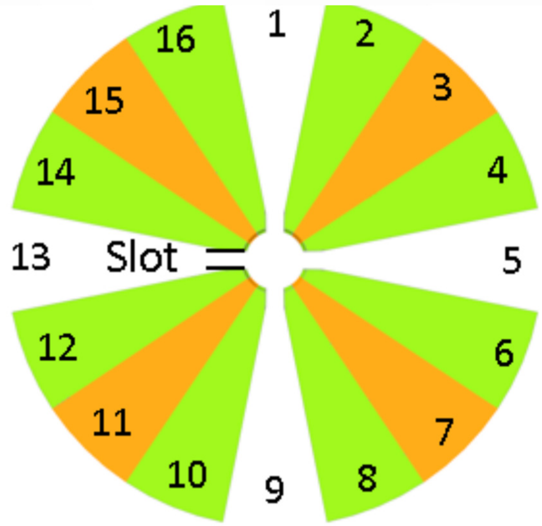
In-vacuum high-gradient Halbach PMQ

S. Sharma et al. "High gradient quadrpoles for low emittance synchrotrons," IPAC2019, Melbourne, Australia, May 2019.

Halbach PMQ for Complex Bend



Standard 16-wedge Halbach PMQ
G~358 T/m



Modified PMQ with exit slot for the x-ray beams.

- G: 254 - 215 T/m with variable slot height
- 3D Opera model, NdFeB with low remanent field, 1.12 T

PMQ field harmonics at 2 mm radii with 3 mm Slot

n	An	Bn
1	-0.1	0.1
2	-0.2	10^4
3	-0.3	0.1
4	0.0	0.2
5	0.0	0.0
6	0.0	-55.0*
7	0.0	0.0
8	0.0	0.0

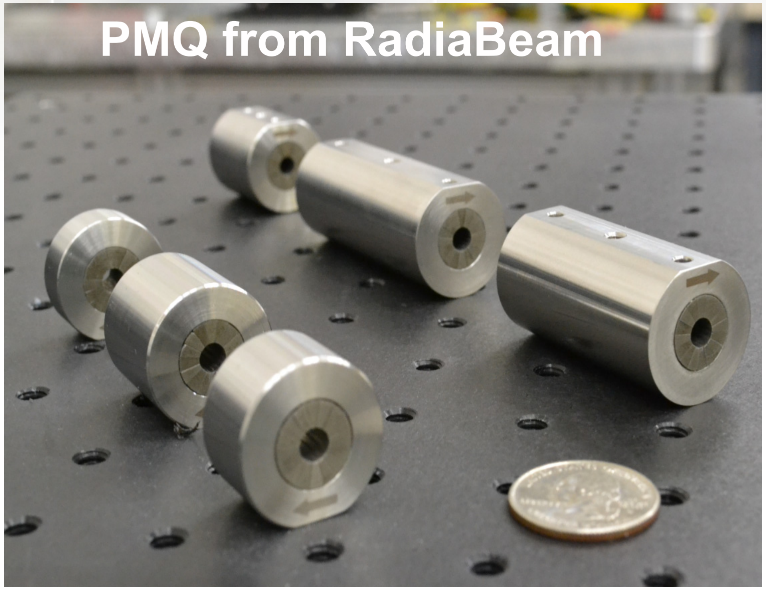
*can be reduced by shimming of the poles

Complex bend: Prototype of Complex Bend

- Properties of the element
- Integration into lattice design
- Magnet design
- Prototype of Complex Bend
- Synchrotron radiation

Prototype of Complex Bend II

- Engineering design for a prototype of CBII
- Downscaled *E* from 3 GeV to 50 MeV
- Maintain high gradient magnetic field and reduce the size of the pole and overall length of CBII
- Build the prototype from an array of Permanent Magnet Quadrupoles (Commercially available)
- Commission the device at ATF's beamline in FY20
- Characterize properties of the CB element, create kick maps and study both geometric and chromatic aberrations
- Motivate the future proposal to build the full-scale CB for 3 GeV machine.



Parameters of CB and NSLS-II dipole

Parameters	Complex Bend	50 MeV prototype
Length, m	3.1	0.62
Bending field, T	0.26/0.49	0.026/0.049
Cell length, cm	62	12.3
Bending angle per cell, °	1.2	1.2
Gradient, T/m	250/-250	150/-150

Complex bend: Synchrotron radiation

- Properties of the element
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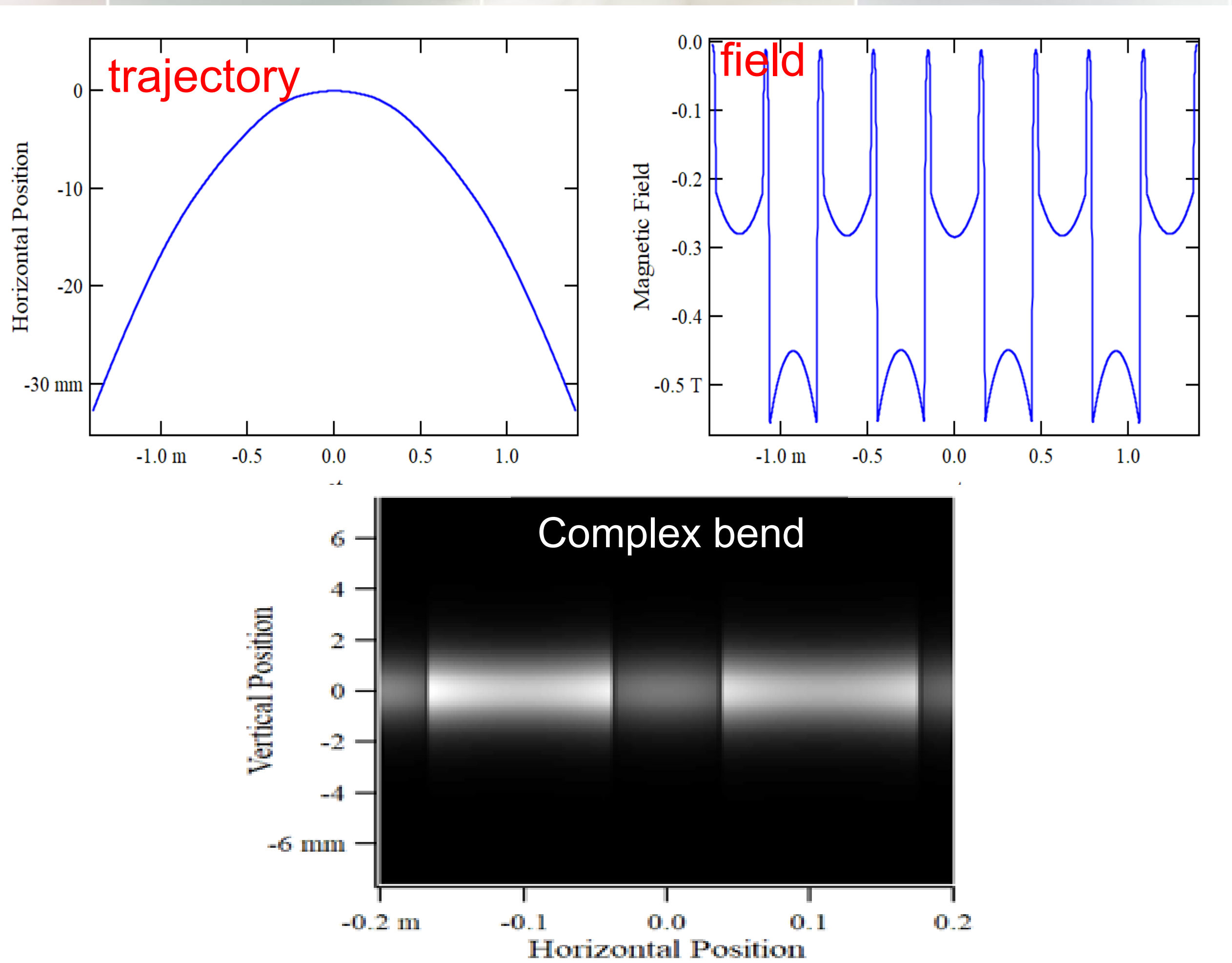
Synchrotron Radiation from Complex Bend



Synchrotron radiation intensity

- Radiation pattern corresponding to intensity peaks from individual poles in CB
- Freedom to modulate some pole to serve bending magnet beamlines

Summary

- NSLS-II operated well over the past 4½ years upto 400 mA, >95% reliability

- One of the paths for upgrading NSLS-II
- Proposed a new concept of a lattice element "Complex Bend" = a sequence of dipole poles interleaved with strong alternate focusing so as to maintain the beta function and dispersion oscillating at low values
- Comprising the ring lattice with Complex Bends, instead of regular dipoles, will reduce emittance to ~20 pm-rad while localize bending to a smaller fraction of the storage ring circumference
- Conceptual designs for high-gradient Halbach permanent-magnet quadrupole, ~250 T/m
- Developed an engineering design for a prototype of CBII and will be tested with 50 MeV beam at BNL's ATF

- Explore solutions of Double CB and Triple CB lattices
- Collaborated with APS, Michael Borland, to study CB II lattice non-linear beam dynamics. Looking for more collaborations!

Acknowledgements

Many thanks to the Complex Bend design team:

- T. Shaftan, V. Smaluk, S. Sharma, C. Spataro, Y. Hidaka, T. Tanabe, C. Spataro, O. Chubar (NSLS-II)
- N. Mezentsev (BINP)

Publications:

- T. Shaftan, V. Smaluk and G. Wang, "Concept of the Complex Bend", NSLS-II tech note 276, Jan. 2018
- "Complex bend: Strong-focusing magnet for low-emittance synchrotrons", G. Wang, T. Shaftan, V. Smaluk, N. A. Mezentsev, S. Sharma, O. Chubar, Y. Hidaka, and C. Spataro, Phys. Rev. Accel. Beams 21, 100703, October 2018
- T. Shaftan, G. Wang, V. Smaluk, Y. Hidaka, O. Chubar, T. Tanabe, J. Choi "Complex Bend-II", NSLS-II tech note 291, Oct. 2018
- "Complex bend: A new optics solution" , G. Wang, T. Shaftan, V. Smaluk, Y. Hidaka, O. Chubar, T. Tanabe, J. Choi, S. Sharma, C. Spataro and N.A. Mesentsev, submitted to Phys. Rev. Accel. Beams