# Low Emittance Lattice Design in Synchrotron Light Sources by Using Complex Bends

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26-30 October 2020, INFN-LNF
8th Low Emittance Rings Workshop

# Outline

- Introduction
- From Double-Bend Achromat to Multi-Bend Achromat lattice
- Complex Bend
    - Properties of the element
    - Integration into lattice design
    - Magnet design
    - Prototype of Complex Bend
- Summary

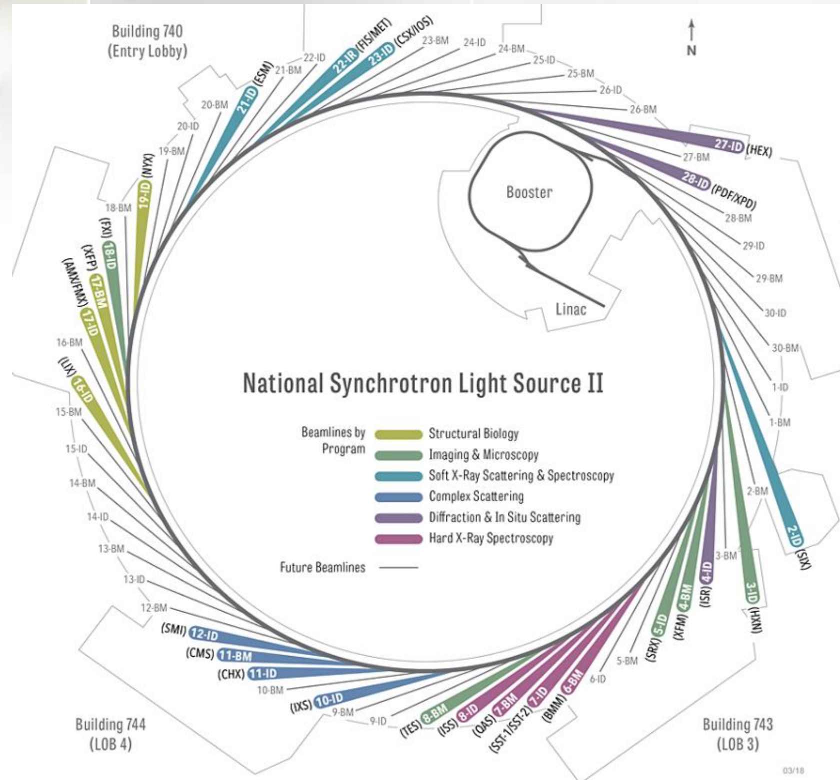
# Introduction

# NSLS II overview

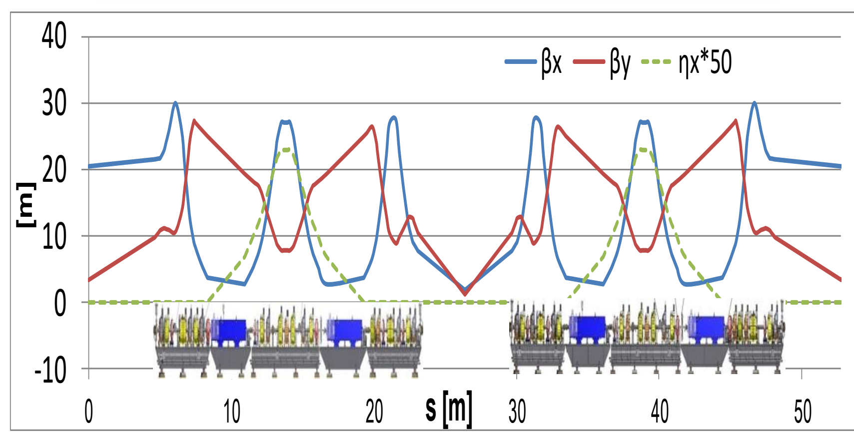
- National Synchrotron Light Source (NSLS-II) is a new 3 GeV, 500 mA, high-brightness synchrotron light source facility at the Brookhaven National Laboratory, funded U.S. Department of Energy (DOE).

- SR commissioning started in later March 2014
- Top off routine operation started in October 2015
- 29 beamlines in top off operation at 400 mA
- Demonstrated 500 mA in Oct. 2019
- Brightness/coherence (→ Low emittance) are essential to enable nanoscale resolution and fast dynamics study into sub-millisecond regime

- 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




One super-period SR Lattice function

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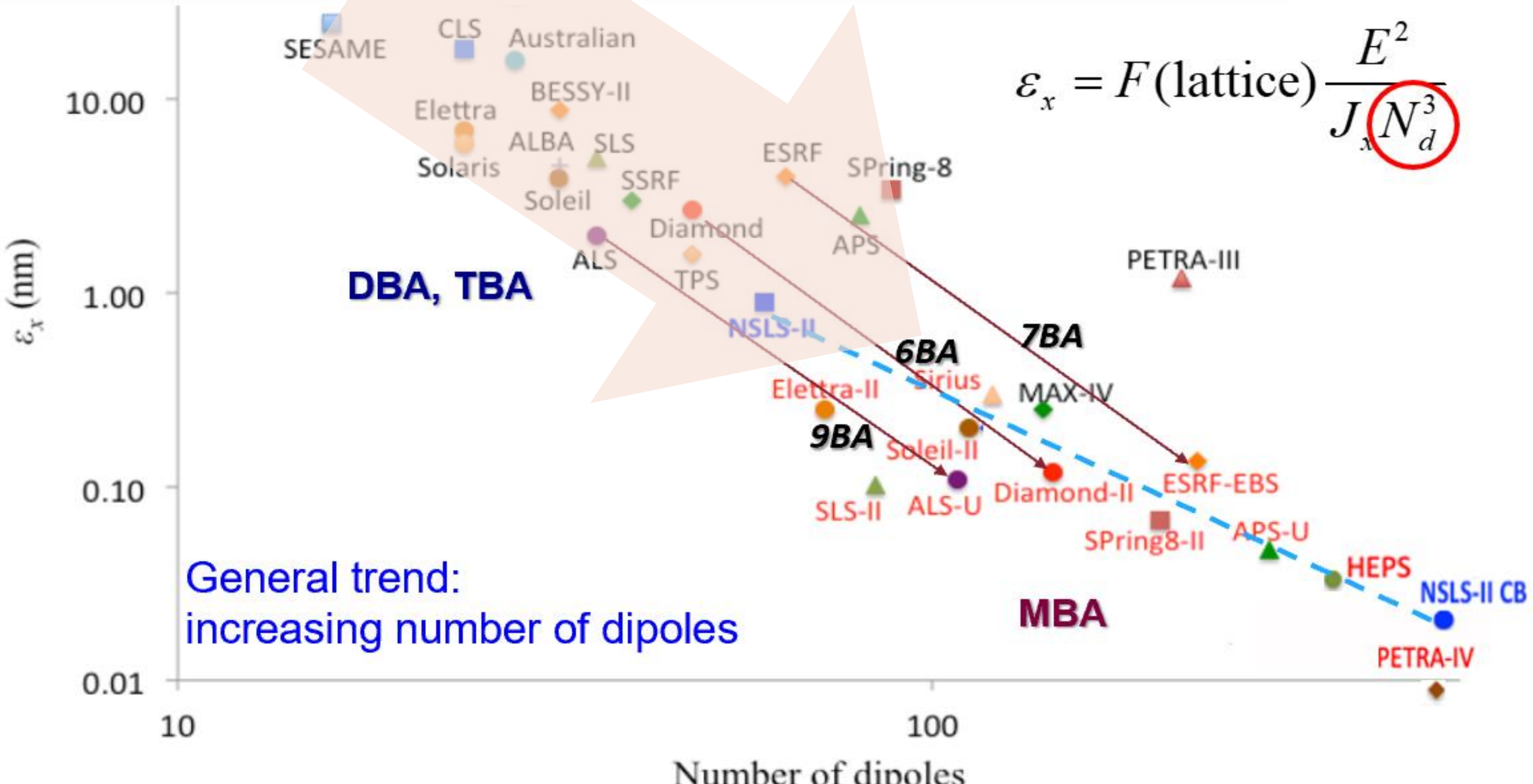
# Synchrotron light source: today and tomorrow

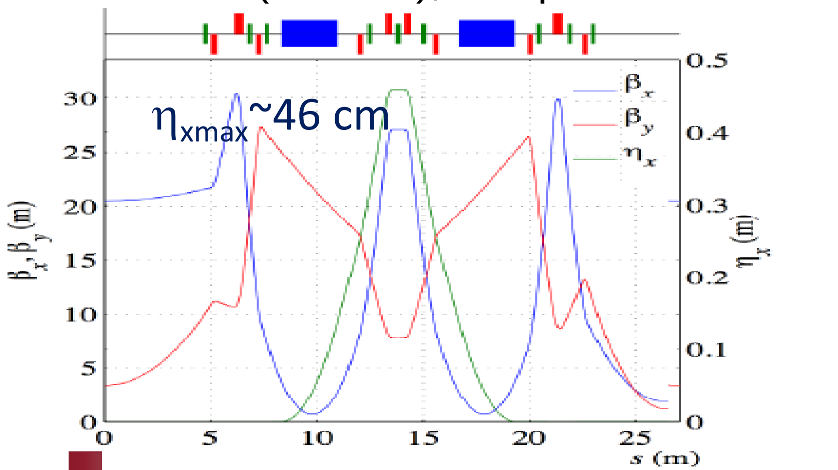
- Two order magnitude of emittance reduction: increasing brightness and coherence
- Transition from Double- and Triple-Bend Achromats to Multi-Bend Achromats
- All MBA-based projects consider significant increase of $N_d$



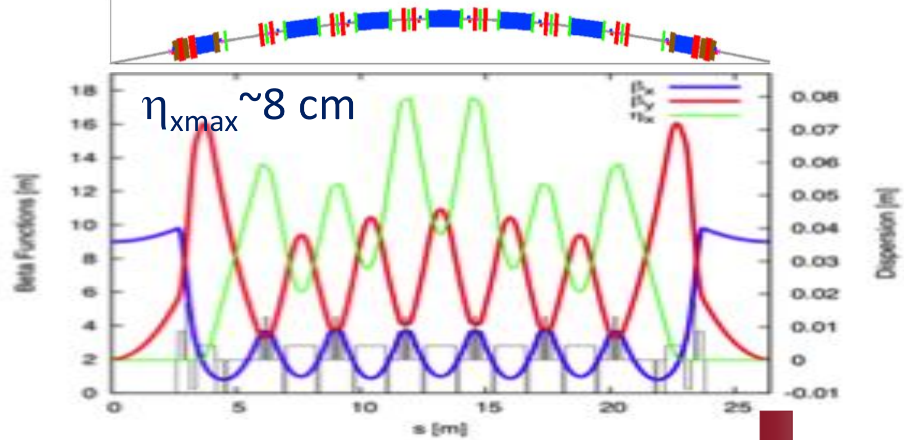
# From DBA to MBA

- Trend of minimizing emittance of modern storage rings translates into reduction of $\eta_x$ and $\beta_x$ in their lattice dipoles
- Further reduction of emittance leads to dense and complex MBA lattices
- An alternative solution, Complex Bend (CB): preserve substantial room for SR lattice elements

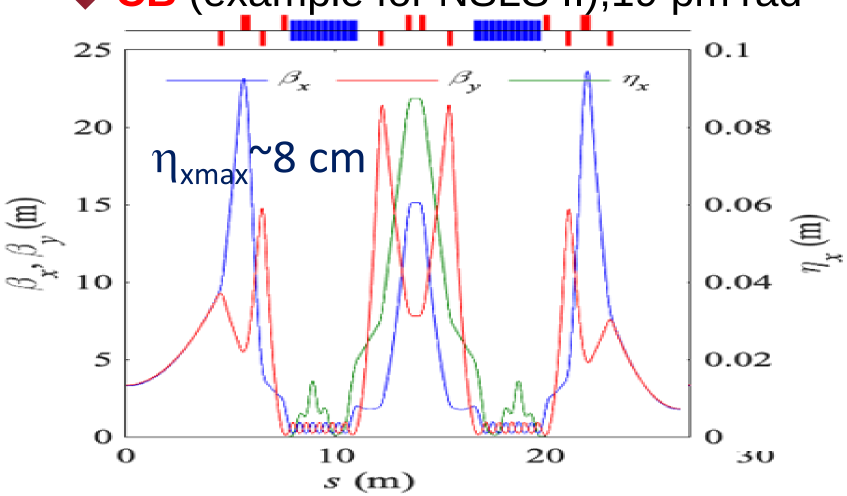
DBA (NSLS II), 900 pm·rad



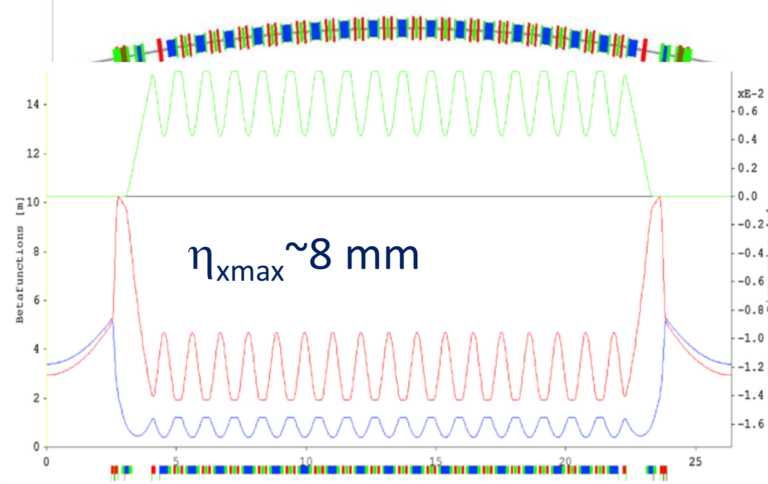

7BA[1] (MAX IV), 250 pm·rad




**CB** (example for NSLS II),19 pm·rad




19 BA[2] (MAX IV upgrade),16 pm· rad




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

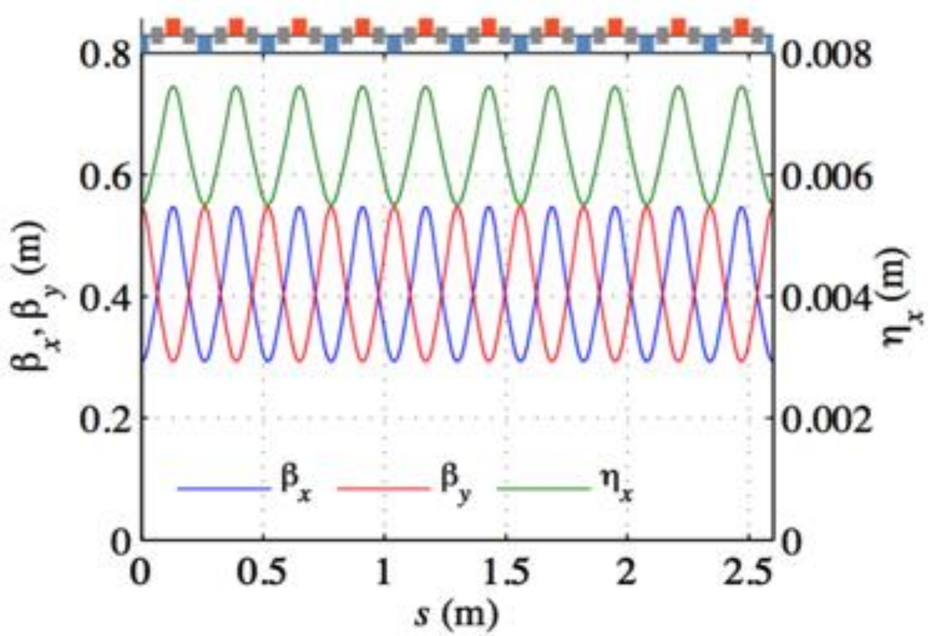
$$\varepsilon_x = F\frac{E^2}{J_x N_d^3} \overset{CB}{\Rightarrow} F\frac{E^2}{J_x\left[N_d N_p\right]^3}$$

Transition from individual dipoles to multiple dipole poles

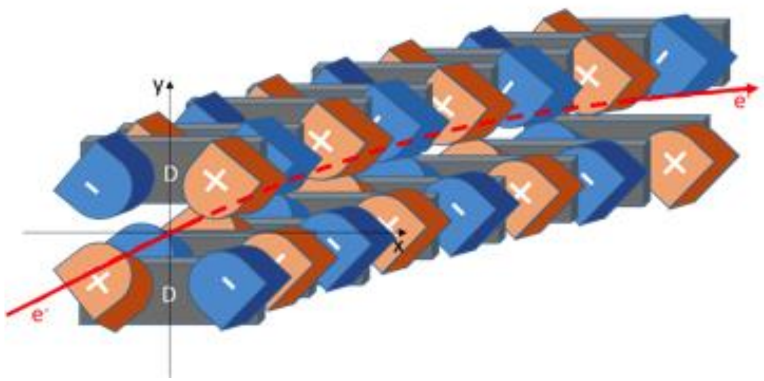
- APS DBA: 40x2=80 dipoles→
- APS-U MBA: 40x7=280 dipoles→
- NSLS-II upgrade: 30x2x10=600 poles

# 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




*T. Shaftan*

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

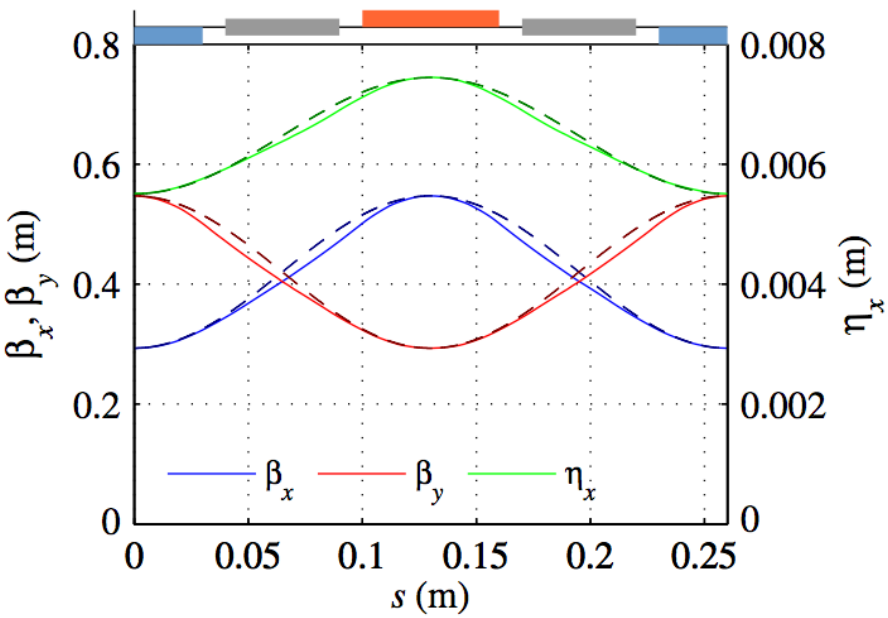
# Analytic results of Complex Bend

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 $K_{1F} = -K_{1D} = K_1$



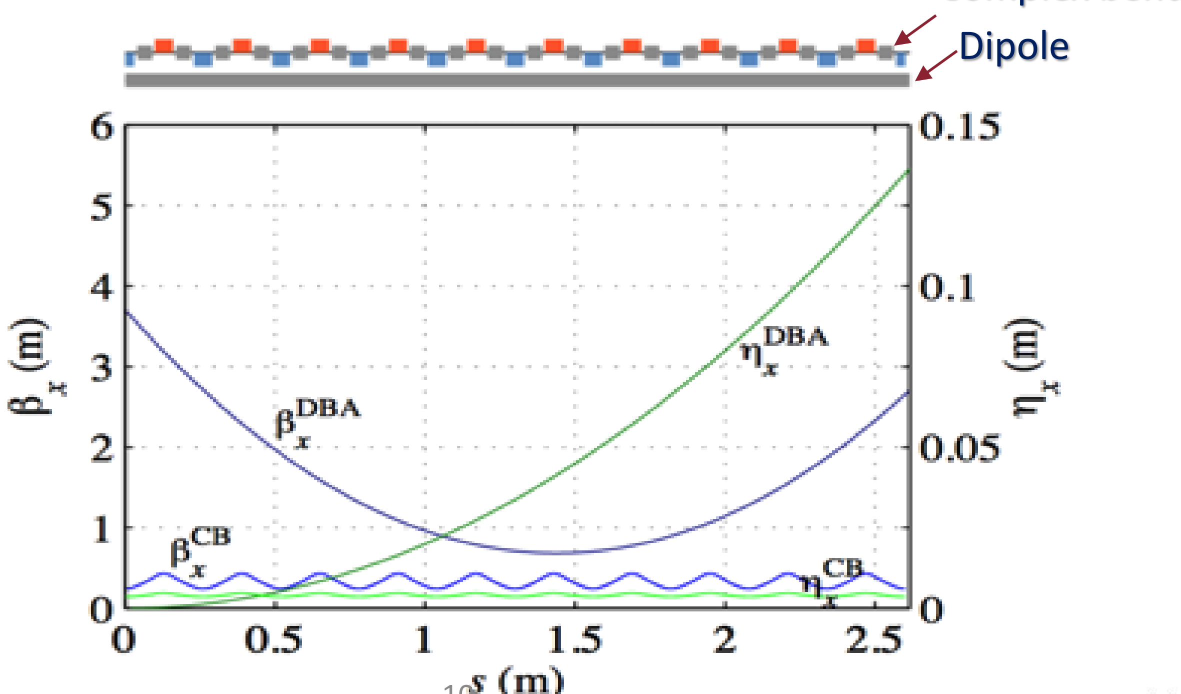

Emittance $\boxed{\varepsilon_x \approx C_q \gamma^2 \frac{\overline{\eta}_x^{\,2}}{R_B \overline{\beta}_x}}$

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

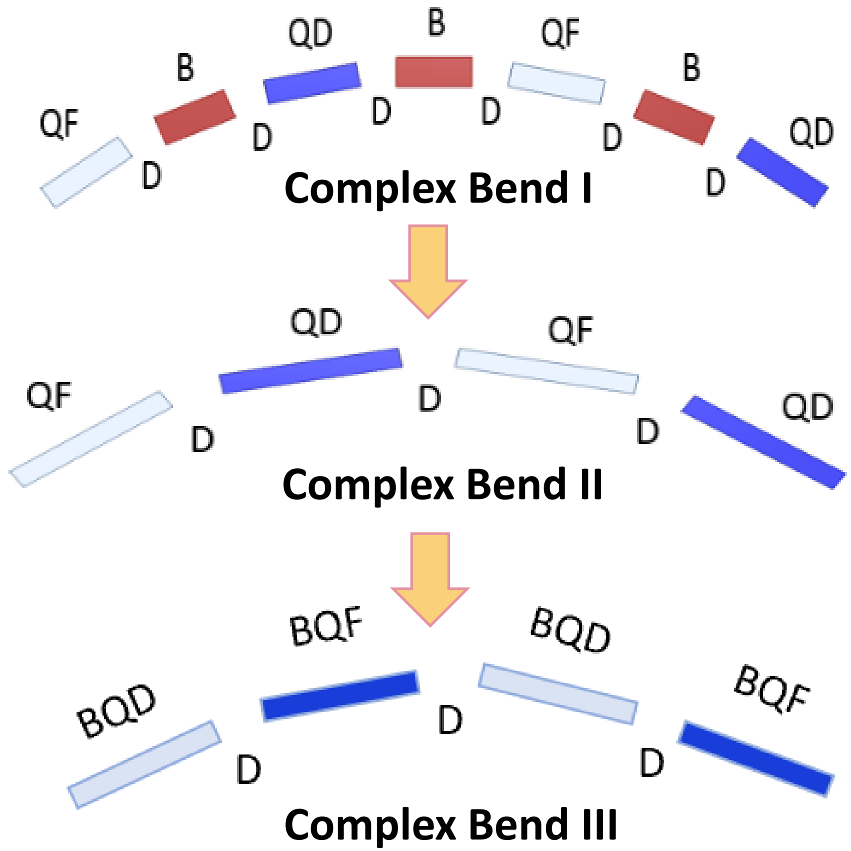
- A Complex Bend magnet (10 periods): same total bending angle and length as NSLS-II dipole results in **70 pm-rad** emittance, 30 times lower emittance than NSLS-II DBA lattice
- Reach **13 pm-rad** emittance with 4.5 m CB
- Very strong quadrupole magnets (hundreds T/m) → *~1 mm horizontal shift introduce 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 |
| $\beta_{max}$ / $\beta_{min}$, m | 3.7 / 0.7 | 0.42 / 0.24 |
| $\eta_{max}$ / $\eta_{min}$, mm | 137 / 0 | 4.7 / 3.6 |
| **Emittance, nm** | **2.09** | **0.07** |

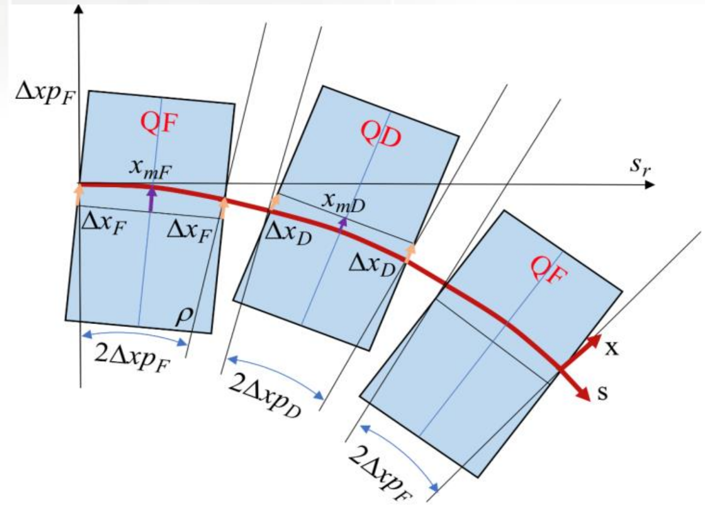


# Evolution to CB II and CB III

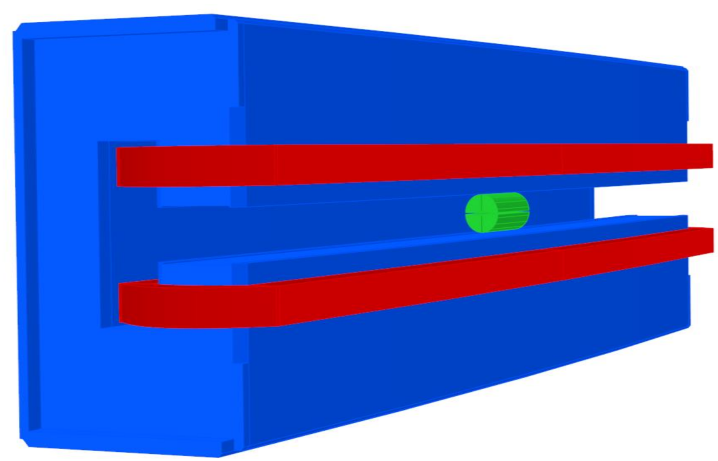
- CB II&III: offer substantially reduce the device length by removing the dipole poles
- CB II Bending: shift the quadrupole poles offset
- CB III Bending: PMQ installed into a wide gap of the conventional electromagnet




1.5 cells of CBII geometry




Permanent Quads inside an electromagnet dipole for CBIII



G. Wang, T. Shaftan, V. Smaluk et al., Complex Bend II: A new optics solution , Phys. Rev. Accel. Beams 22, 110703, 2019

# Stability constraint of ring beam dynamics

- Quads in dipole: 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 the relationship between the B fields of focusing and defocusing poles is satisfied

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

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

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

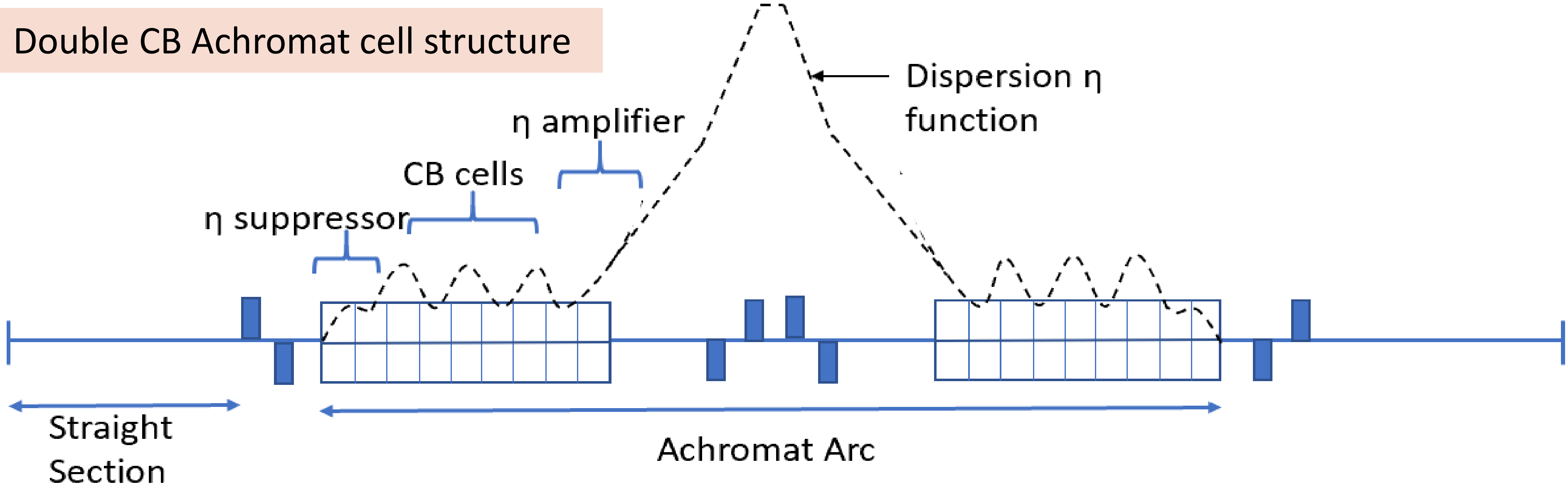
$$\eta_{Fav} K_{1F}^2 B_{Fav}^3 + \eta_{Dav} K_{1D}^2 B_{Dav}^3 \approx 0$$

# Complex bend: Integration into lattice design

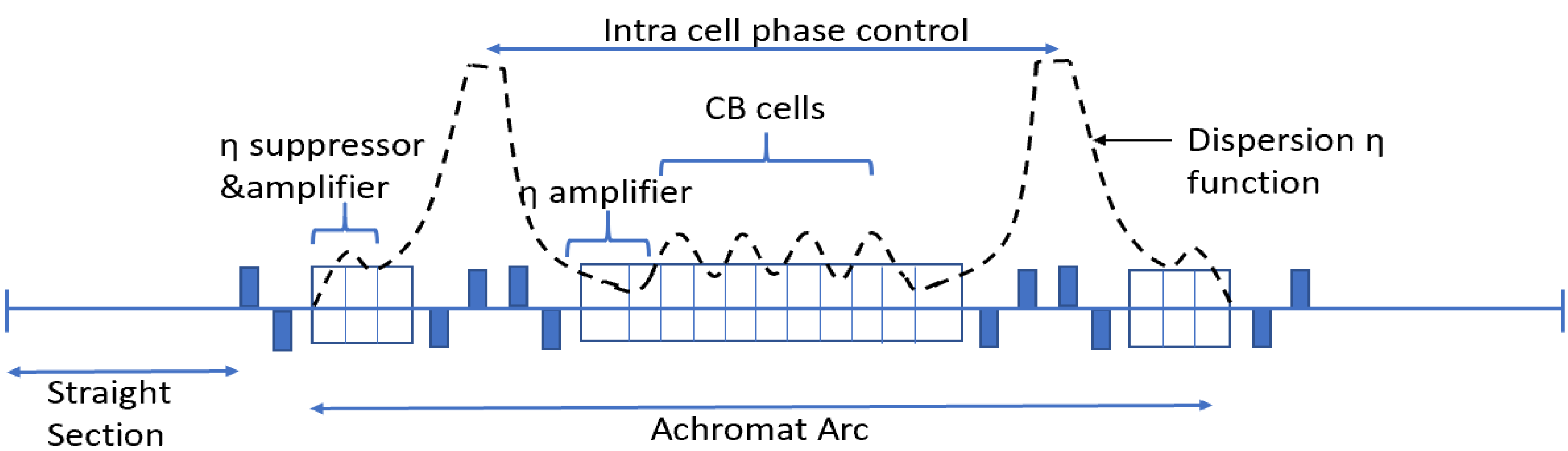
- Properties of the element
- Integration into lattice design
- Magnet design
- Prototype of Complex Bend

# DCBA lattice and TCBA lattice

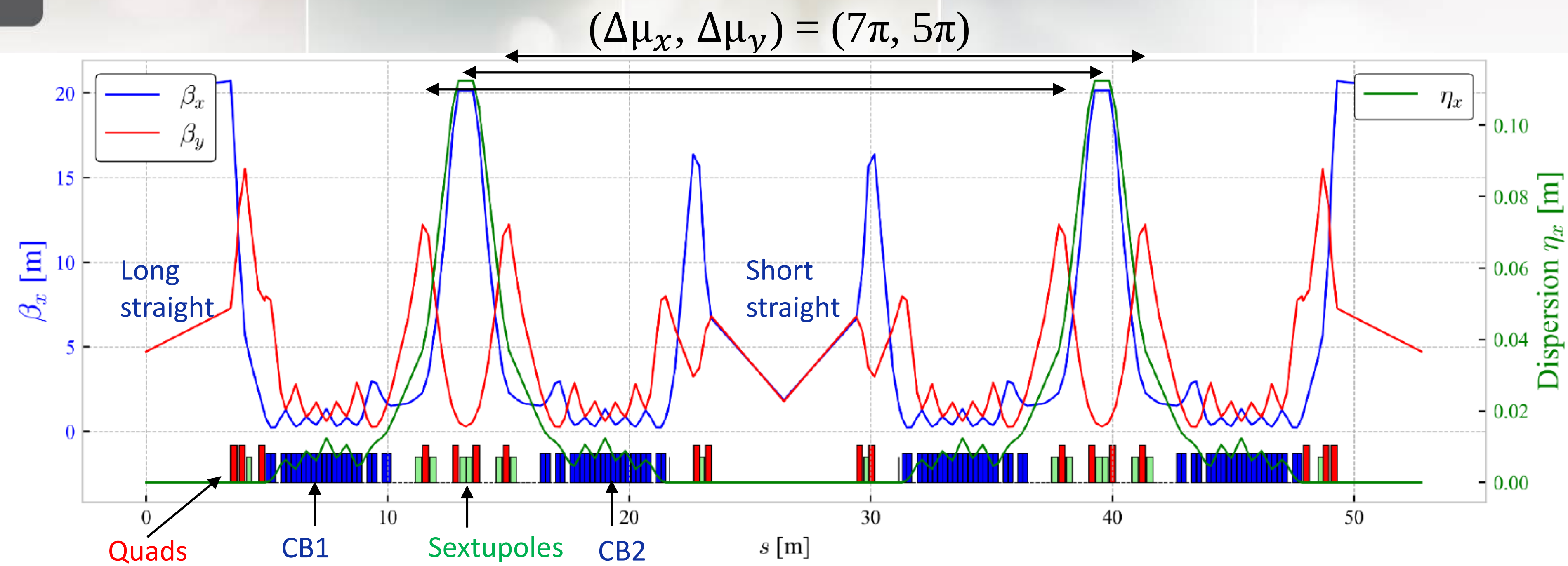
Double CB Achromat cell structure




Triple CB Achromat cell structure



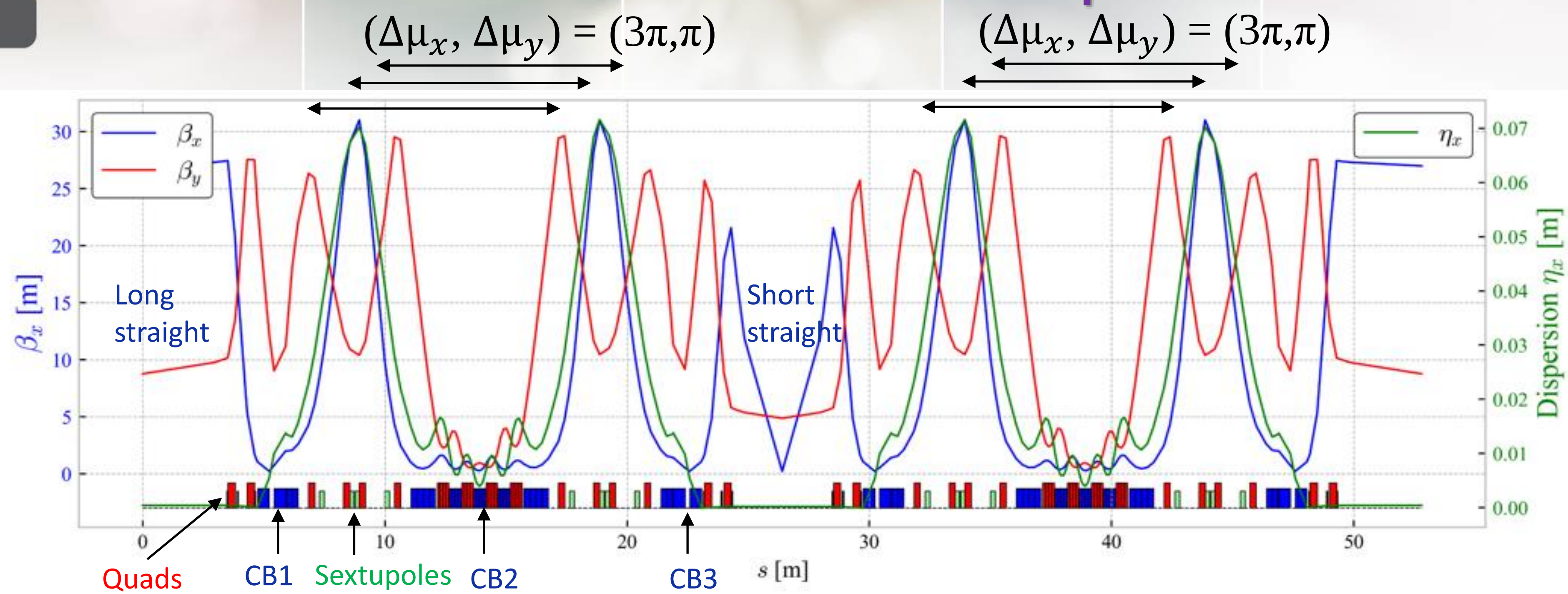
# DCBA lattice for NSLS-IIU: 25 pm-rad




- Similar elements layout as NSLS-II
- Comparable space as DBA lattice for SR other elements
- 2*11 poles CB with gradient ~ 105 T/m
- Phase advance cancellation over one super cell, $\Delta\psi_x = 7\pi$, $\Delta\psi_y = 5\pi$ between sextpoles
- 5 chromatic sextupoles per cell to control chromaticity ($K_2L$ < 75 1/m$^2$)
- 7 mm*1.5 mm (x/y) dynamic aperture, sufficient for the off-axis anti-septum[1] injection

C. Gough and M. Aiba, TOP-UP INJECTION WITH "ANTI-SEPTUM" , IPAC2017, P774-776

# TCBA lattice for NSLS-IIU: 34 pm-rad




- Three CBs to control dispersion: dispersion bump and dispersion suppression
- Two edge CBs' with lower gradient, thus large physical aperture for ID radiation extraction
- Middle CB (G ~100 T/m) focusing poles with no bending to minimize emittance
- Phase advance within one cell, $\Delta\psi_x = 3\pi$, $\Delta\psi_y = \pi$ between sextupoles
- Two dispersion bumps per cell with 3 families of chromatic sextupoles to control chromaticity ($K_2L$ < 50 1/$m^2$)
- Long/short straight structure with zero dispersion: insertion devices, RF cavity, injection
- Lattice was optimized (beta, phase, setupole strength) to provide a self-cancellation of geometric Resonant Driving Terms (RDTs) $h_{jklm}$ (j+k+l+m=3) from chromatic sextupoles. Will consider to implement harmonic sextupoles



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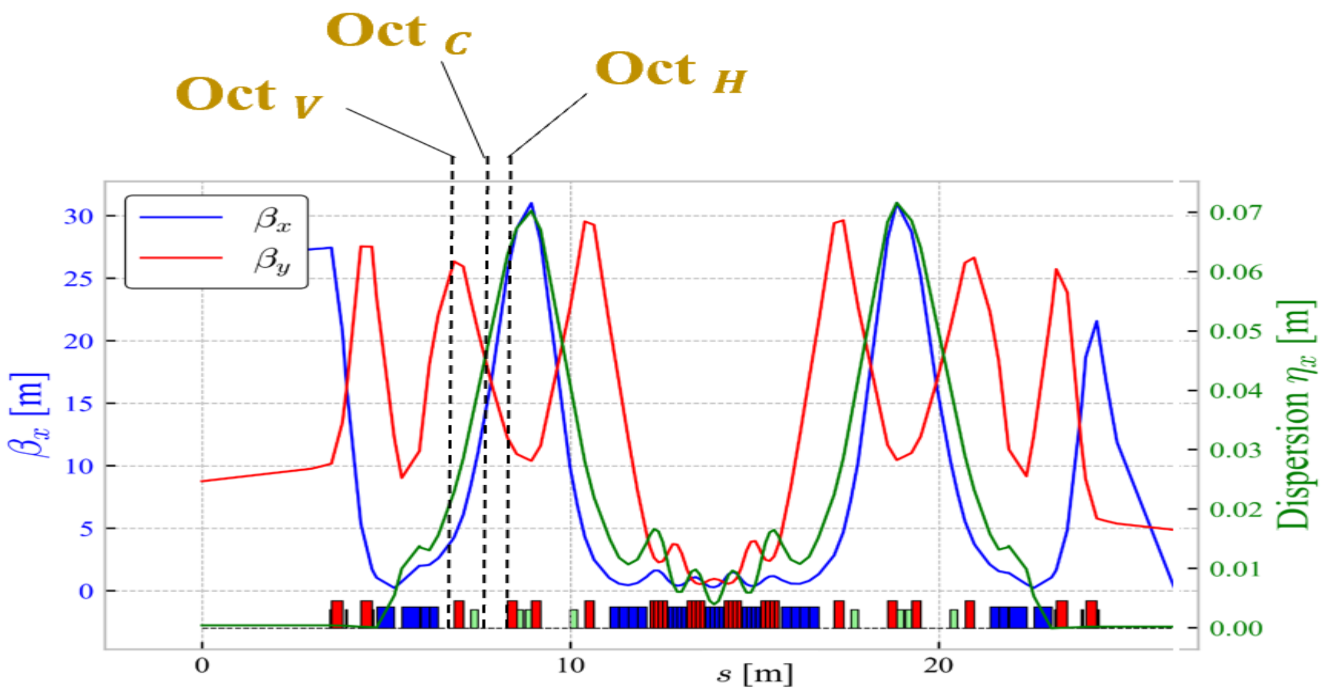
# TCBA lattice: main parameters

| Property | Values |
|---|---|
| Beam Energy $E$ [GeV] | 3 |
| Natural Horizontal Emittance $\epsilon_x$ [pm-rad] | 34.4 |
| Damping Partitions $(J_x, J_y, J_\delta)$ | (1.92, 1.00, 1.08) |
| Damping Times $(\tau_x, \tau_y, \tau_\delta)$ [ms] | (25.98, 50.01, 46.52) |
| Ring Tunes $(\nu_x, \nu_y)$ | (85.180, 22.140) |
| Natural Chromaticities $(\xi_x^{\rm nat}, \xi_y^{\rm nat})$ | $(-215.187, -198.267)$ |
| Corrected Chromaticities $(\xi_x^{\rm cor}, \xi_y^{\rm cor})$ | $(+2.366, +2.625)$ |
| Momentum Compaction $\alpha_c$ | $6.25 \times 10^{-5}$ |
| Energy Loss per Turn $U_0$ [keV] | 317 |
| Energy Spread $\sigma_\delta$ [%] | 0.076 |
| $(\beta_x, \beta_y)$ at Long-Straight Center [m] | (19.82, 3.09) |
| $(\beta_x, \beta_y)$ at Short-Straight Center [m] | (0.22, 2.30) |
| max $(\beta_x, \beta_y)$ [m] | (24.98, 32.26) |
| min $(\beta_x, \beta_y)$ [m] | (0.20, 0.53) |
| $\eta_x$ (min, max) [mm] | $(-0.1, +71.9)$ |
| Length of Long Straight $L_{\rm LS}$ [m] | 7.020 |
| Length of Short Straight $L_{\rm SS}$ [m] | 4.220 |
| Circumference $C$ [m] | 792.000 |
| Circumference Change $\Delta C/C$ [%] | +0.005 |
| Number of Super-periods | 15 |
| Source Point Diff. at LS $(\Delta x, \Delta z)$ [mm] | $(-3.79, +22.89)$ |
| Source Point Diff. at SS $(\Delta x, \Delta z)$ [mm] | $(+15.34, +15.05)$ |
| Revolution Frequency $f_{\rm rev}$ [kHz] | 378.526 |

# TCBA lattice: higher order correction

- The lattice performance is strongly limited by higher order effects from the sextupoles, especially amplitude dependent tune shift (ADTS) terms
- **Octupoles are used here to correct large linear ADTS**
- The strength of 3 octupole families are calculated from solving the linear system to cancel for the horizontal, vertical and cross term of linear amplitude detuning
- Oct[H, V, C] are placed in the lattice with large $\frac{\beta_x}{\beta_y}$, large $\frac{\beta_y}{\beta_x}$, and $\frac{\beta_x}{\beta_y} \approx 1$
- Octupoles are placed in dispersion region close to the chromatic sextupoles



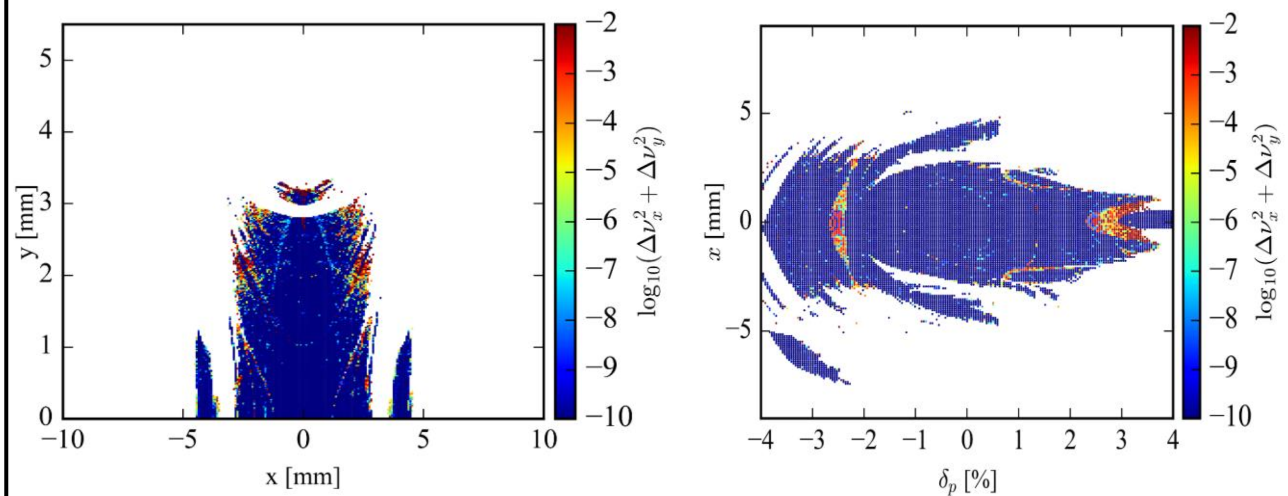



F. Plassard

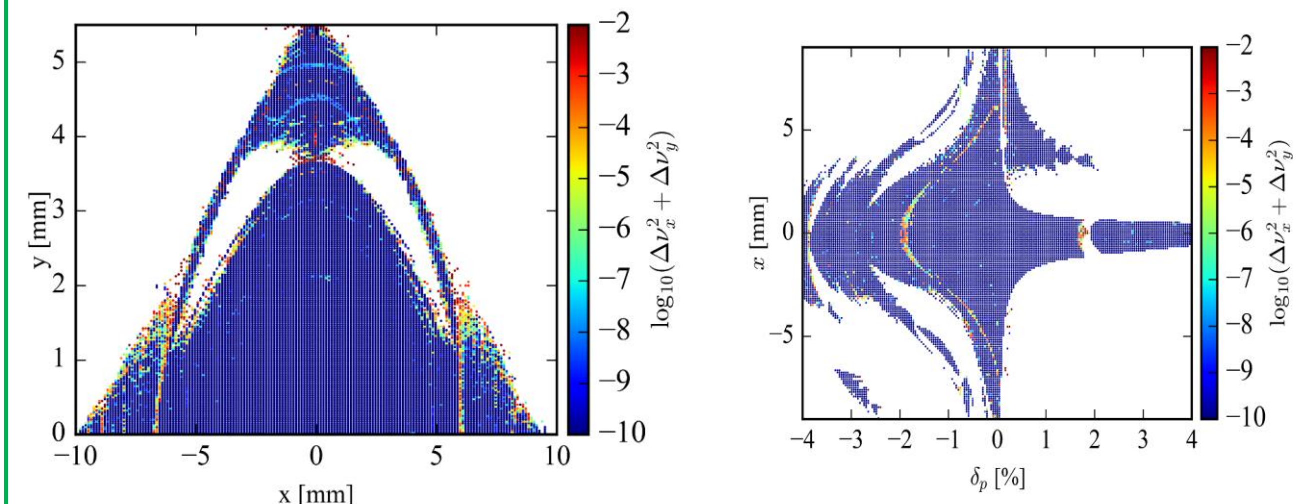
# TCBA lattice: property with and w/o Octupoles correction

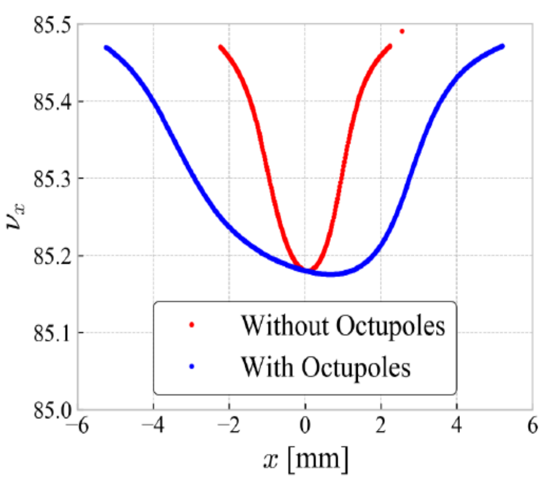
- 3 families of octupoles: $K_3L$ ~ 3600 1/m$^3$
- Improve ADTS
- Improve on-momentum DA: ±~3mm → ±~9mm
- Reduce momentum acceptance due to increase of 2nd order chromaticity. Need further optimization

**Without Octupoles**




**With Octupoles**



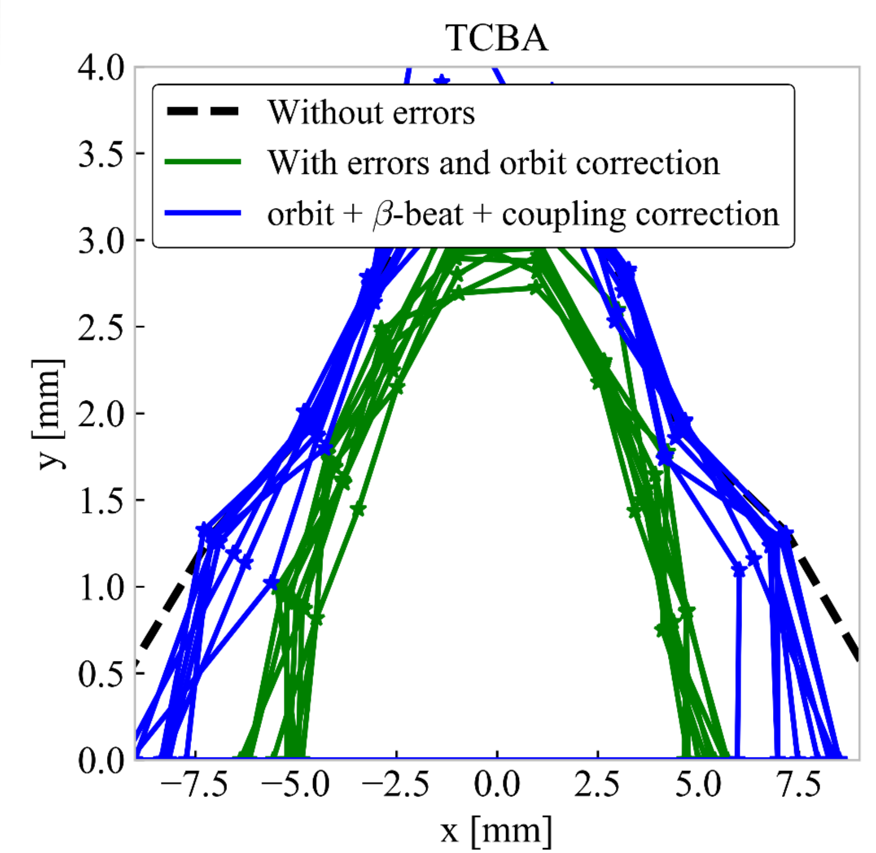






*F. Plassard*

# TCBA lattice: error sensitivity

- The on-momentum DA can be mostly recovered after correction
- Among the different seed simulated, the emittance stays within **~5%** for the TCBA after a full optimization




| *Errors* | *Value* |
|---|---|
| Transverse misalignment $\sigma_{\Delta x,y}$ | **20 μm** |
| Roll angle $\sigma_{roll}$ | **200 μrad** |
| Quad strength error Δk/k | $\mathbf{5\times 10^{-4}}$ |
| Sextupole/ Octupole strength error Δk/k | $\mathbf{1\times 10^{-3}}$ |

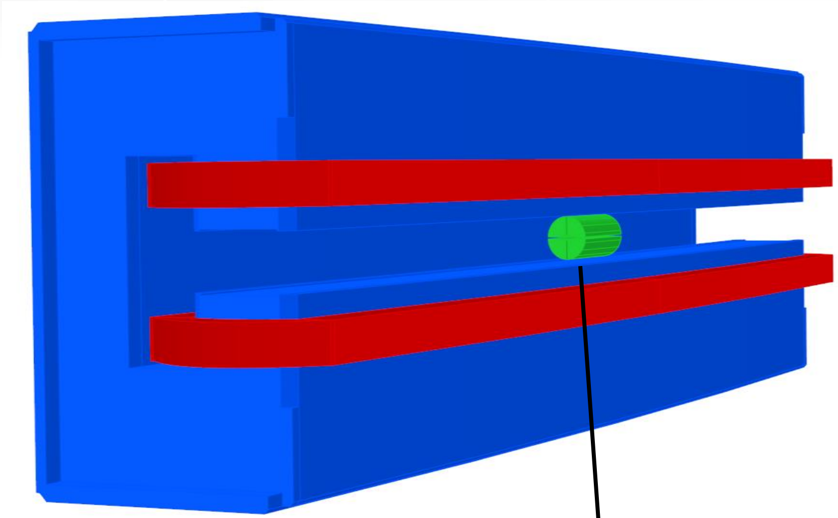
# Complex bend: Magnet design

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

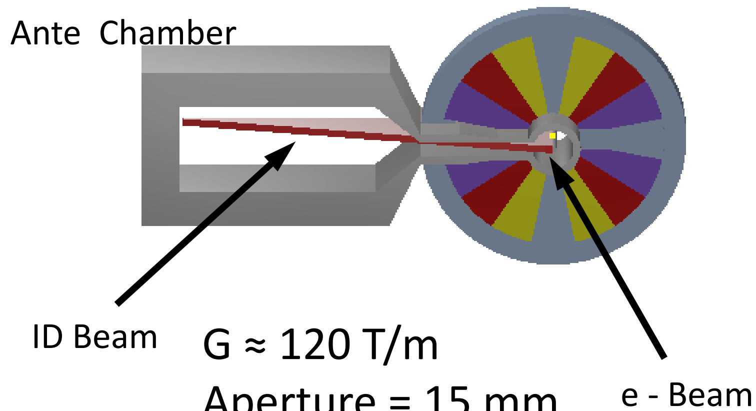
# Conceptual Design of a High Gradient CBIII Quadrupole

- Require Quads offset by 1~2 mm for a dipole field, resulting in large harmonic field of $B_3$ to $B_6$
- Superimposed 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 III



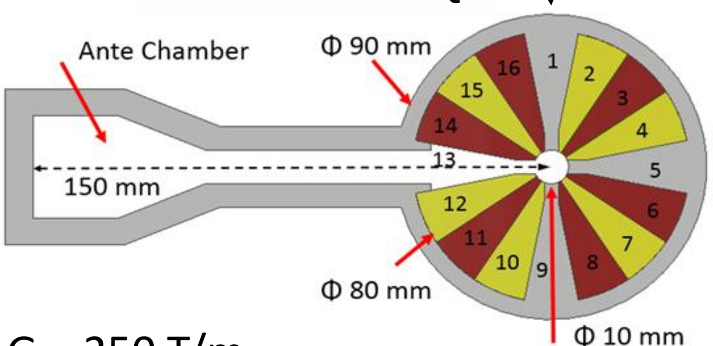
Out-of-Vacuum PMQ




G ≈ 120 T/m

Aperture = 15 mm

In-vacuum PMQ



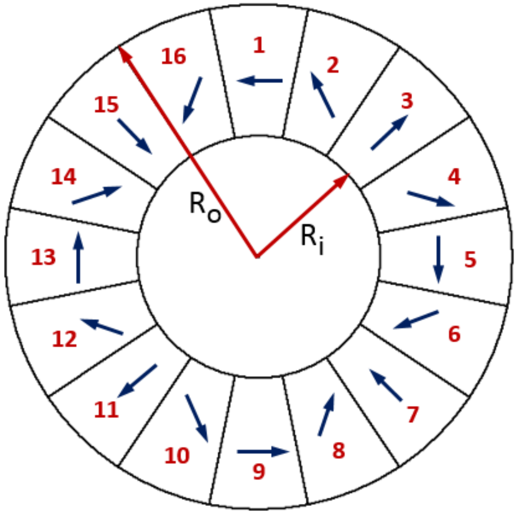

G ≈ 250 T/m

Aperture = 10 mm

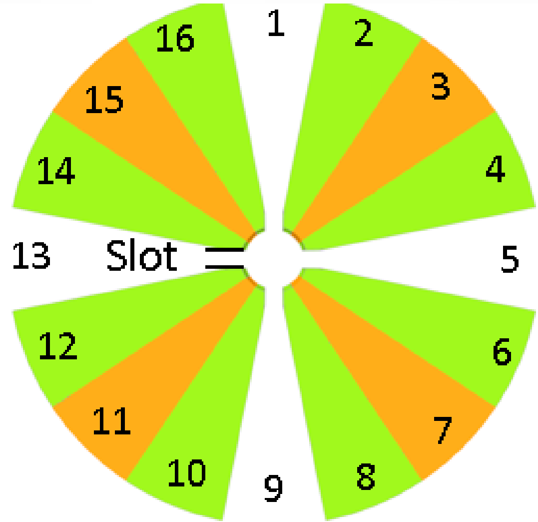
S. Sharma

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

# Prototype of Complex Bend

- Engineering design for a prototype of CB
- Downscaled *E* from 3 GeV to 50-200 MeV
- Maintain high gradient magnetic field and reduce the size of the pole and overall length of CB
- Build the prototype from an array of Permanent Magnet Quadrupoles (Commercially available)
- Commission the device at NSLS-II Linac dump line in FY21
- 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

| | Complex Bend | 50-200 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 |

# Summary and outlook

- An option path for NSLS-II upgrade
- 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, we already went to 25 and 19 pm-rad emittance while localizing bending to a smaller fraction of the storage ring circumference
- Explored different lattices with DCBA and TCBA structure and achieved >5 mm DA
- Conceptual designs for high-gradient quadrupoles with Halbach permanent-magnet quadrupole, ~250 T/m
- Developed an engineering design, 150 T/m, for a prototype of CBIII and will be tested at Linac dump line with 50-200 MeV beam

***CBIII lattice challenges:***

- Further optimization to reach <20 pm-rad emittance
- Short bunchlength. This is usual for all low-emittance lattices
- Increase dynamic aperture and momentum aperture
- Magnetic field superposition
- Superbends seamlessly integrated into CBIII for bending magnet users

# Acknowledgements


- Many thanks to the Complex Bend design team: Bassi, Gabriele; Blednykh, Alexei; Choi, Jinhyuk; Fliller, Raymond; Hidaka, Yoshiteru; Hidas, Dean; Kosciuk, Bernard; Li, Yongjun, Plassard, Fabien; Shaftan, Timur; Sharma, Sushil; Smalyuk, Victor; Spataro, Charles; Tanabe, Toshiya; Tchoubar, Oleg; Wang, Guimei;
- Thanks to Michael Borland, for sharing tools for linear and non-linear beam dynamics optimization
- Thanks to Emanuel Karantzoulis for useful discussions


Publications:


- “Concept of the Complex Bend”, T. Shaftan, V. Smaluk and G. Wang, NSLS-II tech note 276, Jan. 2018
- “Complex bend: Strong-focusing magnet for low-emittance synchrotrons”, G. Wang, T. Shaftan, V. Smaluk, et. al, Phys. Rev. Accel. Beams 21, 100703, October 2018
- “Complex Bend-II”, T. Shaftan, G. Wang, V. Smaluk, et. al, NSLS-II tech note 291, Oct. 2018
- “Complex bend II: A new optics solution” , G. Wang, T. Shaftan, V. Smaluk, et. al, Phys. Rev. Accel. Beams 22, 110703, 2019
- “Realizing low-emittance lattice solutions with Complex Bends”, V. Smaluk, T. Shaftan, J. Phys.: Conf. Ser. 1350 012044.
- “High gradient quadrpoles for low emittance synchrotrons,” S. Sharma et al. IPAC2019, Melbourne, Australia
- “Reaching Low Emittance in Synchrotron Light Sources by Using Complex Bends”, G.M. Wang, T. Shaftan, V. Smaluk et. al, TUZBB2, NAPAC-2019, Michigan, USA