Complex bend lattice design for NSLS-II upgrade

Yongjun Li on behalf of NSLS-II lattice upgrade design team

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CERN, Geneva, Switzerland

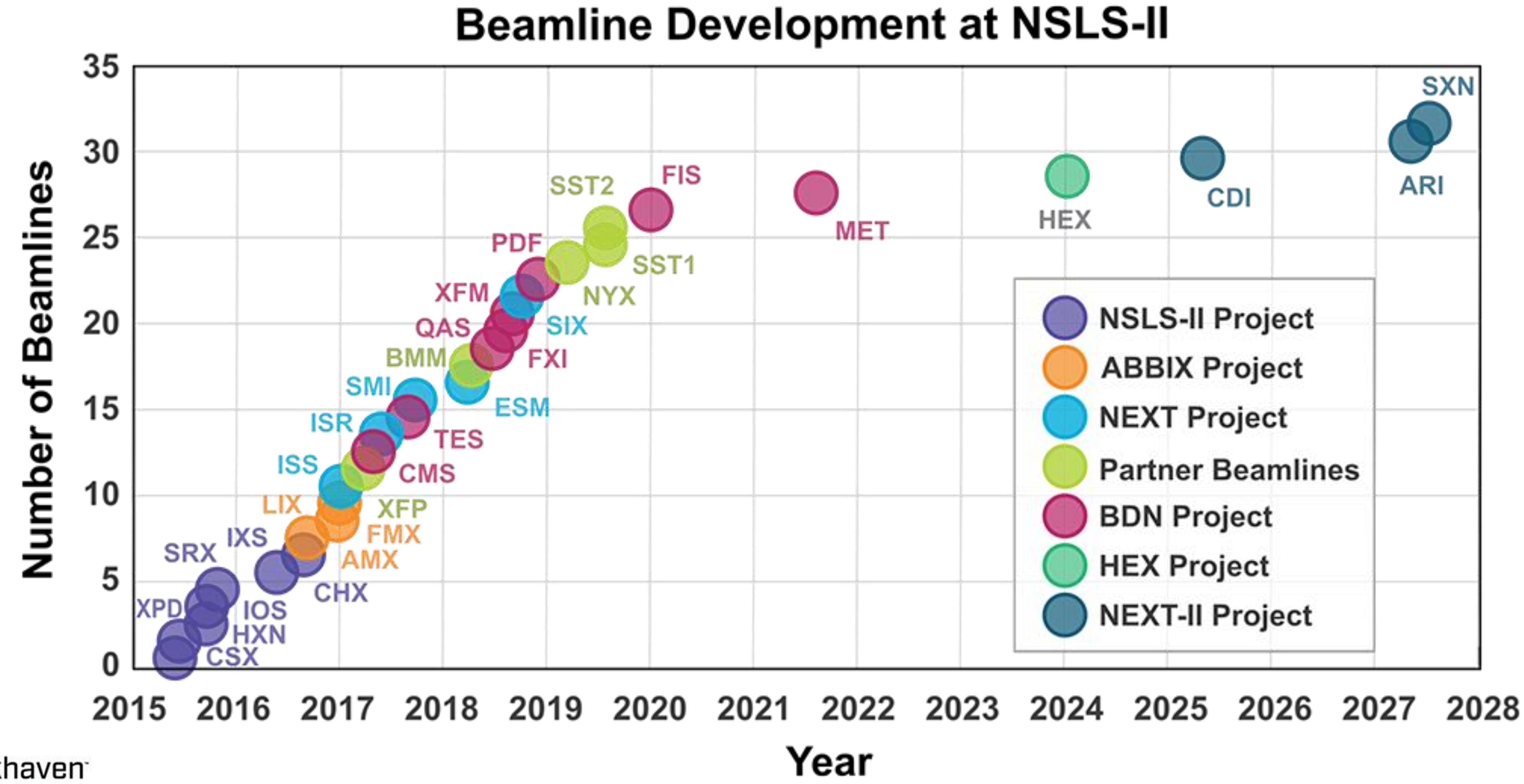
Outline

- Status of NSLS-II
- Upgrade goals
- Concept of complex bend
- Approach of linear and nonlinear optics design
- Complex magnet modelling and integration

Status of NSLS-II: Accelerator

- Operation beam current 400mA, and with successful 500mA test operations
- >97% availability, submicron orbit stability with unified closed orbit feed-back
- >10 hrs beam lifetime with 30pm vertical emittance, 4-5 hrs for 8pm (diffraction limited)
- With 1-2% beta-beat, >95% top-off injection efficiency

Status of NSLS-II: Beamlines



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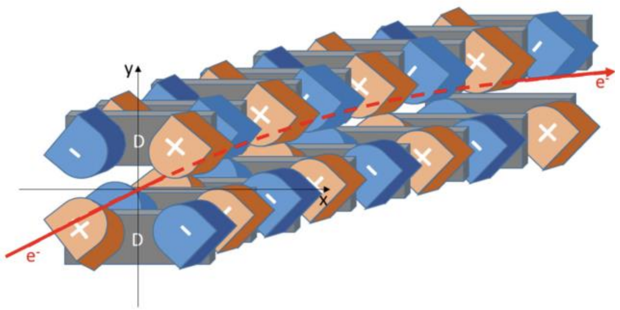
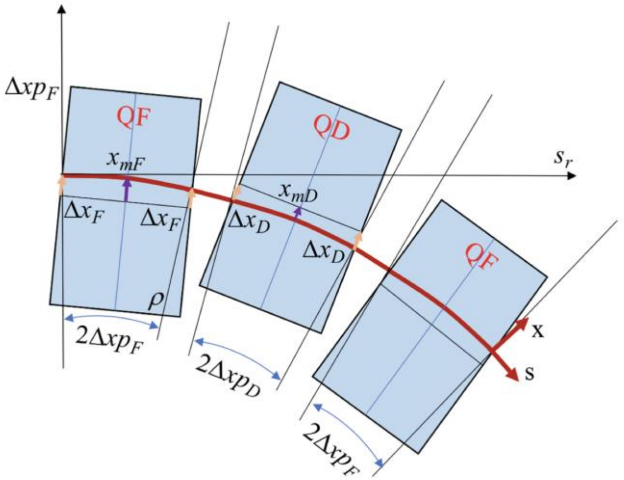
Goal of NSLS-II upgrade

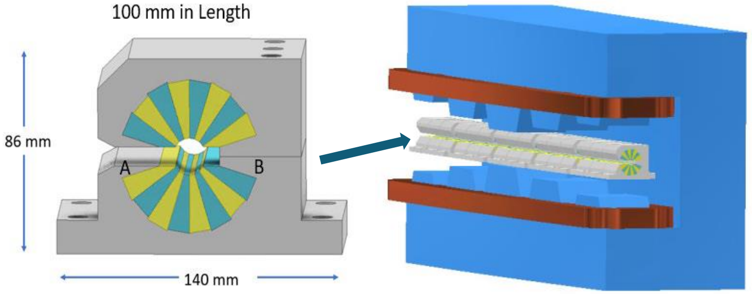
- Competitive brightness: diffraction-limited beam emittance 20-30pm
- High flux with top-off mode
- Fits with existing tunnel and X-ray ports
- Sufficient dynamic aperture for off-axis injection
- Sufficient local momentum aperture for reasonable lifetime
- Green facility with advanced permanent magnet technology

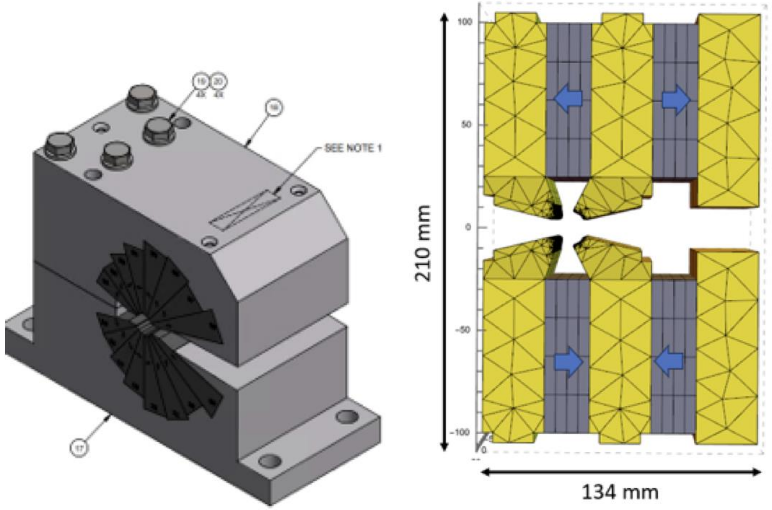
Evolution of complex bend concept

2018









2023 (now)
Hybrid

Shaftan et al., BNL Tech. Rep. (2018).

Wang et al., PRAB 21, 100703 (2018).

Wang, et al., PRAB 22, 110703 (2019)

Song and Shaftan, arXiv:2310.20010 (2023)

Concept of complex bend (cont.)

Novel method to using CB magnet array reduce beam emittance

- Small bend angle, large radius => small dispersion η_x
- Focusing => Minimize β_x, η_x , synchrotron radiation integral I_5
- Damping partition rates re-distribution between $J_{x,s}$

Challenges:

- Magnet module design and fabrication (see Shaftan's presentation, this workshop)
- Compact lattice structure with large betatron phase advance

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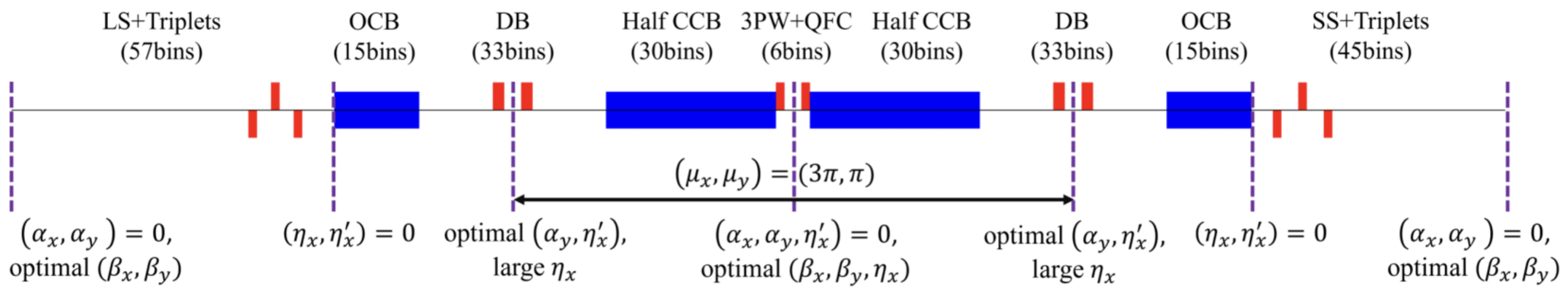
Approach of linear optics design

- Binning space approach for layout
  - Fitting with existing tunnel
  - Compatible with existing X-ray ports
  - Sufficient drift spaces for IDs
  - Local and global optimization modules

0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9	2
2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4
4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8	4.9	5	5.1	5.2	5.3	5.4	5.5	5.6	5.7	5.8	5.9	6
6.1	6.2	6.3	6.4	6.5	6.6	6.7	6.8	6.9	7	7.1	7.2	7.3	7.4	7.5	7.6	7.7	7.8	7.9	8
8.1	8.2	8.3	8.4	8.5	8.6	8.7	8.8	8.9	9	9.1	9.2	9.3	9.4	9.5	9.6	9.7	9.8	9.9	10
10.1	10.2	10.3	10.4	10.5	10.6	10.7	10.8	10.9	11	11.1	11.2	11.3	11.4	11.5	11.6	11.7	11.8	11.9	12
12.1	12.2	12.3	12.4	12.5	12.6	12.7	12.8	12.9	13	13.1	13.2	13.3	13.4	13.5	13.6	13.7	13.8	13.9	14
14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15	15.1	15.2	15.3	15.4	15.5	15.6	15.7	15.8	15.9	16
16.1	16.2	16.3	16.4	16.5	16.6	16.7	16.8	16.9	17	17.1	17.2	17.3	17.4	17.5	17.6	17.7	17.8	17.9	18
18.1	18.2	18.3	18.4	18.5	18.6	18.7	18.8	18.9	19	19.1	19.2	19.3	19.4	19.5	19.6	19.7	19.8	19.9	20
20.1	20.2	20.3	20.4	20.5	20.6	20.7	20.8	20.9	21	21.1	21.2	21.3	21.4	21.5	21.6	21.7	21.8	21.9	22
22.1	22.2	22.3	22.4	22.5	22.6	22.7	22.8	22.9	23	23.1	23.2	23.3	23.4	23.5	23.6	23.7	23.8	23.9	24
24.1	24.2	24.3	24.4	24.5	24.6	24.7	24.8	24.9	25	25.1	25.2	25.3	25.4	25.5	25.6	25.7	25.8	25.9	26
26.1	26.2	26.3	26.4																

One cell geometry spaced with 0.1m bins

	K_0	K_1	K_2	K_3	Type
(grey)	0	0	0	0	Drift
(blue)	1	1	0	0	CB
(red)	0	1	0	0	Quadrupole
(green)	0	0	1	0	Sextupole
(purple)	0	0	0	1	Octupole



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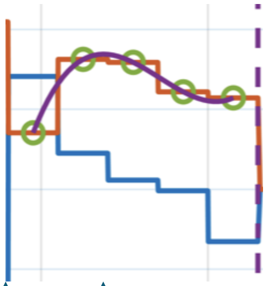
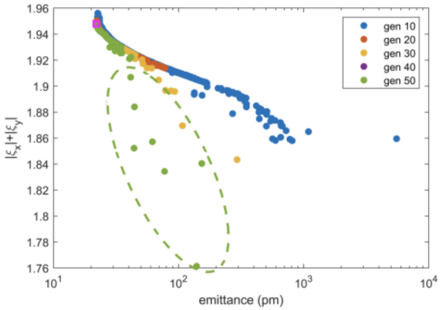
Divide, conquer and integrate

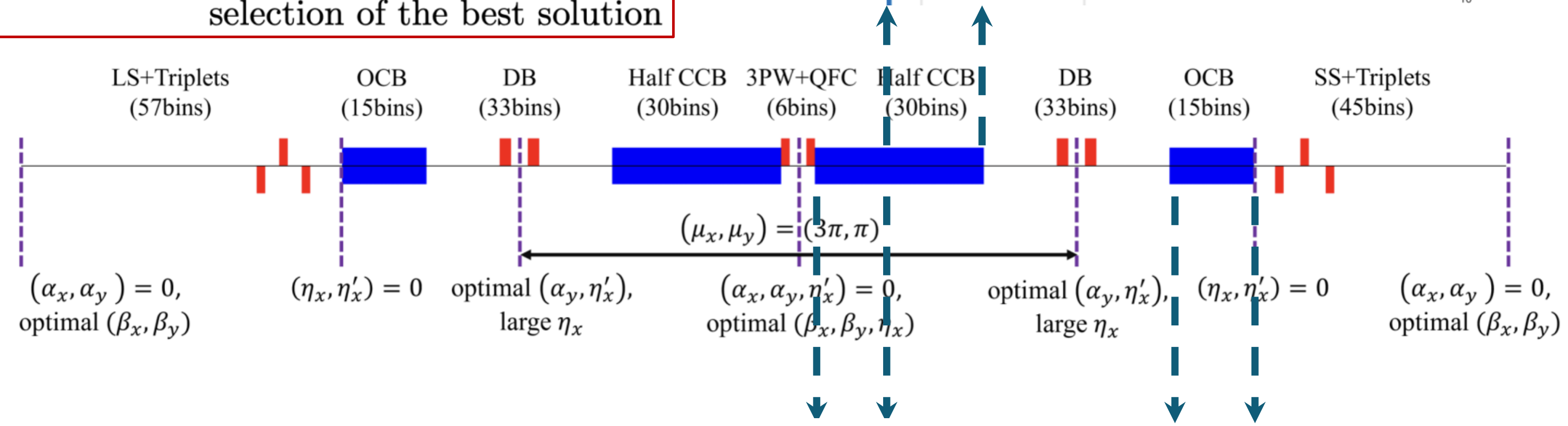
$$O(\underbrace{\Delta O}_{\substack{\text{constraints:}\\ J_x\\ \alpha_c\\ \boldsymbol{L_s}\\ \beta_{ID}}}) = \mathcal{M}(\underbrace{\Delta\mathcal{M}}_{\substack{\text{constraints:}\\ geometry\\ Twiss}})P(\underbrace{s,p}_{\substack{\text{variables:}\\ strengths\\ positions}}, \underbrace{\Delta s, \Delta p}_{\substack{\text{constraints:}\\ strengths\\ positions}}),$$

$\mathcal{F} = \mathcal{F}(O, weight)$ is the lattice figure of merit used for selection of the best solution

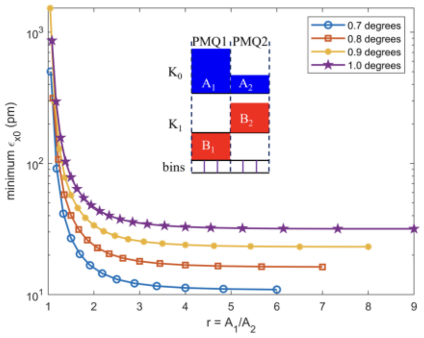


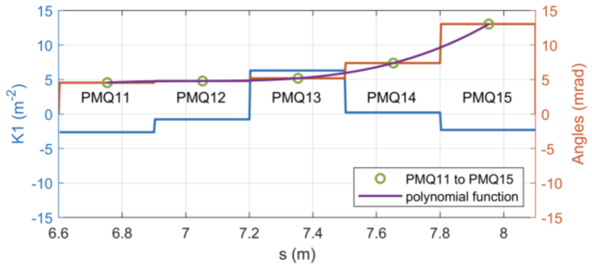
MOGA

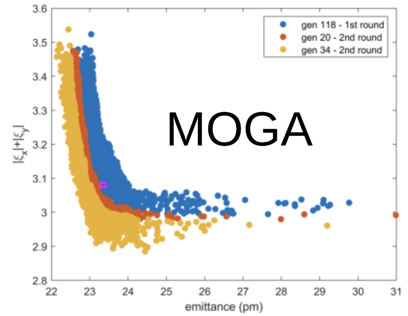




$$\mathcal{F} = \sum_i \omega_i C_i$$

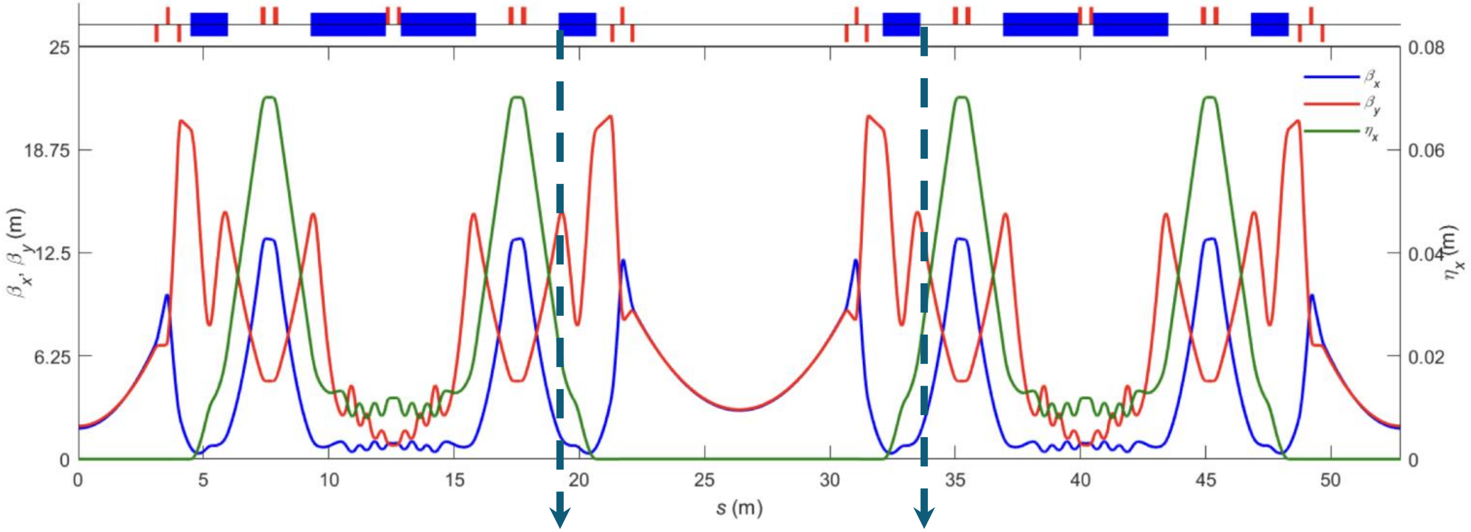




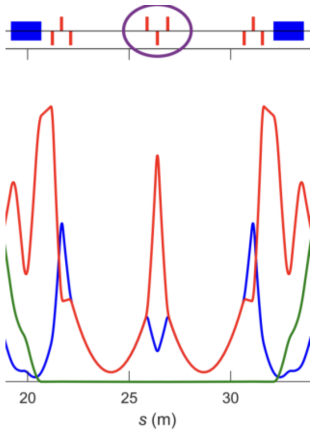


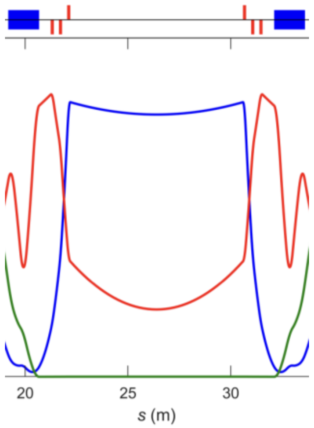
Song and Shaftan, arXiv:2310.20010 (2023)

Standard cell and variations



Double mini-beta





High horizontal beta

Comparison with NSLS-II

Paramters	Values	
	NSLS-II bare lattice	NSLS-IIU (
Circumference C [m]	791.958	791.7679
Beam energy E [GeV]	3	3
Natural emittance ϵ_{x0} [pm-rad]	2086	23.4
Damping partitions (J_x, J_y, J_δ)	(1, 1, 2)	(2.24, 1, 0.76)
Ring tunes (ν_x, ν_y)	(33.22, 16.26)	(84.67, 28.87)
Natural chromaticities (ξ_x, ξ_y)	(-98.5, -40.2)	(-135, -144)
Momentum compaction α_c	3.63×10^{-4}	7.76×10^{-5}
Energy loss per turn U_0 [keV]	286.4	196
Energy spread σ_δ [%]	0.0514	0.073
$(\beta_x,\ \beta_y)$ at LS center [m]	(20.1, 3.4)	(2.95, 2.99)
$(\beta_x,\ \beta_y)$ at SS center [m]	(1.8, 1.1)	(1.87, 1.99)
$(\beta_{x,max},\ \beta_{y,max})$ [m]	(29.99, 27.31)	(13.37, 20.82)
$(\beta_{x,min},\ \beta_{y,min})$ [m]	(1.84, 1.17)	(0.35, 0.84)
$(\beta_{x,avg},\ \beta_{y,avg})$ [m]	(12.58, 13.79)	(3.99, 7.51)
Length of LS [m]	9.3	8.4
Length of SS [m]	6.6	6.1

Nonlinear optics

- Taking advantage of MBA’s phase cancellation principle*
- Using octupoles triplet to control high order geometrical resonances**
- Using quadrupole triplets to adjust tune
- Intensive numerical studies on nonlinear lattice optimizations (next page)

*Raimondi *et al. Commun Phys* **6**, 82 (2023)
Plassard et al., PRAB **24, 114801 (2021)

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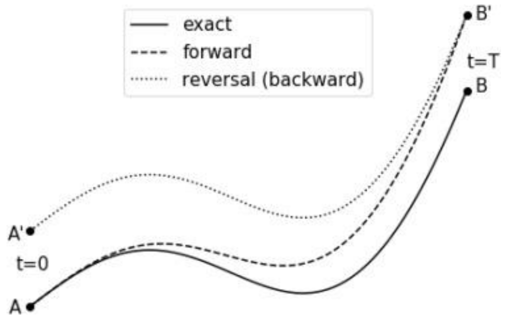
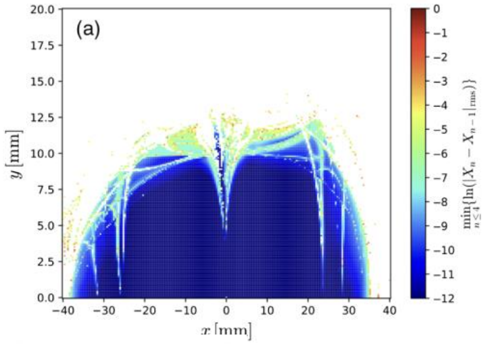
Nonlinear optics optimizations

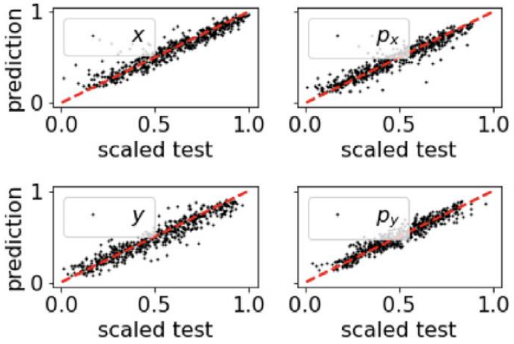


- Chaos map using forward-reversal integration (Li, 2021)

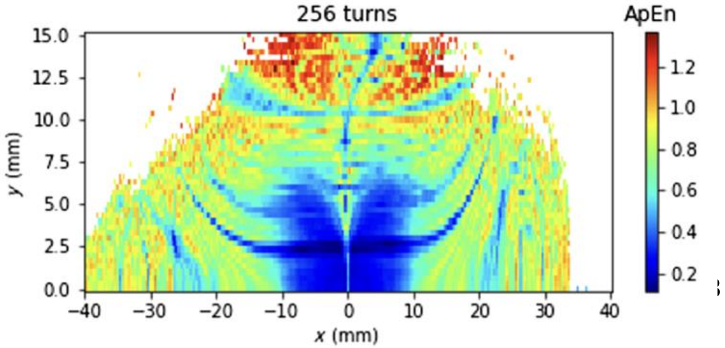


- Convergence map using square matrix (Yu, 2023)
- Control of NDT using octupole triplet (Plassard, 2021)

$$\vec{k_{\mathrm{oct}}} = \mathcal{U}_{\mathrm{oct}}^{-1}.\vec{\alpha} \qquad \mathcal{U}_{\mathrm{oct}} = \frac{1}{8\pi}\begin{pmatrix} \frac{1}{2}\beta^2_{x|\mathrm{oct}_1} & \frac{1}{2}\beta^2_{x|\mathrm{oct}_2} & \frac{1}{2}\beta^2_{x|\mathrm{oct}_3} \\ \frac{1}{2}\beta^2_{y|\mathrm{oct}_1} & \frac{1}{2}\beta^2_{y|\mathrm{oct}_2} & \frac{1}{2}\beta^2_{y|\mathrm{oct}_3} \\ -\beta_x\beta_{y|\mathrm{oct}_1} & -\beta_x\beta_{y|\mathrm{oct}_2} & -\beta_x\beta_{y|\mathrm{oct}_3} \end{pmatrix}$$



- Data-driven chaos map (Li, 2022)
- Approximate Entropy chaos maps (Li, 2024)
- …



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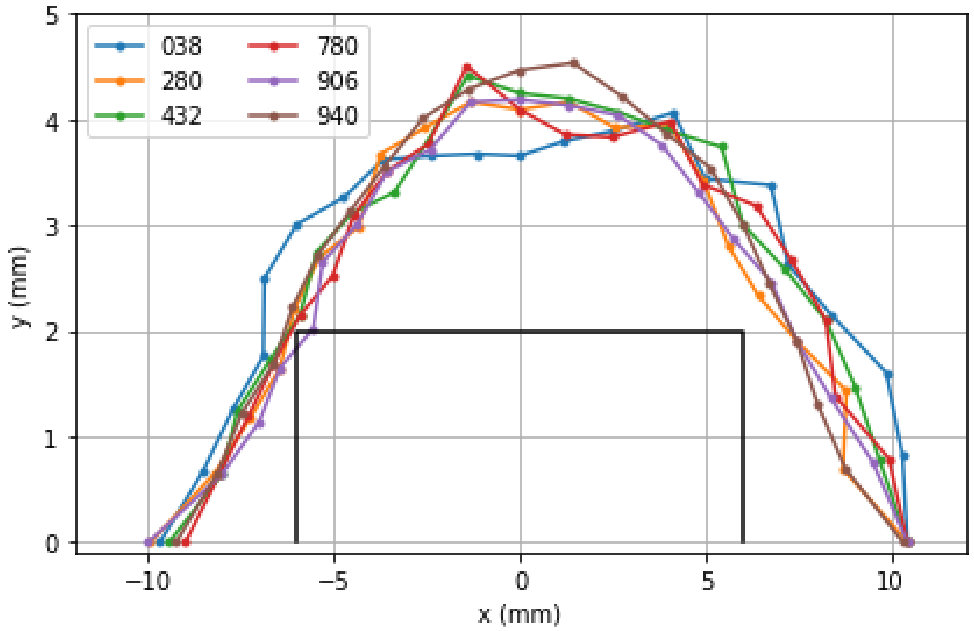
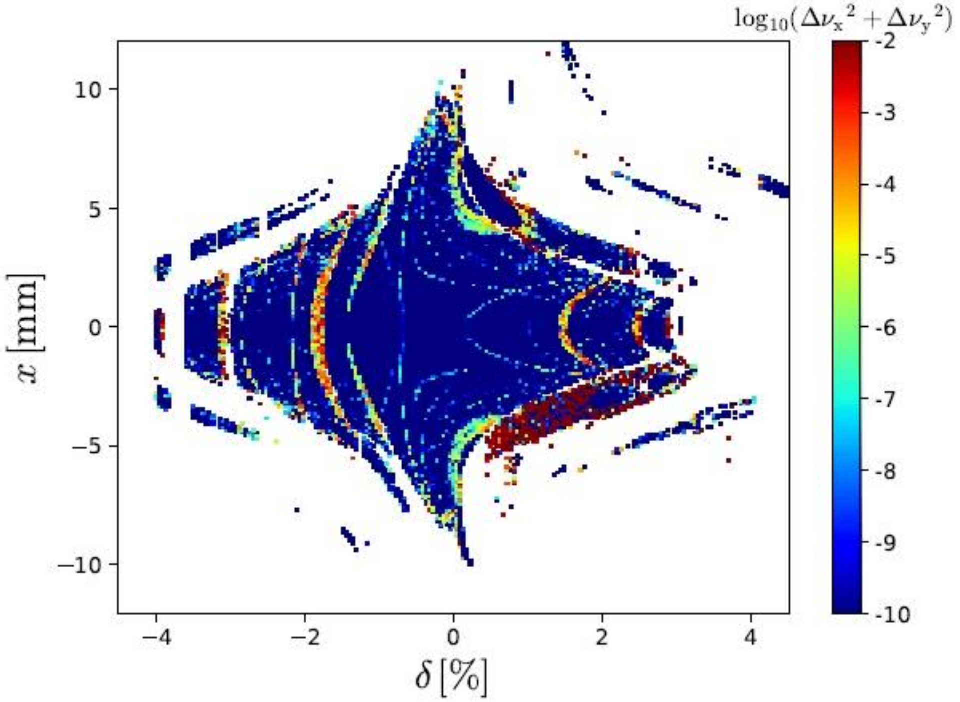
Dynamic aperture and momentum aperture



On-momentum Dynamic apertures with different sext(3 Fam.)/oct(3 Fam.) settings



FMA at x-dp plane

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Complex magnet modelling and integration into simulation

- Hard-edge models might not be sufficiently accurate
- Working with magnet experts on modelling
- In-house developed numerical method (Li and Huang, arXiv:1511.00710, 2015)
- Planning to adopt newly-developed techniques (see Lindberg's presentation, this workshop)

- Robustness check including imperfections, errors and corresponding correction
- Worst case (commissioning) simulations as APS-U and ALS-U

Mitigation of intra-beam scattering effect

- IBS: Beam emittance blow-up and short lifetime due to small beam emittance
- Mitigations
  - Bunch lengthening with harmonic cavity, reducing J_s, longitudinal impedance
  - Strong radiation damping from insertion devices
  - Round beam mode (Li, PRAB **25**, 040702, 2022)
  - **Increasing beam energy (rigidity) from 3 to 4GeV**

Summary

- Complex bend achromat scheme was proposed for NSLS-II upgrade
- Preliminary optics is available, intensive design studies are needed to boost its maturity
- Engineering R&D carried out parallelly with optics design

Acknowledgments

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