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Lattice design progress of the HALF storage ring

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Outline

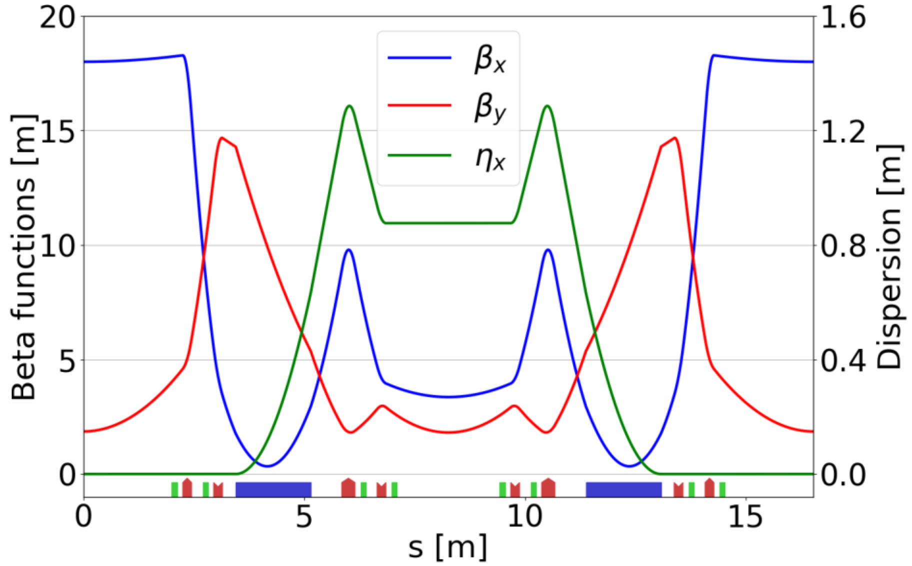
- NSRL and HALF
- Design option
- Lattice concept and comparison
- Lattice design and optimization
- Other design issues
- Conclusion

NSRL

- At NSRL, two accelerator facilities are operated:
  - Hefei Light Source (HLS)
  - Infrared FEL (IR-FEL)
- HLS: second-generation synchrotron light source
  - First light in 1989
  - Upgrade completed in 2014
  - Full-energy linac + 800 MeV storage ring
  - DBA lattice with two straight sections in each cell

The present HLS storage ring:

- Circumference: 66.13 m, with 4 cells
- Natural emittance: 36 nm·rad
- 8 straight sections: 4×4.0 m + 4×2.3 m



HALF: Hefei Advanced Light Facility

- HALF: a soft X-ray and VUV diffraction-limited storage ring (DLSR) at NSRL
  - The concept was first proposed in 2008 (EPAC2018)
  - In 2019, main design goals and parameters were changed
  - Recently, the HALF project was approved
- Location of HALF
  - Near 20 km from HLS to HALF
  - About 15 km from HALF to the airport
  - Some other scientific facilities near HALF

- Goals of HALF
  - Natural emittance: < 100 pm·rad @ 2.2 GeV
  - Larger number of straight sections is preferred to provide more insertion devices (IDs)

MBA lattice options for HALF

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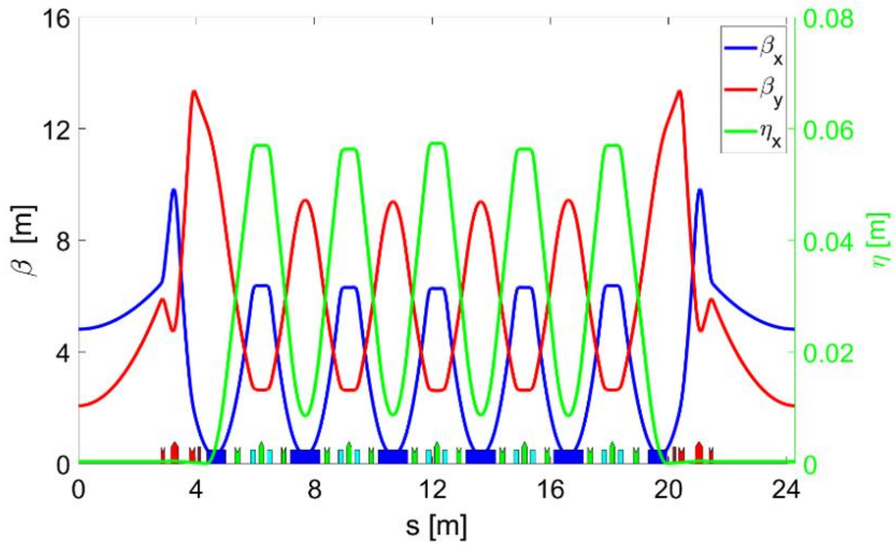
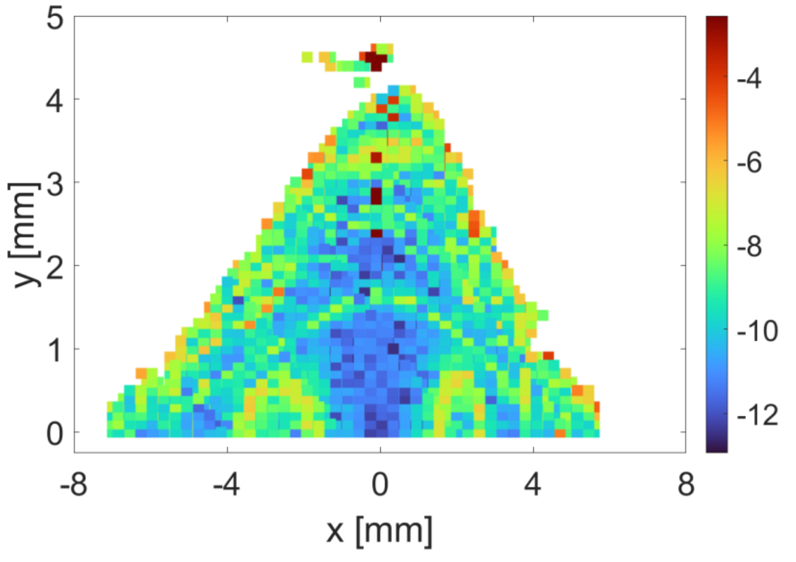
- HALF: a green-filed DLSR, with more freedom in design
- MBA lattices:
  - Conventional MBA: distributed chromatic correction, such as MAX IV and SLS-2 lattices
  - Hybrid MBA (HMBA): a pairs of dispersion bumps accommodating all chromatic sextupoles, such as ESRF-EBS and APS-U lattices
- Options for HALF with natural emittance < 100 pm·rad:
  - Conventional MBA: 16×6BA (considered), 14×7BA (not considered for less straight sections)
  - HMBA: 20×H7BA (considered)
- Moderate spaces between elements in lattice design
  - 16×6BA: cell length of ~24 m (circumference: 380~390 m)
  - 20×H7BA: cell length of ~22 m (circumference: ~440 m)

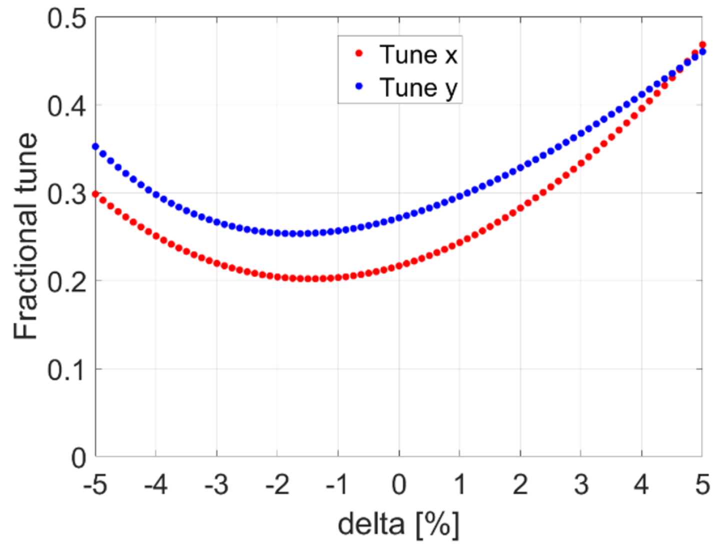
MBA lattice options for HALF

➢ 16×6BA design

- Unit lattice cell: combined-function bend and reverse bend (RB)
- Higher-order-achromat (HOA): H/V tunes of TME-like unit cell are (0.4, 0.1) for sextupole cancellation over 5 identical unit cells
- Natural emittance: 94 pm·rad
- Dynamic aperture (DA): hard to adopt off-axis injection when errors are included
- Good off-momentum nonlinear dynamics

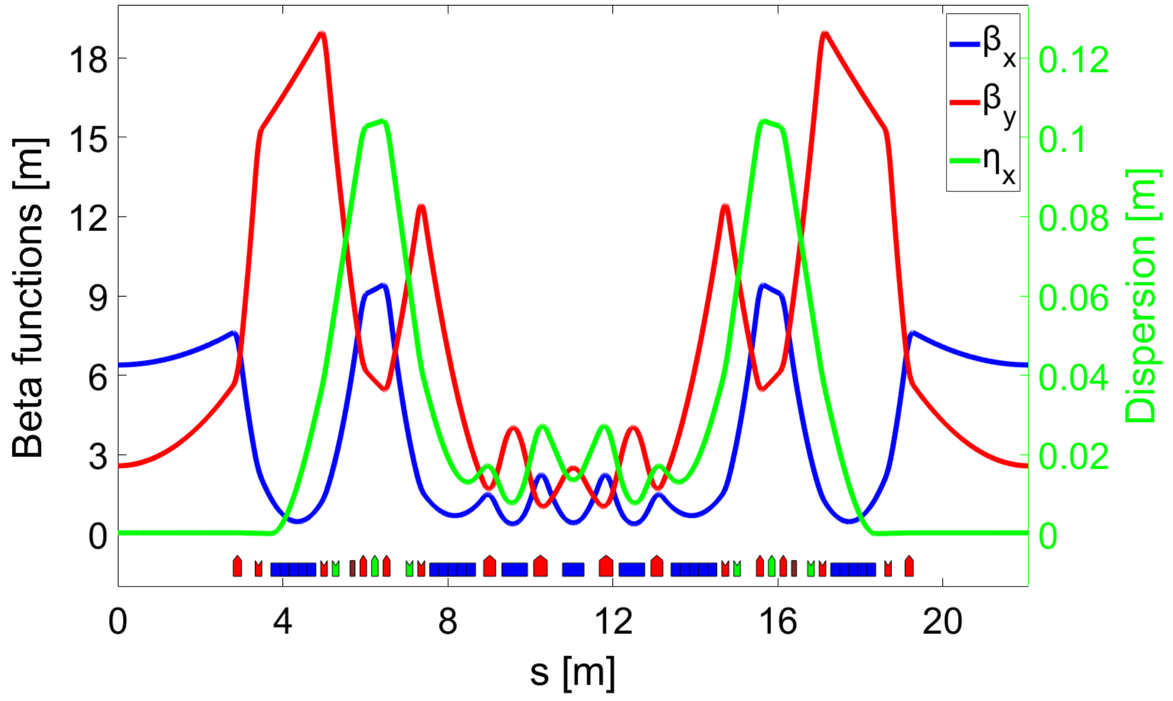


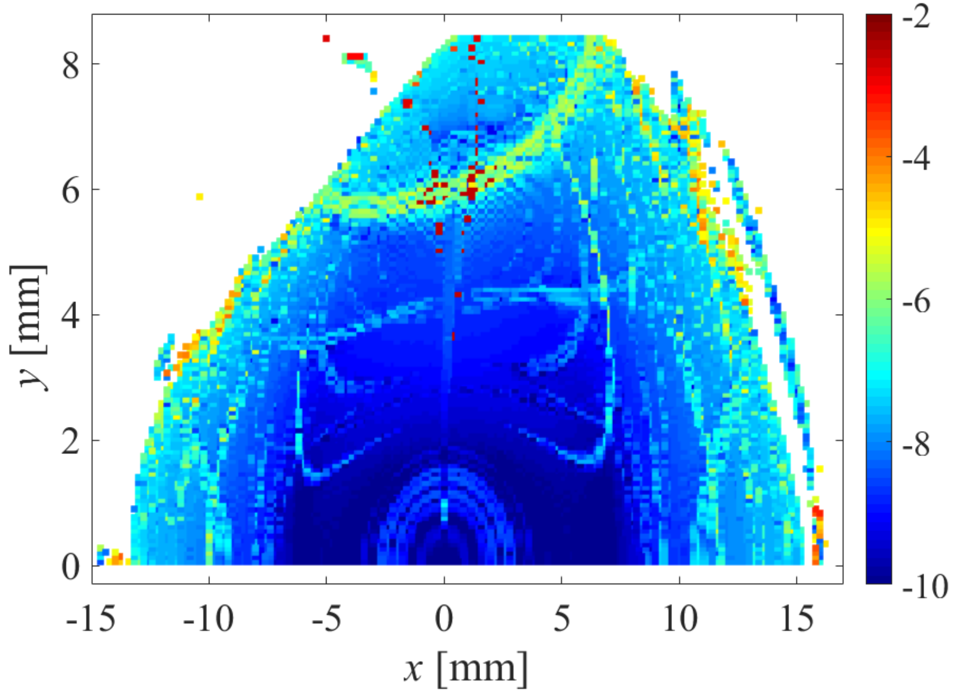




MBA lattice options for HALF

- 20×H7BA design
  - Following ESRF-EBS lattice, without RB
  - Natural emittance: 84 pm·rad
  - Large DA: allow off-axis injection with errors included
  - Acceptable off-momentum nonlinear dynamics (due to moderate cell length)





MBA lattice options for HALF

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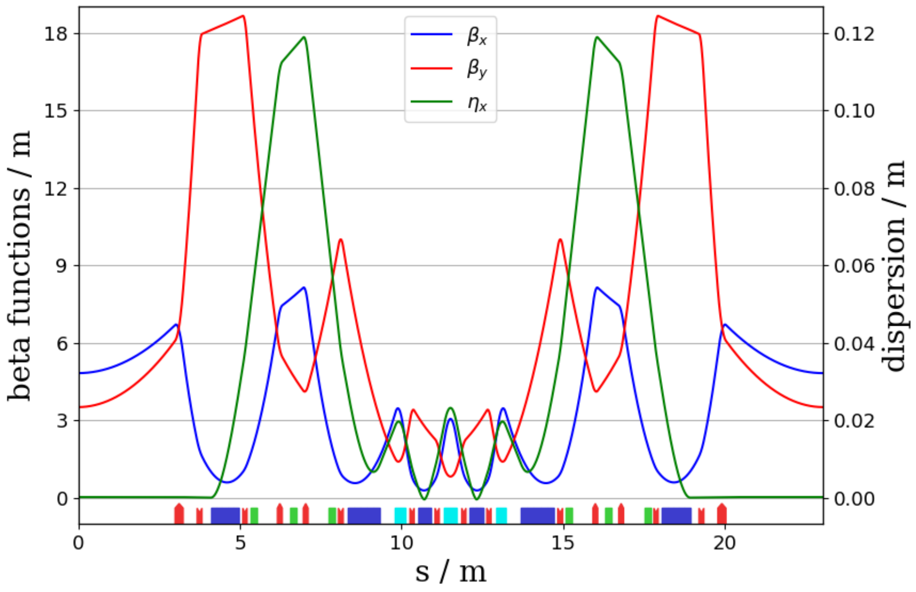
- Main storage ring parameters of 16×6BA and 20×H7BA designs
  - The design based on 20×HMBA was chosen for HALF due to more straight sections and larger DA for off-axis injection
  - 20×H7BA: very long natural damping times due to longer bends and weaker dipole fields, causing very serious intra-beam scattering (IBS) effect and thus significant emittance increase

Parameters	16×6BA	20×H7BA
Energy	2.2 GeV	2.2 GeV
Circumference	388.8 m	441.6 m
Natural emittance	94 pm·rad	84 pm·rad
Transverse tunes (H/V)	42.22/14.27	48.17/17.17
Momentum compaction factor	0.92×10^{-4}	1.73×10^{-4}
Damping partition number (H/V/L)	1.95/1.0/1.05	1.50/1.0/1.50
Natural damping times (H/V/L)	14.4/28.1/26.7 ms	36.4/54.6/36.4 ms

HALF lattice concept

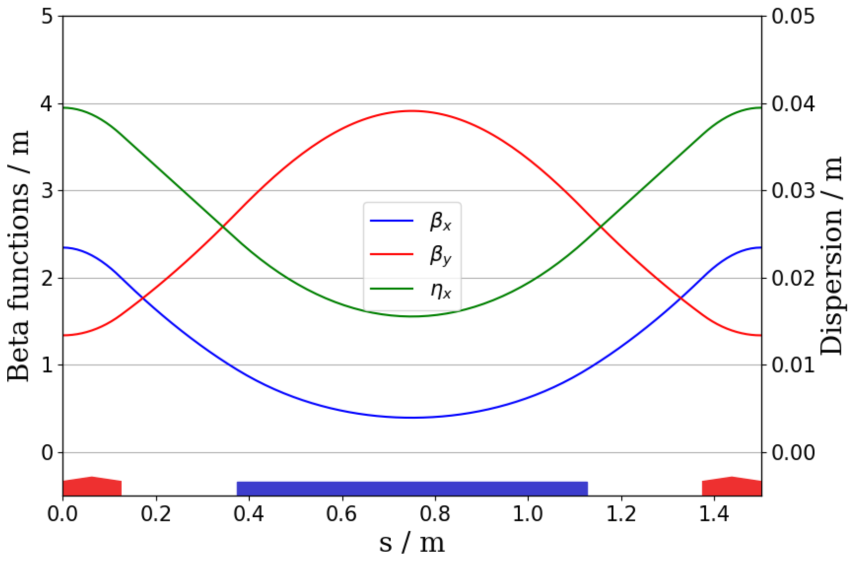
- To reduce the damping times as well as natural emittance, we combined the HMBA lattice proposed by ESRF-EBS and LGB/RB unit cell proposed by SLS-2 (LGB: longitudinal gradient bend)
  - LGB: non-homogenous dipole field can increase energy loss
  - RB: increase the total absolute bending angle and thus increase energy loss
  - Combination of LGB and RB: significantly reduce the emittance
  - Replace the three combined-function bend cells in the middle part by two LGB/RB cells

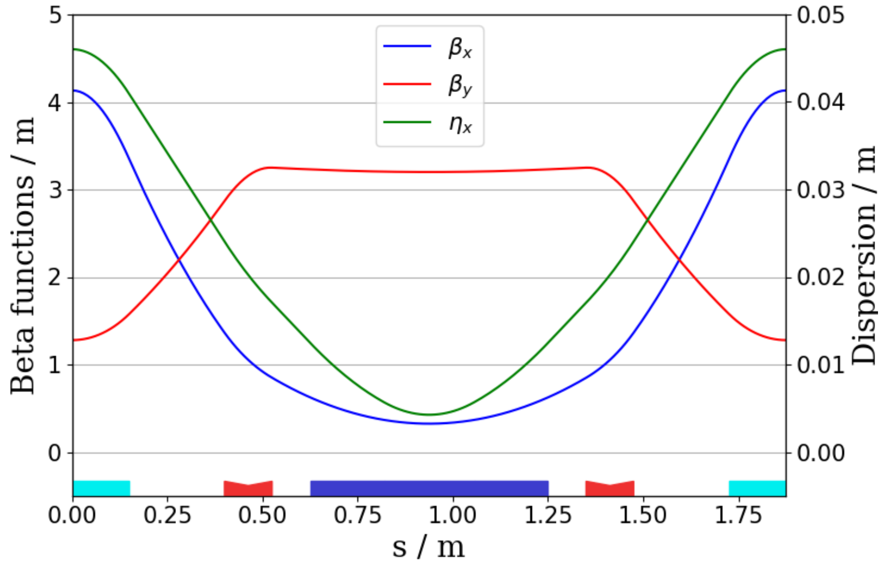
- Compared to the H7BA lattice, in this new lattice:
  - The vertical damping time (Jy=1) is reduced from 55 ms down to ~30 ms
  - The natural emittance is reduced from 84 pm·rad down to ~70 pm·rad



HALF lattice concept

- For simplicity, consider two unit cell cases:
  - Case A: 5 combined-function bend cells
  - Case B: 4 LGB/RB cells (LGB with 3 slices)
  - Case A and Case B have: the same total length and the same H/V phase advances of (1.5, 0.5) × 2π as that between two dispersion bumps in HMBA lattice
- The natural damping time of Case B is <50% of that of Case A
- The natural emittance of Case B is ~70% or less of that of Case A





HALF lattice concept and design

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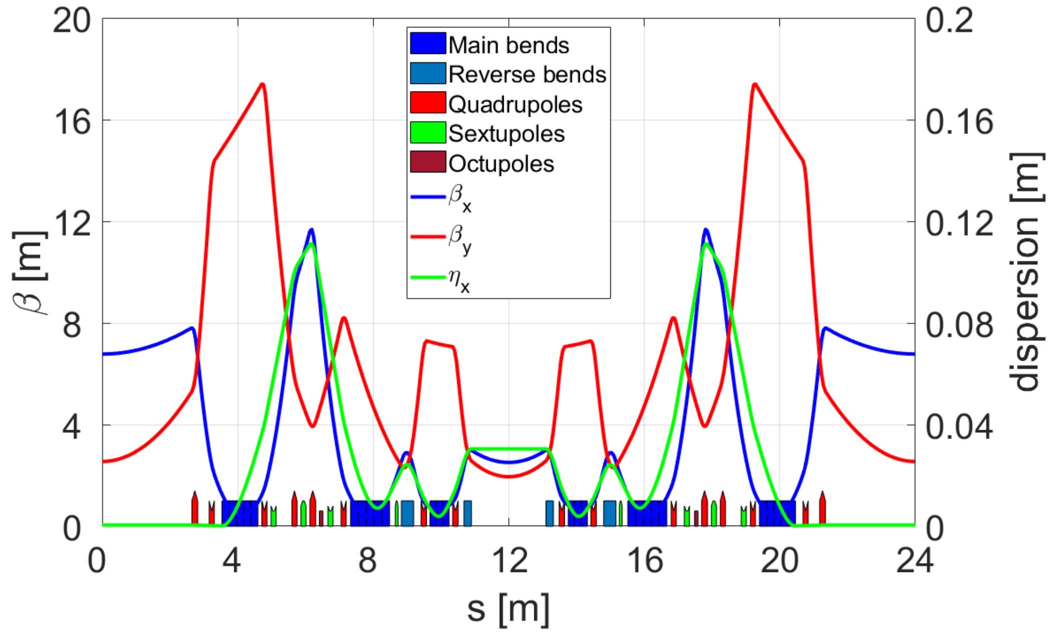
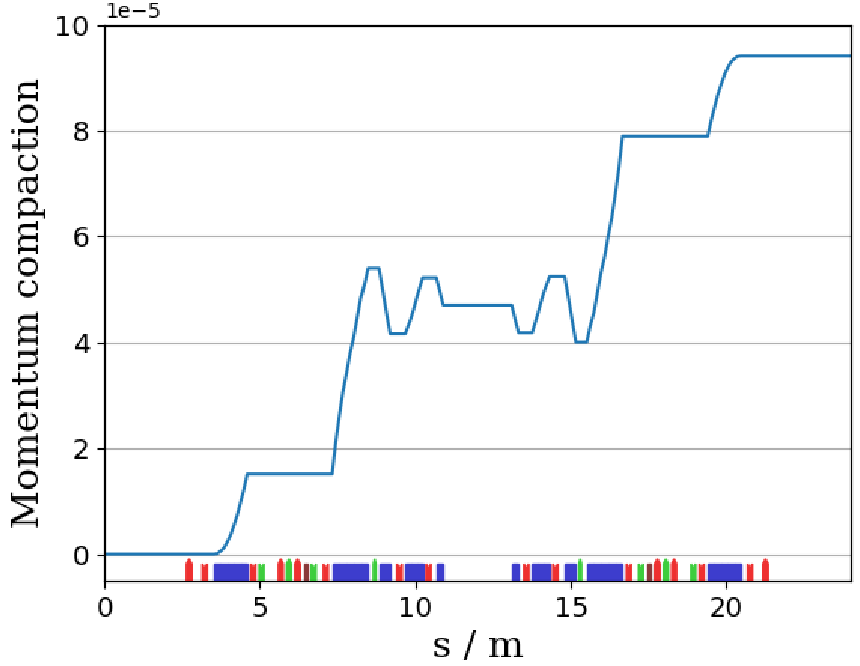
- The previous new lattice has relatively small momentum aperture (MA) due to large higher-order chromaticities.
- Inserting a mid-straight section in the middle can increase MA, but with some emittance increase and damping time increase, which produces the HALF modified hybrid 6BA lattice.



The present HALF lattice of one cell



HALF storage ring parameters

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Parameters	Values
Energy	2.2 GeV
Circumference	479.86 m
Number of cells	20
Natural emittance	85.8 pm·rad
Transverse tunes (H/V)	48.19/17.19
Natural chromaticities (H/V)	-81.6/-56.6
Momentum compaction factor	0.94×10^{-4}
Damping partition number (H/V/L)	1.36/1.0/1.64
Natural damping times (H/V/L)	28.5/38.8/23.7 ms
Natural energy spread	0.61×10^{-3}
Total absolute bending angle	438.6°

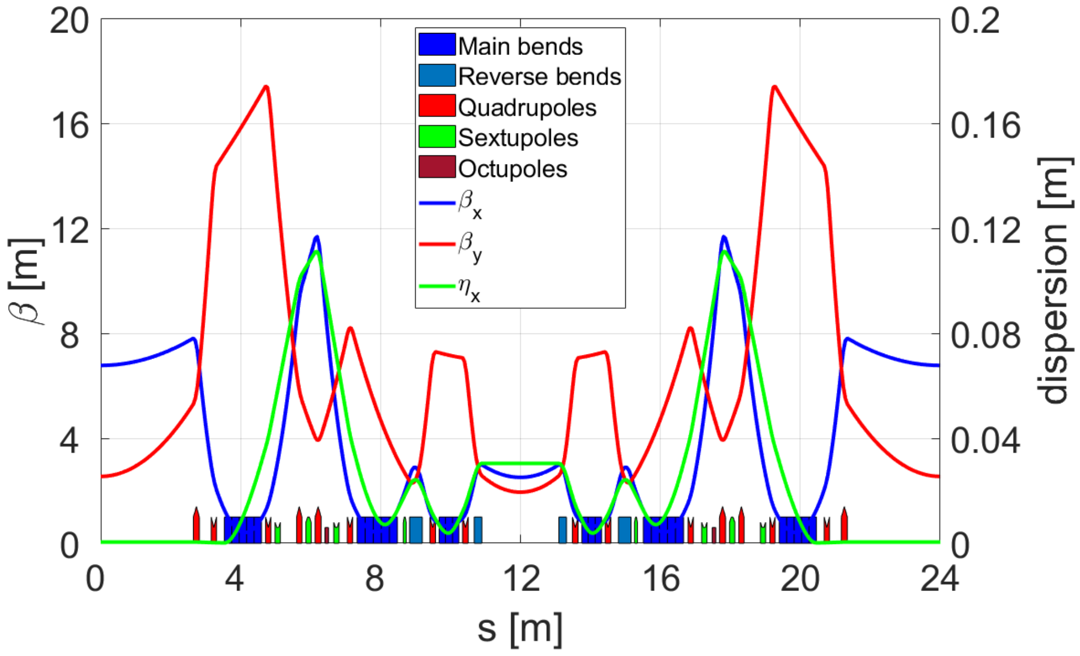
- Number of straight sections: 20 long (5.3 m) + 20 short (2.2 m)

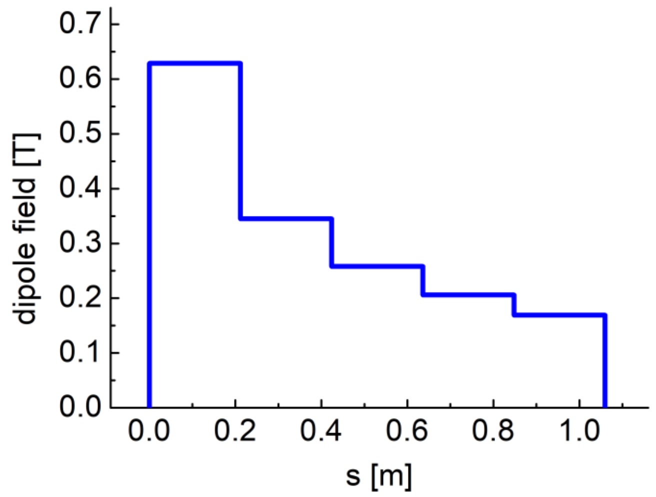
Linear optical functions at the middle of straight sections

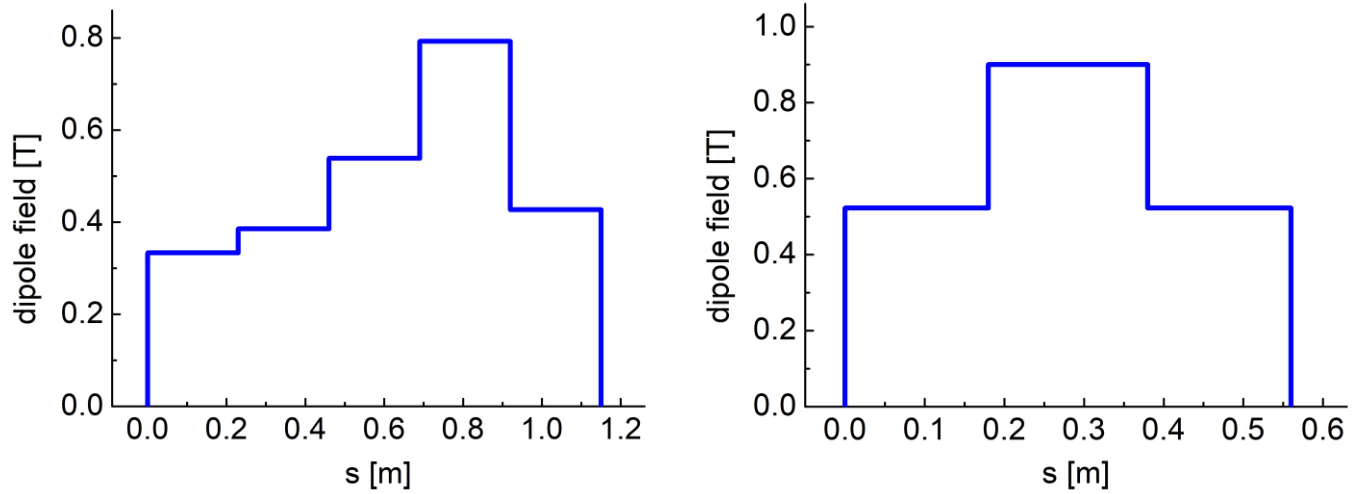
	Long straight	Short straight
beta x	6.78 m	2.51 m
beta y	2.55 m	1.95 m
dispersion	0.0 m	0.03 m

LGBs and RBs of HALF lattice

- All six main bends are LGBs
  - For the 2nd LGB, the 4th slice has the highest dipole field due to the effect of RB
- Two families of RBs:
  - increase Jx from 1.0 to 1.36





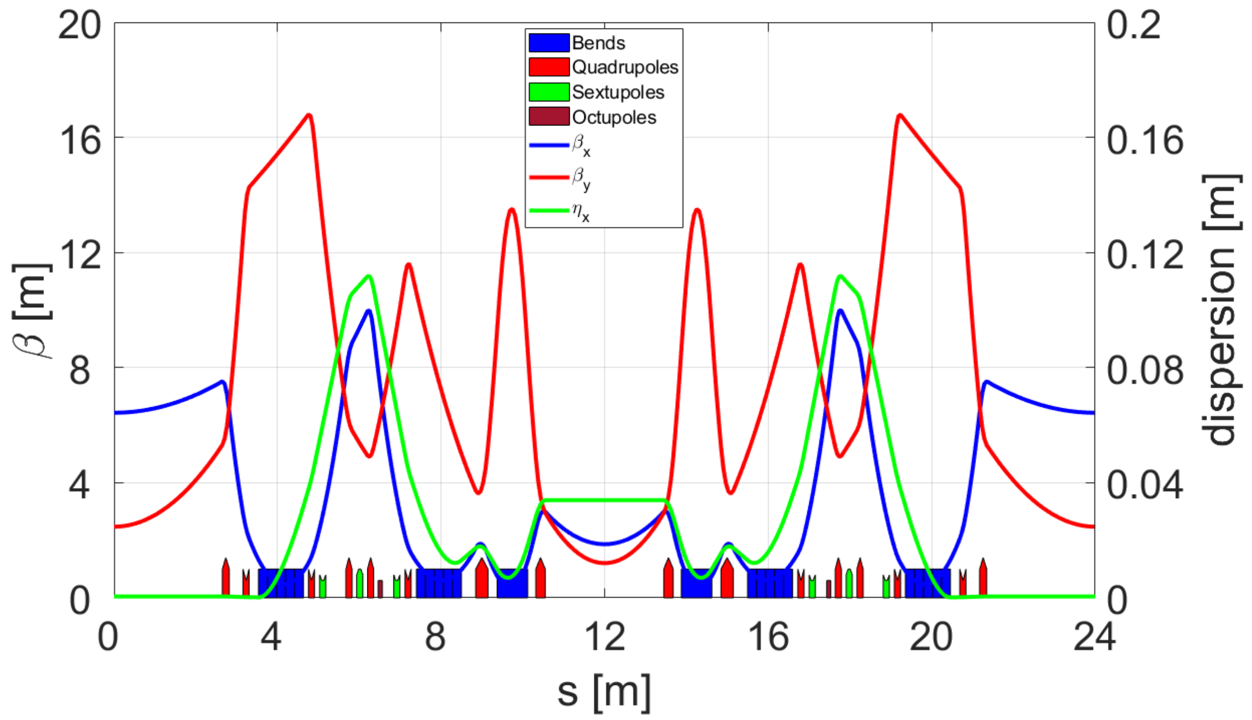


Dipole field profiles of the 1st, 2nd and 3rd LGBs

Comparison with Diamond-II type H6BA

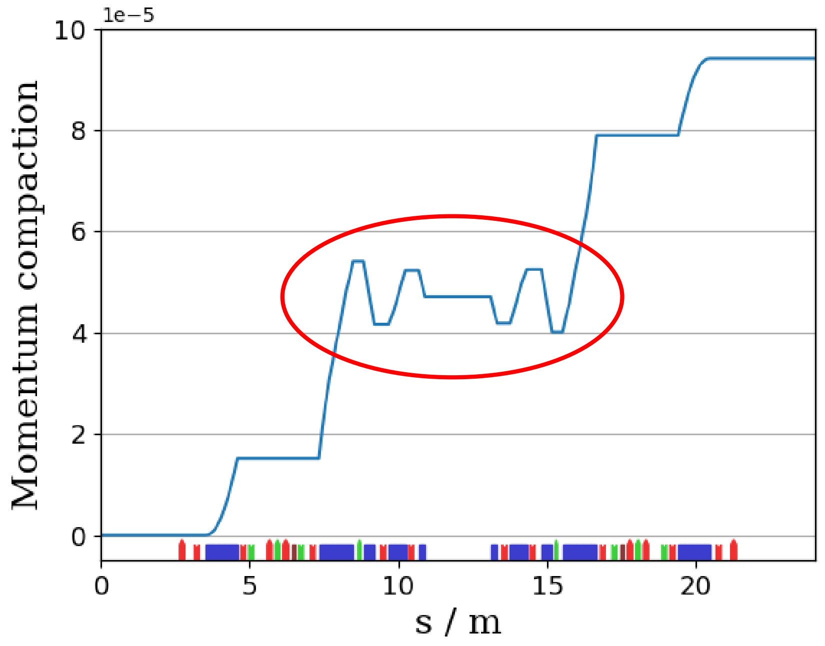
➢ A Diamond-II type modified H6BA lattice was also designed for HALF:

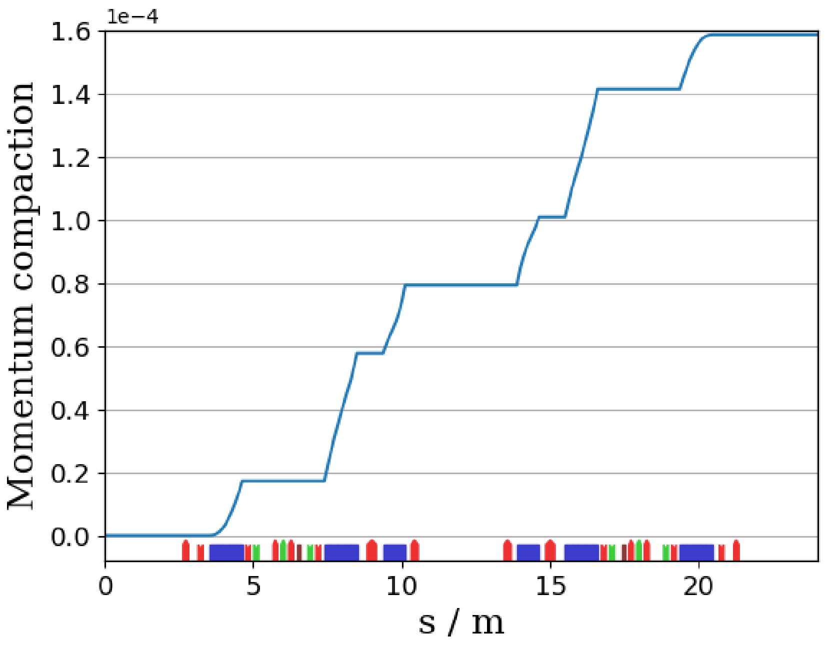
- The same circumference: 479.86 m, and the same number of cells: 20
- Larger natural emittance: 103.3 pm·rad, and longer natural damping times (H/V/L): 43.9/57.3/33.8 ms
- Larger momentum compaction: 1.59×10^{-4}, and longer short straight section: 2.9 m



Momentum compaction

- The central part of the HALF modified H6BA lattice has no contribution to the increase of momentum compaction
  - The central part reduces the emittance and damping times
  - The part on two sides increases the momentum compaction





The change of momentum compaction along one cell for HALF type H6BA lattice (left) and Diamond-II type H6BA lattice (right)

Comparison with other HMBA lattices

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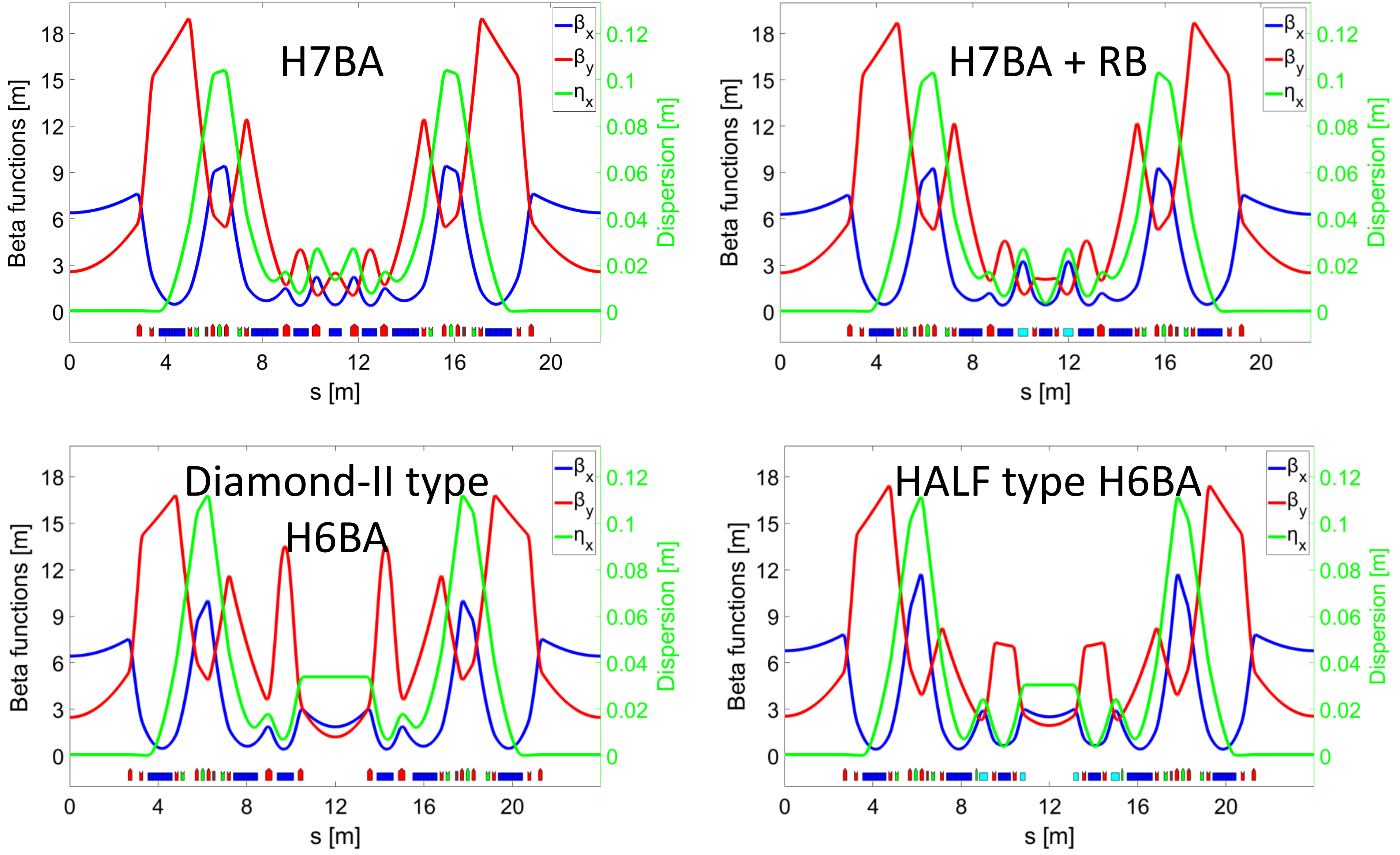


- In each lattice, there is no RB in the dispersion bump region.
- In the H7BA + RB, the middle bend uses LGB for bend radiation beam line.

Comparison with other HMBA lattices

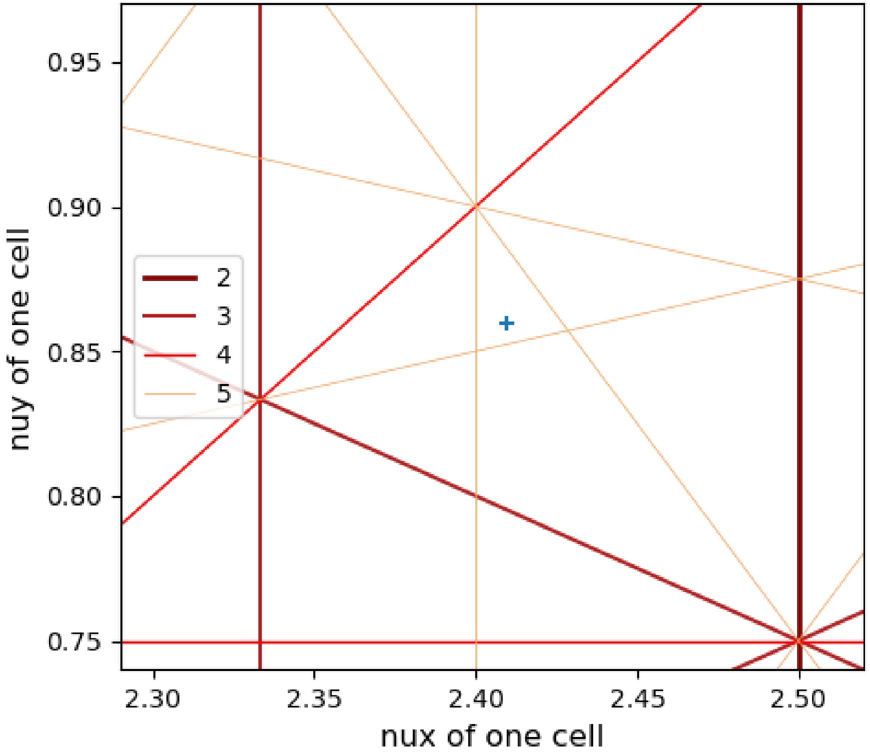
- Four HMBA lattices have the same energy and number of cells
- The HALF modified H6BA lattice has:
  - almost the same emittance as that of H7BA
  - relatively short damping times but also relatively small momentum compaction
  - more straight sections

Parameters	H7BA	H7BA + RB	Diamond-II type H6BA	HALF type H6BA
Circumference (m)	441.6	441.6	479.86	479.86
Natural emittance (pm·rad)	84.1	71.5	103.3	85.8
Momentum compaction factor	1.73×10^{-4}	1.31×10^{-4}	1.59×10^{-4}	0.94×10^{-4}
Natural damping times (H/V/L) (ms)	36.4/54.6/36.4	26.3/41.2/28.7	43.9/57.3/33.8	28.5/38.8/23.7
Straight sections: number and length	20×5.6 m	20×5.6 m	20×5.3 m + 20×2.9 m	20×5.3 m + 20×2.2 m

Linear lattice design for nonlinear dynamics

- Nonlinear dynamics cancellation (tune choice)
  - Cancellation within one cell: -I transformation between dispersion bumps
  - Cancellation over 5 cells: H/V tunes of one cell near (2.4, 0.9) to make HOA

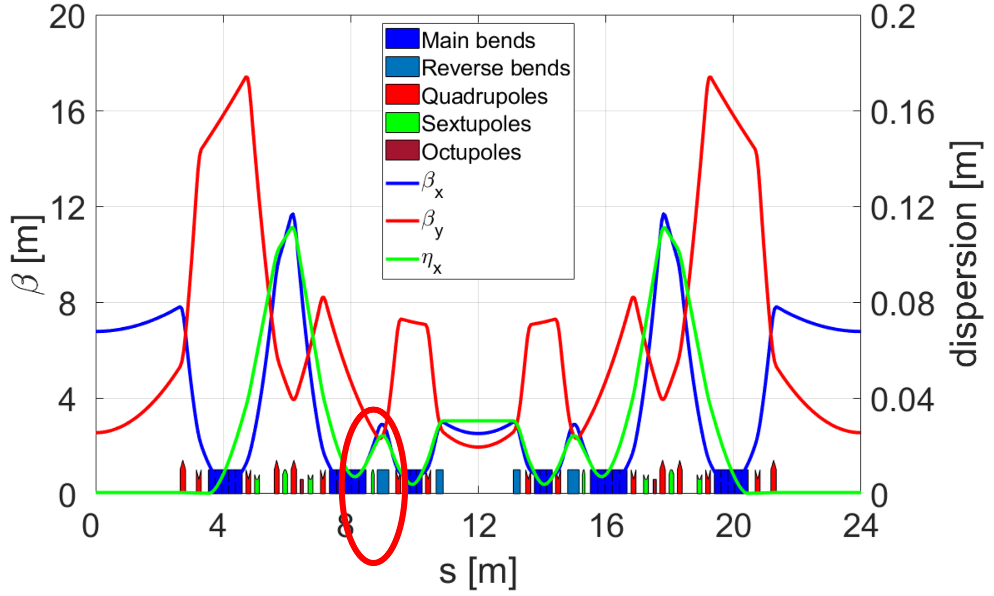
- Linear and nonlinear optimization
  - Using MOPSO algorithm
  - Variables: strengths and positions of bends, quadrupoles, sextupoles and octupoles, and lengths of bends
  - Objectives: emittance and tune shifts with amplitude
  - Tune shifts with momentum are controlled by limiting βx at mid-straight section (lower βx will generally give smaller tune shifts for HALF lattice)
  - No DA and MA particle tracking (fast optimization speed)



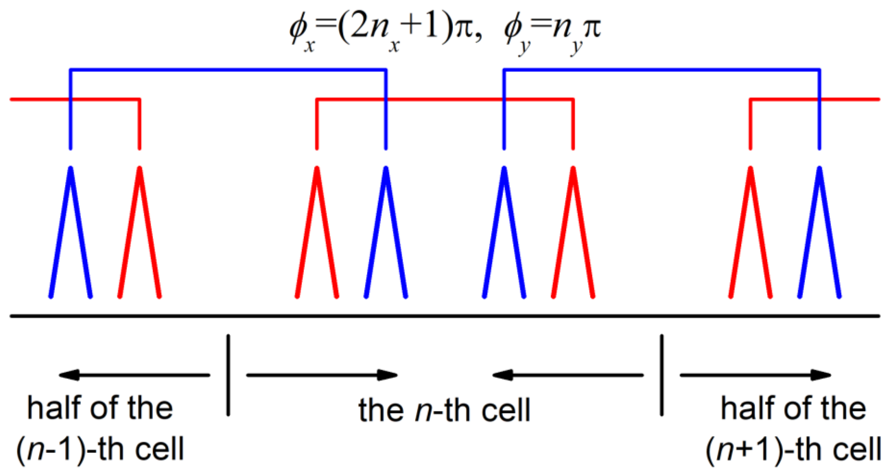
Betatron tunes of one cell

Adding thin sextupole SH1

- 4 families of sextupoles (including thin sextupole SH1) and 1 families of octupoles for nonlinear optimization



- Thin sextupole SH1
  - Located between LGB2/LGB5 and RB1
  - For better control of amplitude dependent tune shifts
  - Also as corrector
  - H/V phase advances between the 1st SH1 of the present cell and the 2nd SH1 of the previous cell: roughly near (1.5, 0.5)×2π [idea from IDB-MBA]



Schematic of MBA with interleaved dispersion bumps (IDB-MBA)

Dynamic aperture

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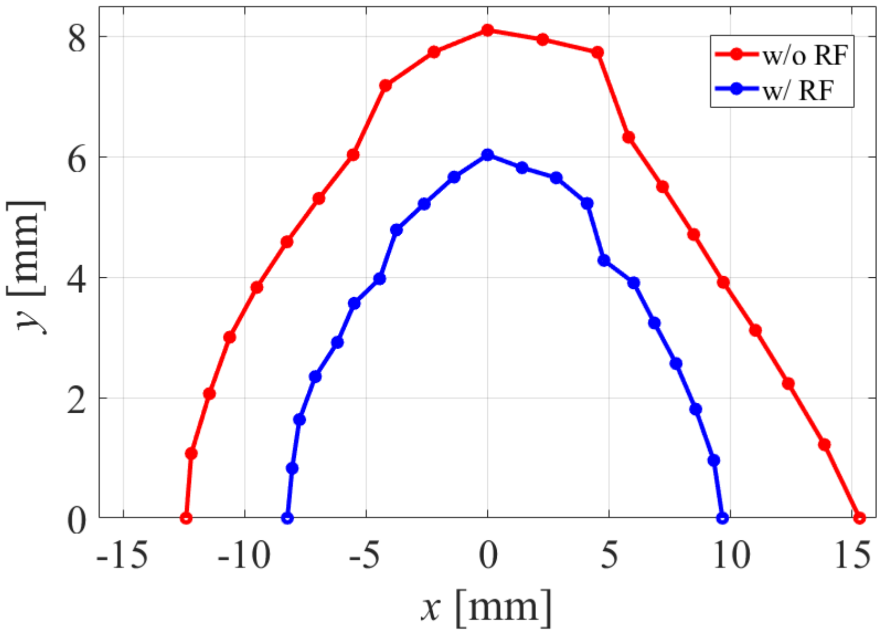
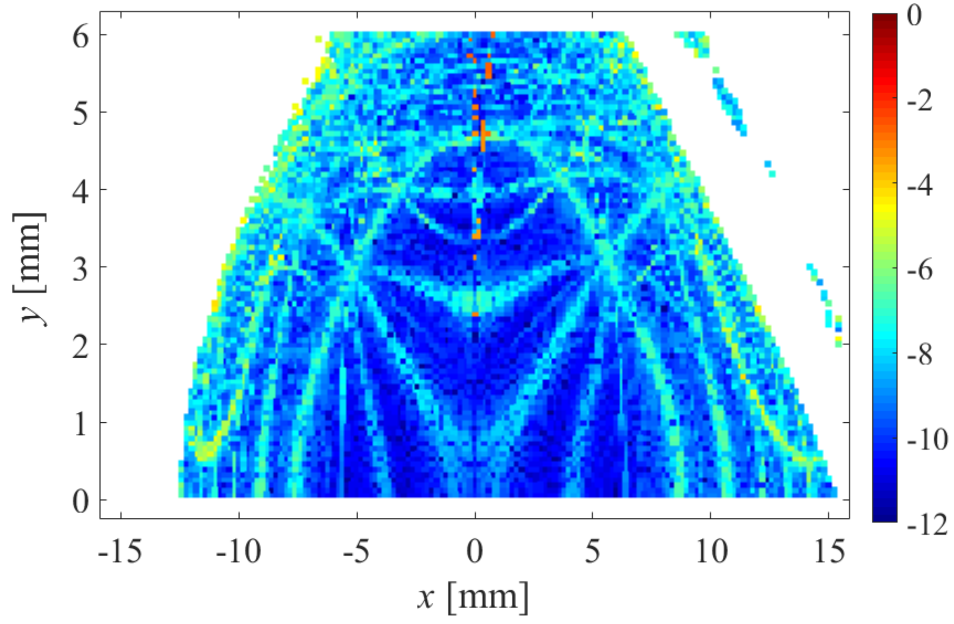
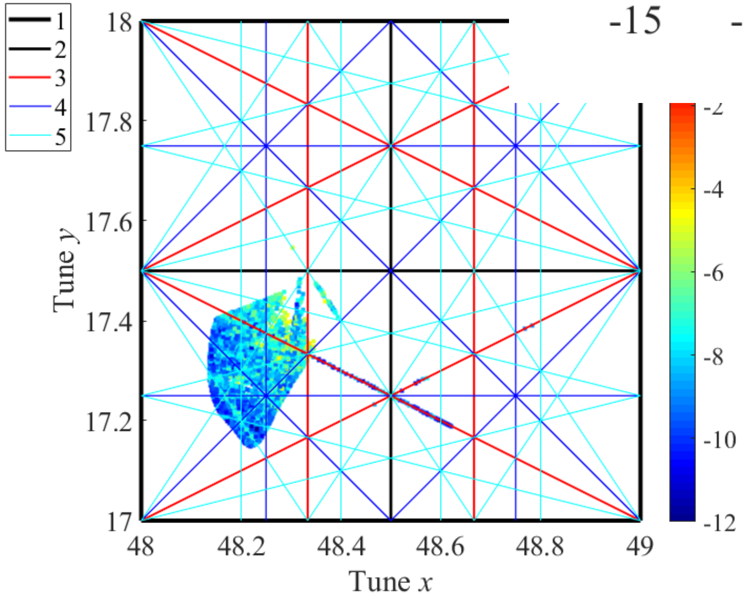
- H/V chromaticities: corrected to (3, 3)
- On-momentum DA
  - 4D DA: larger than 10 mm
  - DA with RF cavity: 9~10 mm (+ x direction)
  - Beam injected from + x direction

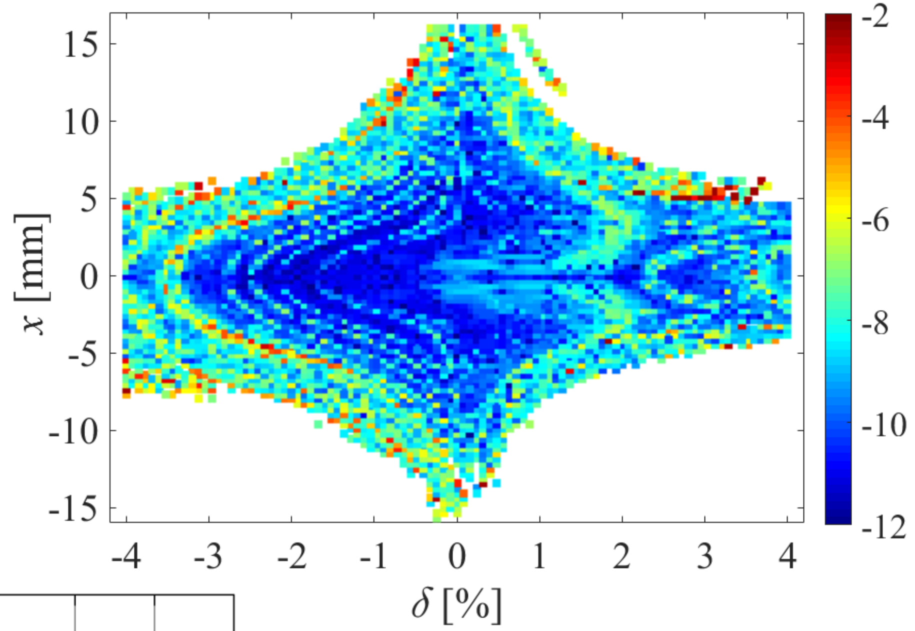




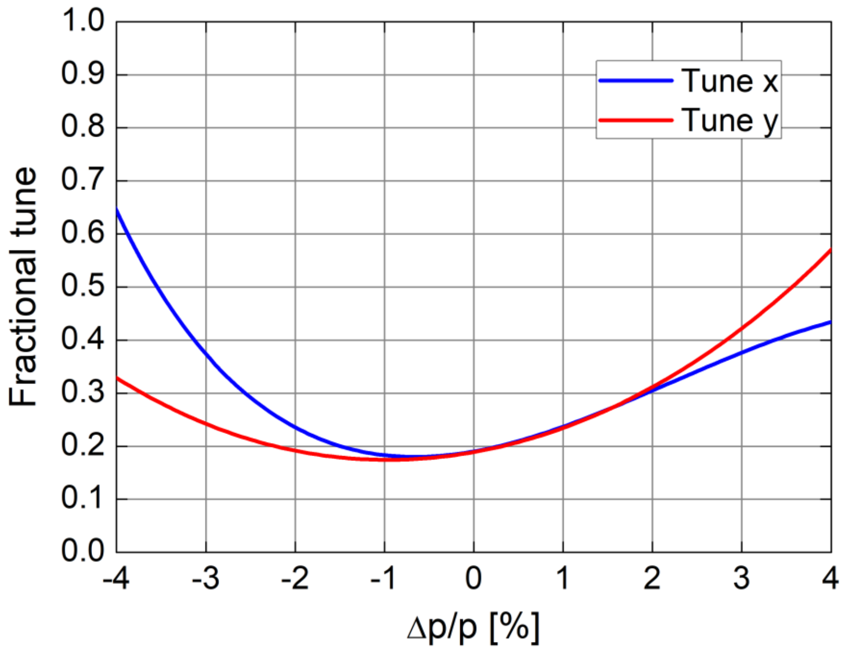


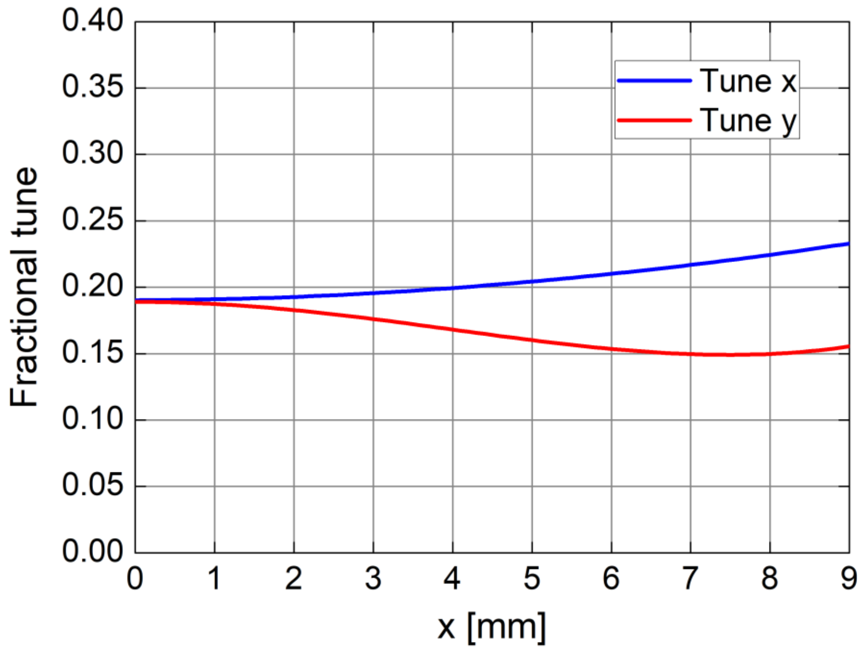
Tune shifts and off-momentum DAs

- Tune shifts with momentum:
  - Not cross half-integer lines for (-3.5%, 3.5%)
- Tune shifts with horizontal amplitude
  - Seperated tunes at large H amplitude
  - To avoid the coupling of large H motion to V plane for beam off-axis injected



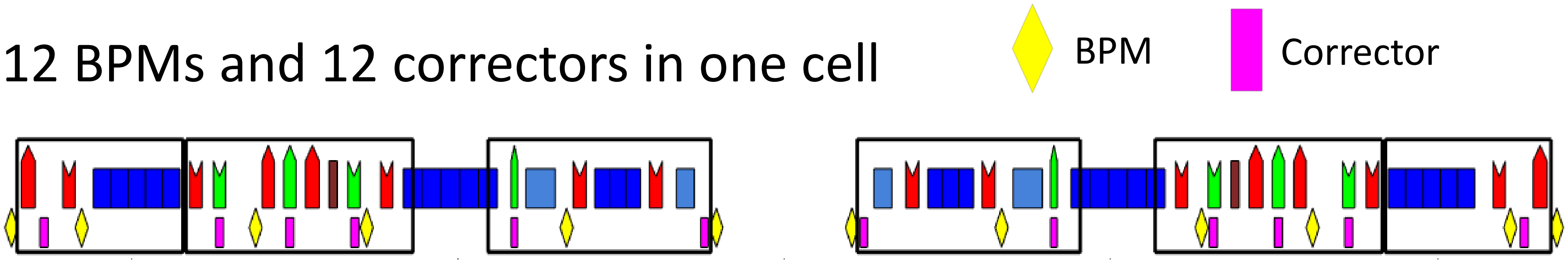
Horizontal DAs for (-4%, 4%)



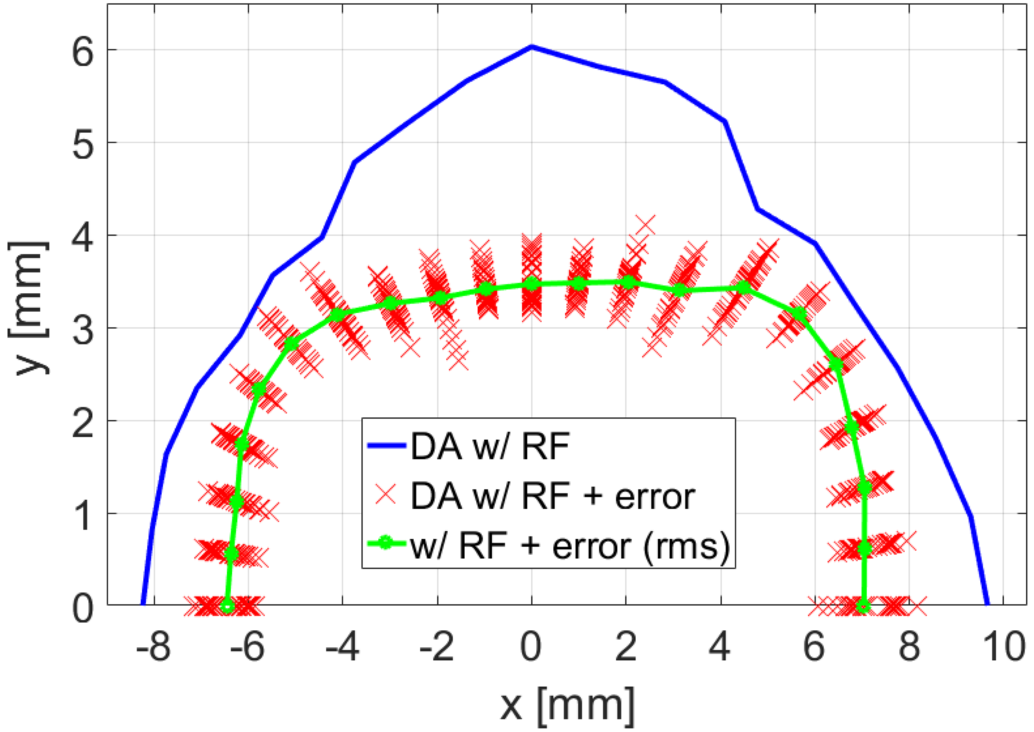


Error effect on DA

- 12 BPMs and 12 correctors in one cell

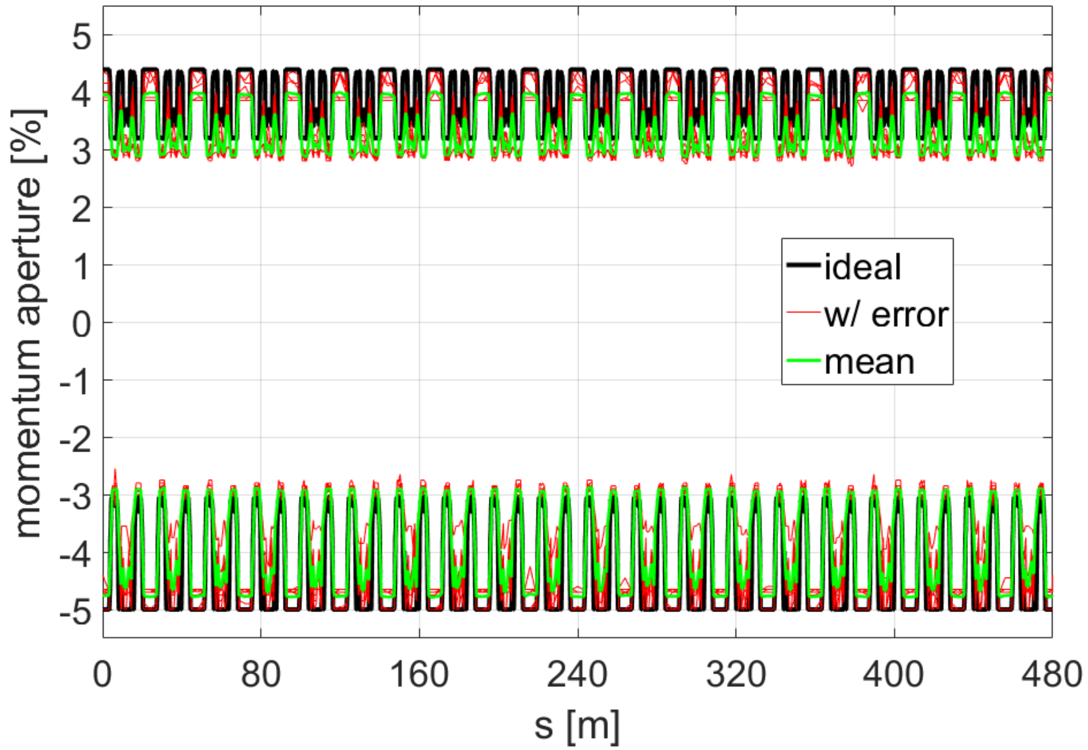


- DA with errors (RF cavity included)
  - Average DA: ~ 7 mm (+ x direction)
  - ID effect: being carefully considered
  - Allow for off-axis injection scheme



Touschek lifetime and IBS effect

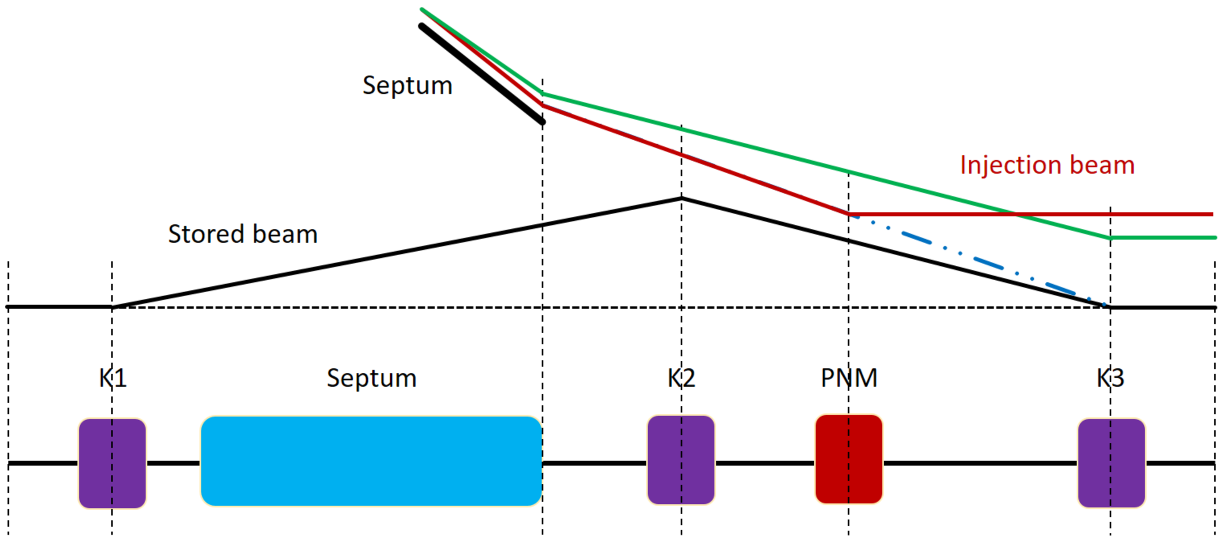
- Touschek lifetime calculated based on local MA
  - 1 nC (corresponding to 400 mA current, with 80% buckets uniformly filled), bunch lengthened by a factor of 3 with harmonic cavity
  - Touschek lifetime: >5 hours for 10% coupling, >10 hours for full-coupling beam
  - Particle loss at momentum deviation of ~4.4% in 6D tracking

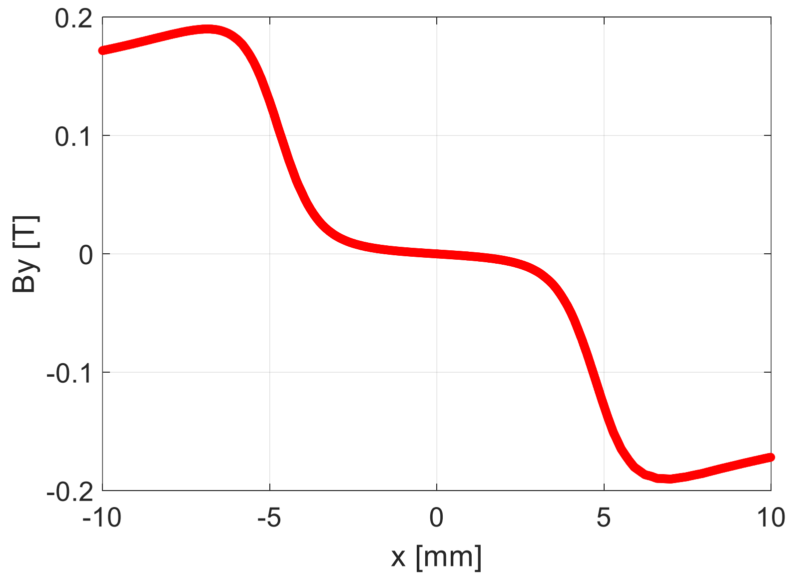


- Intra-beam scattering (IBS) effect
  - 1 nC, bunch lengthened by a factor of 3, full-coupling beam
  - IBS emittance (bare lattice): ~90 pm·rad (very serious)
  - IBS emittance with two damping wigglers and IDs: 60~70 pm·rad

Injection complex

- Injector: full-energy linac
- Injection schemes: being discussed
  - On-axis injection scheme (Septum + K3): for early commissioning
  - 3-kicker bump with anti-septum scheme (Septum + K1, K2, K3): for commissioning and operation in the first stage, required DA > 4 mm
  - Pulsed nonlinear magnet (PNM) injection scheme (Septum + PNM) transparent injection for the next stage, required DA > 5 mm

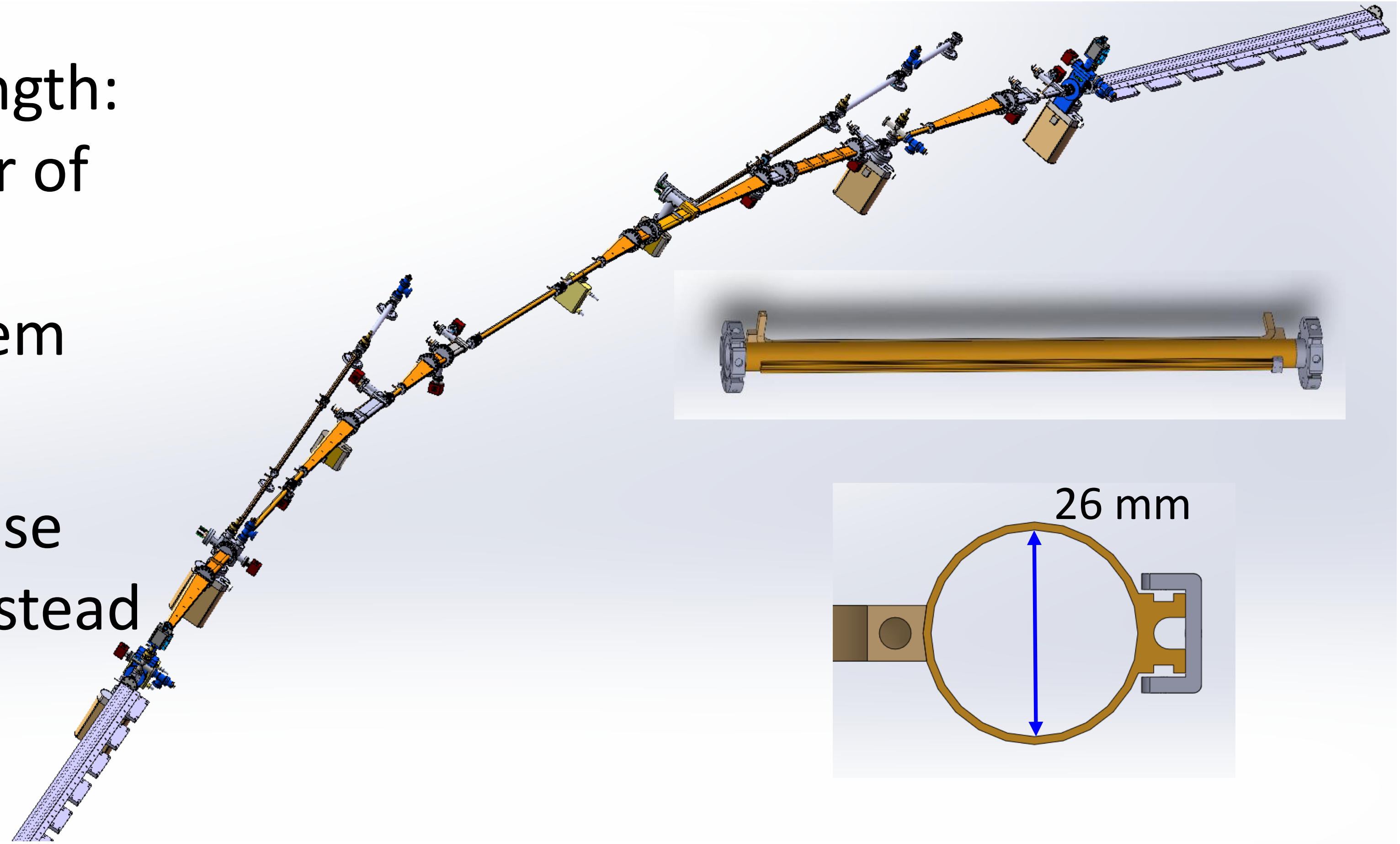


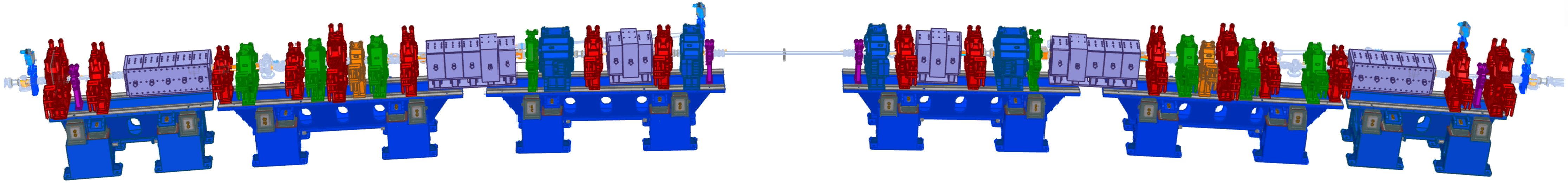


Field strength of PNM

Magnet and Vacuum

- Maximum quadrupole strength: ~50 T/m, and inner diameter of vacuum chamber: 26 mm
  - Preliminary vacuum system was designed
- Recent decision: LGBs will use electromagnetic magnets instead of the previous permanent magnets





Conclusion

- HALF is a soft X-ray and VUV diffraction limited storage ring to be built in Hefei.
- The HALF storage ring lattice uses a modified H6BA lattice, combining HMBA lattice and LGB/RB unit, which also has two straight sections in each cell as in the Diamond-II lattice.
- The HALF storage ring adopts off-axis injection scheme with a full-energy linac as the injector.
- Further lattice design and optimization is on-going, and all accelerator systems are advancing steadily.

Many thanks to Dieter Einfeld and Ryutaro Nagaoka for discussing the HALF lattice during they visited NSRL at the end of 2019 (before COVID19)!

Many thanks to all colleagues of HALF team!

Thank you for your attention!