Lattice design towards 1 pm emittance

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I.FAST Low Emittance Rings Workshop 2025
Hamburg Germany
9 October 2025

Outline

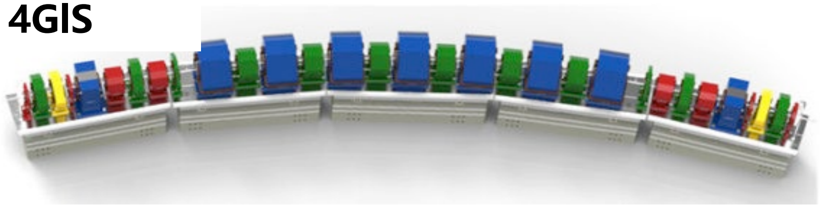
- Emittance of the fourth generation light source
- Brightness and coherence of the pm-level latttice design
- Approach for achieving 1 pm-level emittance
- New lattice concept
  - Linear optics design
  - Nonlinear optimization
  - Combined HOA and -*I* cancellation
- Challenges
- Summary

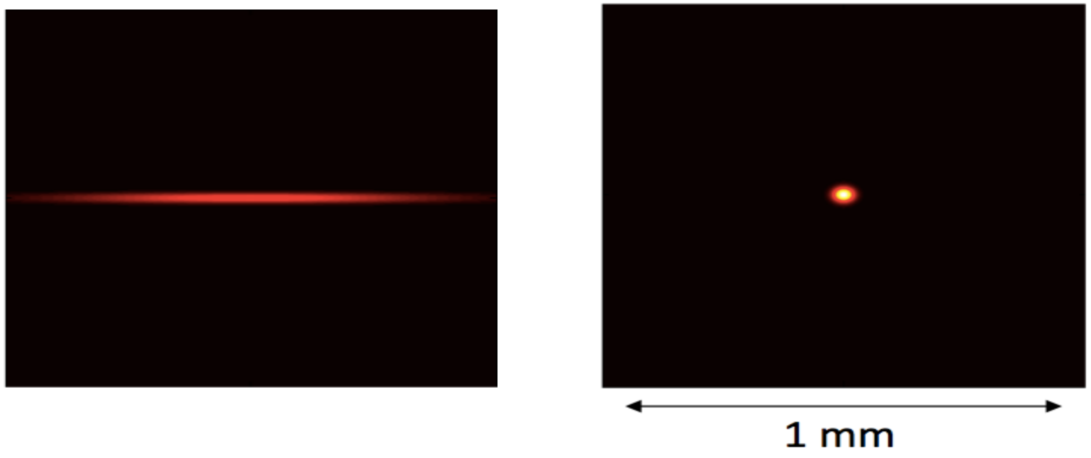
The fourth generation light source(4GLS)

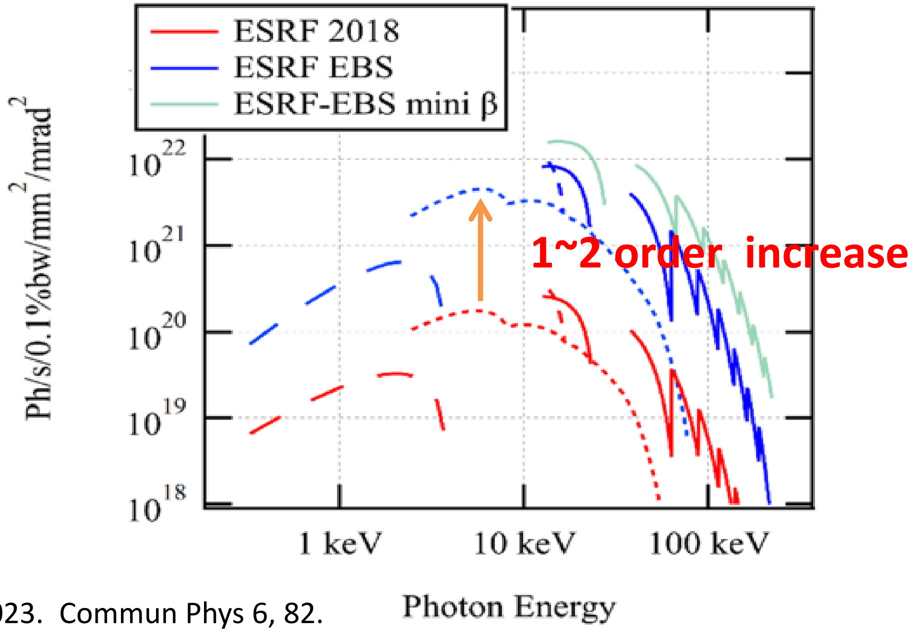
3GLS

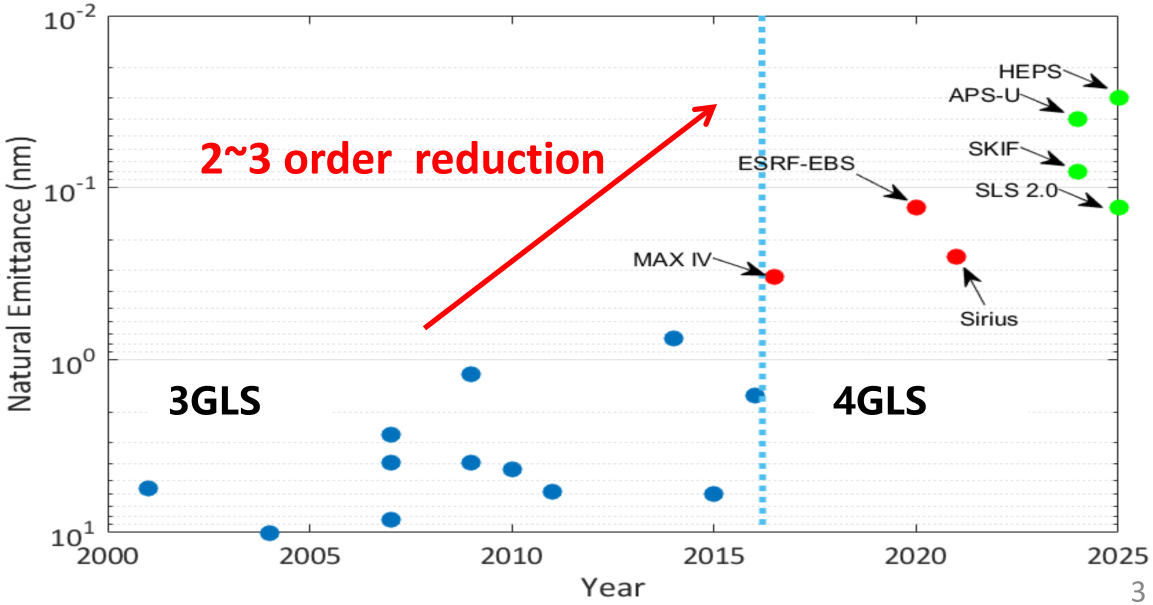
compact MBA lattice

4GlS









Raimondi, P., 2023. Commun Phys 6, 82.

4GLSs Wordwide

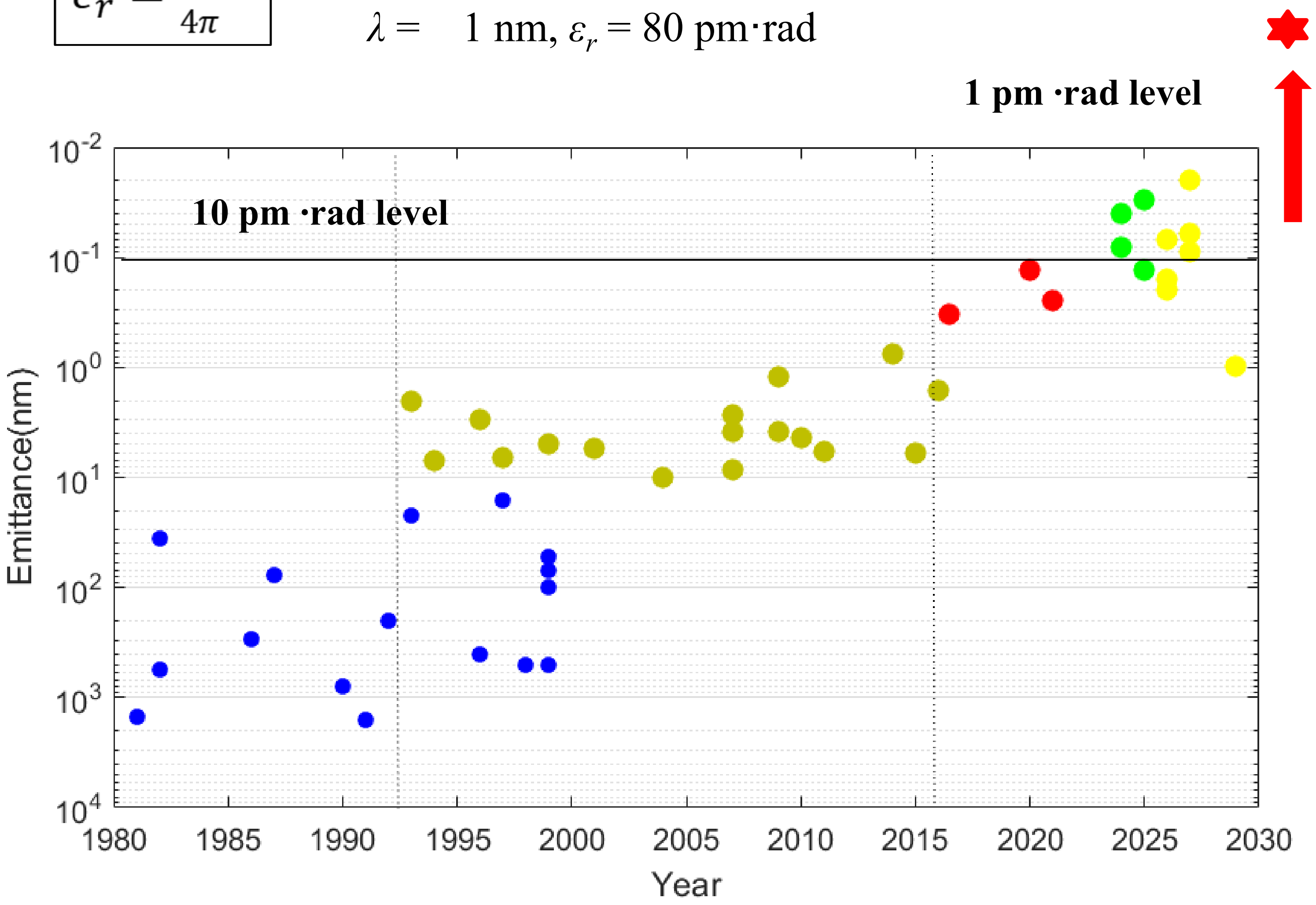
Hard X-ray diffraction-limited emittance?

$$\epsilon_r = \frac{\lambda}{4\pi}$$

$\lambda = 0.1$ nm, $\varepsilon_r = 8$ pm·rad

$\lambda = 1$ nm, $\varepsilon_r = 80$ pm·rad

diffradtion-limited emittance for hard X ray not reached!



Two important figures of merit for the storage ring:

Brightness: $$B \sim \frac{F(\omega)}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'} (\Delta\omega/\omega)}$$

Coherence: $$\zeta = \frac{(\lambda/4\pi)^2}{\Sigma_x \Sigma_{x'} \Sigma_y \Sigma_{y'}} \, .$$

$$\Sigma_{x,y}^2 \equiv \sigma_{x,y}^2 + \sigma_r^2 \, , \quad \Sigma_{x',y'}^2 \equiv \sigma_{x',y'}^2 + \sigma_{r'}^2 \, .$$

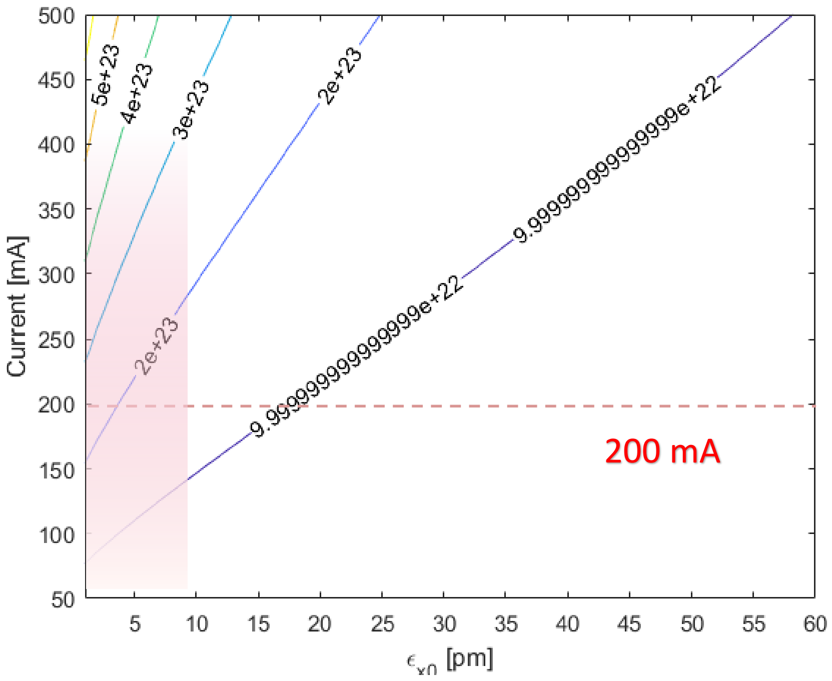
Emittance、Brightness and Coherence

- **Brightness Gains** : significant numerical gain
- **Coherence Gains**:

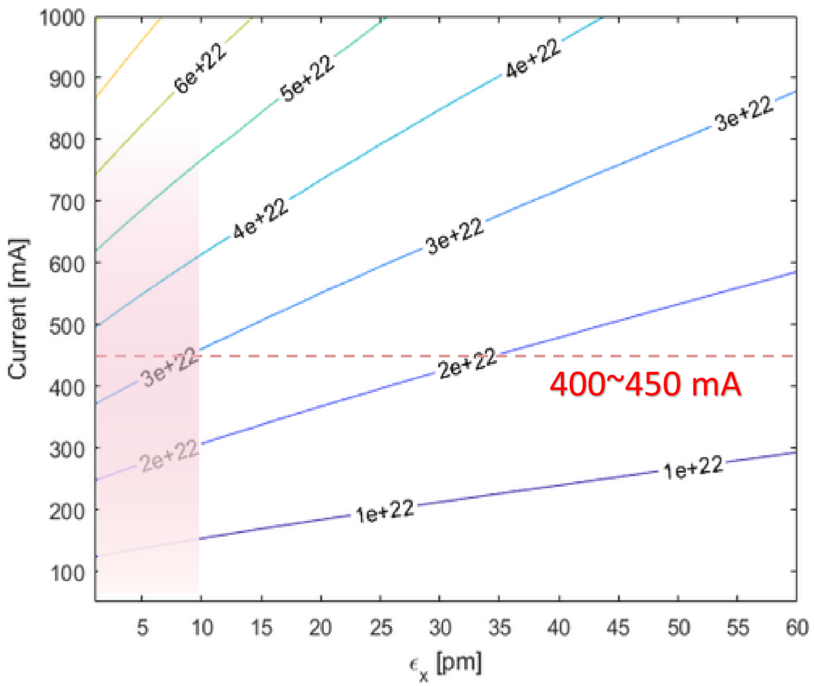
Further reduction of emittance to ~1 pm is required!

soft X-ray: a nearly order-of-magnitude increase

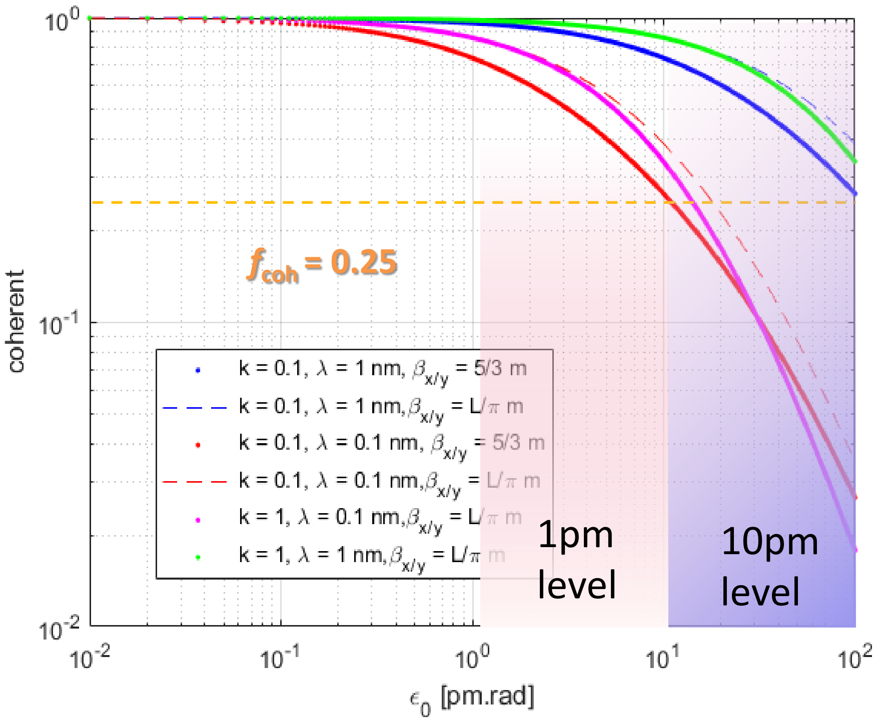
Hard X-ray: several-fold increase in coherence (~1)



E=6 GeV(@20 keV)



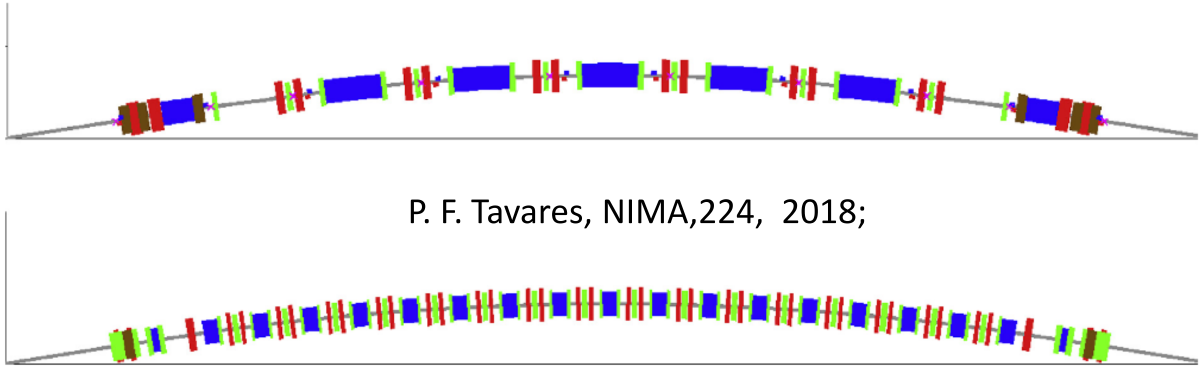
E=3.5 GeV@ 4 keV



- **Settings**: undulator length = 5 m, β function at LSS is 5 m and 3 m , energy spread is 1.1×10^{-3}

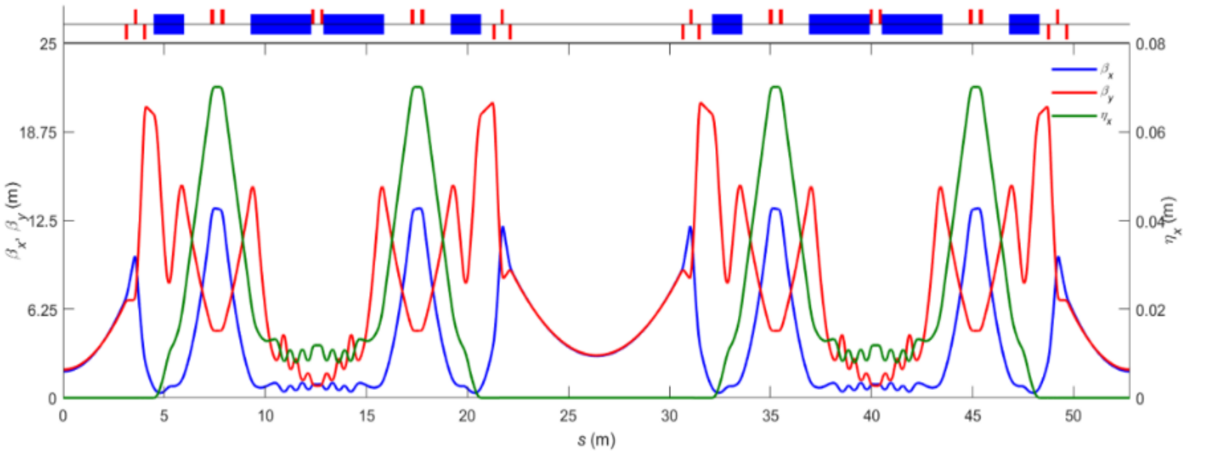
Approaches for achieving 1 pm-level emittance

- further increase the number of dipoles (the most effective solution) $\varepsilon_x = F(lattice)\frac{E^2}{J_x N_d^3}$



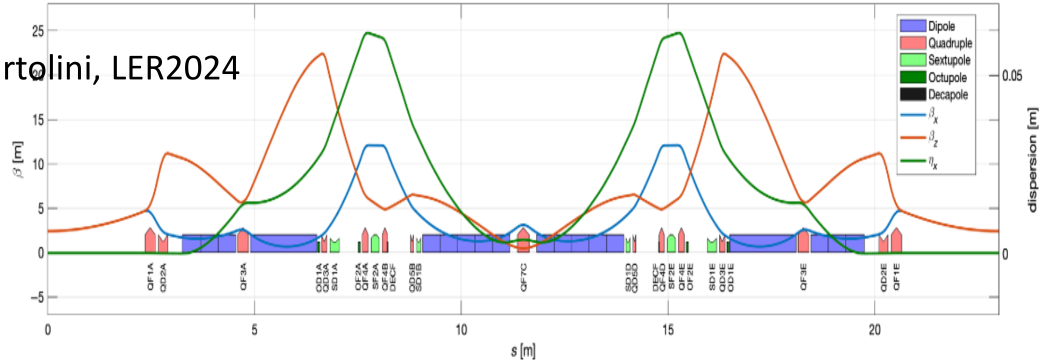
P. F. Tavares, NIMA,224, 2018;

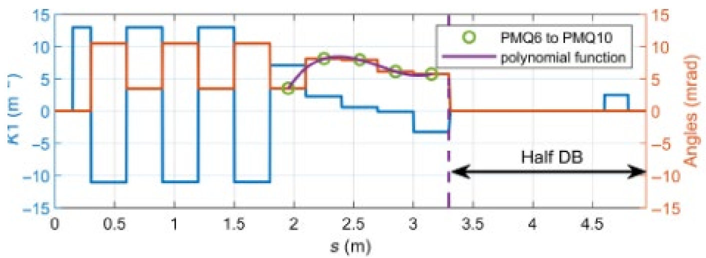
MAX-IV: 528m, 7BA-> 19 BA, 250 pm -> 16 pm

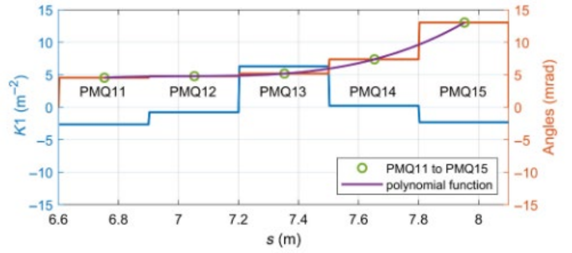


M.H. Song and T. shaftan, PRAB 27, 2024;

R. Bartolini, LER2024





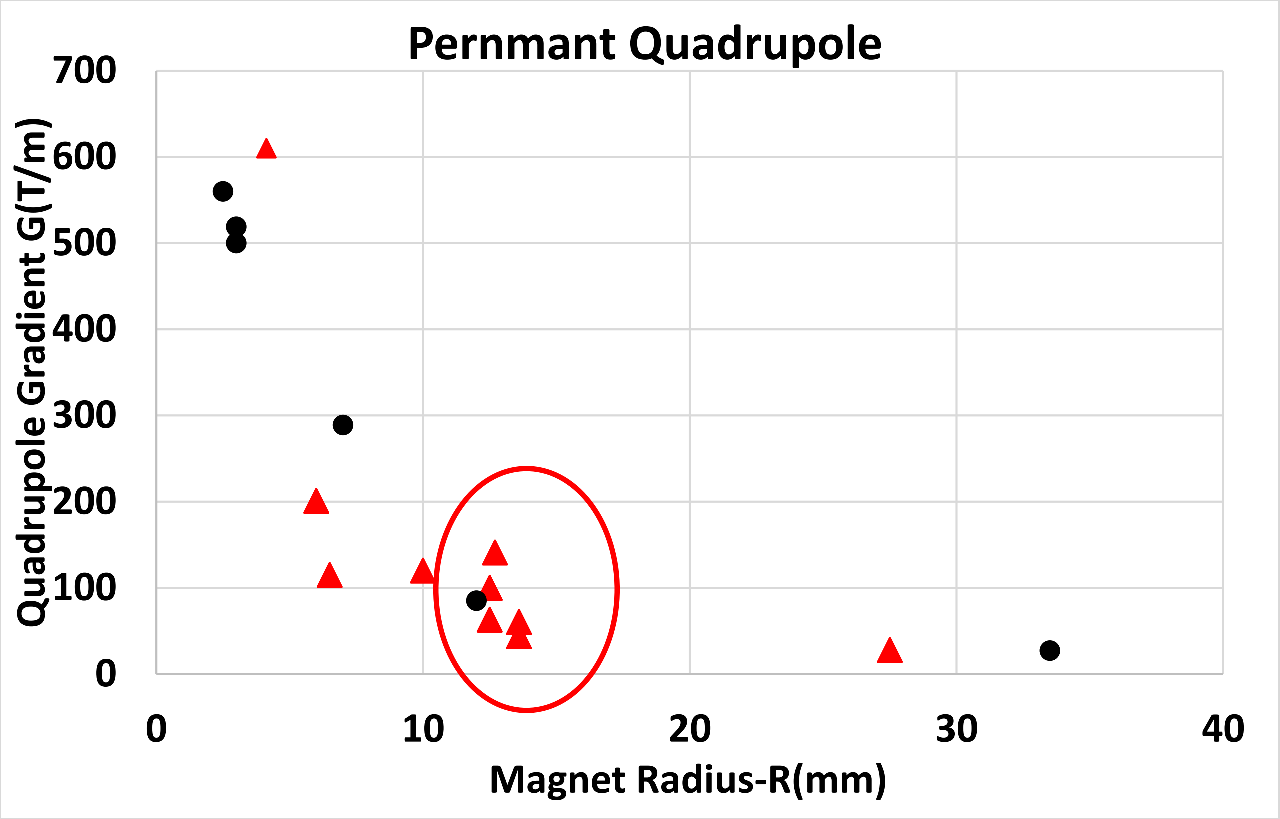


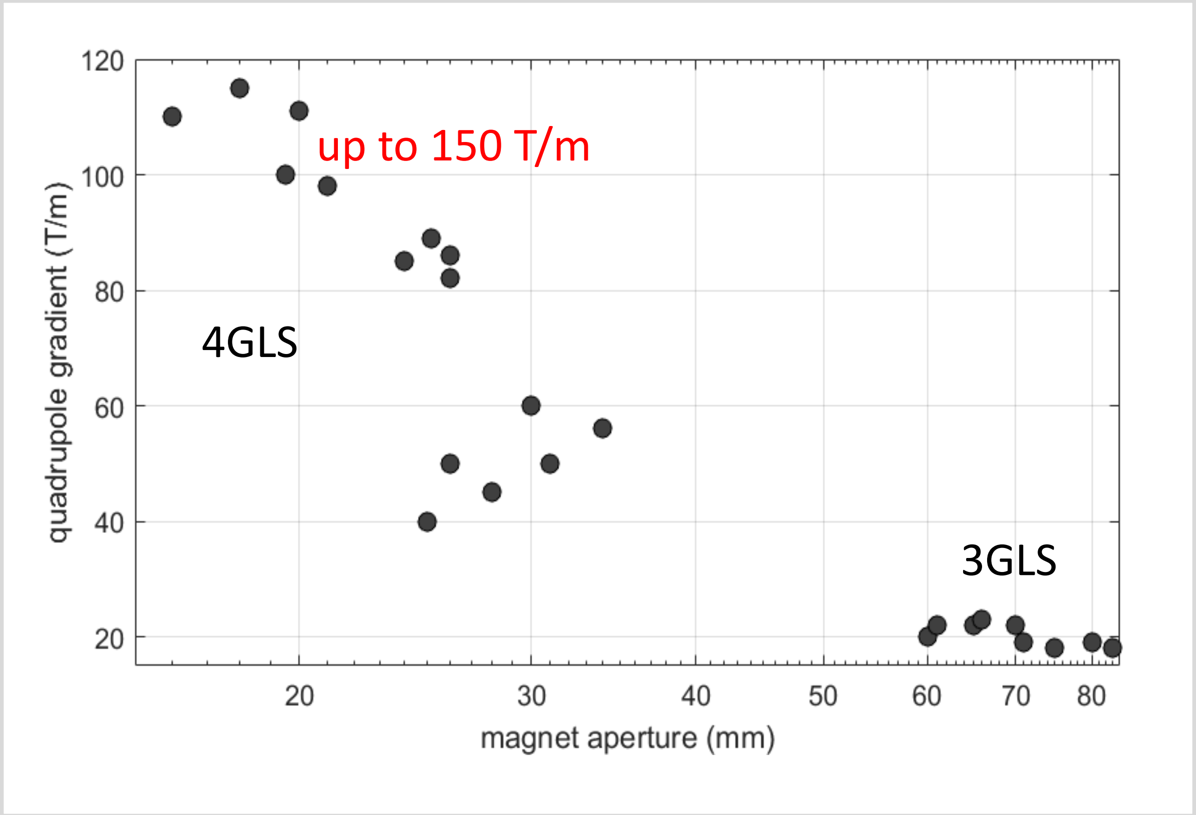
NSLS-II-U: complex bend, 792m, 3GeV, 20 pm

PETRA-IV: H-6BA+damping wiggler, 42 pm -> 20 pm

Approaches for achieving 1 pm-level emittance

- further increase the number of bends
- stronger focusing— higer gradient quadrupole





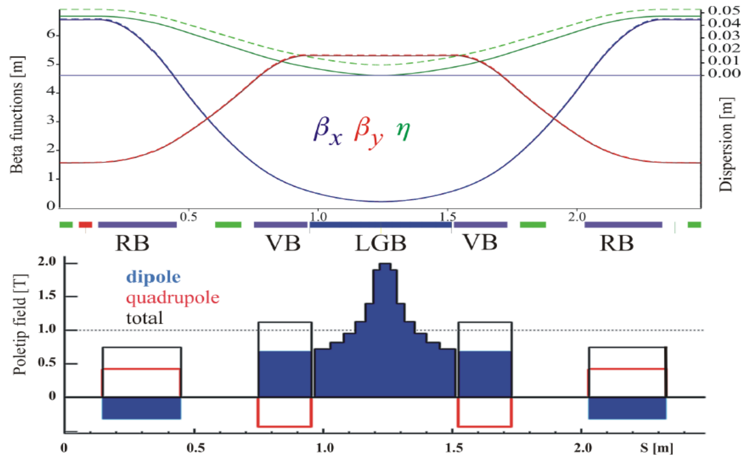
Hard-edge model is considered in this presentation!

Approaches for achieving 1 pm-level emittance

- further increase the number of di

$$\epsilon_x = C_q \frac{\gamma^2}{J_x} \frac{\oint \mathcal{H}(s)\, h(s)^3 ds}{\oint h(s)^2 ds}$$

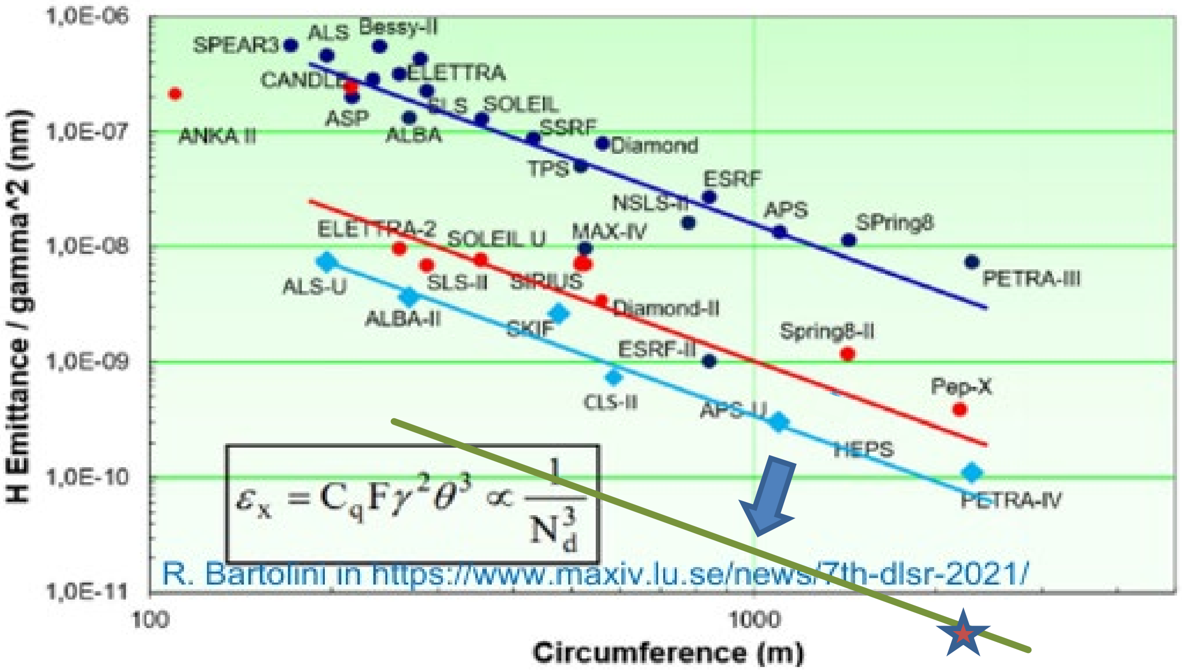
- strong focusing
- combined function dipoles(LGB/RB etc.)
- mitigate collective effects with adequate beam current
- long LSS for IDs
- reasonable circumference



scale HEPS lattice to about 1 pm level (eg. 3~4 pm), the circumference will increase to about 2000 m；

however, increased impedence will influence the current threshold, finally influence brightness

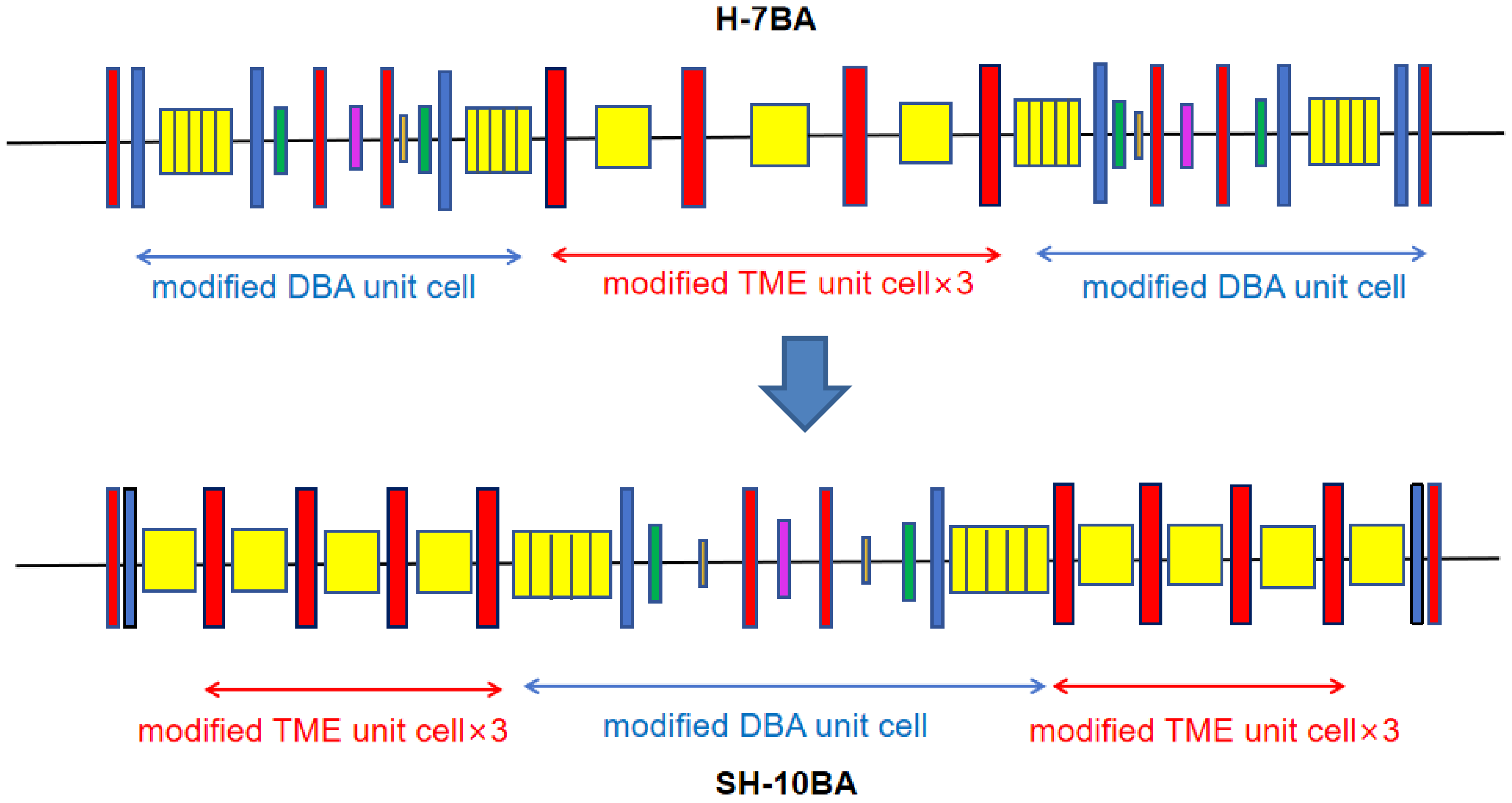
Realize 1 pm emittance through a compact reasonably-sized design.



A new compact reasonably-sized lattice concept

- Remove one dispersion bump in the hybrid MBA to free up space for additional bending magnets (named single hybrid MBA lattice, **SH-MBA**)

taking HEPS lattice as an example, from H-7BA to SH-10BA, E = 6 GeV, C = 1360.4 m, 34 pm-> 15 pm



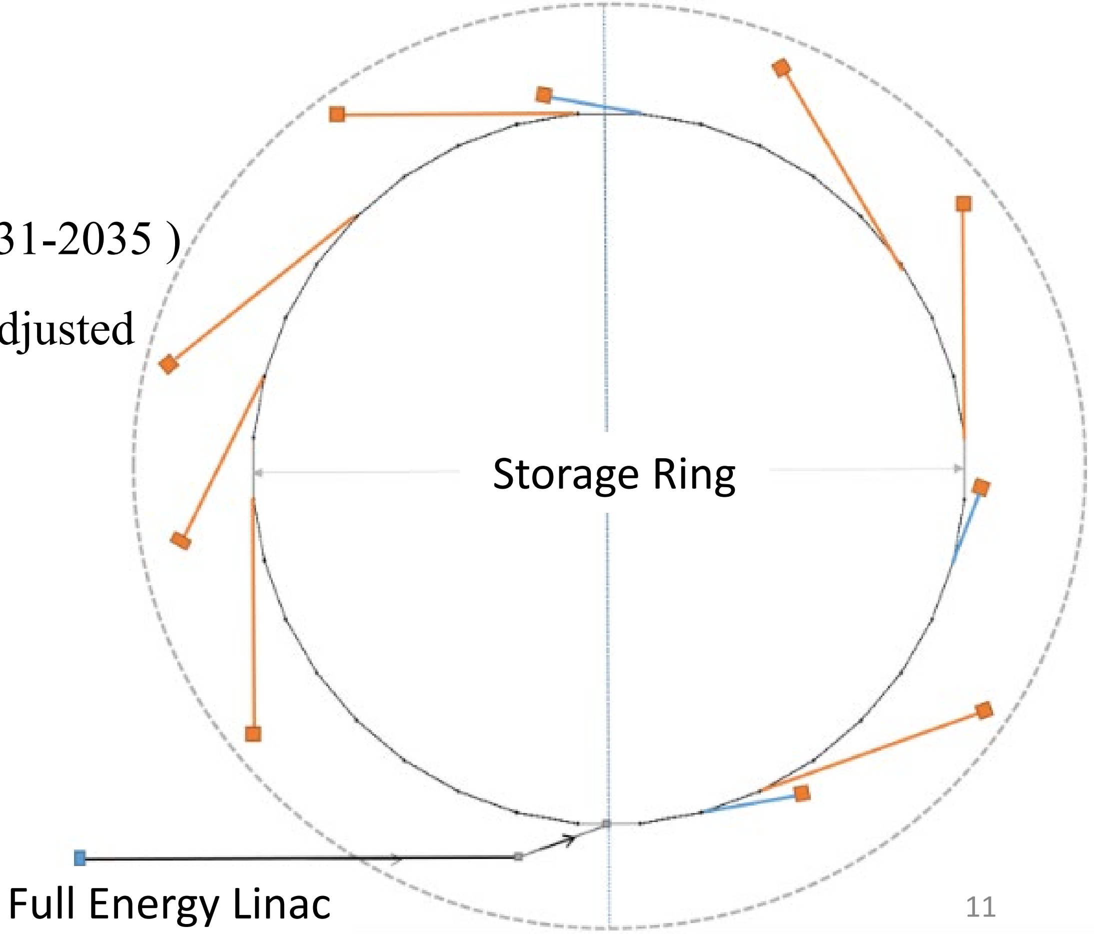
Based on SAPS parameter, to achieve 1 pm emittance

- Medium- and low-energy rings face greater IBS challenges, limiting emittance reduction.
- The 1 pm design will be based on a medium-energy source.

■ Southern Advanced Photon Source (SAPS)：

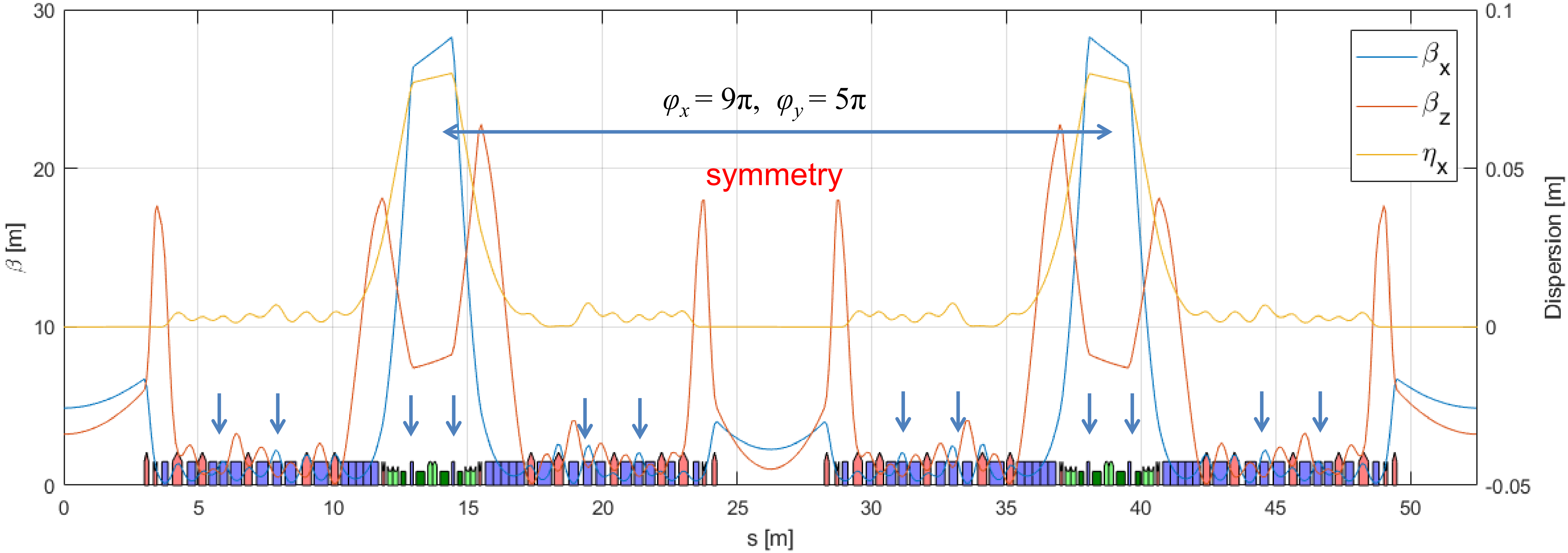
- planned to built adjacent to CSNS in GuangDong, China
- plan to apply for the "16th Five-Year Plan" of the country(2031-2035)
- before receiving the funding, the design can still be further adjusted and optimized.

Main parameters	Unit	Value
Beam energy	GeV	3.5
Natural emittance	pm·rad	≤ 60
Brightness	phs/s/mm^2/mrad^2/0.1%BW	> 10^{22}
Beam current	mA	≥ 400
Circumference	m	<1000



Linear optics design

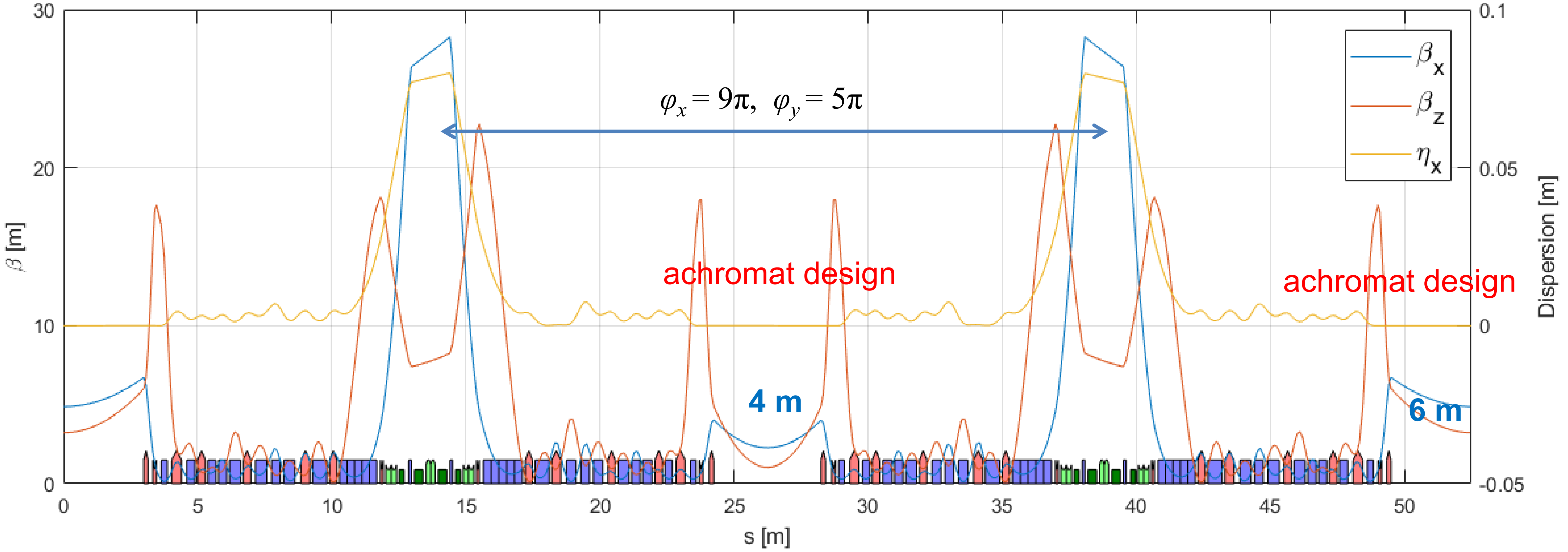
➢ SH-16BA, ~150 T/m (magnet diameter = 22 mm), 36 periods, 945 m



- 6 reverse-bends are added in each SH-16BA
- phase advance between the sextupoles adjacent two dispersion bumps are configured for *-I* cancellation.
- two standard periods are merged to form a single superperiod.

Linear optics design

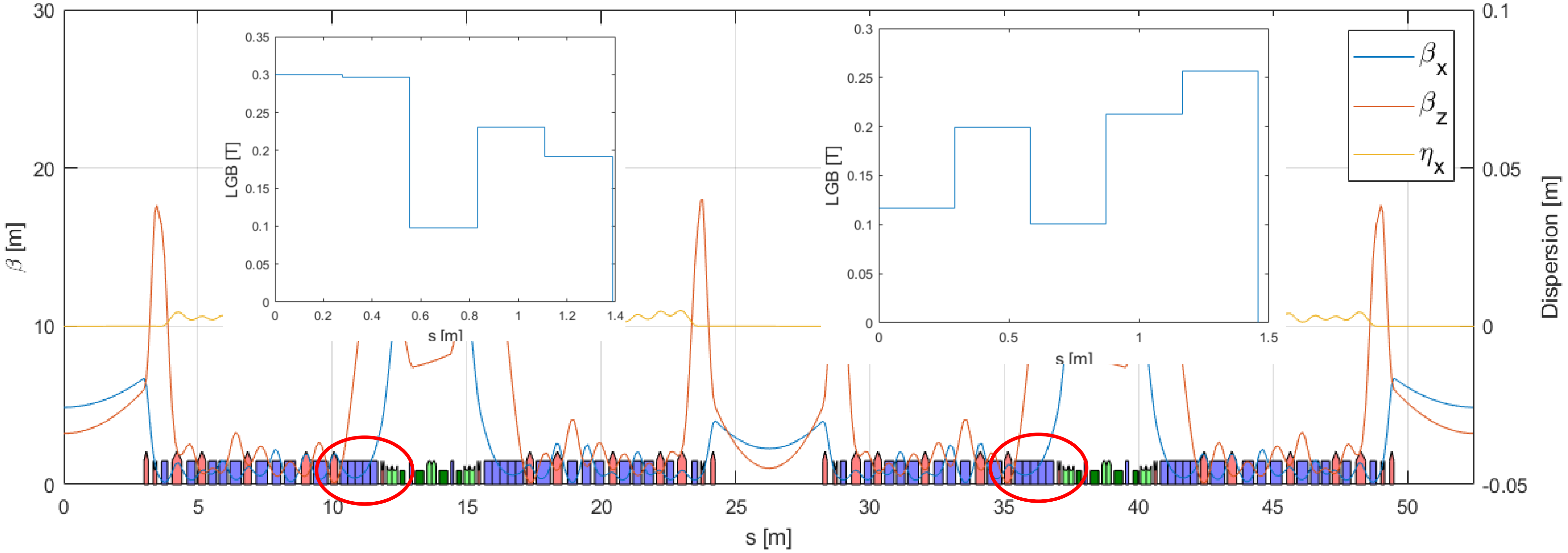
- SH-16BA, ~150 T/m (magnet diameter = 22 mm), 36 periods, 945 m



- phase advance between sextupoles and periods can not be the same.
- the superperiod incorporates two long straights of different lengths (6 m & 4 m).

Linear optics design

➢ SH-16BA, ~150 T/m (magnet diameter = 22 mm), 36 periods, 945 m



- longitudinal gradient bend with horzontally defocusing gradient (B/G~ 22 mm)
- the segments of LGB are different from the typical LGB, which to further increase the height of the dispersion bump

M. Gehlot, IPAC23, WEPM100

Bare lattice parameters

Parameters	Value	Unit
Energy	3.5	GeV
Circumference	945	m
Natural emittance	5.568	pm·rad
Damping partitions	2.52/1/0.48	
Ring tunes	165.383 /94.365	
Natural chromatities	-279.51/-343.1	
Momentum compaction factor(α_c)	1.53×10^{-5}	
Energy spread	1.1×10^{-3}	
Energy loss per turn	0.4	MeV
Damping time（$x/y/z$）	21.8/55/115.4	ms
LSS length	6/4	m
β_x and β_y at LSS center	4.88/3.23　2.28/1	m

lower α_c is more sensitive to collective effect

daming wiggler are required to further reduce emittance and damping time

Mitigation of intra-beam scattering effect

- Beam emittance blow-up due to the medium energy and low natural emittance
  - Considering the RF frequency is 166.6 MHz, and 90% filling mode, with the beam current of 100 mA (0.67 nC per bunch)
  - round-beam mode, coupling = 1
  - bunch length is strectched with the ideal condition(4.4 mm -> 26.4 mm)
  - IBS emittance is **6.482/6.482** pm·rad
  - energy spread increases to 1.4×10^{-3}

  - if beam current is 200 mA, 1.33 nC per bunch
  - with the same condition, the ibs emittance will blow up to **8/8** pm·rad
  - energy spread increases to 1.52×10^{-3}

  - with damping wiggler, final emittance could be smaller

Nonlinear optics

- MOPSO and MOGA are used to optimize nonlinear acceptance
- super-period: 4 sextupoles and 4 octupoles are free variables
- two sextupoles are used to correct chromaticity to postive

- While dispersion bumps help reduce sextupole strength, their effectiveness diminishes at pm-level emittances.
- At such low emittances, the required sextupole strength still exceeds practical limits.
- Simply increasing sextupole length is not feasible, as it would result in them being longer than the quadrupoles.

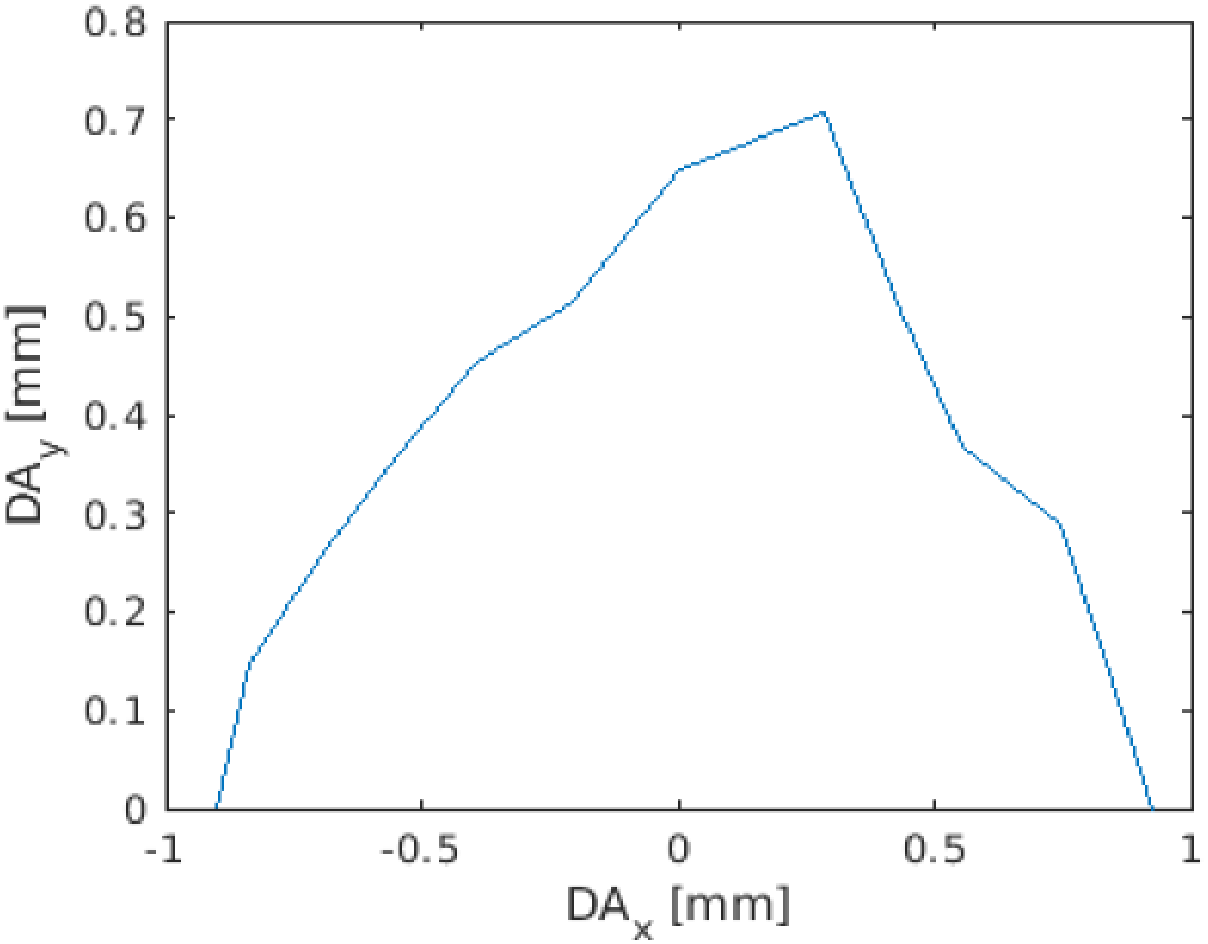
Nonlinear Driving Terms: 3 Orders of Magnitude Above Standard 4G Sources

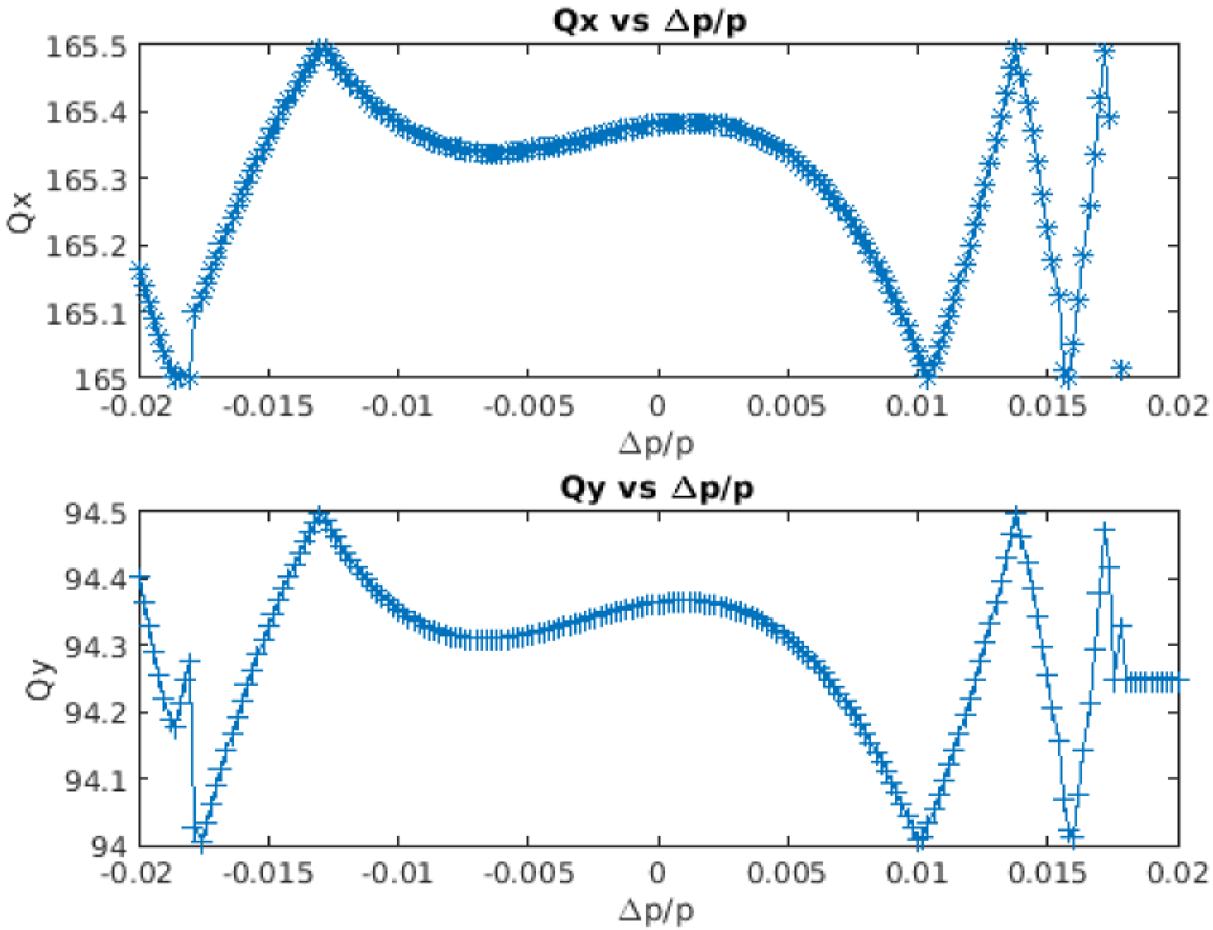
- compared with SAPS lattice (bare lattice emittance is 26.3 pm·rad), nonlienar driving terms significantly increase

		SAPS lattice	1pm level lattice
ADTS	dnux/dJx	3.1393e+04	1.1242e+07
	dnux/dJy	-1.6187e+04	-1.1996e+06
	dnuy/dJy	5.5187e+03	-7.8822e+06
second order chromoaticy terms（bare lattice）	horizontal	251.7971	-6.6987e+04
	vertical	19.7496	-4.4198e+04
second order chromoaticy terms（with sextupoles and octupoles）	horizontal	0.9799	-1.6474e+03
	vertical	1.7449	-2.0751e+03

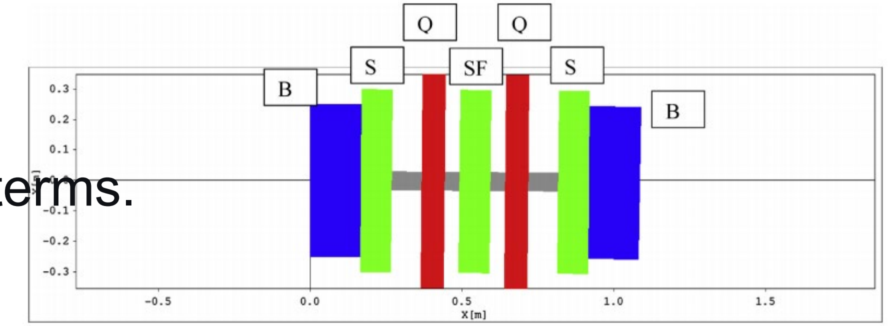
Dynamic aperture and momentum aperture

- DA is nearly 1 mm, and MA is so small, about 1% (w.o. errors)





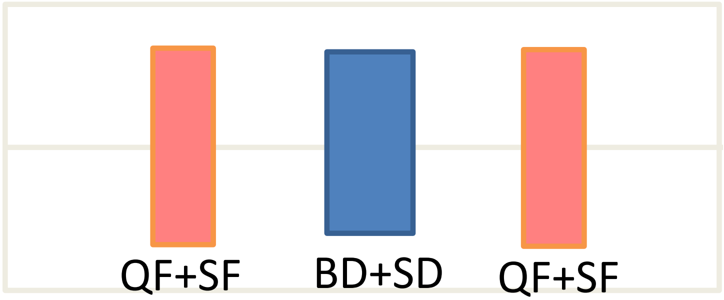
Nonlinear optics optimization (HOA and -*I* cancellation)



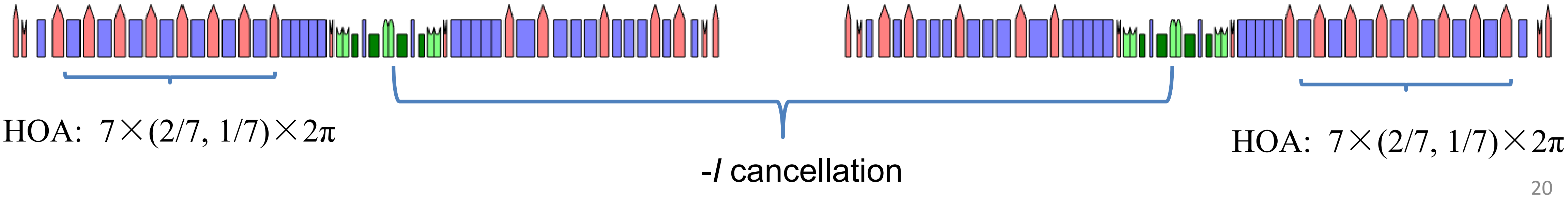
H-MBA with -*I* Cancellation

- **Pro**: Excellent cancellation of geometric resonance driving terms.
- **Con:** Large chromatic terms lead to a small MA.

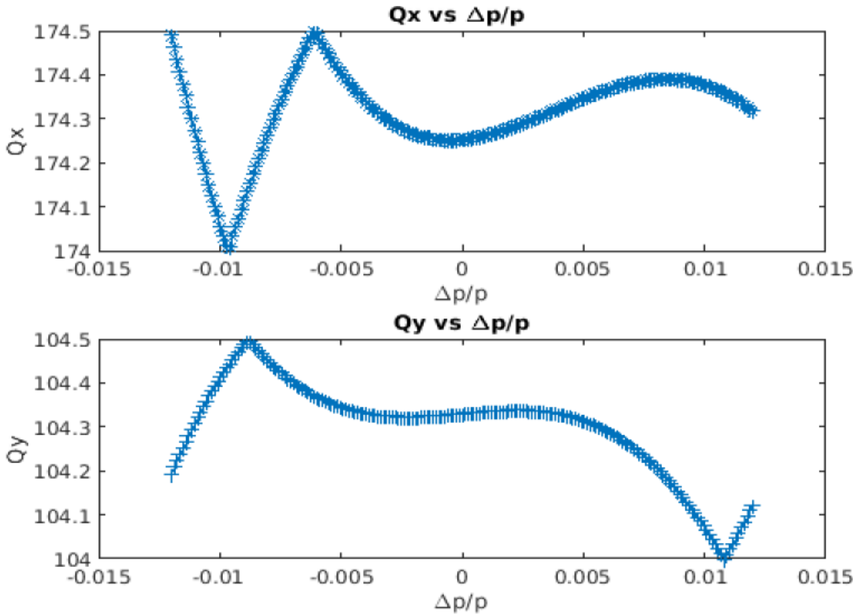
Standard MBA with HOA Cancellation

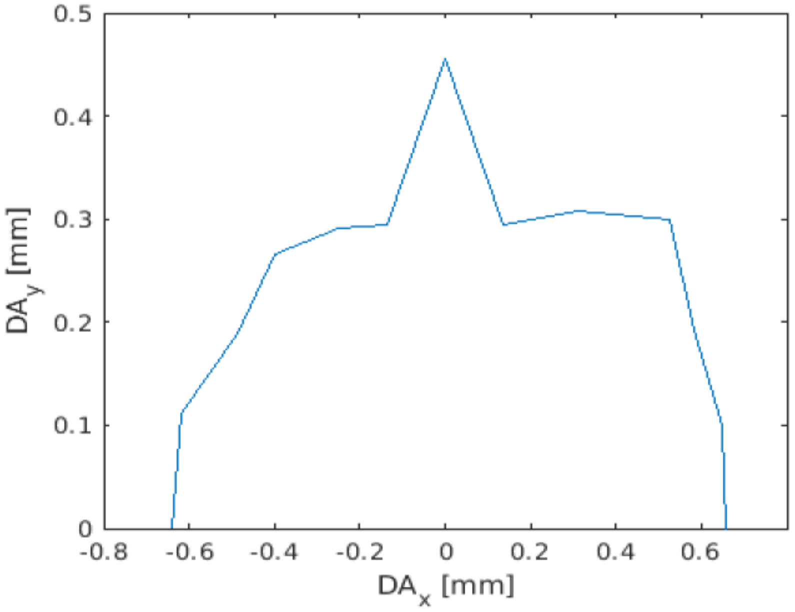


- **Pro**: Lower chromatic terms and a reasonable MA.
- **Con:** Results in a smaller DA.

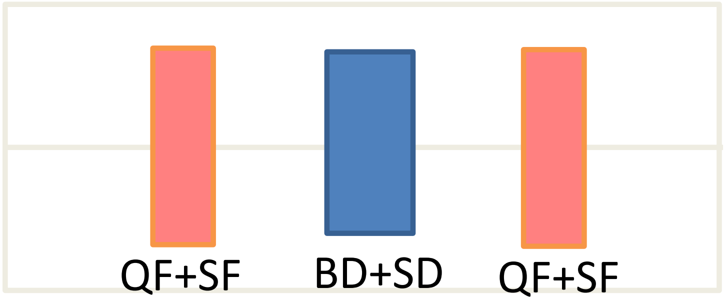


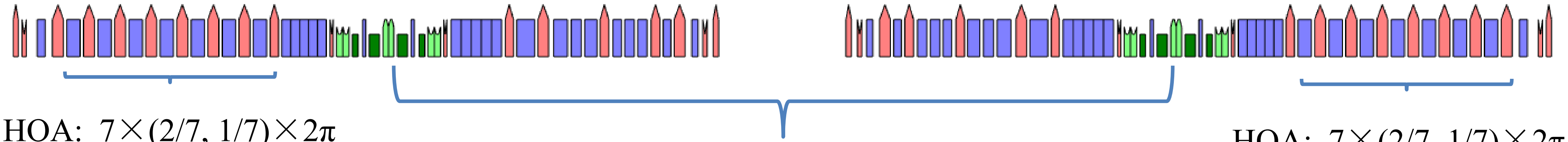
Nonlinear optics optimization (HOA and -*I* cancellation)





- **Unexpected Result:**
  The combined approach did not yield better nonlinear acceptance. Instead, it highlighted the weaknesses of each method in canceling nonlinear terms.



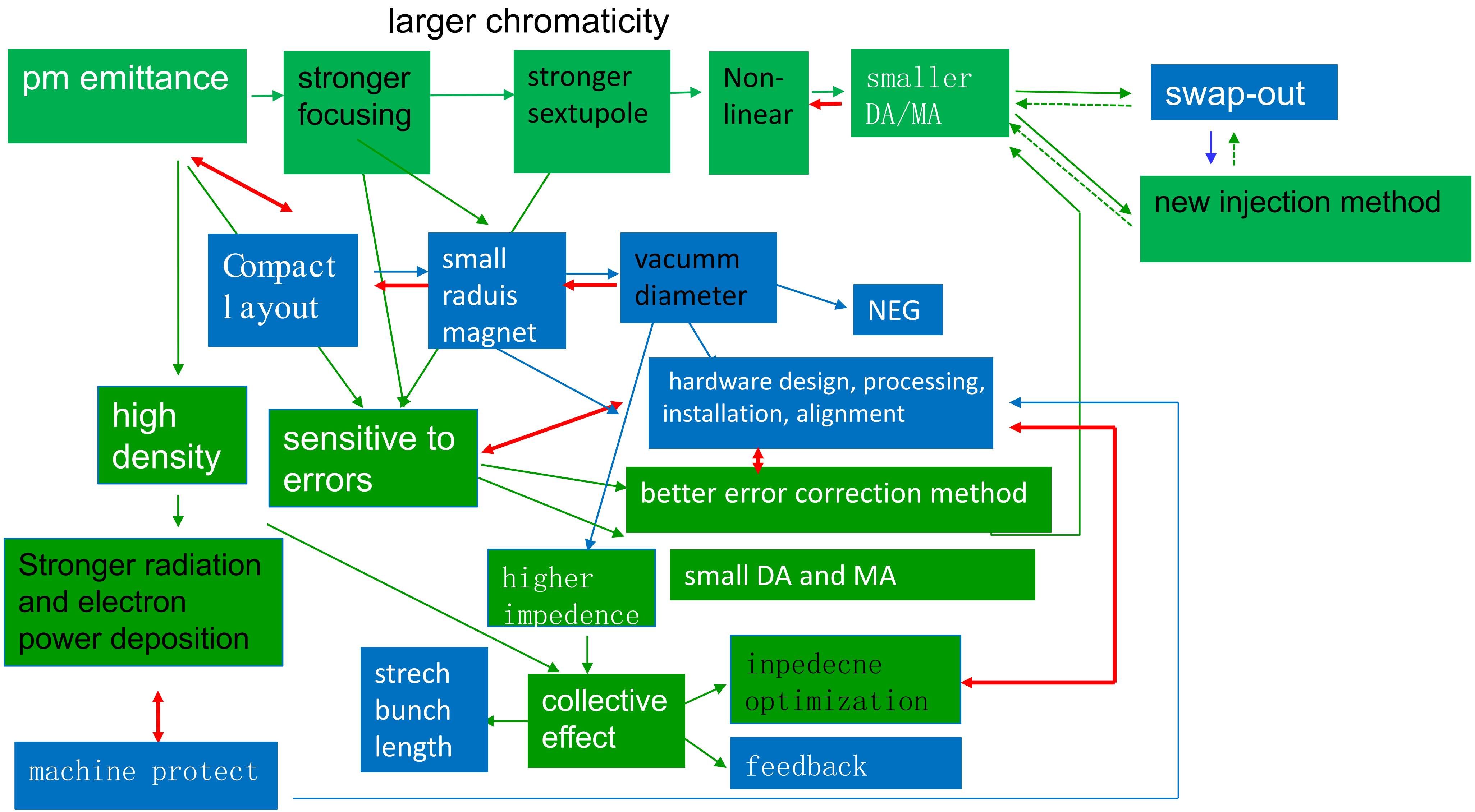


HOA: 7×(2/7, 1/7)×2π

-*I* cancellation

HOA: 7×(2/7, 1/7)×2π

Challenges


larger chromaticity
pm emittance
stronger focusing
stronger sextupole
Non-linear
smaller DA/MA
swap-out
new injection method
Compact layout
small raduis magnet
vacumm diameter
NEG
high density
sensitive to errors
hardware design, processing, installation, alignment
better error correction method
Stronger radiation and electron power deposition
higher impedence
small DA and MA
strech bunch length
collective effect
inpedecne optimization
feedback
machine protect

Summary

- Our novel concept successfully pushes emittance to the pm-level in a compact ring, meeting hard X-ray requirements under IBS.
- This comes at the cost of intense nonlinearities. Current combinations of two cancellation techniques (HOA & -*I*) are inadequate, failing to improve performance.
- Breaking this nonlinearity barrier demands the exploration of entirely new suppression methods.
- Further optimization and exploration are still under way and never ends.

Thank you for your attention !